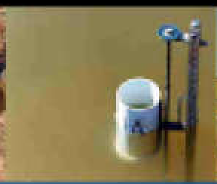
Open Channel Seepage & Control - Vol 1.3 Documentation of Seepage Measurement Trials

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January 2003

AUSTRALIAN NATIONAL
COMMITTEE ON IRRIGATION
AND DRAINAGE

Foreword

In response to concerns over the lack of information available on seepage from open channel supply systems, in October, 1998, the Australian National Committee on Irrigation and Drainage (ANCID) conducted a two-day workshop. The workshop was held at Moama in southern New South Wales and had major support from the Murray Darling Basin Commission, Land and Water Australia, the Commonwealth Department of Primary Industries and Energy and 16 other industry organisations. The workshop brought together 90 stakeholders and experts in the field of channel seepage from throughout Australia.

The key outcomes from the workshop were a suite of recommendations seeking new and extensive investigations aimed at improving the level of knowledge about channel seepage.

In response to the recommendations, ANCID formed an industry Task Force to advance the investigations. It has developed a three-stage project designed to implement the recommendations.

Each stage of the project is briefly described as follows:

Stage 1 *This project will investigate best practice, easy to use standards to be used in identifying, measuring and quantifying channel seepage.*

Stage 2 *This project is aimed at providing best practice procedures and processes involved in undertaking remedial work to seal channels suffering from seepage.*

Stage 3 *This project is designed to provide an easy to use User Support System needed to assist industry in making decisions on whether or not to undertake what is often very expensive remedial works on seeping channels.*

This three-staged project is now well underway and will involve a total expenditure of close to $2.5 million. Stage 1 has now been completed and Stages 2 and 3 are scheduled for completion in December, 2003.

The major outcomes from each of the Stages of the project work will be in the form of reports and Best Practice Guidelines Manuals. This report is one of the suite arising from the project. It documents all of the field trials undertaken in Stage 1 of the project, and provides the technical underpinning for the Stage 1 Best Practice Guidelines Manual.

I would like to also acknowledge the significant support and funding provided to this project by the Murray Darling Basin Commission, Land and Water Australia and several rural water authorities and natural resource management agencies. Without their valued support and interest, the project and this report would not have been possible.

Stephen Mills
Chairman
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This report is one in a series detailing the outcomes of a three-stage project investigating the measurement, remediation and associated decision making for channel seepage.

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Sunwater, Queensland
Goulburn-Murray Water
Land and Water Australia
Murray Irrigation
Murrumbidgee Irrigation
Southern Rural Water
Wimmera Mallee Water

There has also been wide interest in this study and significant input has been provided by a wide and diversified range of interested people for which ANCID is very appreciative.

This document has been prepared on behalf of ANCID by Sinclair Knight Merz Pty Ltd.

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Executive Summary

E.1 Introduction

As the driest inhabited country in the world, Australia is dependent on its water resources. One of the main mechanisms for the transport and delivery of water is via earthen channels. Recent surveys have indicated that around 4% of the total water supplied for rural use is lost due to channel seepage (ANCID, 2000b). Seepage from earthen channels has therefore become an important issue in Australia for several reasons, including the loss of an economically valuable resource and the contribution of seepage water to land degradation issues such as salinity and waterlogging.

The Australian National Committee of Irrigation and Drainage (ANCID), in conjunction with the Murray Darling Basin Commission (MDBC), initiated a three-stage project to provide best practice information on channel seepage measurement (Stage 1) and remediation (Stage 2) and to develop a suitable user support system (Stage 3). An international literature survey on channel seepage measurement and an Australia wide channel seepage survey of more than 40 rural water authorities have been conducted as part of the Stage 1 investigation (ANCID, 2000a and ANCID, 2000b). This report documents the three years of field trials which were conducted as part of the Stage 1 investigation.

Based on the Stage 1 trials, literature review and RWA survey, a guidelines manual for channel seepage measurement has also been developed (ANCID, 2003). The guidelines are intended to be for practical use in undertaking channel seepage investigations across the Australian water industry. The guidelines are to be linked to the channel seepage user support system (in progress) which provides a structured management tool for channel managers.

Channel seepage measurement trials were conducted from early 2000 to mid 2002, within Wimmera Mallee Water (WMW), Murray Irrigation Limited (MIL) and Murrumbidgee Irrigation (MI). In addition, results from channel seepage measurement investigations conducted on the Waranga Western Channel (by Goulburn Murray Water) were incorporated into the final year of trials.

E.2 Overview of Trials Conducted

E.2.1 Technique Selection

The main channel seepage measurement techniques referred to in the literature, and those discussed in the literature review (ANCID, 2000a) include:

- Pondage Tests
- Point measurement (channel full and empty)
- Geophysical Techniques
- Groundwater Techniques
- Soil Classification
- Remote Sensing
- Inflow - Outflow
- Mathematical Modelling
- Hydrochemical / Isotopic Mass Balance
- Tracing Leaking Plume

The most important criteria for selecting techniques suitable for channel seepage measurement and identification are cost and accuracy. Significantly, RWAs rank cost as the most significant factor in selecting seepage investigation techniques, with technical accuracy of lesser importance (ANCID, 2000b). This finding was of fundamental importance to the development of the trial program, and was the reason why some techniques were not tried at all and why others became the focus of the program.

Based on the outcomes of the literature review (ANCID, 2000a), the RWA survey (ANCID, 2000b), and consideration of the primary objectives of the study, the trials were focussed on the first six of the techniques listed above. The early trial program covered all of these six techniques. The final year of the program was based on the results from the first two years of trials. In order to maximise the usefulness of the output of the trial program, the final year of trials was focussed on geophysics, which demonstrated the greatest potential for meeting RWA requirements for channel seepage assessment.

E.2.2 Trial Program Summary Table

Table E-1 summarises the trials conducted during the program. Pondage tests were conducted at all sites, as they were the basis on which other techniques were assessed. Drilling was also conducted at all sites in order to identify sub-surface conditions. Remote sensing is included in the table even though trials were not undertaken as part of the study. Available data was assessed but deemed unsuitable for use in the project.

E.2.3 Techniques Not Included in the Trial Program

The following techniques were not included in the trials:

- Inflow-Outflow Tests - These tests are not sufficiently accurate for measuring losses over relatively short sections of channel (ie 1-2km). Over relatively long lengths of channel this is an appropriate technique, and therefore the technique is suitable for identifying and prioritising, at an Authority-wide level, channels which have higher losses compared to others in the system.
- Mathematical Modelling - The intensity of data collection and level of specialist input required does not make this method practical for use by RWAs for most channel seepage investigations.
- Hydrochemical Techniques and Tracing of Leakage Plume - The high cost of such trials means they are generally not practical solutions for RWAs.

For additional information on these techniques refer to the Literature Review (ANCID, 2000a) and the Guidelines Manual (ANCID, 2003).

E.2.4 Assessment Methodology

In undertaking these channel seepage investigations, the basic approach adopted was:

- Identification of test site locations;
- Gathering available information on test sites;
- Measuring rates of seepage at test sites using direct measurement techniques - pondage tests were used for this purpose;
- Comparison of the direct measurement technique with indirect techniques; and,

- Extrapolation of results beyond the test zone to interpret seepage distribution - this was applied for techniques which compared favourably with the direct technique.

It is well documented in the literature that while every channel seepage method has certain disadvantages, almost universally pondage tests are regarded as the most accurate method of quantifying seepage (ANCID, 2000a). Therefore the basic method of assessment of the accuracy of each technique adopted in the trial program was by comparison against pondage test data.

E.3 Description of Trial Sites

The seepage investigation sites all lie within the Murray Darling Basin (Figure E-1). The channels investigated were main delivery channels, ranging in capacity from 80 ML/d (Tabbita) to 600 ML/d (Rocklands). With respect to lithology, sites ranged from a clay profile, to a sand profile, as well as sites with rock at or near the surface. Groundwater salinity ranged from moderately fresh to highly saline. Groundwater depths ranged from very shallow (0.5 - 1.5m) to moderately deep (9-10m). Channel dimensions were reasonably similar, with the depth of water at full supply level (FSL) typically 1.5m and wetted perimeters of between 9-16m.

- **Figure E-1 Trial Site Regional Location Map**

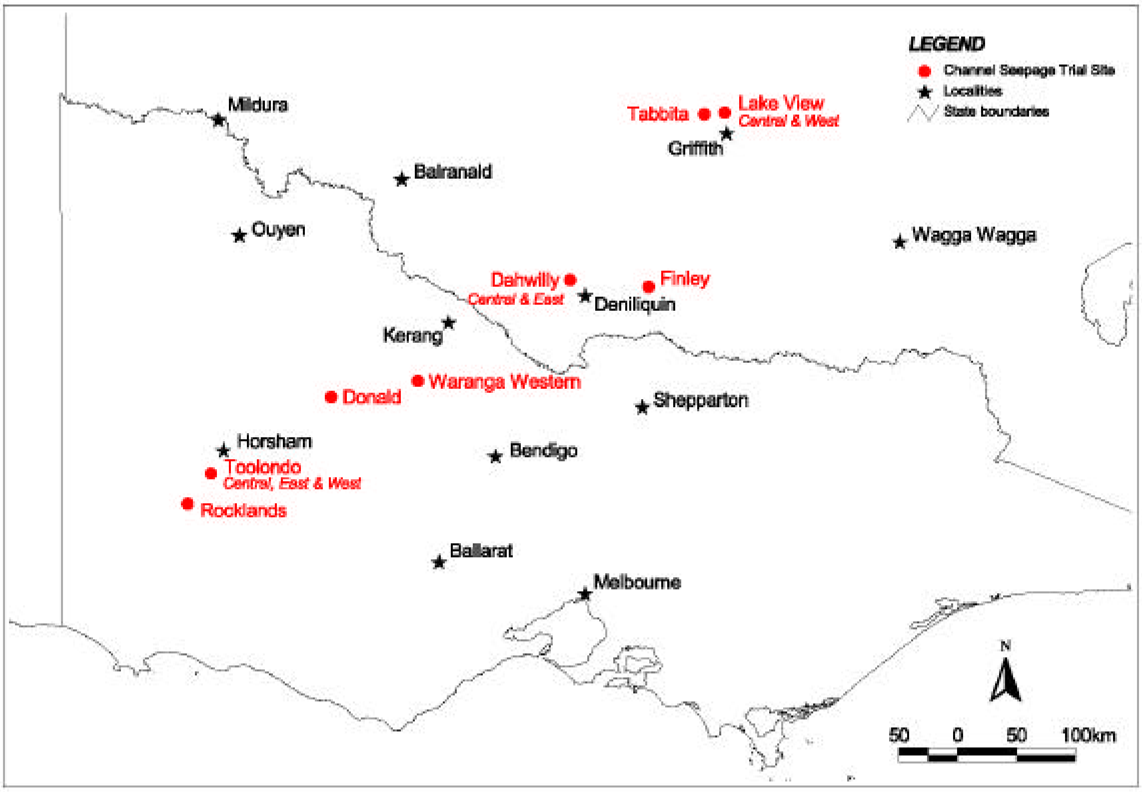


Table E-1 ANCID Channel Seepage Measurement Project - Trials Summary Table

Rural Water Authority	Channel	Technique Date Conducted: Pondage Tests	Geophysics: EM31	Geophysics: EM34 (all land based)	Geophysics: Resistivity (all based on-channel)	Sub-Surface Profiling	Point Tests	Groundwater Techniques	Remote Sensing[1]
Wimmera Mallee Water	Toolondo (Central)	March 01 (6 cells) March 02 (1 cells)	Dec. 00 (land) Aug. 01 (land & boat) March 02 (land)	Aug. 01	March 02	Dec. 00 June 02	Dec. 00 / Jan. 01 (ring infiltrometer & disc permeameter)	-	Sept. 00 ?
	Toolondo (East)	March 02 (4 cells)	March 02 (land)	-	March 02	June 02	-	-	-
	Toolondo (West)	March 02 (4 cells)	March 02 (land)	-	March 02	June 02	-	-	-
	Rocklands	March 01 (6 cells)	Aug. 01 (land & boat)	Nov. 99 Aug. 01	-	Aug. 01	-	-	-
	Donald Main	Dec. 00 (6 cells)	Aug. 01 (land & boat)	Oct. 99 Sept. 01	-	Sept. 01	Oct. 01 (Idaho seepage meter)	Dec. 00 – Aug 01	-
Murray Irrigation[2]	Dahwilly (Central)	June 01 (6 cells) June 02 (7 cells)	June 99 (land) Feb. 02 (land & boat)	Feb. 02	March 02	Nov. 99 May 02	Aug. 00 (ring infiltrometer & disc permeameter) Feb. 01 (Idaho seepage meter)	Aug. 00 – Aug 01	-
	Dahwilly (East)	June 02 (3 cells)	March 02 (land & boat)	-	March 02	May 02	-	-	-
	Finley	July 01 (4 cells) June 02 (3 cells)	July 00 (land) Feb. 02 (land & boat)	-	March 02	July 00 May 02	-	-	-
Murrumbidgee Irrigation[3]	Lake View (Central)	July 01 (6 cells) June 02 (4 cells)	June 00 (land)	-	March 02	Dec. 00 May 02	-	Aug. 00 – Aug 02	-
	Lake View (West)	June 02 (4 cells)	May 02 (land)	-	March 02	June 02	-	-	-
	Tabbita	June 01 (6 cells)	July 00 (land)	-	-	July 00 May 02	July 01 (ring infiltrometer)	Aug. 00 – Aug 01	-
Goulburn Murray Water	Waranga Western	May/June 02 (12 cells)	Nov. 01 (land & boat)	-	-	Nov 01 March 02	-	-	-

1. Available remote sensing data for the Wimmera was assessed but deemed not suitable for use in the project. A remote sensing trial was planned for the Wimmera but not conducted due to budget constraints. The process of planning and preparing for this trial is discussed in the report.
2. Murray Irrigation: Deniboota was removed from the trial program (no works were conducted here) due to the remoteness of the site. The Retreat site (Mulwala Canal) was also dropped from the program due to the size of the channel and associated cost of conducting pondage tests (an EM31 survey, soil surveying and bore installation was conducted at Retreat in June - August 2000).
3. Murrumbidgee Irrigation: Mirrool Creek Branch Canal was removed from the trial program (no works were conducted here)

E.4 Pondage Tests

Pondage tests involve blocking a section of channel for a period and applying a water balance to determine the seepage losses. They are widely considered the most accurate means of channel seepage assessment and were the baseline technique against which other techniques were assessed. Pondage tests were therefore conducted across all sites, totalling 81 ponds. Seepage rates ranged from 0.1 mm/d to 48 mm/d. The average and median seepage rate across all sites was 9.7 mm/d and 7.0 mm/d respectively. Some sites anticipated to have high seepage rates actually contained low rates, while others expected to have low rates were found to have a high rate of seepage. Visible evidence of seepage was found to not necessarily imply high seepage rates. At sites where pondage tests were repeated, a good degree of repeatability was observed; the maximum difference between rates was 25%, with differences attributed to changes in depth to watertable and channel bed properties.

E.5 Sub-surface Characterisation

Sub-surface characterisation was conducted to assist in general site characterisation as well as to assist in geophysical interpretation. An attempt to estimate seepage based on average soil permeability yielded no clear relationship between soil permeability and seepage rate. The absence of a relationship was attributed to limitations inherent in the method adopted (in particular the inadequate sampling density and the process of assigning permeability to soil type), and the fact that in many of the channels studied, factors apart from soil type are the primary control on seepage, including bank dominated seepage and the influence of surface clogging layers. The density of sampling and permeability testing required, in addition to the fact that soil type is not always the factor controlling seepage, means that sub-surface characterisation is not likely to be either an accurate or cost effective means of seepage quantification. However, it remains a critical part of the site characterisation phase of a channel seepage investigation.

E.6 Point Tests

Five point test trials were conducted during the investigation, using ring infiltrometers, disc permeameters and Idaho seepage meters. These trials confirmed that point tests are generally not reliable for directly quantifying seepage. Due to variable and sometimes erratic values obtained in measurements, a large number of tests are required to sufficiently determine the true seepage rate of a section of channel. Therefore point tests are generally not considered reliable for absolute quantitative purposes and should generally be limited to determining the distribution of seepage losses (ie, relative seepage). Even for this purpose a large number of tests are recommended to minimise the effects of local variability. The Idaho seepage meter appeared to provide the most reliable results of the three instruments, probably reflecting the fact that the channel is full during the test and that truly saturated flow is being measured.

E.7 Groundwater Techniques

Quantitative analysis of seepage rates was conducted on the Donald Main Channel based on changes in groundwater level before and after channel filling. Qualitative assessment only was conducted on the Tabbita site. Groundwater levels at the Donald Main Channel were used to estimate seepage using analytical equations and seepage estimates approximately equal to pondage test seepage were obtained, depending on the input aquifer hydraulic conductivity used. Therefore, use of groundwater bores for quantitative analysis of seepage is not considered accurate or cost effective for typical RWA channel seepage investigations, due to the sensitivity of the mathematical solution to hydraulic conductivity inputs and the cost of obtaining sufficiently reliable estimates. In addition, bores are essentially a type of point test and as such do not address the question of where the channel is seeping. A high density of bore transects would be required for meaningful identification of local areas of seepage.

However, groundwater observation bores are a very valuable part of the site characterisation phase of a channel seepage investigation. Further, groundwater bores are a very useful post-remediation assessment tool, particularly for assessing the effectiveness of remediation on reducing near channel land degradation. Where land degradation issues are a significant driver in a channel seepage investigation, groundwater bores are likely to form a key investigative tool, although as discussed above should not be relied upon to provide an accurate quantitative analysis.

E.8 Remote Sensing

A remote sensing investigation was planned as part of the trials but was eventually not undertaken due to budget constraints. Based on the literature review and preparation of the brief for the proposed trials, it is concluded that remote sensing techniques:

- Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage. It should not be used where the seepage mechanism is predominantly vertical;
- Will be most useful where lateral seepage is predominant. For example, sites with a high watertable, shallow impermeable layer or bank seepage are likely to facilitate lateral seepage and cause seepage to have a surface expression;
- Should primarily be regarded as a seepage identification tool and not for seepage quantification purposes;
- Require a suitable spatial resolution to allow definition of seepage zones. Ground resolutions of less than 10 m are suggested;
- Are best conducted in the infra-red range of the electromagnetic spectrum, as this area of the spectrum is strongly absorbed by water and will be able to most clearly separate areas of varying soil moisture and plant water and growth status; and,
- Are generally best collected during late summer and early autumn when surrounding areas (apart from irrigation) will be distinctly drier.

E.9 Geophysics

E.9.1 General Conclusions

Seepage Detection Mechanisms

Geophysical techniques applied to seepage measurement primarily depend upon measuring a contrast in terrain conductivity (or resistivity) in the sub surface profile around the channel. They can be used in one of two ways:

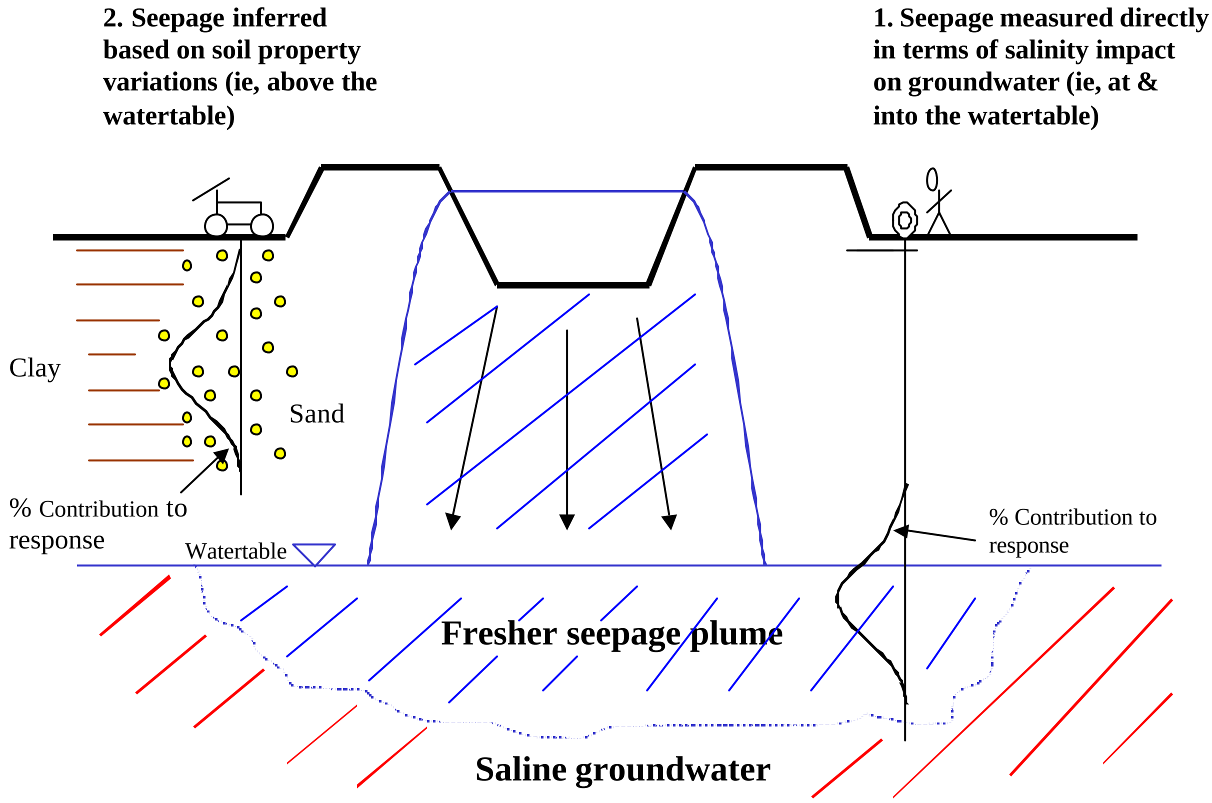
1) Directly measuring the conductivity of the groundwater, and identifying the conductivity contrast of fresher channel water as it seeps into and dilutes saltier

native groundwater. Decreasing the salinity of the groundwater will cause a decrease in electrical conductivity (or an increase in its inverse, resistivity).

2) Identifying contrasts in soil properties and inferring the likelihood of seepage through more permeable materials in the zone above the watertable. Formations more likely to allow seepage, such as sands, are naturally lower in conductivity (higher in resistivity) due to lower porosity and lower cation exchange capacity than tighter clay dominated formations. In addition the higher permeability of such formations leads to better drainage and lower salt content, further reducing conductivity. The magnitude of seepage is assumed to be related to unsaturated zone soil properties beneath or adjacent to the channel.

Figure E-2 visually depicts how these two different approaches can be used to identify or infer seepage.

- **Figure E-2 Comparison of how geophysical techniques can be used to identify channel seepage (LHS - inferred from soil property variations, RHS - direct measurement of salinity impact on watertable)**



Technically the second method of ‘detection’ is not really detection, but the magnitude of seepage is assumed to be related to unsaturated zone soil properties. In many cases this is a reasonable assumption, supported by the fact that the inferred method of detection was successful at most, but not all sites investigated in the trials. The unsaturated zone is not necessarily the controlling influence on seepage, and particularly in Australian conditions seepage is often controlled by a clogging (silt) layer. Therefore, there is less risk in using the direct method of seepage detection. The direct method of detection cannot be used in relatively non-saline groundwater environments, as the fresh seepage water will not contrast with the native groundwater. As a guide it is recommended that groundwater salinity is at least three to four times higher than the channel water salinity. Background variations in groundwater salinity along the channel will affect the results of direct seepage detection and will need to be allowed for during interpretation.

It is very important that the depth to watertable is known at the site before selecting a geophysical technique. Based on this information a decision can be made as to whether direct or inferred measurement will be undertaken and hence the technique that will be adopted.

Comparison of Trialed Geophysical Techniques

The following have been identified as key criteria against which geophysical techniques should be compared:

- Accuracy
- Cost and Speed
- Availability of Operators
- Data Processing

The three geophysical techniques trialed in this investigation (EM31, EM34 and resistivity) are discussed in terms of each of these criteria.

Accuracy

The accuracy of a given geophysical technique will depend on whether inferred or direct seepage detection is used. Generally direct measurement should be considered more reliable than inferred measurement. For direct measurement the accuracy will depend on how well the watertable is targeted. Therefore in theory on-channel resistivity surveying should be the most accurate geophysical technique, as it is based on direct seepage detection and can target the watertable independent of depth. At most sites in the trials resistivity surveying results were comparable to EM31 and EM34, and at three sites correlations with pondage tests were better than the EM correlations.

The fundamental limitation with all EM surveys and other such fixed array type geophysical surveys is that the result is averaged over a specific depth interval, which may not be the critical interval of interest. Therefore (for direct detection) the accuracy depends on how well the watertable is targeted by the particular EM equipment, which in turn depends on the watertable depth. If the correct EM equipment is selected to suit the watertable depth, in theory it should be close to the accuracy of resistivity surveying.

The robustness of EM31, as demonstrated by the consistent results in the trials is due to its relatively shallow depth focus (1-4m). For channels where there is a shallow watertable (eg, surface to 3-4m), EM31 can be used for direct measurement of seepage, which as discussed above is likely to be more reliable. When the watertable is deep, EM31 infers seepage from near surface soil properties, which is suitably accurate in most instances.

Cost and Speed
EM31 surveys are the cheapest geophysical method, due to the speed of data acquisition; EM34 is more expensive as two people are required for operation and the equipment must be carried by hand. Resistivity surveying costs are difficult to quantify given that the on-channel application of the technique is relatively new. Costs are likely to come down as the technique is refined.

Availability of Operators
A number of commercial EM34 and EM31 contractors are in operation in South East Australia. At present on-channel resistivity surveying is still in a development phase and as such there are no commercially operating contractors who specialise in this type of survey, but a number of geophysical exploration / surveying companies have the capability to develop this type of equipment.

Data Processing
Data processing requirements for EM31 and EM34 surveying are minimal. By comparison, data processing requirements for resistivity surveying are much higher, due to the cost of inverting the data to produce a resistivity cross section.

Critical Geophysical Survey Variables

- *Survey timing* – If direct measurement of seepage is used, the survey must be conducted while the channel is running (preferably for at least several weeks), however if seepage is being inferred from soil properties then the timing of the survey is not critical and can be conducted whether the channel is running or empty.

  On-channel versus on-land – Further work is required in this area, but overall in the trials the most consistent results were returned on-land and this is considered the safest option. Evidence collected in this investigation suggests on-channel EM31 surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. Resistivity surveys however, can (and should) be conducted on-channel because of their greater depth penetration capacity.

- *Off-set distance and location for on-land surveys* – The evidence collected in these surveys indicates the best off-set distance for on-land surveys is immediately adjacent the outside toe of the channel.

Repeatability

Generally a high degree of repeatability was observed between duplicate surveys. At two sites where there was a significant difference in the results, changes in groundwater conditions due to channel operation accounted for the observed differences.

Regional Assessment of Key Relationships

For all of the sites used in the final year of analysis, multiple and simple linear regression was undertaken to look for potential regional correlations between seepage rates and geophysical response (for both EM31 and resistivity). The multi-variate regression analysis indicated that, apart from the geophysical response, depth to watertable was the next most significant explanatory variable.

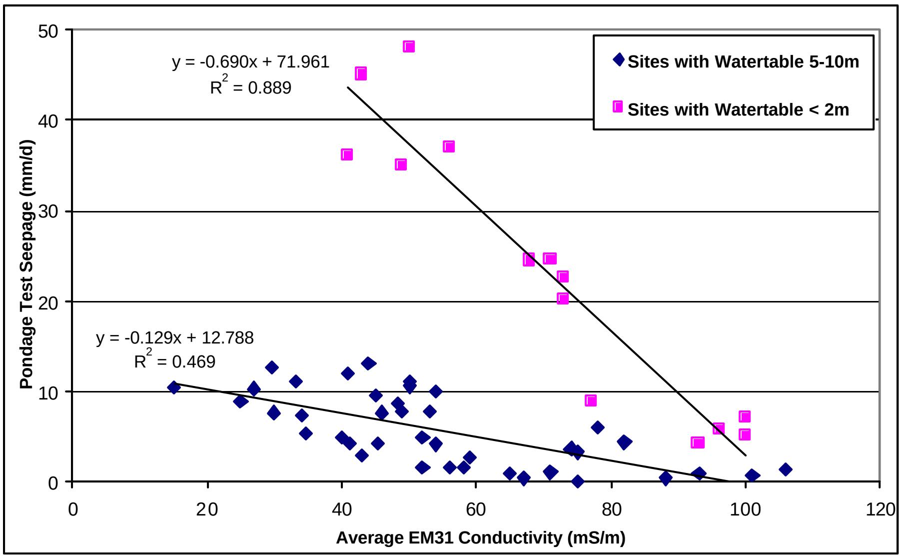
Based on distinct trends between sites with shallow and deeper watertables, the sites were split into two data sets based on depth to watertable, in order to improve the accuracy of the fitted regression model. This is most clearly illustrated in Figure E-3, which shows EM31 data for all sites divided into two categories based on depth to watertable. For sites with a deep watertable (5-10m below surface) the permeability of the top 2m of the profile was shown to be an explanatory variable of secondary importance.

Statistically the regional fitted regression models were generally moderate to good, with correlation coefficients of around 0.5 – 0.6 and standard error of estimates of around 50%. In some cases a higher correlation coefficient and relatively low standard estimate of error was obtained, however this was for data sets with fewer data points – greater number of points are required to improve confidence in these models. Confidence intervals (80% and 90%) for the regression lines were generally fairly broad, indicating that these regional equations can only be used to broadly classify seepage rates (eg, into low, medium and high categories). Consequently it is recommended that there is currently insufficient confidence in these regression equations for their use to predict seepage at new sites without local calibration against pondage tests.

In most instances the multi-variate analysis did not significantly improve the regression model. The addition of the soil permeability parameter (for sites with a deep watertable), while statistically significant, generally only resulted in marginal improvements to the model. The cost of field tests to collect this data therefore probably outweighs the benefits.

For the resistivity analysis, the ten metre depth slice was adopted as the variable for use in the model. While a more accurate analysis could be conducted using the depth at and just below the watertable, for the purpose of a consistent approach, this depth slice was selected. It is likely the analysis could be significantly improved by using resistivity data at and immediately below the watertable for each of the sites.

■ **Figure E-3 Regional EM31 Assessment: Pondage Test Seepage Versus EM31 Conductivity with Sites Divided Based on Depth to Watertable**



Confidence in Derived Relationships and Extrapolation of Results

Two key issues regarding relationships derived between channel seepage and geophysical response need to be assessed:

1. *What confidence is there that the derived relationship accurately describes seepage within the area tested*? - Confidence in the derived seepage-geophysical relationship within the area tested can be assessed by a number of statistical indicators, including: the correlation coefficient, standard error of estimate, and prediction interval. The number of data points and seepage rate range represented should also be considered.
2. *How confidently can the relationship be used outside of the area tested in order to predict seepage*? - When extrapolating a geophysical-seepage relationship outside of an area from which it was developed, firstly the strength of the original relationship needs to be assessed (refer above). Secondly, the representativeness of the new area in comparison to the conditions where the relationship was derived should be evaluated.

Preferred Methodology

Based on the trials conducted in this investigation, and the methodology outlined in the guidelines (ANCID, 2003) the following methodology for using geophysics to identify and measure seepage is recommended:

1. *Define project objective* – The key issue that needs to be addressed is identification of the primary reason the work is being undertaken.
2. *Collate Site Data* – Basic site information including depth to groundwater, groundwater salinity, soil type and channel hydraulics should be collated at the testing site and over the area the results are to be extrapolated.
3. *Evaluate Site Data* - This should be at a level to enable development of a first cut conceptual model of the seepage mechanism, to detect where parameter changes may impact on geophysical response, and to assist in technique selection.
4. *Select Technique* - The preferred geophysical seepage measurement technique is one that directly detects the impact of seepage on the groundwater. To do this it must have a depth focus on and immediately below the watertable. The recommended technique for a given depth to watertable, for both direct and inferred detection, is outlined below:

Direct Detection

- *Shallow watertable* (surface to approximately 5m): *EM31* is recommended.
- *Watertable deeper than 5m: EM34* (in vertical dipole mode, with the coil spacing dependent on the depth to watertable) or on-channel *resistivity* can be used. However, particularly for deeper watertables, it is easier to focus on a given depth using resistivity.

Note that direct detection requires native groundwater salinity to be at least three to four times more saline than channel water salinity.

Inferred 'Detection'

- *EM31* (vertical dipole) adjacent the channel can be used effectively in areas with deeper watertables to infer seepage based on upper soil layer properties.

A decision to use EM31 in an area with a deep watertable might be made due to budget constraints, where a potentially slightly lower level of accuracy is considered acceptable, or due to a lack of alternatives (eg, EM34 or resistivity contractors not readily available). It this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes. A more detailed description of preferred geophysical techniques for seepage detection is presented in Table E-2.

5. *Conduct Field Trials*

5a. Conduct geophysical survey – Undertake geophysical survey in section of interest.

5b. Evaluate results – Plot survey results and overlay with known site conditions (soils, hydrogeology, etc). Identify areas of suspected high, low and moderate seepage.

5c. Conduct test drilling – Soil bores should be drilled at appropriate intervals along the section to assist with interpretation of the geophysical survey. Bore locations should be based on the geophysical survey results, and should cover a range of low, moderate, and high conductivity / resistivity response;

5d. Conduct pondage tests – The number of pondage tests will depend on the length of channel surveyed and the variability of conditions along the channel. Pondage tests should be conducted across a range of low, moderate and high conductivity / resistivity sites so as to establish a regression equation which represents the range of geophysical response and should also cover the range of soil types. Individual cells must be conducted over areas of like conductivity / resistivity.

5e. Develop and evaluate the relationship between seepage and geophysical response – This involves plotting average geophysical response against pondage test seepage, removal of outliers as appropriate, fitting of a regression line, statistical analysis to determine the degree of confidence that can be placed in the derived relationship and use of the derived relationship to predict seepage in new areas.

6. Evaluation – Evaluate whether investigation objectives have been met.

E.9.2 Summary of EM34 Results

Good to moderate relationships were obtained between average EM34 conductivity and the corresponding pondage test seepage at most sites. For EM34 at a 10m coil spacing in horizontal mode, the effective depth of penetration is around 6-7m, with a shallow depth focus at around 1-3m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is predominantly via inference based on unsaturated zone soil properties.

The only site where no relationship was observed was at Dahwilly East, which was largely due to the narrow seepage rate range. At the Toolondo Central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence a reasonable trend was observed (a fact reinforced by the success of EM31 at the site). Significantly, the resistivity surveying showed improved correlations compared to the EM34, for the depth slices focussed immediately below the watertable.

■ **Table E-2 Recommended Geophysical Technique for Seepage Detection and Measurement**

Watertable Depth (m)	Recommended Technique [1]	Detection Method [2]	Approximate Depth of Penetration (m) [3]	Depth Focus (m) [4]
Surface to 1.5	EM31 (horizontal dipole)[5]	Direct watertable impact	3	0 - 1
1.5 – 5	EM31 (vertical dipole)[5]	Direct watertable impact	6	1 – 3.5
5 – 12	EM34 – 10m coil spacing (vertical dipole)[6]	Direct watertable impact	15	3 - 10
	OR			
	Resistivity[7, 9]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5
12 – 25	EM34 – 20m coil spacing (vertical dipole)[6]	Direct watertable impact	30	6 - 20
	OR			
	Resistivity[7, 9]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5
> 25	Resistivity[9]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5

1. It is recommended EM techniques are conducted adjacent the channel (additional survey runs can be conducted away from channel). Resistivity surveys should be conducted on-channel.
2. Direct detection of seepage impacts on the watertable is the recommended technique, but inferred 'detection' based on soil property variations will often provide an adequate simulation and may be more convenient for various reasons - refer to body of report for potential errors associated with this method. Note that direct detection relies on a salinity contrast between the channel water and the groundwater. It is recommended the groundwater should be at least 3 to 4 times more saline than the channel water, a condition usually met in Australian conditions.
3. Approximate detection of penetration: referred to in the Geonics manual (McNeil, 1980) as the effective depth of exploration. This is the depth to which approx. 75% of response is attributed.
4. The 'depth focus' is a term used in this report to describe the depth (range) which is most influential in terms of the relative contribution to the overall EM response (McNeil,1980).
5. These can be conducted immediately adjacent to the channel or on-channel. Both are recommended if budget allows. If on-channel is used for a watertable of 0-1.5m, the survey should preferentially collect data in vertical dipole mode where the effects of channel water will be less influential. For sites with a watertable 0-1.5m, EM31 on channel may be preferred if significant land salinisation exists adjacent the channel.
6. Horizontal and Vertical Dipole: Note that as applied to EM34, vertical dipole does not refer to the coil orientation with respect to the ground, and is in fact opposite to the coil orientation. In vertical dipole mode the coils should be horizontal to the ground, which is a slower method than horizontal mode where they are held perpendicular to the ground.
7. Resistivity is the preferred direct measurement technique for this depth to watertable but EM34 is provided as a potentially more accessible alternative.
8. This should be conducted immediately adjacent to the channel.
9. This should be conducted on-channel.
10. Penetration depth of resistivity depends on the particular set up (dipole spacing and length).
11. Resistivity surveys measures resistivity at a range of depths intervals within the profile (ie, there is no fixed depth focus).

The Donald site survey was focussed on the saturated zone, however the EM31 survey at the site demonstrated a slightly better relationship with pondage test seepage compared to the EM34, but neither survey differentiated between the higher seeping ponds. The improved correlation is probably attributable to the deeper depth focus of the EM31 compared to the EM34 (10m, vertical dipole configuration).

At the Rocklands and Dahwilly sites, where the penetration depth (EM34 - 10m coil separation, vertical dipole) was just sufficient to reach the watertable (but the focus was above the watertable), the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone worked to provide a reasonable indicator of seepage. However it is significant that at Dahwilly, where resistivity surveying was conducted, an improved relationship was obtained compared to EM34 when the depth slice was focussed immediately below the watertable, where seepage impacts are most discernible.

E.9.3 Summary of EM31 Results

Good relationships were obtained between average EM31 conductivity and the corresponding pondage test seepage at most sites. For EM31 in vertical dipole mode, the effective depth of penetration is around 6-7m, with a mid-range depth focus of about 2 - 4.5m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is largely via inference based on soil properties in the unsaturated zone.

The only site where no relationship was observed was at Tabbita. A number of possible causes for this were identified, but the predominant contributing factor is unknown. At two sites (Rocklands and Lake View Central), the adjacent channel data was used instead of all survey run data away from the channel. This was required to obtain the best relationship, due to the interference effects of trees and rapid mixing of seepage water away from the channel.

At the Toolondo Central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence good trends were observed. The Donald and Lake View site surveys were focussed on the saturated zone, and seepage was detected as it created a conductivity low against higher background conductivity groundwater.

At the Rocklands and Dahwilly sites, where the penetration depth of the EM31 (in vertical dipole) was just sufficient to reach the watertable, the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone combined to provide a reasonable indicator of seepage. However it is significant to note that at Dahwilly, when the channel was not running, no relationship was observed. This suggests seepage impacts in the watertable are the primary detection mechanism at this site, a fact reinforced by the uniform nature of the unsaturated zone lithology at the site. Seepage at Dahwilly is not controlled by the unsaturated zone but by a clogging layer at the base of the channel. Techniques which purely infer seepage from unsaturated zone soil properties will not work at such sites (including remediated or lined channels).

At Waranga a reasonable relationship was observed, given the distance over which the data forming the relationship was spread. Improvements might be expected using a technique targeting the top of the watertable at this site.

E.9.4 Summary of Resistivity Results

Good relationships were obtained between average resistivity (from depth slices immediately below the watertable) and the corresponding pondage test seepage at most sites, and at three sites correlations were better than the EM results. The two sites where there was no correlation was at Toolondo West and Lake View West. At Toolondo West it appears that the type of sandstone at this site may be dominating the response, however deeper drilling would be required to confirm this interpretation.

The lack of trend at the Lake View West site is probably due to the poor resolution of the resistivity equipment at very shallow depth. This site contains the shallowest watertable across all sites (0.5 - 1m). Improved resolution at shallow depth could relatively easily be improved in future surveys. At Toolondo East also no trend was observed, but this is solely attributed to the very narrow seepage rate range at this site.

E.10 Waranga Western Channel Case Study

It was proposed that the Waranga Western Channel (WWC), an open irrigation channel maintained by Goulburn-Murray Water (G-MW), be upgraded in capacity along approximately 50 km of the channel length. The channel has a well-documented record of existing seepage problems. There was also concern that new seepage paths may be opened up during the upgrading works program. Therefore quantification of sections with existing seepage problems and identification and quantification of sections where new seepage paths might be opened up was required. To this end, geotechnical and geophysical investigations were carried out along the channel, including an EM31 survey coupled with drilling of 128 shallow bores, further geotechnical drilling, involving the drilling of an additional 107 bores, and the conducting of twelve pondage tests.

Initially a combination of the EM31 results and a lithological classification devised for the investigation (based on the amount of clay in the profile) was used to identify sections of channel which were considered to represent ‘very high’ risk areas. It was then recognised that, in addition to the drilling program, pondage tests were required to quantify seepage rates and confirm interpretation of seepage rates based on the geological and EM31 data. Based on the results of the pondage tests, the regression relationship between EM31 and the pondage tests and the drilling program, areas recommended for remediation were finalised. Given the broad confidence intervals in the EM31 – seepage relationship, the EM31 predicted seepage was not used as the sole means of assigning seepage risk but geological data and visual observations were also integrated into the decision making process. The WWC seepage investigation is a good example of the integration of geophysical, geological and pondage test data to determine areas of highest seepage risk.

E.11 Recommendations

This study makes the following recommendations:

- Of the techniques trialed in this investigation, future channel seepage measurement investigations should focus on geophysical techniques, as these have shown the most promise to cost-effectively and relatively accurately quantify channel seepage. Remote sensing trials, however, were not conducted in these investigations. This technique has the potential for rapid assessment of long sections of channel where seepage has a surface expression, and as such deserves carefully planned field trials in Australian conditions. The baseline data collected in this report could be used to assist in calibration of such trials.

- Rural Water Authorities should adopt the preferred technique as outlined in this report (and the Guidelines Manual; ANCID, 2003) for channel seepage measurement investigations. This methodology relies on geophysics to identify seepage, and pondage tests and soil bores to calibrate and interpret the geophysical response.
- A national database be established to record all channel seepage measurement geophysical trials.
- Further study into the best method of establishing a relationship between the geophysical response and seepage rates is required. At present the bulking process of averaging the geophysical response over the entire pondage test area necessarily introduces errors into the geophysical - seepage relationship.
- Further experimental trials to improve the shallow depth resolution of the resistivity equipment are recommended. Investigation into means of reducing resistivity data processing time (and thus costs) are also suggested.
- Exploration of a method which detects seepage by measuring changes from background conditions is recommended. A significant problem encountered in these trials when attempting to extrapolate a relationship from one section of a channel to another, was caused by the fact that the background conditions change along the channel.
- Further testing of the relative merits of on-channel fixed array surveys compared to adjacent channel fixed array surveys are required. The evidence collected in this investigation suggests on-channel (fixed array) surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. However these conclusions are only based on trials at three sites and further work is required to confirm this conclusion.
- A means of calibrating geophysical surveys where pondage tests cannot be conducted needs to be explored.

1. Introduction

1.1 Background

Seepage from earthen channels has become an important issue in Australia for two reasons:
i) The loss of an economically valuable resource; and,
ii) the contribution of seepage water to land degradation issues such as salinity and waterlogging.

In response, the Australian Committee of Irrigation and Drainage (ANCID), in conjunction with the Murray Darling Basin Commission (MDBC) initiated a project to investigate channel seepage measurement. The main objectives of the study were to:

- Assess the current status of channel seepage identification, measurement and quantification techniques;
- Trial and document a range of seepage identification, measurement and quantification techniques; and
- Prepare and publish guidelines on the best practice techniques for identifying, quantifying and monitoring channel seepage.

The first of these objectives was completed through the compilation of a channel seepage literature survey and an Australia wide channel seepage survey of more than 40 rural water authorities (ANCID, 2000a and ANCID, 2000b). Seepage trials were conducted from early 2000 to mid 2002, within the following Rural Water Authorities (RWAs):

- Wimmera Mallee Water (WMW);
- Murray Irrigation Limited (MIL); and
- Murrumbidgee Irrigation (MI).

In addition, results from channel seepage measurement investigations conducted on the Waranga Western Channel (by Goulburn-Murray Water) were incorporated into the final year of trials.

This report summarises the results of the three years of trials. Channel seepage measurement guidelines (ANCID, 2003) were prepared concurrently with this seepage measurement trials report, and are based on the findings of these trials, the literature review and the RWA survey.

The scope and design of the trials were planned by Sinclair Knight Merz, and the trials were carried out by the RWAs. The work was either carried out in-house by the RWAs or sub-contracted, depending on the nature of the trials.

Early in the trials program considerable attention was dedicated to determining how and where the seepage trial programs would be run in each of the Authorities. The importance of ensuring agreement among all key stakeholders as to how the programs were to be designed was important to the success of the entire project. Site visits were carried out at each Authority in February and March 2000. Based on these visits, three sites were selected in each Authority to trial a range of channel seepage techniques:

- Wimmera Mallee Water – Donald Main Channel, Toolondo Channel and Rocklands Channel;
- Murray Irrigation – Dahwilly Main, Deniboota Main and Retreat (Mulwala Canal); and,
- Murrumbidgee Irrigation – Tabbita Channel, Lake View Branch Canal and Mirrool Creek branch canal.

Subsequently, Murray Irrigation removed Deniboota from the list of channels to be trialed (ie. no works were conducted there) due to the remoteness of the site. Finley channel was chosen to replace the Deniboota trial site. In addition, the Retreat site (Mulwala Canal) was also dropped from the trials program due to the size of the channel and associated cost of conducting pondage tests (an EM31 survey was conducted at this site). Murrumbidgee Irrigation also removed Mirrool Creek branch canal from its trials program, choosing to put more resources into assessing the two remaining channels.

The Wimmera Mallee Water channel running season is approximately 6 months out of sync with those of Murray and Murrumbidgee, whose channels generally close for several months in the June-August period. Wimmera Mallee Water's channels supply domestic and stock water to irrigation supplies and are run in the cooler months of the year to save seepage and evaporation losses. As a consequence its channels are often shut down for several months over summer. This led to complications in coordinating some aspects of the trials between Authorities (eg first year pondage tests).

1.2 Content and Scope of this Report

The contents of this report are described below:

- *Section 2 – Overview of Trials Conducted:* Presents a summary of the trial program, describes the process by which the program was developed and the methodology behind assessment of the trials;
- *Section 3 – Trial Sites Description:* Provides a summary description of key factors affecting seepage at each trial site;
- *Section 4 – Non-Geophysical Techniques:* Presents the results of all non-geophysical techniques trialed during the program, including:
    - Pondage Tests
    - Sub-Surface Characterisation
    - Point Tests
    - Groundwater Techniques
    - Remote Sensing
- *Section 5 – Geophysical Techniques:* Presents the results of all geophysical techniques trialed during the program, including:
    - EM34
    - EM31
    - Resistivity Profiling
- *Section 6 – Waranga Western Channel Case Study:* Presents the Waranga Western Channel seepage investigation as a case study of developing the methodology and techniques required in a channel seepage measurement program; and,
- *Section 7 – Conclusions and Recommendations:* Summarises the main findings of the trials and presents key recommendations arising out of the study.Overview of Trials Conducted

2. Overview of Trials Conducted

2.1 Technique Selection

The main seepage measurement techniques referred to in the literature, and those discussed in the literature review (ANCID, 2000a) include:

- Pondage Tests
- Point measurement (channel full and empty)
- Geophysical Techniques
- Groundwater Techniques
- Soil Classification
- Remote Sensing
- Inflow – Outflow
- Mathematical Modelling
- Hydrochemical / Isotopic Mass Balance
- Tracing Leaking Plume

Based on the outcomes of the literature review (ANCID, 2000a), the RWA survey (ANCID, 2000b), and consideration of the primary objectives of the study, the trials were focussed on the first six of these techniques. The early trial program covered the six techniques described above. The final year of the program was based on the results from the first two years of trials. In order to maximise the usefulness of the output of the trial program it was decided that the final year of trials should focus on one technique, which demonstrated the greatest potential for meeting RWA requirements for channel seepage measurement / identification. The technique selected was geophysics. The rationale behind this decision is described in section 5.

The most important criteria for selecting techniques suitable for channel seepage measurement and identification are cost and accuracy. Significantly, RWAs rank cost as the most significant factor in selecting seepage investigation techniques, with technical accuracy of lesser importance (ANCID, 2000b). This finding was of fundamental importance to the development of the trial program, and was the reason why some techniques (eg hydrochemical) were not tried at all in the program and why others became the focus of the program. The trials focused on developing general principles which could be applied to identification and measurement under the operating conditions of the managing water authority.

Technique selection requires consideration of the difference between seepage quantification and seepage identification. For the former, pondage tests are the recognised standard. For identification, visual inspection (and to a lesser degree EM techniques) seem to be the current standard used by RWAs (ANCID, 2000b). The objective of the trial program was to develop other approaches (referring to a single technique or a combination of techniques) that could deliver (a) quantification of channel seepage in either a more cost effective or accurate way than pondage tests and (b) identify seepage in a more accurate or cost effective way than visual inspection. In all cases there is a trade off between cost and accuracy.

2.2 Trial Program Summary Table

Table 2-1 summarises the trials conducted during the program. This table shows that pondage tests were conducted at all sites, as they were the basis on which other techniques were assessed (refer section 2.4). Drilling was also conducted at all sites in order to identify sub-surface conditions. The emphasis placed on geophysics is readily apparent from this table. Remote sensing is included in the table even though trials were not undertaken as part of the study. Available data was assessed but deemed not suitable for use in the project. However due to the significant planning and preparation for the remote sensing trial, sufficient background information was collated and considered worthy of inclusion in this report (refer section 5). Channels which were initially included in the program, but removed for various reasons, are listed at the bottom of the table.

2.3 Techniques Not Included in the Trials Program

The following section briefly describes techniques which were not used in the trials and the reason for their exclusion.

2.3.1 Inflow-Outflow Tests

Inflow-outflow tests were initially included on the list of techniques to be trialed, however investigation into the level of accuracy obtainable using this method led to its exclusion from the program. Measurements using a current meter are, at best, accurate to 2%, i.e. 4% for the two measurements at either end of the section (Thiess, pers. comm., 2000). Typically seepage is only 3 to 4% of flow in a given section, and therefore seepage will not be able to be distinguished from the error bounds of the measurement.

Over a relatively long length of channel this is an appropriate technique, due to the greater volume of water lost to seepage. Therefore the technique is suitable for identifying and prioritising, at an Authority-wide level, channels which have higher losses compared to others in the system. It will not identify where within the section the channel is seeping. The emphasis in this study, however was on relatively short (1-2km) sections of channel and the isolation (including identification and/or measurement) of seepage within those sections.

2.3.2 Mathematical Modelling

Mathematical models are based on the physics of groundwater flow and have been found to yield reliable estimates of channel seepage, when the required field data such as watertable elevations, soil and aquifer characteristics, and the hydraulic conditions under which seepage occurs are collected. Groundwater modelling can simultaneous incorporate a range of factors which affect seepage into the analysis. Modelling is valuable if there is a need to understand the details of the flow mechanisms at particular areas.

The flow system can be simulated and calibrated against variation of water levels in the aquifer with time under changed hydraulic conditions in the channel. This enables an understanding of the way seepage occurs, the factors which affect the seepage entering the groundwater, and the potential consequences of seepage on local land degradation. Similarly the impact of remedial works could be assessed using modelling to test scenarios.

To be effective, there is a need to measure soil hydraulic conductivities, which requires personnel competent in performing hydraulic conductivity tests, soil survey crews, and experienced supervising personnel competent in hydrogeology. The detailed field work required to characterise flow paths and hydrogeological conditions in the vicinity of the channel is likely to involve considerable time and expense and require significant expertise. The intensity of data collection to adequately characterise a reach of channel for modelling purposes generally means that this method is not practical for widespread use by RWAs.

However there are valid reasons for considering numerical modelling in investigations requiring detailed studies. Models offer the potential for an understanding of the mechanisms and rates related to the channel, but they can also take into account the impact of regional land management factors such as irrigation or increased groundwater recharge in areas surrounding the channels. Modelling can therefore be very useful in identifying the benefits of channel management and remedial works within the broader land management framework.

2.3.3 Hydrochemical Techniques and Tracing of Leakage Plume

Hydrochemical / isotopic mass balances and tracing of the leakage plume techniques were on the original list of techniques to be trialed but were eliminated due to the considerable expense involved in conducting these type of trials. The high cost of such trials means they are not going to be practical solutions for RWAs to adopt.

■ **Table 2-1 ANCID Channel Seepage Measurement Project - Trials Summary Table**

Rural Water Authority	Channel	Technique Date Conducted							
		Pondage Tests	Geophysics			Sub-Surface Profiling	Point Tests	Groundwater Techniques	Remote Sensing[1]
			EM31	EM34 (all land based)	Resistivity (all based on-channel)				
Wimmera Mallee Water	Toolondo (Central)	March 01 (6 cells) March 02 (1 cells)	Dec. 00 (land) Aug. 01 (land & boat) March 02 (land)	Aug. 01	March 02	Dec. 00 June 02	Dec. 00 / Jan. 01 (ring infiltrometer & disc permeameter)	-	Sept. 00 ?
	Toolondo (East)	March 02 (4 cells)	March 02 (land)	-	March 02	June 02	-	-	-
	Toolondo (West)	March 02 (4 cells)	March 02 (land)	-	March 02	June 02	-	-	-
	Rocklands	March 01 (6 cells)	Aug. 01 (land & boat)	Nov. 99 Aug. 01	-	Aug. 01	-	-	-
	Donald Main	Dec. 00 (6 cells)	Aug. 01 (land & boat)	Oct. 99 Sept. 01	-	Sept. 01	Oct. 01 (Idaho seepage meter)	Dec. 00 – Aug 01	-
Murray Irrigation[2]	Dahwilly (Central)	June 01 (6 cells) June 02 (7 cells)	June 99 (land) Feb. 02 (land & boat)	Feb. 02	March 02	Nov. 99 May 02	Aug. 00 (ring infiltrometer & disc permeameter) Feb. 01 (Idaho seepage meter)	Aug. 00 – Aug 01	-
	Dahwilly (East)	June 02 (3 cells)	March 02 (land & boat)	-	March 02	May 02	-	-	-
	Finley	July 01 (4 cells) June 02 (3 cells)	July 00 (land) Feb. 02 (land & boat)	-	March 02	July 00 May 02	-	-	-
Murrumbidgee Irrigation[3]	Lake View (Central)	July 01 (6 cells) June 02 (4 cells)	June 00 (land)	-	March 02	Dec. 00 May 02	-	Aug. 00 – Aug 02	-
	Lake View (West)	June 02 (4 cells)	May 02 (land)	-	March 02	June 02	-	-	-
	Tabbita	June 01 (6 cells)	July 00 (land)	-	-	July 00 May 02	July 01 (ring infiltrometer)	Aug. 00 – Aug 01	-
Goulburn Murray Water	Waranga Western	May/June 02 (12 cells)	Nov. 01 (land & boat)	-	-	Nov 01 March 02	-	-	-

1. Available remote sensing data for the Wimmera was assessed but deemed not suitable for use in the project. A remote sensing trial was planned for the Wimmera but not conducted due to budget constraints. The process of planning and preparing for this trial is discussed in the report.

2. Murray Irrigation: Deniboota was removed from the trial program (no works were conducted here) due to the remoteness of the site. The Retreat site (Mulwala Canal) was also dropped from the program due to the size of the channel and associated cost of conducting pondage tests (an EM31 survey, soil surveying and bore installation was conducted at Retreat in June – August 2000).

3. Murrumbidgee Irrigation: Mirrool Creek Branch Canal was removed from the trial program (no works were conducted here)

2.4 Assessment Methodology

In undertaking these channel seepage investigation, the basic approach adopted was:

- Identification of test site locations;
- Gathering available information on test sites;
- Measuring rates of seepage at test sites using direct measurement techniques – pondage tests were used for this purpose (refer to following paragraph);
- Comparison of the direct measurement technique with indirect techniques; and,
- Extrapolation of results beyond the test zone to interpret seepage distribution – this was applied for techniques which compared favourably with the direct technique.

It is well documented in the literature that, while every channel seepage method has certain disadvantages, almost universally pondage tests are regarded as the most accurate method of quantifying seepage (ANCID, 2000a). Therefore the basic method of assessment of the accuracy of each technique adopted in the trial program is by comparison against pondage test data. The method by which the pondage test is used for comparison differs for different forms of data (eg point test data verses essentially continuous output from a geophysical survey) However the pondage test seepage rates are the baseline means of assessment in this study. Therefore when terms such as 'accurate' or 'successful / unsuccessful' are used to describe a technique, this is in comparison to pondage test data which are assumed to be accurate for the purpose of this investigation.

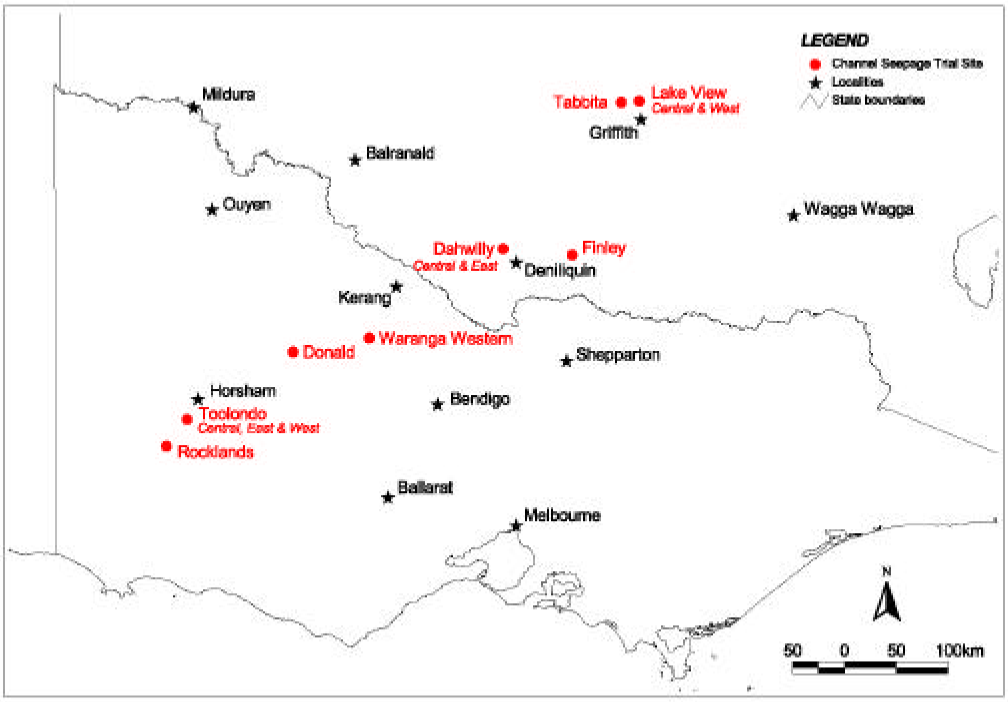
3. Description of Trial Sites

Figure 3-1 presents the location of the channel seepage measurement trial sites. All of the sites lie within the Murray Basin. With the exception of Rocklands and Toolondo channels, which are traverse the flanks of the Grampians ranges, all of the sites are located relatively down-catchment in fluvial and alluvial deposits of sands, silts and clays. All of the channels investigated were main delivery channels, ranging in capacity from 80 ML/d (Tabbita) to 600 ML/d (Rocklands).

Table 3-1, Table 3-2, and Table 3-3 summarises the key characteristics at each of the sites, including soil and geological properties, and channel hydraulic characteristics. Each table represents a separate RWA. Site characteristics for the Waranga Western channel are presented in the case study on this channel, in Section 6.

These tables illustrates the range of conditions across the sites. With respect to lithology, sites ranged from a clay profile (eg Finley), to a sand profile (eg Dahwilly Central), as well as sites with rock at or near the surface (eg Toolondo and Rocklands). Groundwater salinity ranged from moderately fresh (eg 2500 EC at Dahwilly East) to highly saline (eg 30,000 EC at Donald). Groundwater depths ranged from very shallow (eg 0.5 – 1.5m at Lake View) to moderately deep (eg 9-10m at Toolondo). Channel dimensions were reasonably similar, with the depth of water at full supply level (FSL) typically 1.5m and wetted perimeters of between 9-16m.

Figure 3-1 Trial Site Regional Location Map



Appendix A contains geological long sections for each of the sites, based on soil bores drilled along the channel sections (and groundwater bores where available). These sections also present pondage test bank locations and seepage rates and provide an excellent summary of the site geology which is useful to reference while reading the body of the report.

■ **Table 3-1 Wimmera Trial Sites: Summary of Key Characteristics**

Characteristic	Rocklands	Toolondo	Donald
Soil / Geology Surface channel soils Soil / rock beneath & around channel	Has not been assessed but casual observations suggest clayey soils are predominant Predominantly sandy clay in southern half of site overlying sandstone at depth. Sand at 1-2m rising to surface, also in south. Sandstone rises to near surface in northern part of site, underlying shallow clay soils.	Silty sand to medium grained sand of 0.05 – 0.1m thickness overlying a generally stiff clay. **Toolondo Central:** Predominantly clay to sandy clay overlying sandstone varying across the site between 3 – 9m depth. Fine to medium grained sand 1-2m deep located sporadically across site. **Toolondo West:** Surface layer (0.5 - 1m) of weakly cemented fine sand overlying 1-2m of sandy clay, overlying medium clay to 7m, with underlying sandstone **Toolondo East:** Heavy – medium clay to 3-4m, overlying shallow sandstone	Generally over test section: 0-0.1m: Sand – Silty Sand 0.1 – 0.5m: predominantly Clayey Sand (Sandy Clay in part) Surface layer (approx 0.5 - 1m) of clayey sand overlying predominantly clay, but replaced by fine-med. grained sand in southern half of trial site, starting near surface and dropping to 2-3m below surface in the centre of the section
Hydraulic Average depth of water at FSL Average depth to watertable and groundwater salinity Channel Wetted Perimeter at FSL	Approx. 1.6m Exact depth not known. EM31 drilling indicates >4m. Potentiometric contours (SKM, 1995) indicate likely depth to potentiometric surface is in the 5-7m below NS range. Approx. 15-17m range	Approx. 1.5m Exact depth to watertable not known. EM31 drilling indicates >8m. Groundwater bores in area indicate likely to be 9-10m range. Toolondo Central: 14-16m Toolondo West: approx. 14-16m Toolondo East: 13-15m	Approx. 1.4m 1.5-3m, with 1-2m fluctuations adjacent channel due to channel influence Approx. 8 - 10m
Channel Water Salinity	800 EC (µS/cm)	800 EC (µS/cm)	800 EC (µS/cm)

■ **Table 3-2 Murray Irrigation Trial Sites: Summary of Key Characteristics**

Characteristic	Dahwilly	Finley
Soil / Geology Surface channel soils Soil / rock beneath & around channel	Predominantly silty clay, overlain by silty crust (generally 0.05m thick) **Dahwilly Central**: Medium to coarse grained sand to at least 10m depth. Sandy clay to clay loam in top metre along most of channel length **Dahwilly East**: Medium to coarse grained sand to approx 6-8m, underlain by clayey sand. Sandy clay to clay to 1-2 m at surface	Heavy clay to 8-9m, overlying sandy clay.
Hydraulic Typical depth of channel water at FSL Average depth to watertable & groundwater salinity Channel Wetted Perimeter at FSL	Approx. 1.25m Approx. 4-5m Approx. 5000 EC at Central, 2500 EC at East Approx. 8-9m	Approx. 1.5m Approx. 1.5m Approx. 20,000 EC Approx. 9m
Channel Water Salinity	75 EC (µS/cm)	75 EC (µS/cm)

Table 3-3 Murrumbidgee Irrigation Trial Sites: Summary of Key Characteristics

Characteristic	Tabbita	Lake View
Soil / Geology Surface channel soils Soil / rock beneath & around channel	0.1m silty surface crust, underlain by silty grey clay, in turn underlain by a heavy grey clay. Channel walls intersect approximately 0.5m interval of clayey sand. Generally low permeability clays and sandy clays to 7-8m	**Lake View Central** - Sandy clay – sandy clay loam overlying medium to heavy clay starting from between 2-6m below surface **Lake View West** - Surface layer (approx 1m) of sandy clay overlying 3-4m of gravelly clay, overlying medium clay
Hydraulic Average depth of channel water at FSL Average depth to watertable & groundwater salinity Channel Wetted Perimeter at FSL	Approx. 1.25m Approx. 1 - 1.5m Approx. 8000-10000 EC Approx. 8-9m	Approx. 1.5m Approx. 1.5 m at Central, 0.5-1m at West Approx. 6000 EC Approx. 10m
Channel Water Salinity	220 EC (µS/cm)	220 EC (µS/cm)

4. Non-Geophysical Techniques

This section discusses all non-geophysical techniques assessed during the trials program. The following type of trials are covered in this section:

- Pondage tests;
- Sub-surface profiling;
- Point Tests;
- Groundwater techniques;
- Point Tests; and,
- Remote Sensing.

4.1 Pondage Tests

4.1.1 Methodology

Principle
The pondage test method applies a water balance to an isolated reach of channel to determine the seepage losses. Seepage losses constitute the drop in water level over time in the channel after accounting for evaporation and rainfall (and any potential diversions). They are widely considered the most accurate means of measuring channel seepage and generally regarded as the best technique against which other methods can be assessed. Therefore, as discussed in Section 3, pondage tests were used as the baseline measurement technique for the trials, and were conducted at every trial site.

Methodology
In these trials pondage tests were conducted by blocking a section of channel with embankments at each end and filling the section with water up to, or slightly higher than, the level at which it usually flows during operation. Most of the pondage tests were conducted at the end of the irrigation season, and in this situation the banks were generally constructed while the channel was full, as shown in Figure 4-1 (*look for better photo*). To minimise the risk of seepage through the banks, (most) banks were constructed with a plastic liner. All the pondage cells (except for some at Waranga Western Channel) were constructed back to back, to minimise bank construction costs.

Water level decline in the channel was measured by a hook gauge which was read twice daily (morning and afternoon), or daily during some tests. Evaporation was measured using a class A evaporation pan (located on the channel bank) and rainfall with a standard rainfall gauge.

Pondage tests were analysed using a spreadsheet developed for the project. The method of analysis is briefly described below (refer ANCID, 2003 for further detail). The basic equation for calculating seepage losses using the pondage test method is presented below. The method of analysis assumes that the only inflow into the reach is rainfall. Run-off was ignored in the assessment due to the difficulty in estimation. If the channel is positioned to receive run off and there is sufficient rainfall the test could be effected. However, for most tests there was no rainfall, and only a handful of tests received sufficient rainfall to generate run-off.

■ **Figure 4-1 Pondage embankment construction (a) and installation of plastic liner (b)**

a)

b)

The following equation assumes that the only outflows are due to evaporation and seepage (the terms are also depicted in Figure 4-2):

$$S = \frac{W\left[(d_1 - d_2) - E + R\right]}{P(t_2 - t_1)}$$

Where:

S = Seepage rate [volume / area / time]
W = Average surface width between t_1 and t_2 [length]
d_1 = Water level at t_1 (averaged between u/s and d/s gauges) [length]
d_2 = Water level at t_2 (averaged between u/s and d/s gauges) [length]
E = Evaporation along reach between t_1 and t_2 [length]
R = Rainfall along reach between t_1 and t_2 [length]
P = Averaged wetted perimeter between t_1 and t_2 [length]
t_1 = Time at first measurement of water levels [time]
t_2 = Time at subsequent measurement of water levels [time]

Units must be consistent for all terms in the equation.

Pondage test seepage rates are reported in this project in mm/d. However it is very important to note that this is equivalent to a *volume per area per day* ($m^3/m^2/d \div 1000$ which equals mm/d, which is equivalent to $L/m^2/d$). The area in this equation represents the *channel wetted area* and *not* the surface water area, as is sometimes reported in channel seepage studies.

The pondage test results are presented in this report as the seepage rate between each measurement interval during the tests. A typical graph of the pondage test results is presented in Figure 4-2 below. This particular test shows an initially higher seepage rate due to the wetting up of the soil profile and then levelling out to a reasonable steady seepage rate after four to five days. The degree to which this higher rate at the start occurs will be primarily due to the length of time the pond has been saturated prior to the commencement of readings and the filling height prior to testing.

- **Figure 4-2 Components of Pondage Test Water Balance**

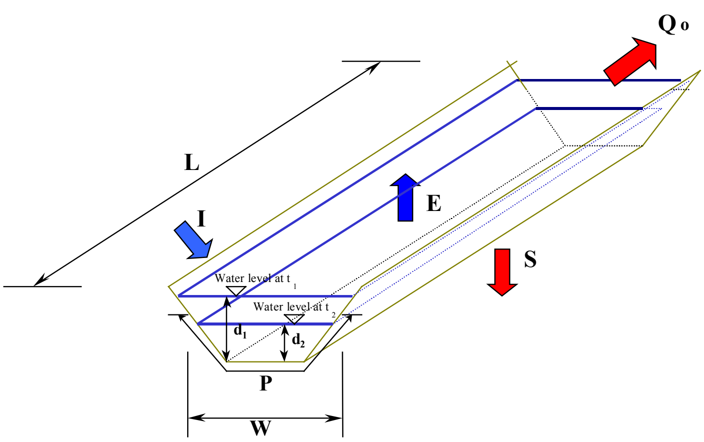
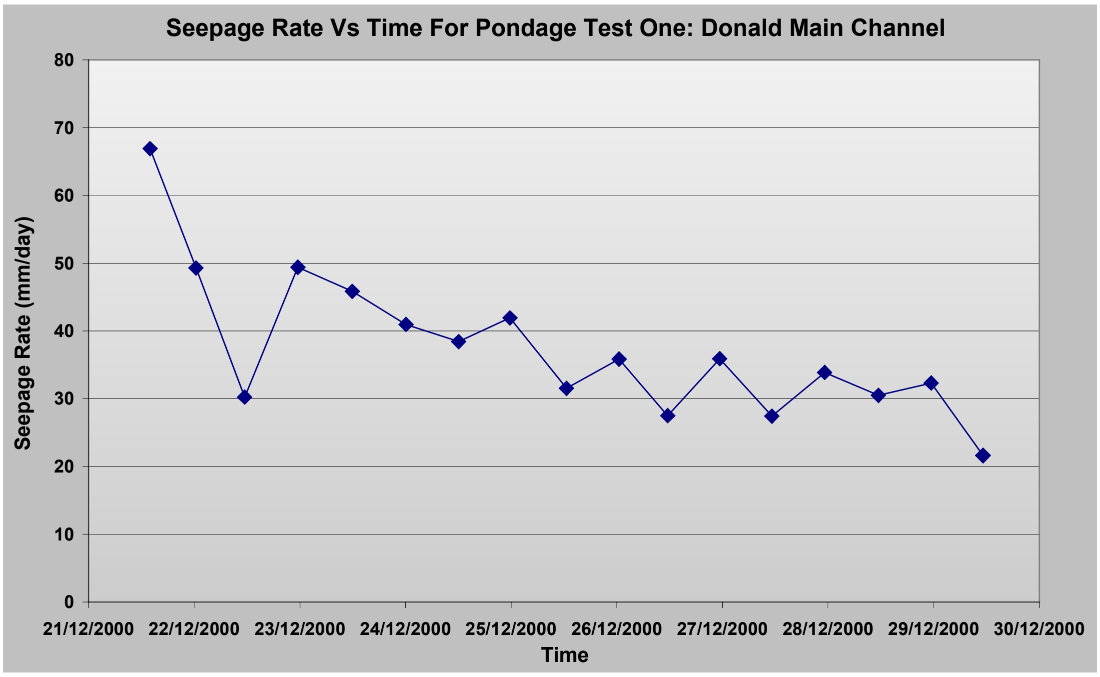


Figure 4-3 represents one of the highest cases of initial loss compared to steady state loss observed during the pondage tests.

■ **Figure 4-3 Example Pondage Test Results**



This figure shows that as well as an overall trend, there are variations between measurements. This variation is in part due to hook gauge reading error, evaporation measurement error and may also be due to diurnal seepage variations [refer p7 of the Literature Review ANCID (2000a) for further details]. The cause of these variations was not be studied in this project. The figure of primary interest in this study is the steady state seepage rate, ignoring daily variations. The actual seepage rate used in the trials is the average seepage rate after any initially high rates or other non-representative conditions (eg heavy rainfall) have subsided or been allowed for. For example, the seepage rate number taken from Figure 4-3 was 32 mm/day. This is the number which will be used for comparison with other techniques and which is presented in the body of this report.

4.1.2 Results

The results of all pondage tests conducted during the trials is summarised in Table 4-1. Graphs of all of the pondage test results are presented in *Appendix* B. Geological long sections in *Appendix* A display pondage test bank locations and corresponding seepage rates for each of the sites.

4.1.3 Discussion

Magnitude of Results

Seepage rates ranged in magnitude across the trials sites from 0.1 mm/d (essentially zero) at the Toolondo East, up to 48 mm/d on the Donald Main Channel. Seepage rates were generally lower than anticipated, particularly given that a number of the trial sites were selected based on suspected high seepage rates.

The average seepage rate across all ponds was 9.7 mm/d (0.0097 $m^3/m^2/d$). However the median rate of 7.0 mm/d (0.007 $m^3/m^2/d$) removes the effect of the high seepage sites and is more representative of typical seepage rates across most of the trial areas. As discussed in the literature review (ANCID 2000a), pondage tests may provide a slight underestimate of seepage rates compared to flowing conditions due to increased clogging effects under no flow conditions.

Some sites which were anticipated to have high seepage rates contained low rates, while other sites which were not expected to have high rates (and were essentially randomly selected from a seepage rate perspective) contained high seepage rates. For example, ponds 1 and 2 at Dahwilly Central (2001 pondage test trials) were expected to have high seepage rates due to the clean, thick sandy profile beneath the channel. However as these ponds were located immediately upstream of a check structure, the silt build up behind the structure caused seepage to be restricted to around 5 mm/d.

Further, on the Waranga Western Channel, a number of seepage sites which had been mapped as 'known seepage sites', due to visible surface evidence of seepage, were actually found to have very low seepage rates (< 3 mm/d) during pondage tests. This demonstrates that high rates are not necessarily required to cause surface seepage effects.

In contrast, the four ponds at Lake View West were not anticipated to have high seepage rates, (there were no surface signs of seepage etc) and therefore the RWA was surprised to find seepage rates of 20 – 25 mm/d at the site. Seepage through a loamy surface material, predominantly through the banks of the channel, is the most likely seepage mechanism at this site.

Visible evidence of seepage does not necessarily imply high seepage rates (this does not necessarily mean that it is not of concern however) and conversely the absence of visible signs of seepage does not mean that significant seepage is not occurring. Even knowledge of soil types and the sub-surface profile does not always translate to an accurate understanding of seepage rates or seepage processes. The pondage tests and assessment of geological and other data help to develop an understanding of the seepage mechanism. The combined data can help to determine if seepage is vertical through the base of the channel or lateral through the banks.

It should also be noted that the seepage rate obtained from pondage test data is a bulk value which represents the average seepage rate over several hundred metres of channel. Obviously within the pond section the actual seepage rate will vary above and below the section average. The degree of variability in the seepage rate will depend on the variability of sub-surface conditions and channel characteristics (particularly the presence / absence and thickness of a silt layer and bank material and construction techniques).

Repeatability
At several sites pondage tests were repeated in the same location, (or at least overlapping), as pondage tests from the previous year. The following comments relate to the repeatability of pondage tests as observed at these sites.

- Toolondo Central – Pond 4 recorded a seepage rate of 10 mm/d during the March 2001 pondage tests at Toolondo Central. In March 2002 a pondage test was conducted within this cell, but in a section slightly shorter than the original cell, in order to straddle an area of suspected higher seepage (based on the EM31 results). The 2002 pondage cell recorded a seepage rate of 12 mm/d, which is essentially what would be expected for this repeat test;

- Finley – Ponds 1-3 at Finley were conducted in exactly the same locations in July 2001 and July 2002. Rates of 5.2, 5.6 and 4.1 mm/d were recorded in the 2001 tests and 7.0, 5.3, and 5.4 mm/d in the 2002 tests, for Ponds 1, 2 and 3 respectively. The difference between the two years is: 1.8, -0.3 and 1.3 mm/d, While these rates are comparable, except for pond 2, rates were slightly higher in 2002. The increase in rates could be explained by a deeper watertable at the site in 2002, creating a steeper discharge gradient.
- Lake View – The four pondage cells conducted in June 2002, covered approximately the same areas as ponds 3-6 in the July 2001 tests, but the bank locations were not the same. The following points summarise the overlap (refer to the Lake View Long Section in *Appendix* A for a visual presentation of the location of these ponds) Suffixes refer to year of pondage tests:
  - $P1_{(02)}$ = 7.1 mm/d coincided with $P3_{(01)}$ = 9.0 mm/d & $P4_{(01)}$ = 7.0 mm/d
  - $P2_{(02)}$ = 5.8 mm/d & $P3_{(02)}$ = 4.3 mm/d coincided with $P5_{(01)}$ = 7.1 mm/d

  Using a weighted average method, a comparison of the two areas is:
  - 7.1 mm/d $_{02}$ vs 8.3 mm/d $_{01}$, and
  - 5.5 mm/d $_{02}$ vs 7.1 mm/d $_{01}$,

  This represents a decrease of 1.2 mm/d and 1.6 mm/d for the 2002 pondage tests, or in term of percentage, 16-23%.

In summary, at the three sites where information is available to compare pondage test results, a reasonable degree of repeatability was observed. Differences of up to 25% in seepage rate were observed between pondage tests conducted in 2001 and 2002. These differences are considered acceptable for the purposes of this investigation, and are not necessarily attributable to error inherent in the pondage test method. Differences of this magnitude could be attributable to changes in site characteristics. The two most likely natural characteristics to change, include:

- Changes in depth to watertable - This will have greater effect at sites with shallow depth to watertable. Apart from the background watertable depth, depth to watertable can change due to seasonal fluctuations as well as channel related fluctuations. Depth to watertable at the time of the pondage test will be related to the length of the time the channel has been running prior to the test or since it had been running prior to the test;
- Changes in channel bed properties – This is most likely to be caused by natural siltation of the channel, which will generally increase over time. Man-made changes such as de-silting of a channel can have dramatic effects on seepage rates.

4.1.4 Conclusions

Pondage tests involve blocking a section of channel for a period and applying a water balance to determine the seepage losses. They are widely considered the most accurate means of channel seepage assessment and were the baseline technique against which other techniques were assessed. Pondage tests were therefore conducted across all sites, totalling 81 ponds.

Seepage rates ranged in magnitude across the sites from 0.1 mm/d (Toolondo East) to 48 mm/d (Donald). The average and median seepage rate across all sites was 9.7 mm/d and 7.0 mm/d respectively. Some sites anticipated to have high seepage rates actually contained low rates (due to surface clogging layer), while others expected to have low rates were found to have a high rate of seepage. Visible evidence of seepage was found to not necessarily imply high seepage rates.

At three sites where pondage tests were repeated, a good degree of repeatability was observed. The maximum difference between seepage rates was 25%. Differences in pondage tests rates from one season to another are probably attributable to changes in depth to watertable and channel bed properties. The differences are considered acceptable for the purposes of this investigation, and not considered to be significantly due to errors in the pondage test method.

Table 4-1 Summary of Pondage Test Results

Rural Water Authority	Channel	Date of Test (no. of cells, test duration)	Seepage Rate Range (mm/d)	Results by Pond (mm/d) (Pond 1, Pond 2 ……)	Comment
Wimmera Mallee Water	Toolondo (Central)	March 01 (6 cells, 13 days)	1 – 11	(11, 11, 3.7, 10, 1.1, 2.8)	High variation in seepage observed in some ponds due to run-off and delayed seepage associated with a relatively large rainfall event on 20th March (20mm)
		March 02 (1 cell, 14 days)	12	(12)	Largely centred over pond 4 in 2001 pondage tests; good repeatability.
	Toolondo (East)	March 02 (4 cells, 14 days)	0 – 1	(0.1, 0.4, 0.4, 0.7)	Very low rates
	Toolondo (West)	March 02 (4 cells, 15 days)	1 – 5	(1, 1.6, 3, 4.9)	
	Rocklands	March 01 (6 cells, 15 days)	4 – 13	(8.7, 11, 13, 5.4, 4.3, 4.3)	High variation in seepage observed in some ponds due to run-off and delayed seepage associated with a relatively large rainfall event on 20th March (20mm)
	Donald Main	Dec. 00 (6 cells, 9 days)	9 – 48	(45, 35, 36, 37, 48, 9)	Mid-range test values were used rather than steady state due to low initial water levels (approx. two-thirds normal supply level)
Murray Irrigation	Dahwilly (Central)	June 01 (6 cells, 14 days)	4 – 16	(4.8, 4.4, 13, 7.6, 12, 16)	First few days excluded from analysis due to erratic behaviour. Low rates in P1 & P2 despite sandy profile, due to silt accumulation upstream of check
		June 02 (7 cells, 15 days)	4 – 10	(4.2, 4.9, 9.5, 7.7, 7.8, <u>1.1, 2.8</u>)	Only P6 & P7 overlap with June 01 tests. P6 & P7 (02) are P1 & P2 (01). These two cells (underlined) were remediated in July 2001, reducing seepage from 4.8 mm/d to 1.1 mm/d and from 4.4 mm/d to 2.8 mm/d.
	Dahwilly (East)	June 02 (3 cells, 22 days)	9 – 10	(10, 10, 9)	Very narrow seepage range
	Finley	July 01 (4 cells, 15 days)	4 – 6	(5.2, 5.6, 4.1, 3.9)	Due to absence of survey data seepage rate calculated based on average gauge drop multiplied by estimate of wetted perimeter to surface water ratio of 1.05
		June 02 (3 cells, 19 days)	5 – 7	(7, 5.3, 5.4)	Ponds 1-3 for 01 and 02 correspond. There is an increase of 0.3-1.8 mm/d compared to 01. Some of difference may be due to lack of survey data in 01 tests.
Murrumbidgee Irrigation	Lake View (Central)	July 01 (6 cells, 7 days)	7 – 9	(9, 9.3, 9, 7, 7.1, 8.5)	Very narrow seepage range
		June 02 (4 cells, 7 days)	4 – 7	(7.1, 5.8, 4.3, 5.2)	Areas between 01 and 02 tests overlap, but banks were in different locations. Approx. 1-2mm higher rates in 01 tests, possibly due to longer drying period?
	Lake View (West)	June 02 (4 cells, 7 days)	20 – 25	(20, 23, 25, 25)	High rates given soil type. Probably due to seepage through top metre of the profile
	Tabbita	June 01 (6 cells, 7 days)	6 – 10	(6.4, 6.0, 9.8, 8.5, 6.2, 6.7)	
Goulburn Murray Water	Waranga Western	May/June 02 (11 cells, 12 days)	1 – 13	(6.1, 3.3, 1, 1.7, 1.4, 1.6 7.7, 7.7, 7.3, 13, 4.4)	Pondage tests were conducted over a large area: P1 was approximately XX km from P11

4.2 Sub-surface Characterisation: Soil and Geological Profiling

4.2.1 Purpose of sub-surface profiling

Sub-surface profiling of soils and geological conditions can be conducted in a channel seepage investigation for various reasons, including:

1) As part of site characterisation, to identify the distribution of zones of higher and lower potential seepage (including preferred pathways);
2) To help define seepage mechanisms; and / or,
3) To assign seepage rates to soil types and hence determine seepage through changes in soil type (this can be conducted at a regional scale, using available soil maps and published data on seepage rates, or at a local scale involving local soil mapping and seepage testing)

In this investigation sub-surface profiling was conducted for the first two reasons. Site characterisation is an important component of any channel seepage investigation and site stratigraphy is probably the most important aspect requiring characterisation. Interpretation of test results of essentially all techniques will be underpinned by the conceptual understanding of the site, and therefore it is important that this is established as accurately as possible.

As the trial program developed and the focus of the investigation became more strongly focussed on geophysics, it was important that the characterisation of the sub-surface was particularly targeted to assist in geophysical interpretation. In addition to information on lithology, geophysical interpretation is assisted by information on soil moisture, depth to watertable and groundwater salinity.

4.2.2 Data collection

Information on the sub-surface was collected via drilling bores. The key issues addressed in developing a drilling program for each site were:

- Where and how many bores to drill;
- What depth to drill to, and,
- What type of drilling to use;
- How to log the drilling.

All of these issues were tightly constrained by cost. The approach adopted in this study is described below:

- *Location and number of bores*: Bores were drilled immediately adjacent the outside toe of the channel banks (or as close as practical to the bank). This coincided with the location of the EM31 and EM34 surveys adjacent the channel bank. While drilling in the channel may also be of assistance to determine the stratigraphy directly beneath the channel, this is generally not practical due to the considerable expense of drilling from a barge or boat. Interpolation between drilling results on either side of the channel, provided by stratigraphic interpretation, is sufficiently accurate.

  The greater variability at the site, the greater the number of bores required to characterise the site. In the final year drilling program (year 3) approximately 12-

14 bores were located along each channel section (300m – 1000m). Bores were usually located in order to cover the range of geophysical responses at the site, as well as in locations representing changes in geophysical response, which potentially represent changes in geology.

- *Depth*: The most influential depth on seepage rates is considered to be the upper profile, particularly the top 2-3 metres. The depth of drilling may be limited by the type of drill rig employed, which in turn may be controlled by cost constraints. The minimum depth of drilling in this study was to 4-5m, which coincides with the approximate penetration depth of EM31. When resistivity surveys were used in the final year of the trials, the drilling was increased to 10m. While the resistivity method employed in these trials 'sees' to approximately 20m, a depth limit of 10m was selected due to budget constraints. At some sites drill refusal was reached before 10m. Approximately every third bore was drilled to 10m, and remaining bores to approximately 7-8m.
- *Type of drilling*: Drilling was generally conducted using solid stem augers. This drilling method causes some disturbance of the samples but even given the sampling limitations, this method was considered suitable for the level of accuracy required for this investigation.

  The trailer mounted drill rig employed at most of the sites for the drilling is shown in Figure 4-4.
- *Logging*: Ideally a geologist or soil scientist should be available to log the bores. One of the most important aspect of logging is consistency which is best achieved by logging to recognised standards (such as the United Soil Classification System or an Australian standard such as the Northcote system). Logging in these trials was based on the Northcote classification system.

  Across the 11 sites, drilling was undertaken by the two EM31 contractors, who each have significant drilling and logging experience. Soil samples at one metre intervals were collected in the third year drilling program to provide a record of drilling and a means of checking on the logging results.

■ **Figure 4-4 Trailer mounted drill rig used for soil bore drilling**

4.2.3 Results

Results of the drilling program are presented in geological long sections of each of the channels are presented (*Appendix* A). To determine whether averaging of soil properties could assist in estimating seepage, average permeabilities were compared with pondage test seepage rates.

Based on the geological long sections, a bulk vertical hydraulic conductivity was calculated for each of the ponds. Hydraulic conductivity was based on text book vertical hydraulic conductivities for the given soil texture. The vertical hydraulic conductivity for each soil type was assigned using published rates based on the Northcote classification system (*Reference, 19XX*). Layered heterogeneity was accounted for using the equation outlined in Freeze and Cherry (1979, p34). For each pond, four different vertical hydraulic conductivities were calculated. These are described below and graphically presented in Figure 4-5:

i) Weighted according to typical EM31 response - most heavily weighted around 1 – 3m depth and terminated at 7m;
ii) Representative of surface permeability and evenly weighting over the top 2m of the profile;
iii) An average across the top 10m of the profile but giving more weight to upper surface layers and less to layers at depth; and,
iv) Evenly weighted across the top 10m of the profile.

Details of the calculations, and an example calculation are provided in *Appendix* C.

■ **Figure 4-5 Cumulative Weighting Applied to Different Soil Permeability Explanatory Variables**

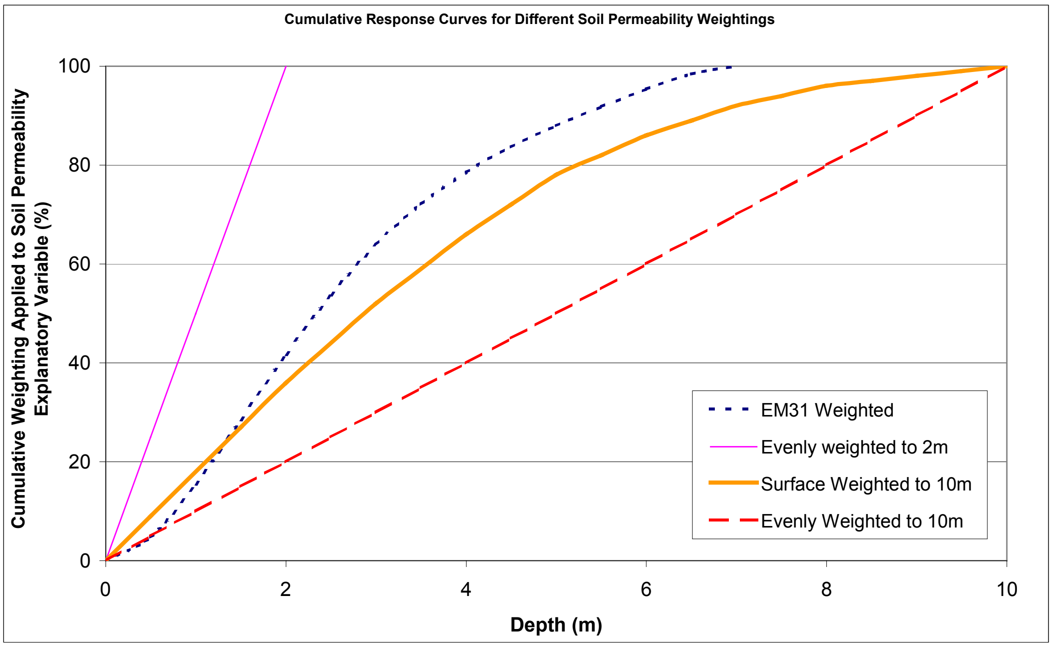
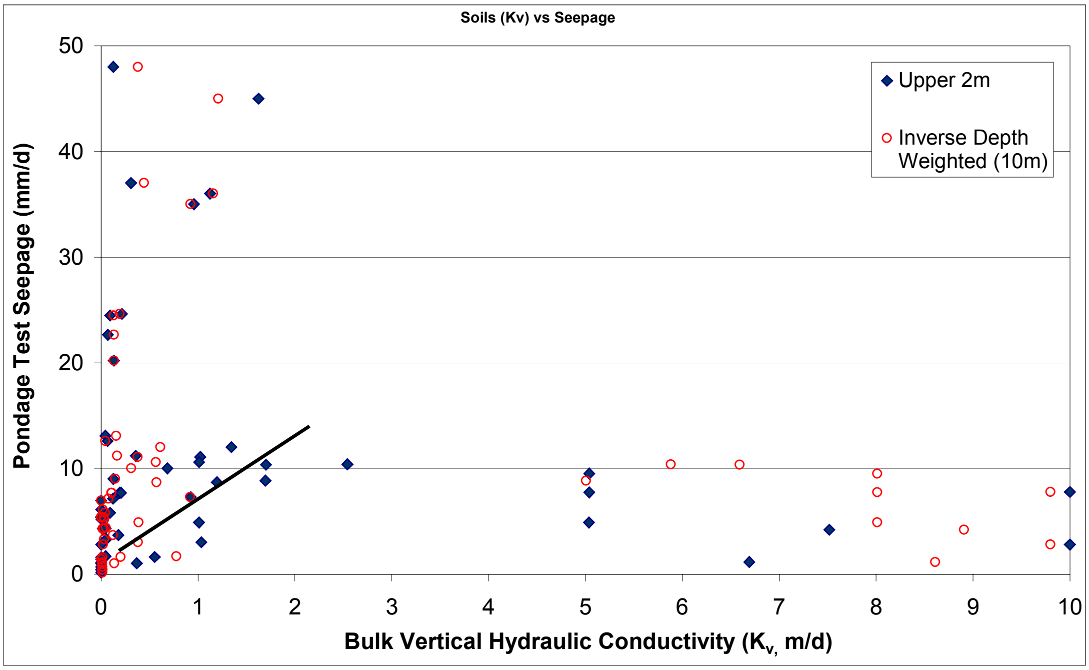


Figure 4-6 presents the vertical hydraulic conductivity (K_v) value for the upper two metres and the 10m inversely weighted scenarios, for all of the sites investigated in the year 3 program. The absence of a clear correlation between K_v and seepage indicates

■ **Figure 4-6 Pondage Test Seepage Versus Representative Vertical Hydraulic Conductivity for the Pondage Section (for Year 3 Drilling Sites)**



that this approach may not be valid, or alternatively that no clearly defined direct relationship does exist.

Reasons why this approach may not be valid is due to errors inherent in the method. These include:

- The bulking and averaging process (of both seepage and K_v values) over the pond length;
- Interpolation between bores; and,
- The process of assigning K_v values to soil type (ie infiltration tests were not conducted in each soil type and the true conductivity is assumed based on the described texture).

However, if it is assumed that the errors inherent in the method are relatively minor, and that Figure 4-6 is accurate, two main factors could cause the scatter observed in the data. Two main types of variation from an 'expected' trend, can be observed in Figure 4-6:

- *Sites with low vertical conductivity but relatively high seepage rates* – There are three main reasons why this may occur:
  i) Seepage may be isolated to very short sections of high seepage which may have been missed by the drilling program. Many measurements are required to obtain a reliable estimate of the mean. Seepage will tend to be underestimated as local high seepage zones go undetected.
  ii) The predominant seepage mechanism could be lateral and shallow, through the channel banks or immediately beneath the channel base – therefore soils data collected at the edge of the channel will not be highly related to seepage rates. In this case seepage will be dependent on the bank hydraulic properties which in turn will be dependent on bank construction techniques and materials.
  iii) The predominant seepage mechanism is not through primary soil porosity but through secondary porosity, such as cracking, or fractures (in hard rock), or macro invertebrate activity (eg yabbies). Assigning a seepage rate based on soil texture will therefore not be an accurate indicator of the true permeability of the soils.
- *Sites with high vertical conductivity but relatively low seepage rates* – This occurs where natural lining or clogging of a channel via silting or biological processes is the dominant factor controlling seepage, ie the surface layer is the most restrictive layer in the profile. This effect will be most prominent at sites with high permeability soils, as the silt layer is relatively more influential and more likely to be the most restrictive layer.

Summary

This analysis suggests that using soil data alone to estimate seepage rates is not likely to be successful. The drilling undertaken in this study was not of sufficient density to adequately characterise the site to determine seepage rates. Therefore the density of sampling required to accurately represent seepage rates will generally be prohibitive for most RWA channel seepage assessment studies. In addition, for this method to be satisfactorily accurate, field assessment of seepage rates in different soil types is likely to be required, rather than estimation based on the soil texture and published data.

Finally, the effects of surface clogging can often dominate seepage rates to the extent that the permeability of underlying layers can be irrelevant.

4.2.4 Conclusions

Sub-surface characterisation by soil and geological profiling was conducted to assist in general site characterisation (provided information on soils, depth to groundwater and groundwater salinity) as well as to assist in geophysical interpretation. Bores were generally drilled adjacent to the channel, up to 10 m in depth.

An attempt was made to estimate seepage based on average soil permeabilities, using different weightings to test the influence of the soil across a range of depths. The upper 2m of the soil profile gave the best indication of some relationship between permeability and seepage rate, however no clear relationship between soil permeability and seepage rate was obtained. A combination of factors is likely to contribute to the absence of a relationship. Two types of factor contribute to the absence of a clearly defined relationship between seepage and soil Kv:

- *Errors inherent in method* – There was insufficient definition of changes in soil type along channel (ie low sampling density). Further, the process of assigning Kv to soil type is inaccurate. The hydraulic conductivity for the particular soil type should be field tested rather than assigned from literature
- *Factors apart from soil type are the primary control on seepage rate*: The two most common factor are:
  - Bank dominated seepage (ie due to poor bank construction etc) and,
  - Surface clogging layer.

  These factors explain why sites like Finley and Dahwilly can have such similar seepage rates, even though the underlying soil at Dahwilly has permeability many orders of magnitude higher than the clay at Finley. Seepage rates at Dahwilly are controlled by the clogging layer on the base of the channel while seepage rates at Finley are controlled by lateral bank seepage.

Soil mapping at a regional level to identify sites of potentially high seepage is a useful first cut approach for prioritising areas for further investigation. Sub-surface characterisation is also a very important part of developing a conceptual model of the site, which will be used in interpreting other test results. However at the density required for sufficient accuracy to be obtained compared to other methods, local soil mapping (and point seepage tests) to quantify seepage rates and extrapolate to other areas will not be cost effective, aside from the potential errors in this technique described above. These conclusions regarding the usefulness of soil surveying are confirmed by the literature review (ANCID, 2000a).

4.3 Point Tests

4.3.1 Introduction

Point measurement refers to any technique which measures seepage at a given point within a channel, usually involving the application of water to the surface or constructed hole within the channel and measurement of the rate at which it drains away. Point tests can be divided into techniques which can be used while the channel is operating and those used when the channel is empty.

Some techniques provide a direct estimate of seepage (eg seepage meters), whereas others estimate hydraulic conductivity, which can be used as a relative indicator of seepage, or can be used to calculate seepage. The advantage that channel operating techniques have over channel empty techniques is that measurements reflect real operating conditions, particularly the seepage processes and hydrogeological conditions.

Five point test trials were conducted during the investigation and are reported on in this section, including:

- Ring Infiltrometer and Disc Permeameter tests (Toolondo Central and Dahwilly Central);
- Ring Infiltrometer (Tabbita); and,
- Idaho Seepage Meter (Dahwilly Central and Donald Main Channel).

These three techniques are briefly described below (refer to ANCID, 2000a, for additional information).

Idaho Seepage Meter
The most common form of point measurement conducted under channel operating conditions is the seepage meter. Seepage meters are essentially cylindrical infiltrometers modified for use under water. The seepage meter method involves the use of a water tight bell housing embedded into the channel bed where the water lost per unit area through the base of this bell is the seepage loss from the channel. Seepage meters generally are based on either a variable or constant head. The Idaho seepage meter is a type of constant head seepage meter, which operates using a Mariotte siphon reservoir from which seepage rate can be calculated directly from the rate of fall in the reservoir level. Seepage meters cannot be used in deep channels, fast flowing channels, or in channels with hard or gravelly beds, or where there is significant weed growth.

Disc Permeameter
The disc permeameter is an instrument used to measure the hydraulic conductivity of soil at (or near to) saturation. A disc covered with a semipermeable membrane (typically 0.2 m in diameter) is placed on a surface and the subsequent infiltration of water allows calculation of the hydraulic conductivity of that surface. Water is supplied to the disc at a constant head at or near to a surface matric potential of zero. This measurement method can only be used in empty channels. The method can be used on an undisturbed channel bed, in some cases a thin layer of contact material may be used to provide a level surface but this does not affect the measurement. In this study, unsaturated disc permeameters were used and a small negative head was

applied to the disc to avoid leakage of water. This may result in the measured values of hydraulic conductivity being marginally (but not significantly for the purposes of this study) lower than the saturated value. Soil samples were extracted before and after use of the disc permeameter and analysed for volumetric soil water content.

Ring Infiltrometers
Single and double ring infiltrometers are devices for determining the rate of infiltration into soil from a circular source. Single ring infiltrometers were used in these trials. Ring infiltrometers are normally metal rings with a diameter of 20 – 100 cm and a height of about 20cm. The ring is driven into the ground about 5 – 10 cm, water is applied inside the ring with a constant head device, and intake measurements are recorded until a steady infiltration rate is observed. If a constant head device is not available to add water to the ring, a constant head can be maintained by manually adding water and recording the volume. In these trials both manual and automatic methods were used to maintain a constant head.

4.3.2 Methodology

The approach adopted in all the trials was also applied to the points tests. That is, that the results were tied back to the pondage tests to attempt to determine their accuracy. Depending on the pond length, a certain number of point tests were conducted at approximately even intervals (where possible) along the pond. Based on the length of channel represented by each test, a weighted average was applied to determine the representative seepage from that pond. (If the tests were exactly evenly distributed along the pond the representative seepage would be equivalent to the test average). Due to the effect of very high individual seepage rates on the overall average, in some instances the median rate was also examined as a potentially more representative number.

In addition to comparison with pondage tests, at some sites the point tests were compared with the immediately surrounding EM31 values and potential relationships between these two variables examined.

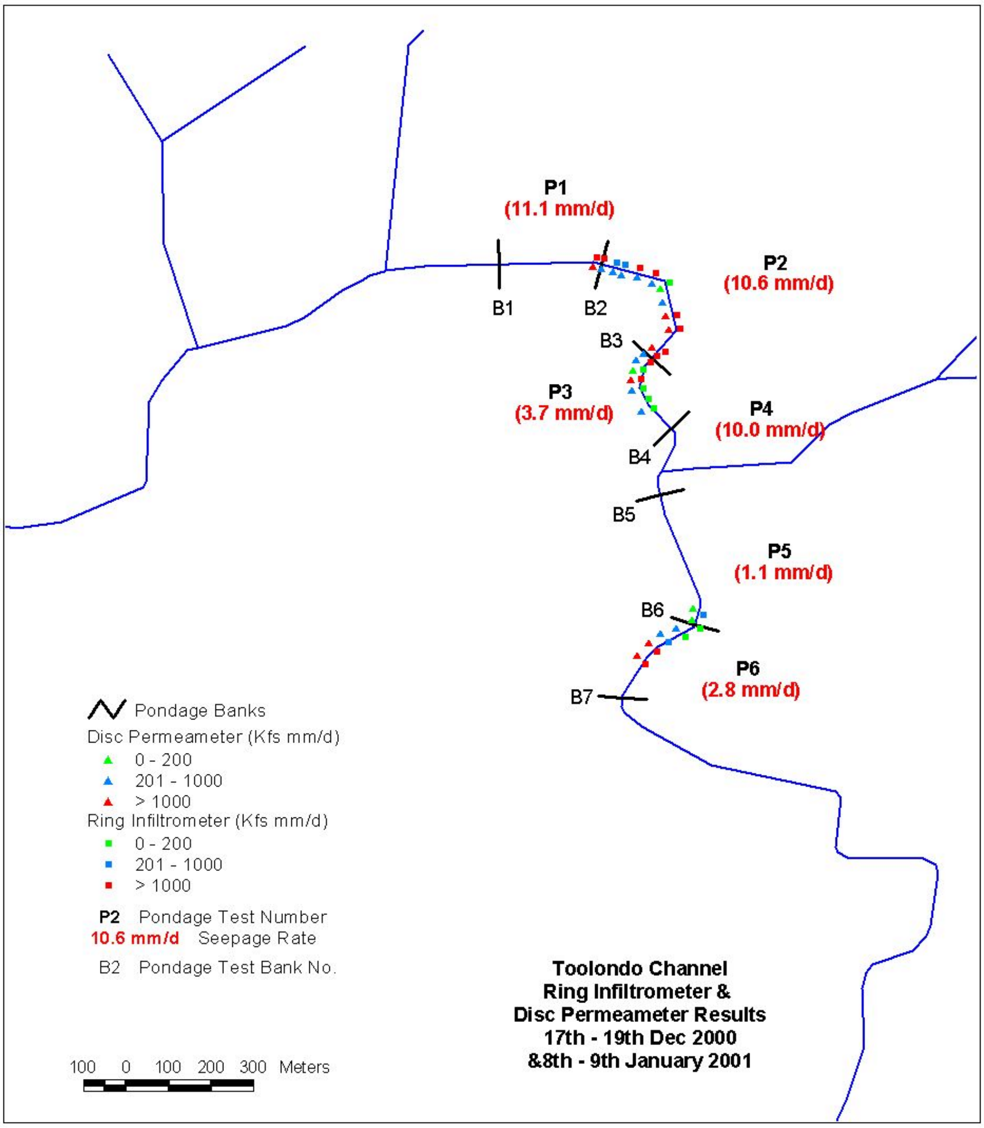
4.3.3 Ring Infiltrometer and Disc Permeameter – Toolondo Central

Ring infiltrometer and disc permeameter tests were conducted on the Toolondo channel on December 17th - 19th December 2000 and 8th - 9th January 2001. Tests were conducted at intervals ranging between 20m and 40m along the channel, in three corresponding pondage sections:

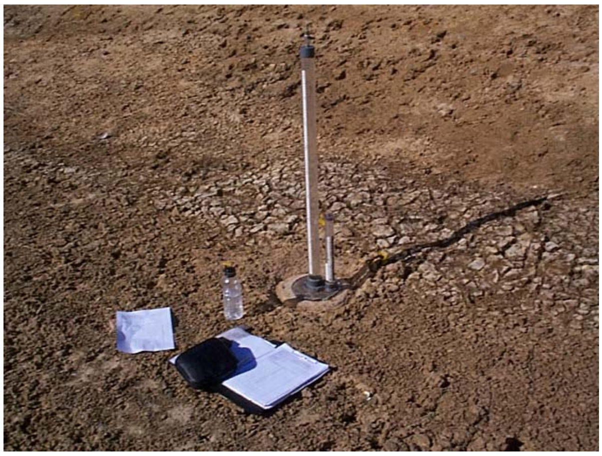
- one of relatively high seepage (Pond 2; 10.6 mm/d); and,
- two of relatively low seepage (Pond 3; 3.7 mm/d and Pond 6; 2.8 mm/d).

Figure 4-7 shows the location of the tests. The ring infiltrometer test and the disc permeameter test were conducted as close to each other as possible (typically 1-2m). The results of the tests are shown in Table 4-2, with the average, median and lower quartile of the results presented. Figure 4-8 shows the instruments in use at the channel.

■ **Figure 4-7 Toolondo Point Test Locations and Results**



■ **Figure 4-8 Ring Infiltrometer (left) and Disc Permeameter (right) in use at the Toolondo Channel**



Comparison to Pondage Tests

The most obvious fact from the data is the high values recorded during the tests. These are very high compared to the pondage test seepage rates for the cells. Different results to pondage test numbers are expected as these results are not seepage rates but saturated hydraulic conductivity values. This is closely related to the seepage rate, but will also depend on other factors. The most important is the head of water in the channel and the watertable elevation relative to the channel. For the conditions at the Toolondo channel (watertable approximately 10m below channel water level and a wetted perimeter of approximately 15m), based on some simple assumptions regarding the flow pattern beneath the channel flow net analysis indicates that that seepage rates of approximately two-third the hydraulic conductivity are expected

Therefore, recognising that saturated hydraulic conductivity values are not directly equal to actual seepage rates, but that they should generally be similar, (and that in this case seepage rates should be approximately two-thirds of the hydraulic conductivity), it is evident that these values are much higher than they should be, if they are a true reflection of seepage rates. Even the lower quartile values of the data represent seepage 30-70 times greater than pondage test seepage rates.

The reason for these results is due to the soil profile in the base of the channel. Over most of the channel in this section, a medium to coarse grained sand layer of 0.1- 0.2m thickness overlies a silty clay. It is the clay which acts as the limiting layer to channel seepage, but the ring infiltrometer and disc permeameter tests (which were conducted on top of the channel) are essentially measuring the hydraulic conductivity of this sand layer. In a select few of the tests (eg Pond 2, test 7 and Pond 3, test 4) it appears that this sand layer was quite thin and values approaching the true field saturated hydraulic conductivity for the restricting layer may have been measured.

■ **Table 4-2 Toolondo Channel Ring Infiltrometer and Disc Permeameter Results (Field Saturated Hydraulic Conductivity)**

Test No.	Ring Infiltrometer (mm/day)	Disc Permeameter (mm/day)
P2-T1	1620	2248
P2-T2	1340	866
P2-T3	720	512
P2-T4	516	407
P2-T5	1830	793
P2-T6	1067	749
P2-T7	42	71
P2-T8		349
P2-T9	1424	2327
P2-T10	2130	2201
Average	1299	1082
Lower Quartile	1067	449
Median	1424	771
P3-T1	2017	1938
P3-T2	2442	870
P3-T3	2374	699
P3-T4	35	26
P3-T5	1255	2378
P3-T6	173	212
P3-T7	112	
P3-T8	152	226
Average	684	708
Lower Quartile	122	212
Median	163	226
P6-T1	237	51
P6-T2	118	103
P6-T3	104	295
P6-T4	860	274
P6-T5	2260	2310
P6-T6	2190	2303
Average	962	889
Lower Quartile	148	146
Median	549	285

The test methodology aims to ensure measurements are conducted under saturated conditions. In reality, field saturated hydraulic conductivity is often half of that under saturated conditions. The relationship between the true saturated hydraulic conductivity (Ks) and the field saturated hydraulic conductivity (Kfs) is approximately: Ks = Kfs x 1.2.

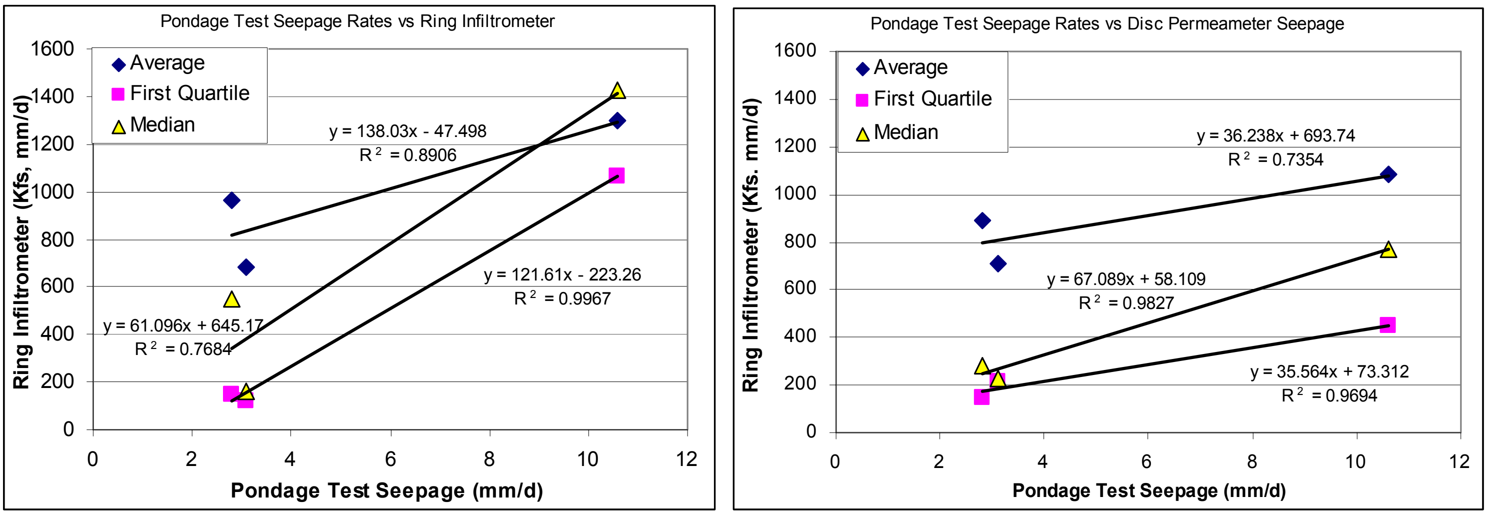
Given that there was little to be gained from direct comparison to the pondage tests rates, analysis was conducted to compare in a relative sense the point tests results to the pondage test results. Figure 4-9 presents these results, where the average, median and lower quartile figures for each pondage section were plotted against the corresponding pondage test seepage rate for the section.

The first thing to observe from this data is that the point tests did record lower seepage rates in the lower seepage ponds than in the higher seepage ponds, which is demonstrated by the positive gradient in the lines of best fit in Figure 4-9. This is important, as it indicates that these particular points tests, despite providing no quantitative indication of seepage rates, may still be able to be used to determine sections of channel with higher rates relative to other sections. Meaningful statistical interpretation however is not possible with only three data points. Nevertheless, the lines of best fit and their correlation coefficient have been plotted, primarily to compare: a) the two point source methods, and b) the median, average and lower quartile values generated from the point source data as indicators of the overall seepage from the pond.

Figure 4-9 indicates the best statistical indicator of seepage for the Toolondo point tests is the lower quartile of the data. This suggests that the high seepage rate results are unreasonably biasing the true seepage results, which is more realistically reflected in the lower end of the range of the seepage results. The data offers no clear indication as to which of the methods might be a more accurate predictor of seepage, but marginally indicates more confidence in the disc permeameter results. For example, pond 2 has a pondage test seepage rate approximately 3 times that of pond 3 and 6. The median and lower quartile results for pond 2 are approximately 2-3 times that of pond 3 and 6, while for the ring infiltrometer pond 2 is 4-6 times higher.

In terms of field procedures, the disc permeameter was more user friendly for operators. Some inaccuracies were introduced to the ring infiltrometer method by the float valve mechanism used to maintain the constant head of water in the ring, which would sometimes stick and require manual fixing, and therefore the required consistent head was not always continually sustained.

- **Figure 4-9 Toolondo Pondage Test Seepage vs Point Source Tests Figure**

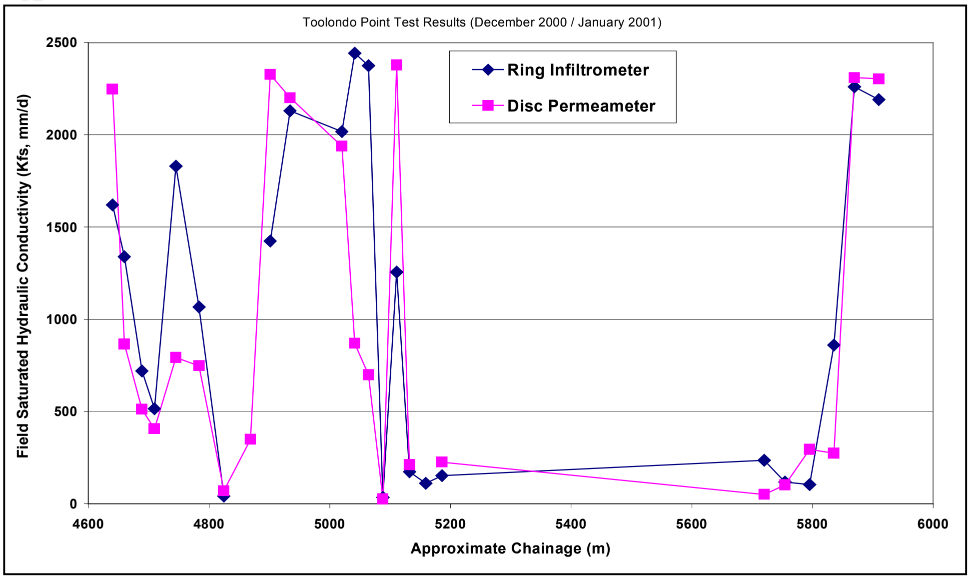


Comparison of the Two Techniques

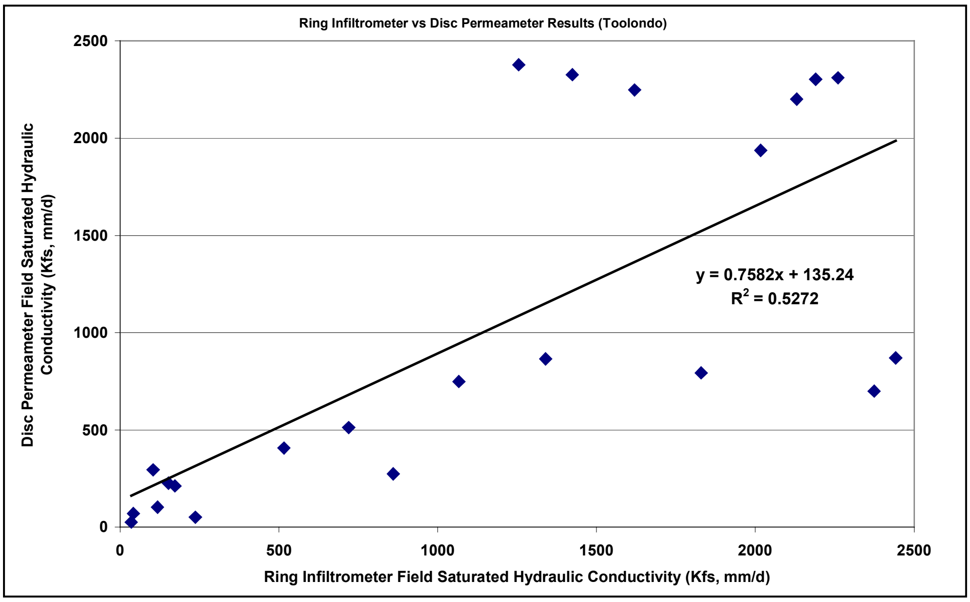
Figure 4-10 (A and B) compares the two point test techniques. There is only a moderate degree of correlation between the two methods of testing. While differing absolute numbers might be expected, a stronger correlation between the two techniques was anticipated. Figure 4-10 B in particular illustrates the high number of tests for which there is significant discrepancies between the results, and this is reflected in the correlation coefficient of 0.52. Such discrepancies are due either to local differences in soil properties, inherent equipment error or operator error. Tracing the source of such errors is beyond the scope of this project, however it highlights the variability and resultant uncertainty in point test measurement techniques.

■ **Figure 4-10 Toolondo Ring Infiltrometer Results Plotted Against Disc Permeameter Results**

A



B



Conclusions

The following concluding remarks can be made regarding the Toolondo point tests:

- Both ring infiltrometer and disc permeameter results significant overestimated pondage test seepage. Even the lower quartile values of the data represent seepage 30-70 times greater than pondage test seepage rates. This was due to the fact that the tests were measuring the conductivity of the sand layer in the channel, rather than the more restrictive underlying layer.
- The points tests recorded lower seepage rates in the lower seepage ponds than in the higher seepage pond. This result does not preclude the use of points tests for

determine relative seepage. The disc permeameter appeared to estimate relative seepage slightly better than ring infiltrometer.

- The side by side disc permeameter and ring infiltrometer results only compared moderately well with each other, with significant discrepancies particularly at the higher seepage rate range.

A true evaluation of point test techniques at the Toolondo channel site should involve repeating the tests, but after removal of the layer of sand covering the restricting layer. However, enough data was collected in these trials to conclude that the variability in the soil (and the associated large number of tests required to characterise a given section), the technical expertise required to properly conduct and analyse results, and the inherent limitations of the equipment, generally do not make channel empty point tests cost efficient or technically accurate. Channel full point tests (eg Idaho seepage meter) would probably have more chance of succeeding under the particular conditions encountered in the channel bed at the Toolondo channel.

4.3.4 Ring Infiltrometer and Disc Permeameter – Dahwilly Central

Ring infiltrometer and disc permeameter tests were conducted on the Dahwilly channel on 21st - 24th August 2000. The tests were conducted on three adjoining pondage sections: Pond 3 (13 mm/d), Pond 4 (7.6 mm/d) and Pond 5 (11.6 mm/d). The results of the point tests are presented in Table 4-3 and although the disc permeameter results fall in a very tight band (within 2-3 mm).

Figure 4-11 displays the location of the tests. The ring infiltrometer test and the disc permeameter tests were conducted as close to each other as possible (typically 1-2m) at intervals generally between 30m - 40m.

This figure illustrates that not all of the tests were evenly spaced within the pondage section, and in fact six tests lay outside the areas included in the pondage tests (this was due to a misunderstanding on the part of the RWA regarding the location of the pondage tests). Unfortunately this limits the analysis of the results, as pond 3 and 5 have only several tests points contained within them.

Table 4-3 and Figure 4-13 indicate that the disc permeameter produced more consistent results than the ring infiltrometer. As Table 4-3 indicates, a number of the ring infiltrometer results had to be discarded due to irregularities observed during field measurement. Generally this was due to seepage appearing on the surface around the outside of the ring, indicating that the assumed flow conditions for the test were breached. These results are therefore likely to be substantially higher than they should be. (A figure of 20 mm/d was used for analysis purposes in these instances, as shown by the bracketed result in the table). Due to further uncertainty this introduces to the results, the disc permeameter results are the more reliable data set for analysis purposes.

- **Table 4-3 Dahwilly Channel Ring Infiltrometer and Disc Permeameter Results (Field Saturated Hydraulic Conductivity[1])**

Test No.	Ring Infiltrometer (mm/day)	Disc Permeameter (mm/day)
P3-T1	2.8	5.4
P3-T2	12	4
P3-T3	8.0	2.5
P3-T4	31	16.0
Average	13.5	7.0
Lower Quartile	6.7	3.6
Median	10.0	4.7
P4-T4	31	16.0
P4-T5	1.0	2.3
P4-T6	30	18.8
P4-T7	3.1	12.5
P4-T8	4.7	7.0
P4-T9	115 (20)	6.0
P4-T10	2.1	6.4
Average	13.1	9.8
Lower Quartile	2.6	6.2
Median	4.7	7.0
P5-T10	2.1	6.5
P5-T11	98 (20)	13.9
P5-T2	412 (20)	4.8
Average	14.0	8.4
Lower Quartile	11.1	5.6
Median	20.0	6.5

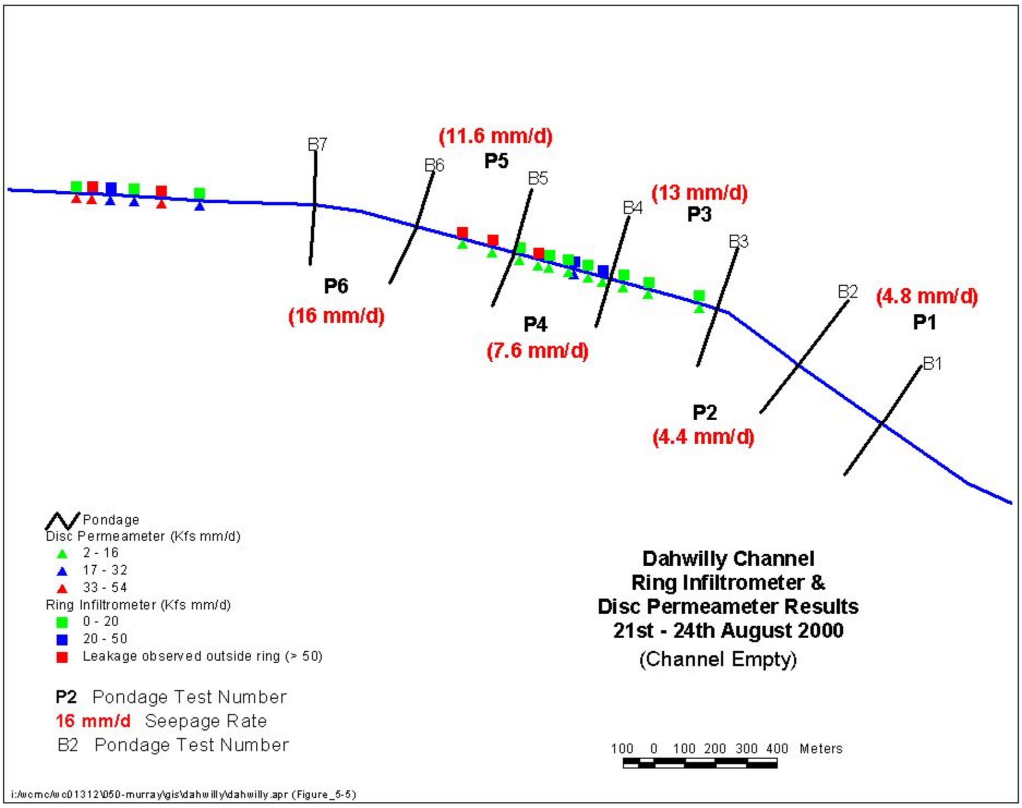
1. The test methodology aims to ensure measurements are conducted under saturated conditions. In reality, field saturated hydraulic conductivity is often half of that under saturated conditions. The relationship between the true saturated hydraulic conductivity (Ks) and the field saturated hydraulic conductivity (Kfs) is approximately: Ks = Kfs x 1.2.
2. Bracketed figures represent the figure used in the actual analysis (average, lower quartile etc). The actual number recorded was not used due to irregularities observed during the test (most commonly due to seepage appearing on the surface around the outside of the ring), and is likely to be a significant over estimate of seepage.

Comparison to pondage tests

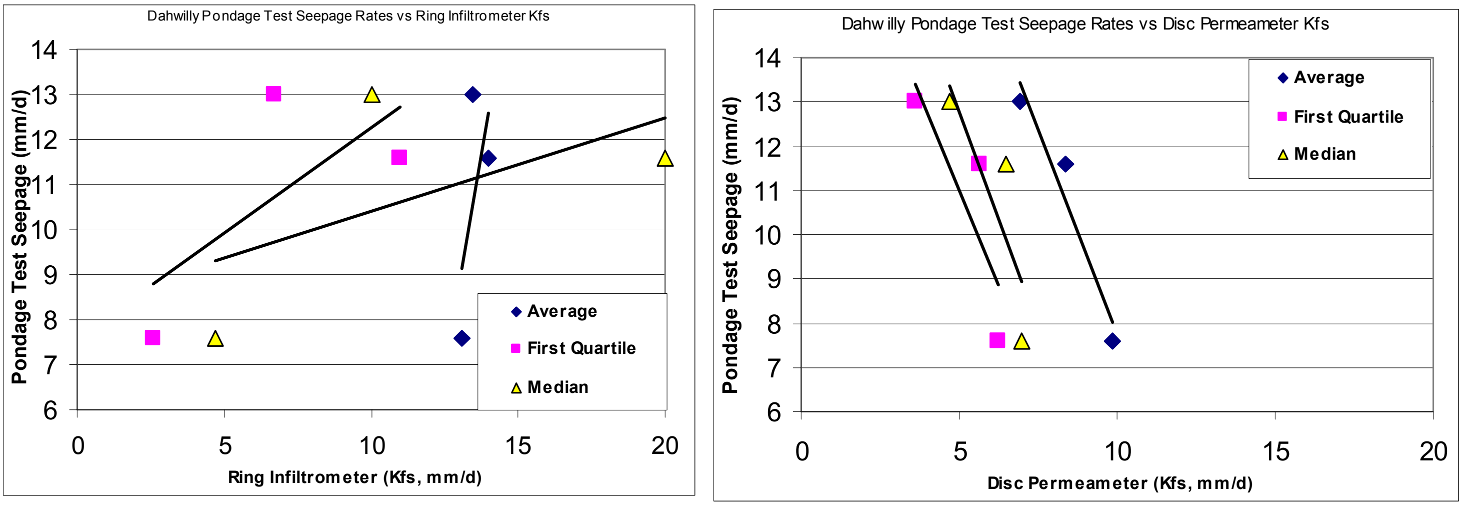
Analysis was conducted to compare the point tests results to the pondage test results for each section. The first point to note is that, compared to the point tests at Toolondo, these seepage rates are of the right order of magnitude. For a watertable depth of 5m and wetted perimeter of 10m, we would expect pondage seepage (in terms of volume/area/day) to be very approximately half the saturated hydraulic conductivity (based on some simple assumptions regarding seepage flow patterns beneath the channel). The results are therefore well within an order of magnitude of the true seepage rate.

Figure 4-12 presents these results, where the average, median and lower quartile figures for each pondage section are plotted against the corresponding pondage test seepage rate for the section. The disc permeameter results interestingly suggest a negative relationship between pondage test seepage and the point tests (ie pondage test seepage increasing with decreasing disc permeameter seepage), although the disc permeameter results fall in a very tight band (within 2-3 mm).

- **Figure 4-11 Dahwilly Point Test Locations (August 2000)**



- **Figure 4-12 Dahwilly Pondage Test Seepage vs Point Source Tests**



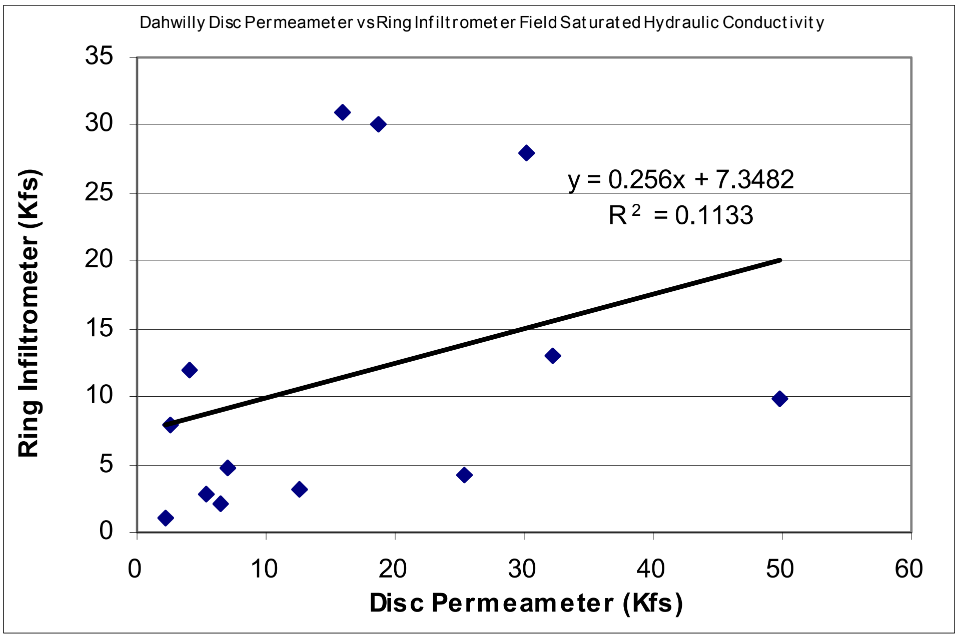
This demonstrates the failure of the disc permeameter results to characterise the true seepage rate of the pond. This is most likely due to the inadequate density of the testing program. The ring infiltrometer results are generally also inconclusive. The average rates lie in a very narrow band, and do not distinguish between ponds. The median results suggest some type of trend between the variables, and the lower quartile data produces the best line of fit. However the high degree of uncertainty in a number of the infiltration tests means that there can be little confidence in this relationship (eg, Pond 5 has only 3 tests points and only 1 reliable test, so figures such as median and lower quartile begin to lose their meaning). Again the conclusion must be that there is inadequate sampling density to sufficiently characterise the ponds.

Comparison of the Two Techniques

Figure 4-13 plots the results of the two techniques against each other. This figure shows that the results of the two techniques are very poorly correlated. While different numbers may be expected from each technique, it would be expected that overall there would be a strong correlation between the results. The figure shows that there are a high number of tests for which there are significant discrepancies, and this is reflected in the very poor correlation coefficient of 0.11. Such discrepancies are due either to local differences in soil properties, equipment malfunction or operator error.

As discussed above, it appears that the greater source of error is in the functioning of the ring infiltrometer. In addition to breaches of assumed seepage paths, as discussed under the Toolondo point test section, some inaccuracies are introduced to the ring infiltrometer method by the float valve mechanism which is used to maintain the constant head of water in the ring. Due to the reduced number of reliable results from the ring infiltrometer, the disc permeameter results are considered the more reliable data set for this analysis.

- **Figure 4-13 Dahwilly Point Tests: Ring Infiltrometer Results plotted against Disc Permeameter Results**



Conclusions

The following concluding remarks can be made regarding the Dahwilly point tests:

- Point tests were not evenly distributed across the pondage sections which limited the conclusions able to be drawn from the results (two of the three ponds had only several points tests contained within them).
- The results correlated poorly with pondage test seepage rates. In fact, the disc permeameter results (which in these tests were deemed to be more reliable than the ring infiltrometer results) showed an inverse relationship to pondage test seepage. This demonstrates the failure of the disc permeameter results to characterise the true seepage rate of the pond at the density of the testing program employed in the trial. This confirms findings of investigations documented in the literature – that one of the greatest barriers to being able to reliably use point test data is the variability in the soil, and many tests are required to adequately characterise a given section using this method.
- Unlike the Toolondo point tests, both the ring infiltrometer and disc permeameter results were of the same order of magnitude as the pondage test seepage results, which demonstrates that the upper layer at this section of the Dahwilly channel is the limiting layer (a point confirmed and discussed in section 4.2, Sub-Surface Characterisation)
- The results of the two techniques were very poorly correlated. This is more likely attributable to error in the seepage rings than the disc permeameter results.

4.3.5 Idaho Seepage Meter - Dahwilly Central

Idaho seepage meter tests were conducted on the Dahwilly channel in February 2001. The tests were conducted by Yanco Agricultural Institute, with assistance provided by Murray Irrigation. Twelve locations were tested in four pondage sections comprising P3, P4, P5 and P6. Table 4-4 presents the results of the testing at Dahwilly and Figure 4-14 displays each test location. There were six individual tests undertaken at each test location at right angles to the channel [Left (L), Left of Middle (LM1), Middle 1 (M1), Middle 2 (M2), Right of Middle (RM1) and Right (R)].

The median value of these six tests at each particular chainage is presented in Table 4.4 below as the representative seepage rate for each location. Using these figures a representative seepage rate for each pondage section was calculated. This was calculated by summing weighted seepage rates for each test. The value of each weighted result is dependent on the length of channel the test represents as a fraction of pond length (ie based on geographic location alone and not on soil type or EM31 response).

■ **Table 4-4 Dahwilly Idaho Seepage Meter Results: January, 2001.**

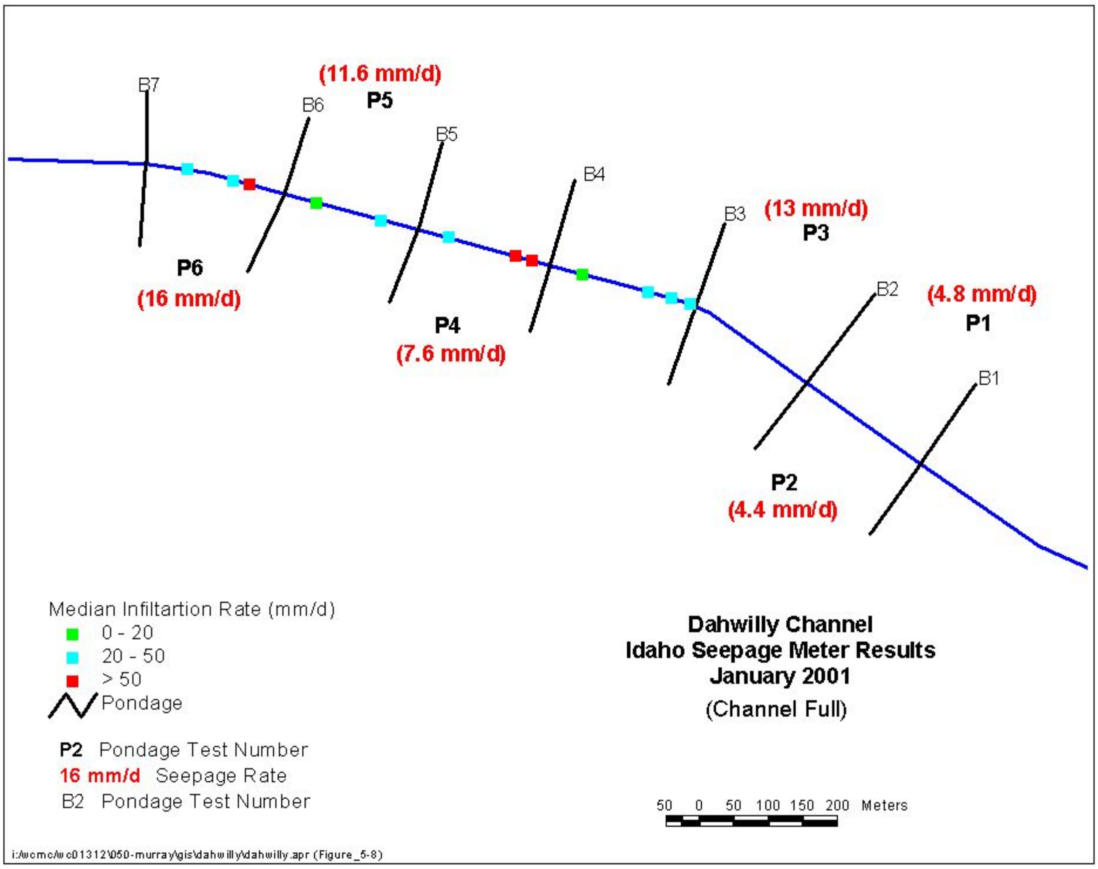
Pond No. (Pondage test seepage)	**Test No.**	**Median Seepage Rate (mm/d)**	**Chainage (m)**	**Representative Distance (m)**	**Weighted Seepage (mm/d)**
3 (13 mm/d)	1	33	1345	25	4
	2	32	1376	25	4
	3	49	1411	60	13
	4	15	1511	110	7
				Sum	**28**
4 (7.6 mm/d)	5	81	1586	40	16
	6	151	1611	40	30
	7	21	1711	120	13
				Sum	**59**
5 (11.6 mm/d)	8	37	1811	100	19
	9	5	1911	100	3
				Sum	**21**
6 (16.3 mm/d)	10	79	2011	60	24
	11	38	2036	50	9
	12	36	2103	90	16
				Sum	**49**

4.3.5.1 Comparison with Pondage Test Results

An attempt was made to compare these representative seepage rates with the pondage test seepage rates. As **Figure 4-15** indicates, the results are inconclusive. There appears to be some type of linear trend between three of the points, but the lowest pondage test result of 7.6 mm/d (Pond 4) returned a high Idaho meter seepage rate (as calculated according to this method) of 59 mm/d which throws any sort of correlation in the results.

Two main problems with this analysis are apparent. The first is that the number of tests which lead to the representative seepage rate are too few, given the length of the ponds (approximately 2-4 tests per 200m length). Ideally one test should represent no more than 20-30m length of channel and previous studies indicate a much higher density may be required [Smith and Turner (1982) found that for a section of channel 366 metres long, 110 measurements (almost one every three metres) were required for a 20% error in the overall seepage rate]. The second problem was discussed in the previous section: that is that statistically, four points are not ideal for determining correlations between variables. However due to time and financial constraints, the tests were limited to the four pondage cells only.

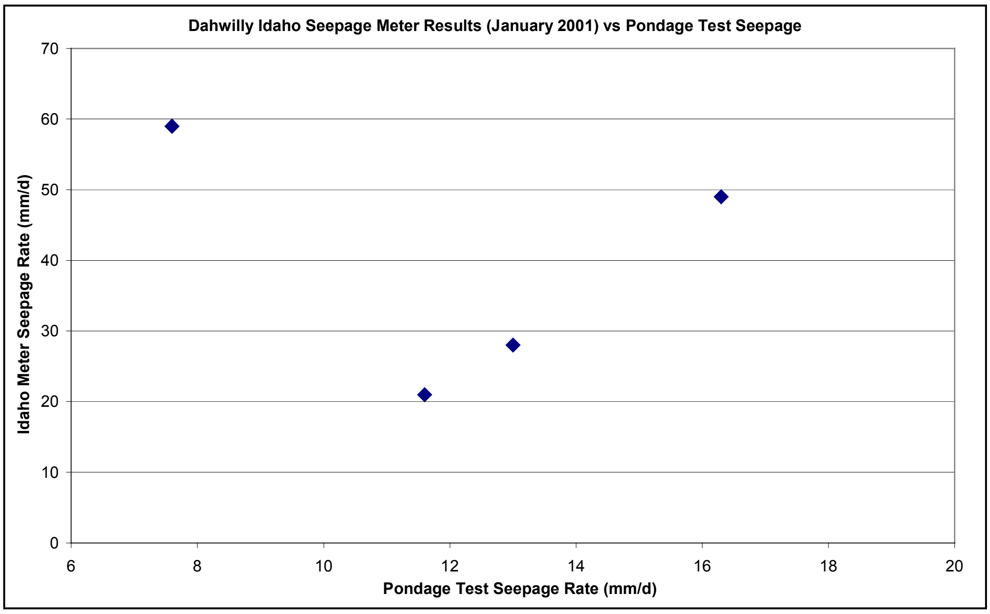
■ **Figure 4-14 Idaho Seepage Meter Test Locations (January, 2001)**



A general conclusion that can be drawn is that the seepage rates as measured by the Idaho seepage meter are consistently higher than the pondage test seepage rates. Normally when point tests are conducted, values significantly lower than actual seepage rates are detected. This is due to the relatively large contribution of 'hot spots' to the overall seepage rate, and the inability to detect these spots with point tests. The cause of a variation from this trend might be that the bed of the channel actually seeps significantly more than the banks of the channel. Consideration of the Dahwilly channel geological long-section (refer *Appendix* A) lends support to this theory. This section shows that along the test section, the base of the channel consistently intersects the top of the fine sand layer, which is overlain by a sandy clay. It is therefore reasonable to presume that the base of the channel would seep at a higher rate than the banks, which would lead to point tests in the base of the channel overestimating seepage compared to pondage tests which measure seepage across the entire wetted perimeter of the channel.

It is also acknowledged that pondage test seepage rates may be slightly lower than actual seepage rates due to settling of suspend solids under still water conditions, which will be significantly reduced while the channel is running. This alone would not account, however for the large differences observed between the pondage test and the Idaho meter seepage rates.

■ **Figure 4-15 Idaho Seepage Meter Results vs Pondage Test Seepage**



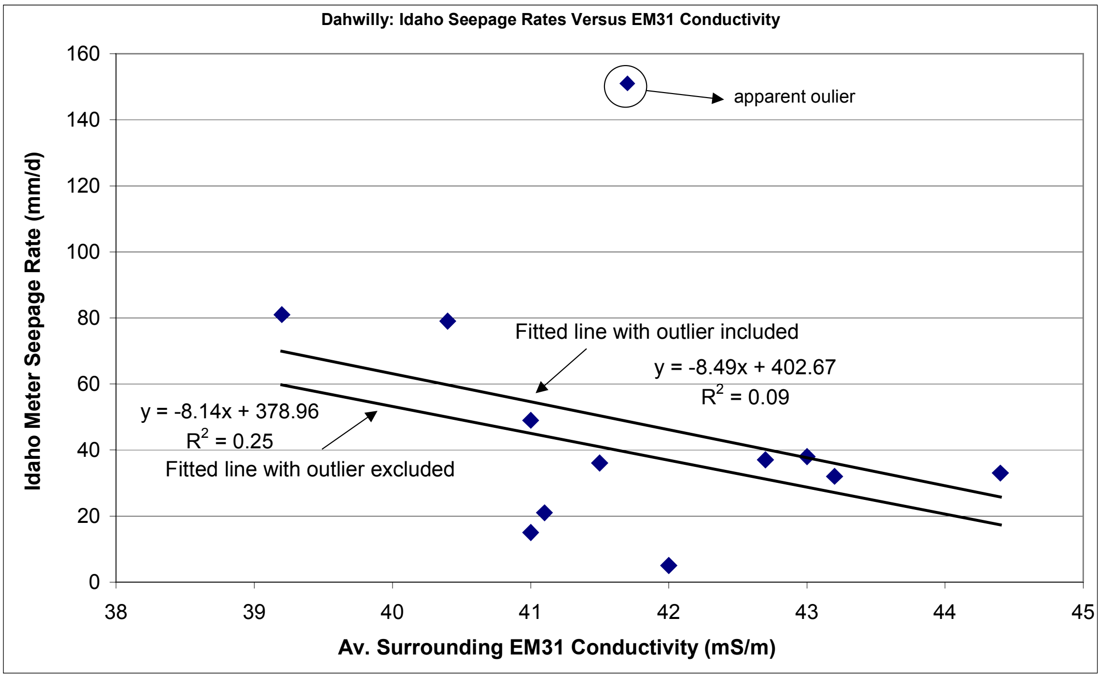
4.3.5.2 Comparison with EM31 Results

An attempt was also made to correlate the Idaho seepage meter tests and the EM31 2002 survey data. The four to five EM31 values immediately surrounding an individual Idaho test were averaged to obtain the representative apparent conductivity for that location. The results of this analysis are presented in Figure 4-16. There was one apparent outlier in the results, as highlighted in the figure. Trend lines with both the outlier included and excluded are presented.

This figure shows an 'expected' inverse correlation between the EM31 conductivity and the Idaho seepage meter results, ie increasing seepage with decreasing EM31 conductivity. However the correlation even with the outlier excluded is poor. The EM31 conductivity average did not distinguish between seepage rate sites between 5 – 40 mm/d (as measured with the Idaho meter), but did to identify the two highest seepage sites, both of which were 80 mm/d.

Definitive conclusions cannot be drawn from these results as the conductivity range is very narrow and the data set too small. It appears that the conductivity has distinguished between moderate and high seepage zones. The limited point methodology of the assessment may also contribute to variability in the results. Improvements could probably be made by averaging seepage and conductivity readings over 20-30m lengths of channel, rather than lines across the channel. This bulking process could assist in smoothing out local variations and anomalies that may occur in isolated sections of channel.

■ **Figure 4-16 Idaho Seepage Meter Results vs EM31 (2002) Apparent Conductivity**



4.3.6 Ring Infiltrometer - Tabbita

Ring infiltrometer tests were conducted on the Tabbita channel over the period 18th - 20th July 2001 by a soils specialist sub-contractor. Tests were conducted at approximately 25 m intervals. The tests were conducted in three corresponding pondage sections; one of marginally higher seepage (Pond 4; 8.5 mm/d) than the other two sections (Pond 2; 6.0 mm/d and Pond 5; 6.2 mm/d). In addition to the tests at set intervals, in each pondage section two series of tests across the channel were conducted (LHS, centre and RHS) in order to determine differences in seepage rates across the channel profile.

The bed was saturated at the time of the tests and water was ponded along the centre line of the channel over a considerable length of the channel. This made it impractical to carry out tests along the centre line of the channel as originally designed. Therefore modifications were made to the original methodology to suit the conditions, including:

- Adjustments to the standard distance of 25 m between sites in order to find a site where the surface was free of water;
- Placement of the rings on the right hand side of the bed, just above the waterline in the channel;
- The sites where the three tests were to be carried out across the bed were shifted to locations where the whole bed was exposed. This was usually a point where the silt layer was higher than elsewhere. As the width of the bed was too narrow to place the rings in a line at right angles to the centre line, the rings were placed diagonally at about 1.5 to 2 m spacing; and,

- Some tests could not be carried out as the bed was covered in water and these sites were inaccessible with the equipment used.

The following observations were made regarding the channel soil profile during the test. The batters of the channel are covered with a layer of brown sandy clay about 1 cm thick over the material used to make the banks. The lower parts of the batter are into the parent material which is a heavy clay. The bed is not flat, but is more of a shallow V shape which is covered by about 10 cm of silty material. There is a brown surface crust, but below this the material is a loose grey silty clay. Underlying this silty clay is the parent material, comprised of a grey heavy clay.

The basic test methodology consisted of placing the ring on the surface of the soil and driving it in about 15 cm. (This was to reach firmer soil rather than it being located in the upper uncompacted or disturbed A1 horizon). The ring was filled with water to a depth of about 5 cm (so that the entire surface of the soil was covered) and measurements of loss of water from the ring were made regularly. The readings were taken at about 10 minute intervals initially until the soil profile had saturated and when the final infiltration rate was reached after 30 to 45 minutes the readings were taken at wider time intervals for about 2 hours. The amount of water needed to refill the ring to its original level (mark on the side of the ring or a needle point) was recorded either as the depth by which the water level has fallen since the last reading or as the volume of water needed to bring the water level back to the level of the marker in the ring.

This method of maintaining the constant head varied slightly from previous ring infiltrometer tests conducted during these trials, where a float device was used to regulate a constant head. For low seepage rate soils such as in the Tabbita channel, where the head only falls slightly over the test, this is a more accurate way of determining the infiltration rate. To improve the accuracy of the results, rings were left in place over night on two nights thus giving eight tests with longer duration where the accuracy could be expected to be better because of the longer time for seepage from the rings.

The results of the Tabbita ring infiltrometer tests are presented in Table 4.5. Figure 4-4 displays the location of the tests. The results are presented both in terms of the actual infiltration rate recorded during the test (ie volume/area) and the field saturated hydraulic conductivity (K_{fs}) calculated from the infiltration rate (refer Section 3.3.3 for discussion of the difference in the seepage rate and the hydraulic conductivity). Significantly lower and more consistent K_{fs} values are reported compared to other ring infiltrometer tests conducted in this study (Dahwilly and Toolondo). This is primarily due to the more uniform and less permeable underlying parent material into which the rings were driven. The average K_{fs} for each section is presented in two forms. Firstly as the total average for all tests, and secondly as the average of all locations.

This second average is calculated using an average figure for the two sections in each pondage where tests were done cross the channel, meaning that the three tests only contribute one figure to the total average. This is a more accurate means of determining the total average for the section. Using this method the average K_{fs} for Ponds 2, 4 and 5 is 7.7, 4.0 and 4.5 mm/d respectively. The average for Pond 2 is highly influenced by the one results of 23.8 mm/d. Perhaps a more representative figure is the median K_{fs} for the ponds, which are 4.5, 4.6 and 4.2 mm/d for Ponds 2, 4 and 5 respectively. Essentially the figures indicate that there is no statistical difference between the seepage rates in each pond as determined by the ring infiltrometer tests.

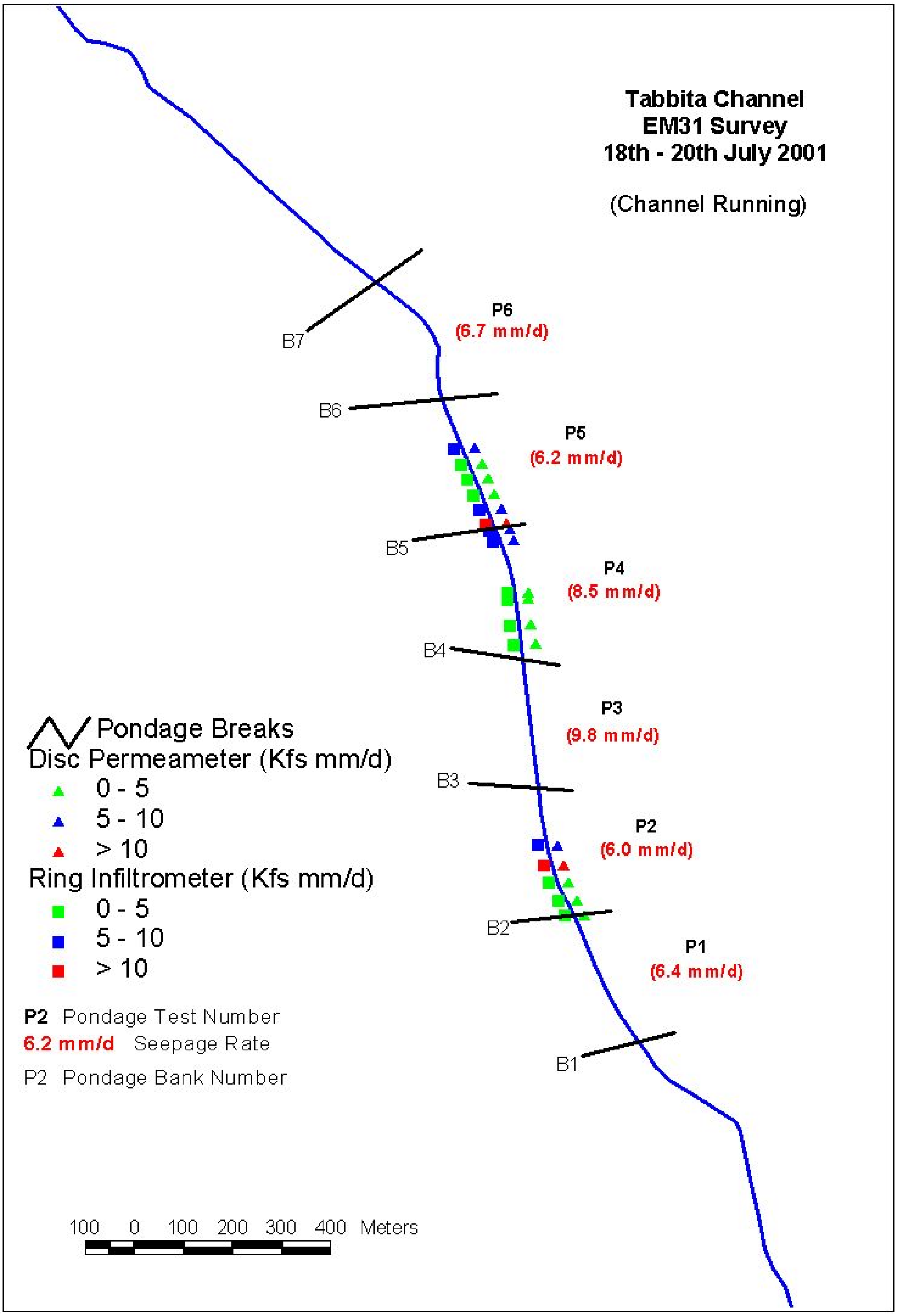
The results do indicate a significant difference between the seepage rates along the centre line of the channel compared to the sides of the channel base. Summing results from all ponds, the average value (K_{fs}) for the centre line of the channel is 1.0 mm/d, compared to 6.8 mm/d for the sides. The median value indicates just as significant a difference of 0.3 mm/d for the centre and 4.2 mm/d for the channel sides.

- **Table 4-5 Tabbita Channel Ring Infiltrometer and Disc Permeameter Results**

Test No.	**Actual Infiltration Rate** (mm/day)	**Field Saturated Hydraulic Conductivity** (Kfs, mm/d)	**Average** Kfs **For Location** (mm/d)	**Length of Test** (mins)	**Chainage and Position**
P2-T1	0	0.0	0.0	49	4913 m, RHS
P2-T2	8	3.8	3.8	62	4937 m, RHS
P2-T3	0	0.0		101	4967 m, RHS
P2-T4	0	0.0	4.5	91	4967 m, centre
P2-T5	25	13.6		143	4967 m, LHS
P2-T6	44	23.8	23.8	88	4991 m, RHS
P2-T7	24	12.9		78	5022 m, LHS
P2-T8	0	0.0	6.2	77	5022 m, centre
P2-T9	11	5.7		41	5022 m, RHS
Average	**12.4**	**6.6**	**7.7**		
Lower Quartile	**0.0**	**0.0**	**3.8**		
Median	**8.0**	**3.8**	**4.5**		
P4-T1	2	0.8	0.8	1060	**5313 m, RHS**
P4-T2	6	3.0	3.0	1015	5338 m, RHS
P4-T3	22	11.6		985	5363 m, LHS
P4-T4	1	0.7	4.6	995	5363 m, centre
P4-T5	2	1.5		105	5363 m, RHS
P4-T6	0	0.0	0.0	74	5382 m, RHS
P4-T7	10	5.3	5.3	160	5463 m RHS
P4-T8	14	7.4		200	5487 m LHS
P4-T9	0	0.0	6.9	110	5487 m centre
P4-T10	25	13.4		185	5487 m RHS
Average	**8.2**	**4.4**	**4.0**		
Lower Quartile	**1.3**	**0.7**	**3.0**		
Median	**4.0**	**2.2**	**4.6**		
P5-T1	34	18.5	18.5	155	5516 m, LHS
P5-T2	18	9.2	9.2	110	5538 m RHS
P5-T3	8	4.2	4.2	127	5558 m RHS
P5-T4	0	0.0	0.0	103	5584 m RHS
P5-T5	4	2.3		1003	5607 m, LHS
P5-T6	2	1.1	2.6	987	5607 m, centre
P5-T7	8	4.2		970	5607 m, RHS
P5-T8	6	3.3		958	5632 m, LHS
P5-T9	8	4.4	6.4	90	5632 m. centre
P5-T10	21	11.6		80	5632 m, RHS
Average	**10.9**	**5.9**	**4.5**		
Lower Quartile	**4.5**	**2.6**	**2.6**		
Median	**8.0**	**4.2**	**4.2**		

These results confirm previous seepage investigations that channels are more prone to seepage at the sides than in the centre. [eg Smith and Turner (1982) studied a number of channels within the Goulburn Valley using the Idaho seepage meter and found that on average seepage rates were between 5-20 times greater at the sides of the channel base compared to the centre].

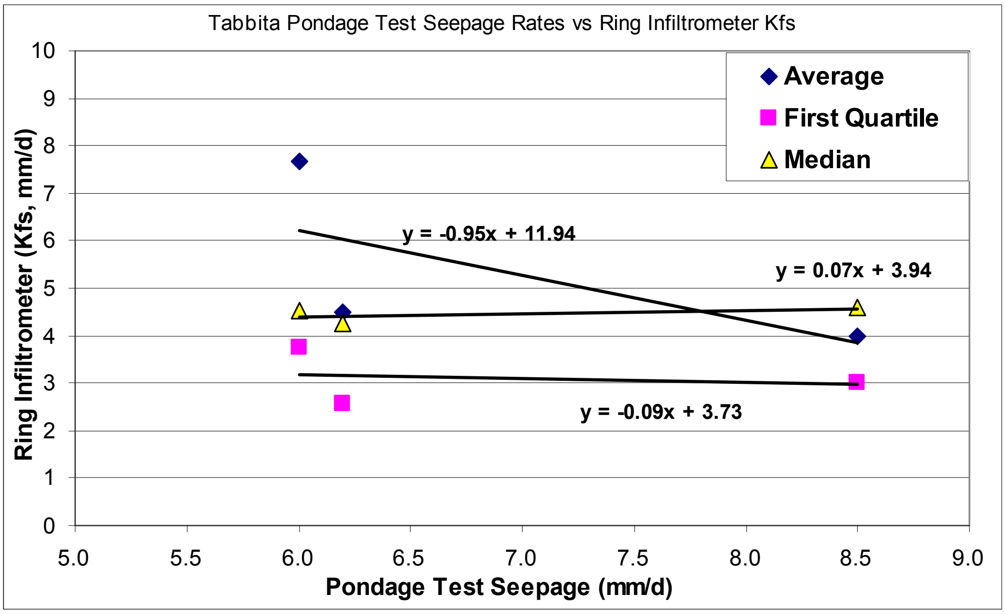
■ **Figure 4-17 Tabbita Channel Ring Infiltrometer Locations and Results**



Finally, analysis was conducted to compare the point tests results to the pondage test results for each section. Figure 4-17 presents these results, where the average, median and lower quartile figures for each pondage section were plotted against the corresponding pondage test seepage rate for the section. This figure confirms the above conclusions that essentially there is no statistical difference between the seepage rates in each pond as determined by the ring infiltrometer tests. The average data shows a negative trend which is not possible and can be dismissed due to the one high seepage result influencing the average in Pond 2. The median results indicated a marginal trend, but is not statistically significant.

The main problem with assessing any seepage measurement technique at the Tabbita site is that the spread of seepage rates as indicated in the pondage tests is very low, and therefore due to potential small errors in both the pondage tests and the particular measurement technique, it is difficult to conduct any assessment that is statistically meaningful.

■ **Figure 4-18 Tabbita Pondage Test Seepage vs Point Source Tests**



However it should be noted that this investigation does not rule out the use of ring infiltrometers as a means of estimating channel seepage. Six tests is probably not enough to adequately characterise a length of channel 200 m long, even given the relatively uniform soil properties of the Tabbita. As was initially suspected, one of the greatest barriers to reliably using point test data is the variability in the soil, and many more tests are required to adequately characterise a given section using this method (ANCID, 2000a). From an economic perspective this means that assessment of channel seepage using ring infiltrometers is not likely to be a cost effective solution.

There was a much better correlation observed between the seepage values from the ring infiltrometer and the pondage test results at this site compared to the Toolondo channel. This is primarily due to the more uniform and less permeable underlying parent material into which the rings were driven at the Tabbita channel. The clayey nature of the soils assists with providing a good seal around the ring, however the key difference is attributable to the surface layer at Toolondo which is not in fact the most restricting layer. At the Tabbita site, the surface soils in the channel are essentially uniform and form the seepage controlling layer, meaning that analysis using surface based instruments is appropriate.

4.3.7 Idaho Seepage Meter – Donald Main Channel

Idaho seepage meter tests were conducted on the Donald Main channel in October 2001. The tests were conducted by Akbar from Yanco Agricultural Institute, with assistance provided by Wimmera Mallee Water. Twenty-two locations were tested in four pondage sections comprising P2, P3, P4 and P6. Figure 4-19 presents the test locations and results. As this figure illustrates, four tests were conducted across the wetted perimeter of the channel at right angles to the channel in each test location. Within each of these four locations a number of tests were conducted to arrive at the average rate for that location.

4.3.7.1 Comparison with Pondage Test Results

The Idaho Seepage meter results were compared with the pondage test seepage rates. A representative Idaho seepage meter rate for each pondage section was calculated by obtaining weighted seepage rates for each section. In addition to using all Idaho tests, a weighted average using the two results from the middle of the channel only was calculated. These results are presented in Figure 4-20.

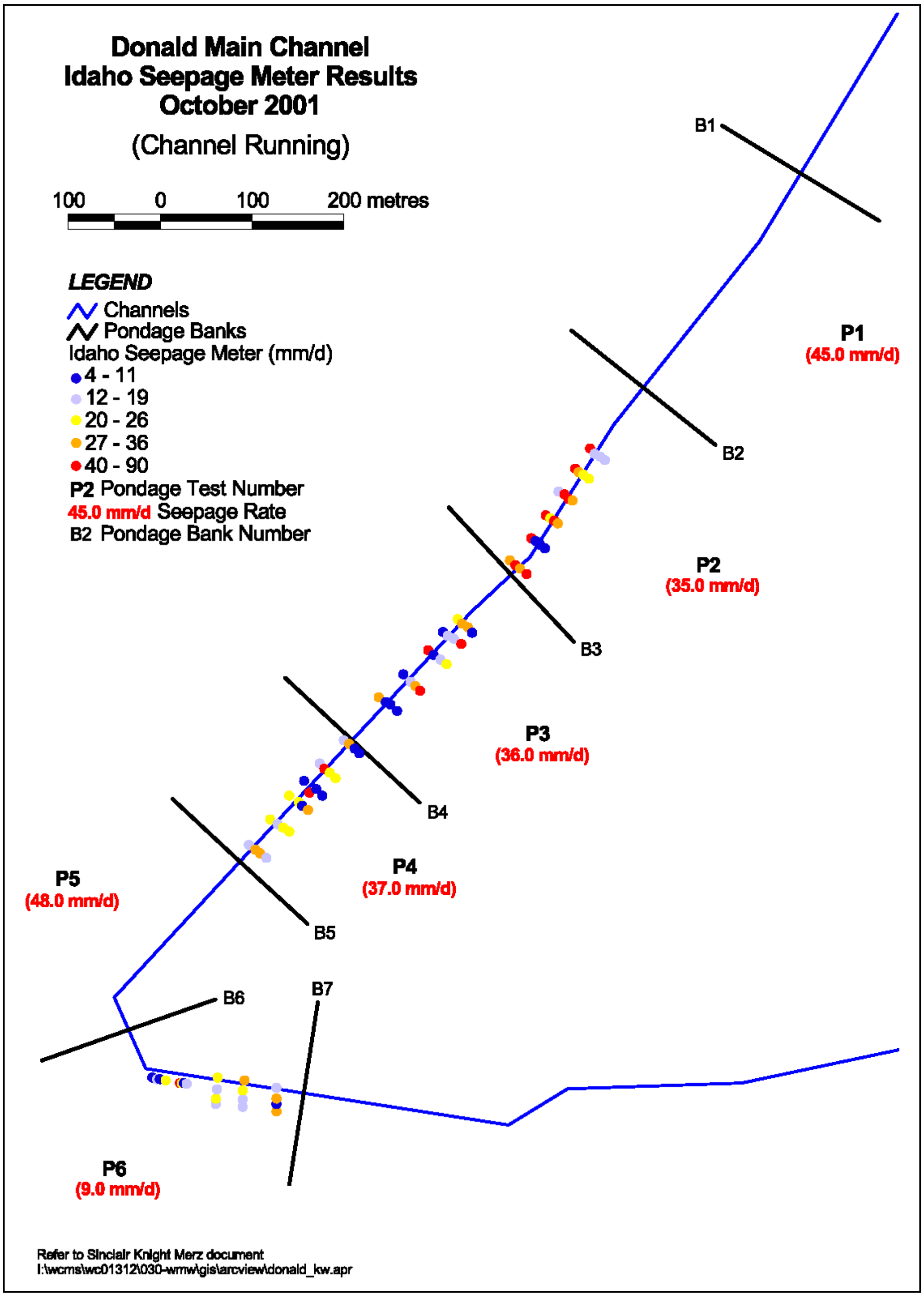
The best result was obtained for Pond 2 which recorded almost the same weighted Idaho seepage meter reading (35 mm/d) as pondage test result (35 mm/d). Pond 4 also recorded similar results between techniques (33 mm/d for the Idaho meter compared to 37 mm/d for the pondage test). Pond 6 and Pond 3 deviated most from this 1:1 linear trend. Using all of the data the results indicate a moderate to poor correlation between the Idaho seepage meter results and the pondage test seepage rates (R^2 = 0.33). Pond 3 (36 mm/d pondage test seepage) is the main cause of the poor correlation, which recorded the same weighted Idaho seepage average as Pond 6 (9 mm/d 36 mm/d pondage test seepage).

Taking the weighted average from only the middle two Idaho seepage tests across the wetted perimeter slightly improves Pond 3 with respect to representing the pondage test seepage however, this further worsens Pond 6 and Pond 4, resulting in overall lower correlation (R^2 = 0.27).

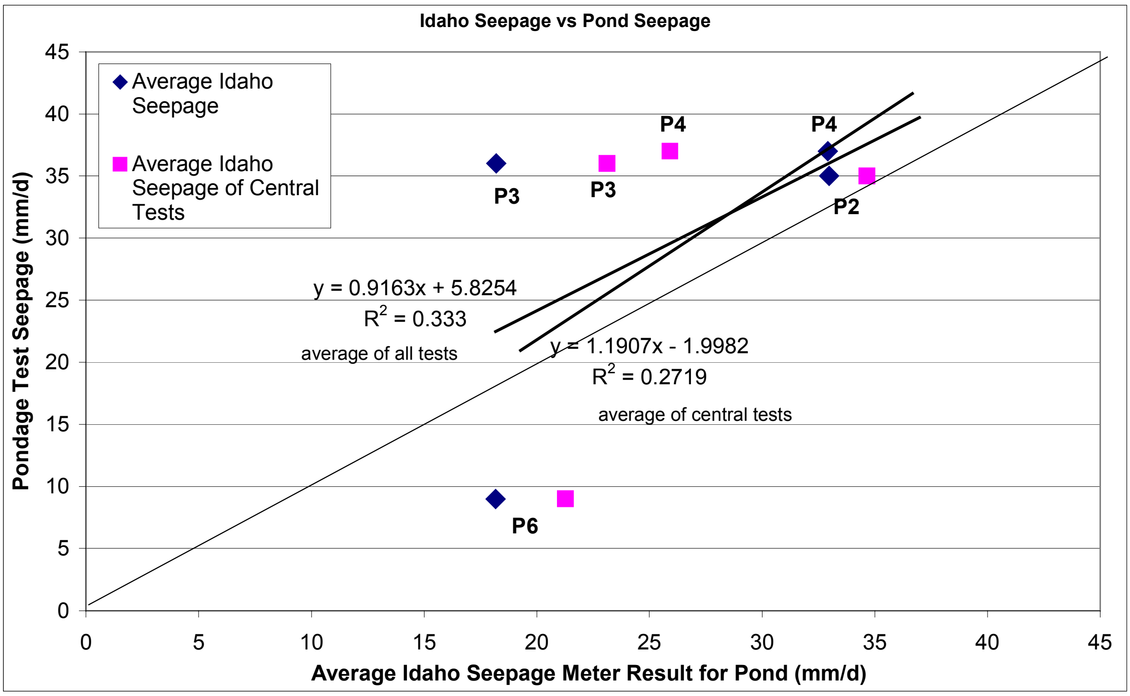
Two main conclusions arise from this analysis:

- The Idaho seepage rates are comparable in magnitude to the pondage test seepage rates;
- There is the suggestion of a linear trend between pondage test seepage and weighted Idaho seepage rates at the Donald Main site, although the correlation is moderate to poor. The limited number of pondage sections on which the trend is based (4) and the limited number of Idaho tests within each pond (5-6) are the main reason for not obtaining a better correlation. The lack of spread within the pondage test data is also a limiting factor.

■ **Figure 4-19 Donald Main Channel Idaho Seepage Meter Test Locations (January, 2001)**



■ **Figure 4-20 Donald Main Channel Idaho Seepage Meter Results vs Pondage Test Seepage**



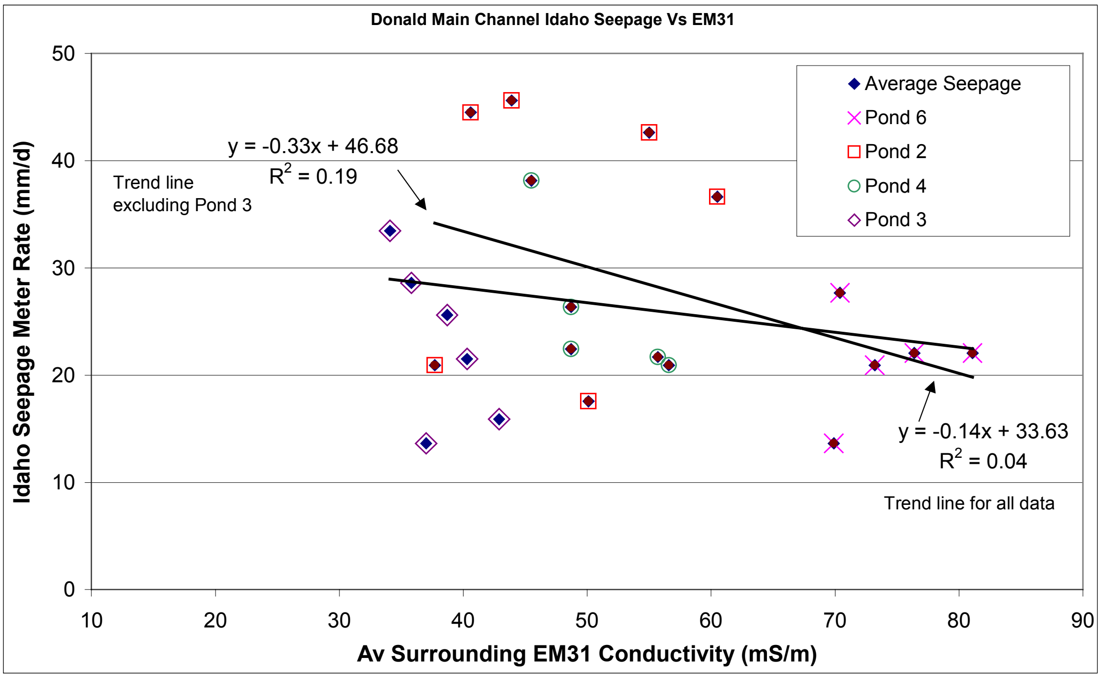
4.3.7.2 Comparison with EM31 Results

An attempt was also made to correlate the Idaho seepage meter tests and 2002 the EM31 survey data. The four to five EM31 values immediately surrounding an individual Idaho test were averaged to obtain the representative apparent conductivity for that location. The results of this analysis are presented in Figure 4-21.

This figure shows no correlation between the EM31 conductivity and the Idaho seepage meter results. When the 'outlying' pond (Pond 3) is removed a weak inverse correlation is observed (ie increasing seepage with decreasing EM31 conductivity). The EM31 conductivity average clearly distinguished between seepage rates (as measured with the Idaho meter) in pond 6 and pond 2, but no distinction at all between pond 3 and 4 is observed. Further investigation would be required to determine the reasons for this.

The limited nature of the point methodology of the assessment may also contribute to variability in the results. Improvements could probably be made by averaging seepage and conductivity readings over 20-30m lengths of channel, rather than lines across the channel. This bulking process could assist in smoothing out local variations and anomalies that may occur in isolated sections of channel.

■ **Figure 4-21 Donald Main Channel Idaho Seepage Meter Results vs EM31 (2002) Apparent Conductivity**



4.3.8 Conclusions

These trials have confirmed that point tests are generally not reliable for directly quantifying seepage. Due to variable and sometimes erratic values obtained in measurements, the trials have illustrated that a large number of tests is required to sufficiently determine the true seepage rate of a section. Therefore they are generally not considered reliable for absolute quantitative purposes and should generally be limited to determining the distribution of seepage losses (i.e., relative seepage). Even for this use a large number of tests are recommended to minimise the effects of local variability. These conclusions equate to the findings of the literature review.

In addition, it was apparent in a number of channels that the bed of the channel was seeping at a different rate to the walls of the channel. This appeared to be occurring at a number of the point test sites, as evidenced by higher seepage rates in the base of the channel than the pondage test rates. This is in contrast to the normal phenomenon with point tests where lower seepage rates than actual are often obtained (due to the non-detection of 'hot spots'). In these cases, even very high density point test sampling in the bed of the channel can not determine the actual seepage rate.

In terms of choice of equipment for point testing:

- The Idaho seepage meter appeared to provide the most reliable results of the three instruments. This concurs with the fact that the channel is full during the test and that truly saturated flow is being measured. However there are very few operators skilled in use of the equipment and therefore testing is limited by their availability. The tests are also very expense, due to the fact two operators are required, including one skilled in use of the meter.

- Definitive comments cannot be made regarding the accuracy of the disc permeameter compared to the ring infiltrometer. Some trouble was encountered however with the ring infiltrometer in terms of seepage outside of the ring. The disc permeameter is simpler to use than the ring infiltrometer, both in terms of operation and manual handling.

4.4 Groundwater Techniques

4.4.1 Introduction

Groundwater observation bores are often required as part of a channel seepage investigation (for geological and hydrogeological characterisation etc). However groundwater bores can also be used to quantify seepage rates based on groundwater level fluctuations. Quantitative assessment of seepage rates was conducted at the Donald Main Channel and a qualitative assessment was conducted for the Tabbita channel.

4.4.2 Methodology

Observation of groundwater levels in a series of piezometers located at right angles to the centre line of a channel provides data to determine the flow lines and equipotential lines of seepage water. The amount of seepage can be estimated by studying the variations in the watertable combined with variations in channel running level. The best period of observation is during the rise in watertable when a channel is put back into operation or during the fall of the watertable at the end of the channel run season. This approach requires a minimum of two groundwater observation bores at right angles on either side of the channel. An estimate of aquifer hydraulic conductivity is also required. This can be estimated based on the textural properties of the material identified during the drilling of the bores, but is preferably obtained by aquifer pumping tests or slug tests.

4.4.3 Donald Main Channel

4.4.3.1 Monitoring Bore Set-Up

Four transects of groundwater bores have been installed at the Donald Main Channel, and fortnightly to monthly monitoring of water levels has been ongoing since the installation of the bores. The location of the bores is presented in Figure 4-22. Transects A and B existed prior to this ANCID study. One additional up-gradient bore was added to Transect A and B and the entire transect C and D were installed as part of this investigation. This drilling was completed from 1st-3rd August 2000. Table 4-6 summarises the bore construction and survey elevation data for the groundwater bores at the Donald site. As labelled in this table, Bores SC3 & SC4 and SC5 & SC6 are nested sites (ie a deep and shallow bore in the same location).

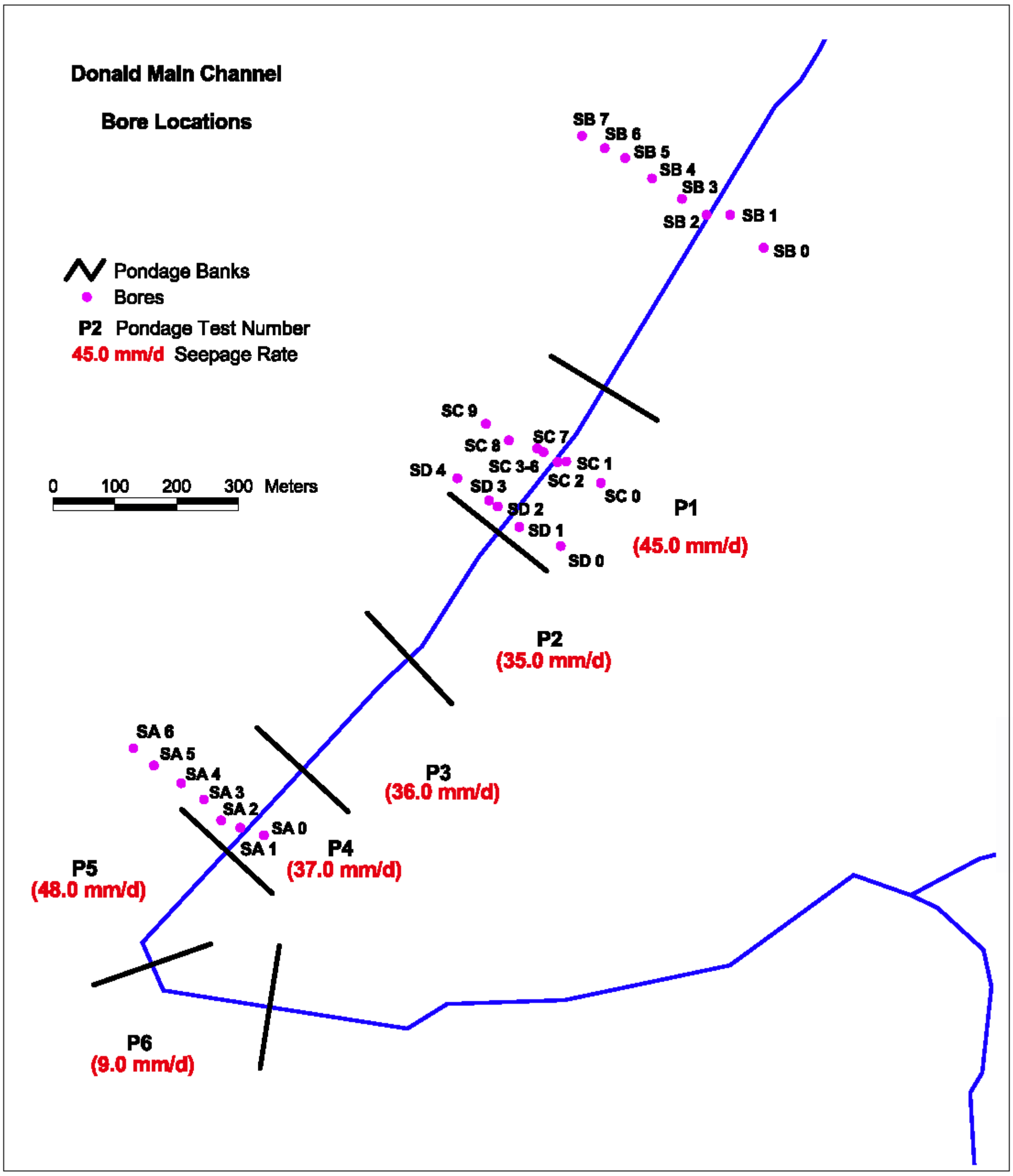
4.4.3.2 Groundwater Level Response

Figure 4-23 and Figure 4-24 present the groundwater hydrographs for Transects A and B, and C and D respectively. Transects A and B have a longer record as they were monitored before the commencement of the project. Plotted on each of these graphs is the gauge level of the channel. Where the gauge line is flat, the channel was not in operation. The groundwater response to the operation of the channel is clearly seen in these graphs. The near channel bores rise 1-2m in a matter of weeks after the filling of the channel (rate dependent on distance from the channel). The hydrograph responses for bores greater than 50m from the channel generally display 0.5-1m rises in groundwater level, suggesting some impact. Although in some cases and at particular times of year there could be an additional variation in water level caused by regional recharge to the aquifer, this is not evident from the hydrographs.

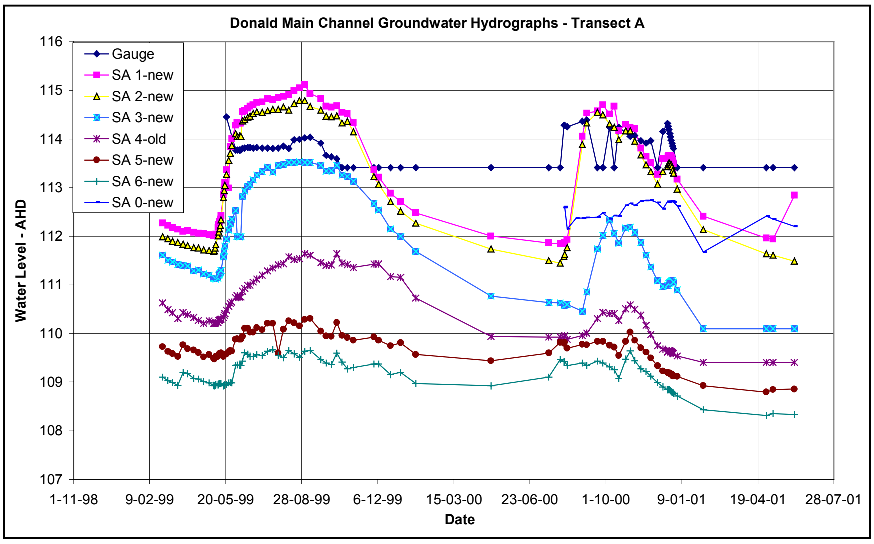
▪ Table 4-6 Donald Main Channel Groundwater Bore Construction Data

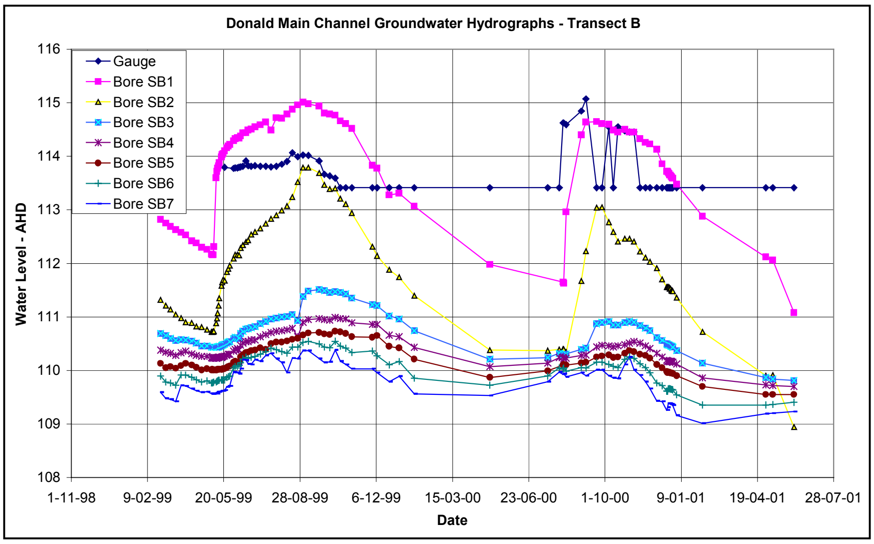
Transect (Nested)	**Bore ID**	**Total Depth (m)**	**Top of Casing (m, AHD)**	**Natural Surface (m, AHD)**	**Screen From (m)**	**Screen To (m)**	**Dominant Lithology**
A	SA0	8.5	118.17	117.58	6	8.5	Sandy Clay
	SA1	6.5	117.71	116.81	3.9	5.9	Sandy Clay
	SA2	5.7	116.07	115.11	3.0	5.0	Sandy Clay
	SA3	4.0	114.64	113.62	1.3	3.3	Clay
	SA4	4?	113.43	111.99	2?	4?	Sandy Clay?
	SA5	4.8	111.26	110.25	2.2	4.2	Sandy Clay
	SA 6	5.0	110.87	109.89	2.4	4.4	Sand
B	SB0	11	121.05	120.60	7.0	11.0	Clay
	SB1	6.5	118.18	117.16	3.9	5.9	Sand
	SB2	5.0	115.54	114.35	2.4	4.4	Sand
	SB3	5.5	114.51	113.47	3.0	5.0	Sandy Clay
	SB4	5.0	114.46	113.40	2.0	4.0	Sandy Clay
	SB5	5.0	114.15	113.13	2.4	4.4	Sandy Clay
	SB6	6.0	113.17	112.16	3.4	5.4	Sandy Clay
	SB7	5.0	111.66	110.60	3.9	5.9	Clay
C	SC0	11	119.56	119.08	8.5	11	Clay
	SC1	8.5	118.14	117.75	6	8.5	Clayey Sand
	SC2	7	117.32	116.96	4.5	7	Clayey Sand
Nested	SC3	3.7	116.93	116.45	1.2	3.7	Sandy Clay
	SC4	8.5	116.83	116.45	6	8.5	Clayey Sand
Nested	SC5	2.5	115.24	114.97	0.5	2.5	Clayey Sand
	SC6	7	115.42	114.98	4.5	7	Sandy Clay
	SC7	7	114.69	114.22	4.5	7	Sandy Clay
	SC8	7	113.24	112.73	4.5	7	Sandy Clay
	SC9	7	113.17	112.69	4.5	7	Clay
D	SD0	10	120.12	119.68	7.5	10	Sandy Clay
	SD1	7	117.37	116.91	4.5	7	Sand
	SD2	7	115.36	114.94	4.5	7	Sandy Clay
	SD3	7	114.43	114.12	4.5	7	Sandy Clay
	SD4	7	112.94	112.49	4.5	7	Sandy Clay

■ **Figure 4-22 Donald Main Channel Bore Locations**

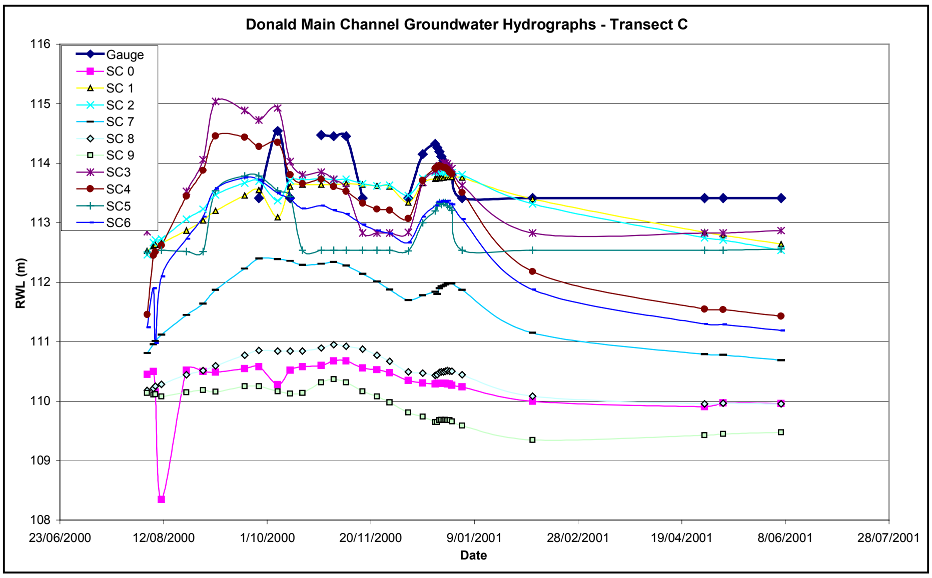


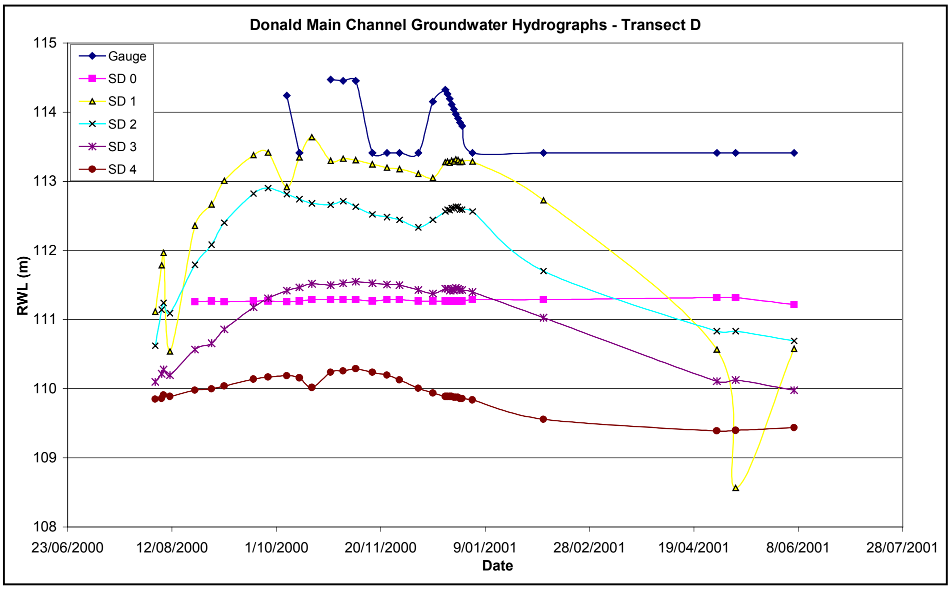
■ **Figure 4-23 Donald Main Channel Groundwater Bore Hydrographs, Transects A & B**





■ **Figure 4-24 Donald Main Channel Groundwater Bore Hydrographs, Transects C & D**





4.4.3.3 Seepage Estimates

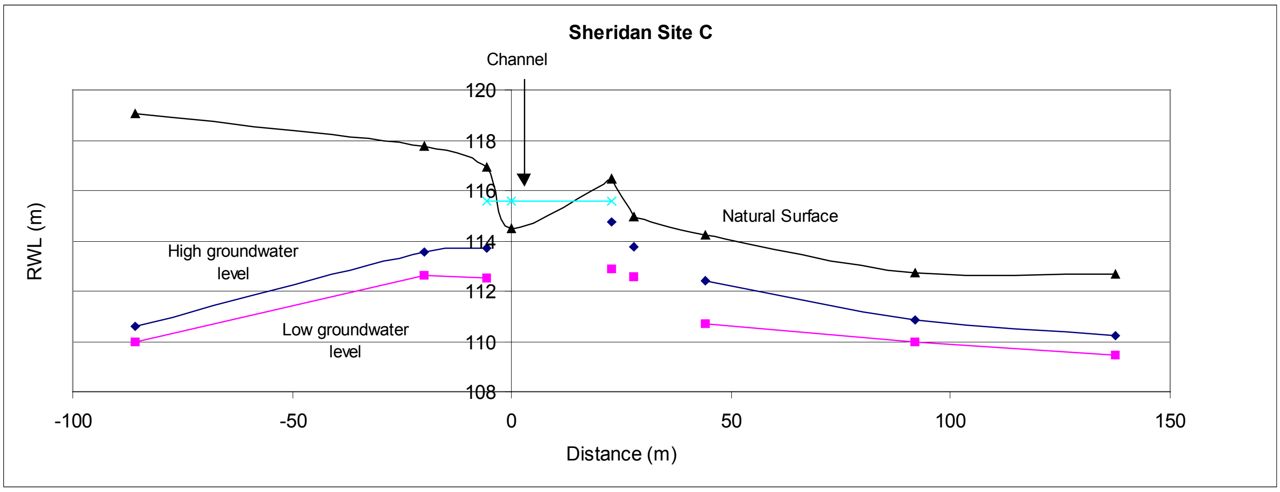
Groundwater levels at the Donald Main Channel were used to estimate seepage beneath borelines C and D. The seepage rates at Donald involved calculating groundwater flow using the Dupuit Forcheimer equation for steady flow in an unconfined aquifer. The solution for *one* side of the flow from the channel is given by:

$$q = -0.5\,K\,\frac{(h_2^2 - h_1^2)}{L}$$

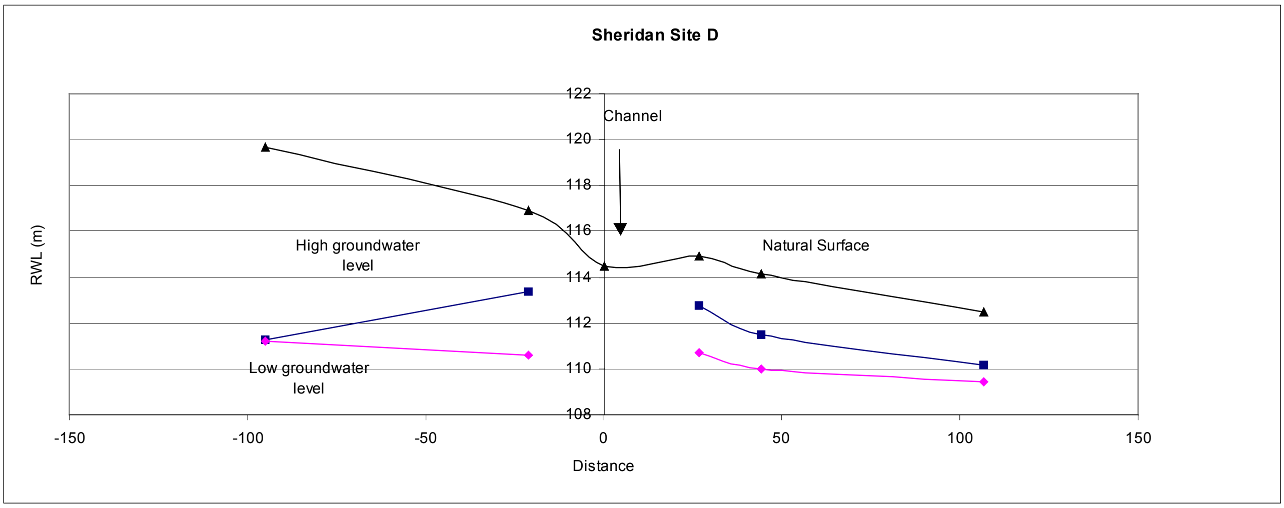
Where h_2 is the head in the channel and h_1 is the head in the observations well.

The hydraulic gradient was calculated using the head in the channel and the most distant bores from the channel at times of channel operation and non-operation for Borelines C and D. These are shown in Figure 4-25 and Figure 4-26.

- **Figure 4-25 Groundwater levels across Boreline C**



- **Figure 4-26 Groundwater Levels Across Boreline D**



The Dupuit Forcheimer equation was applied to a range of groundwater conditions where groundwater levels vary. The hydraulic conductivity (K) was assumed to range between 0.2 and 1 m/day which is typical of a clayey sand/sandy clay aquifer. The results are summarised in Table 4-7 below. The calculation assumes that the base of the flow system is 10m below the "normal" groundwater level.

■ **Table 4-7 Summary of Donald Main Channel Seepage Estimates from Groundwater Data**

Conditions			
Transect C			
Hydraulic Conductivity	**0.2 m/day**	**0.5 m/day**	**1m/day**
Elevation of Datum (base of Aquifer)	100	100	100
Head in the Channel (h2)	114.5	114.5	114.5
Head in the Observation Bore (h1)	111	111	111
Distance between edge of channel and obs bore	70	70	70
Discharge (m3/day)	0.1275	0.31875	0.6375
Estimated seepage into aquifer (mm/day per m length) for half of 6m wetted perimeter	42.5	106.25	212.5

Conditions			
Transect d			
Hydraulic Conductivity	**0.2 m/day**	**0.5 m/day**	**1m/day**
Elevation of Datum (base of Aquifer)	100	100	100
Head in the Channel (h2)	114.5	114.5	114.5
Head in the Observation Bore (h1)	110	110	110
Distance between edge of channel and obs bore	100	100	100
Discharge (m3/day)	0.11025	0.27563	0.55125
Estimated seepage into aquifer (mm/day per m length) for half of 6m wetted perimeter	36.75	91.875	183.75

The seepage estimates (42.5mm/d Transect C and 36.75 mm/day for Transect D) based on analytical groundwater flow calculations results for the assumed hydraulic conductivity of 0.2m/d are consistent with the pondage test results (45mm/day) for Pond1 where these transects are located.

The estimated rates using higher hydraulic conductivity values are clearly much higher than the observed results. Further investigation (including slug tests to determine actual hydraulic conductivities) are required to provide greater confidence in the estimates based on piezometric levels alone.

4.4.4 Tabbita

Two groundwater monitoring bore transects were installed at the Tabbita trial site in August 2000. The bore locations are shown in Figure 4-27, with bores 1-8 on Transect 1 and bores 9-13 on Transect 2. Drilling information is detailed in Table 4-8.

■ **Table 4-8 Tabbita Groundwater Bore Construction Details**

Nested Sites	Bore ID	Depth (m)	TOC (Bore Stick Up) m	Depth below surface	Screen From (m)	Screen To (m)	Dominant Lithology	Hydraulic Conductivity (m/d)
Bore 1&2 nested	1	9.47	0.53	8.94	8.5	6.5	Clay	0.00055
	2	4.31	0.56	3.75	3.25	2.25	sandy clay	-
Bore 3&4 nested	3	9.38	0.58	8.8	8.3	6.3	Clay	0.058
	4	6.73	0.55	6.18	5.6	4.6	Clay	-
Bore 5&6 nested	5	9.86	0.48	9.38	8.8	6.8	Clay	0.26
	6	4.25	0.48	3.77	3.2	2.2	sandy clay	-
	7	9.27	0.62	8.65	8.1	6.1	Clay	0.00018
	8	6.95	0.67	6.28	5.8	3.8	sandy clay	0.00013
Bore 9&10 nested	9	9.03	0.75	8.28	7.8	5.8	Clay	0.0011
	10	4.97	0.58	4.39	3.9	2.9	Clay	-
	11	7.14	0.36	6.78	6.3	4.3	Clay	0.5
	12	9.02	0.3	8.72	8.2	6.2	Clay	-
	13	8.53	0.8	7.73	7.2	5.2	sandy clay	-

Water level monitoring commenced on these bores from 27th September 2000 and is currently ongoing. Hydrographs have been prepared for each transect up to 7th August 2001. Figure 4-28 and Figure 4-29 displays the hydrographs for transects 1 and 2 respectively.

4.4.4.1 Transect 1

Essentially 3 types of response are observed in the hydrograph behaviour in Transect 1:

iv) Bores adjacent the channel (nested site 1 & 2 and nested site 5 & 6);

v) Bores 10-15m away from the channel (nested site 3 & 4 and bore 7); and,

vi) Bore 8 which is well away from the channel.

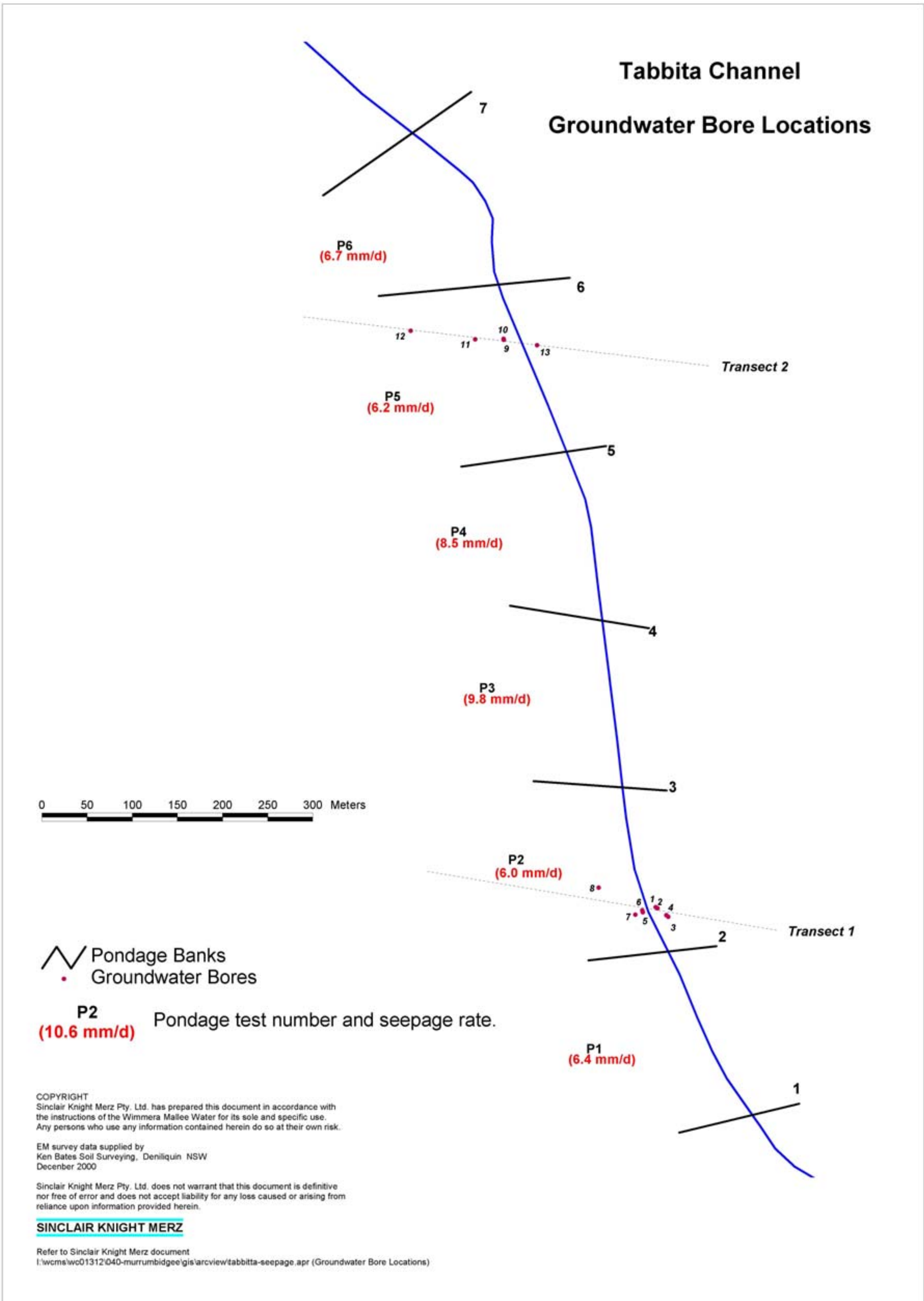
These three categories of response are briefly discussed below:

The hydrographs of the adjacent channel bores in Transect 1 (bores 1& 2 and bores 5 & 6) indicate relatively constant water levels between October 2000 and June 2001, with relatively minor fluctuations only observed in this period. This corresponds with the fact that the channel was running throughout this time, largely masking any other influences on hydrograph groundwater behaviour. The channel ceased operation in early June 2000, however water was held upstream and released for the pondage tests which finished on 26th June 2001. The rapid decline in groundwater levels can be seen in the bores adjacent the channel following this period (approximately 0.7m between monitoring periods). A delayed response was observed in the bores on the west side of the channel (nested bores 5 & 6) compared to the response observed on the east side (nested bores 1 & 2).

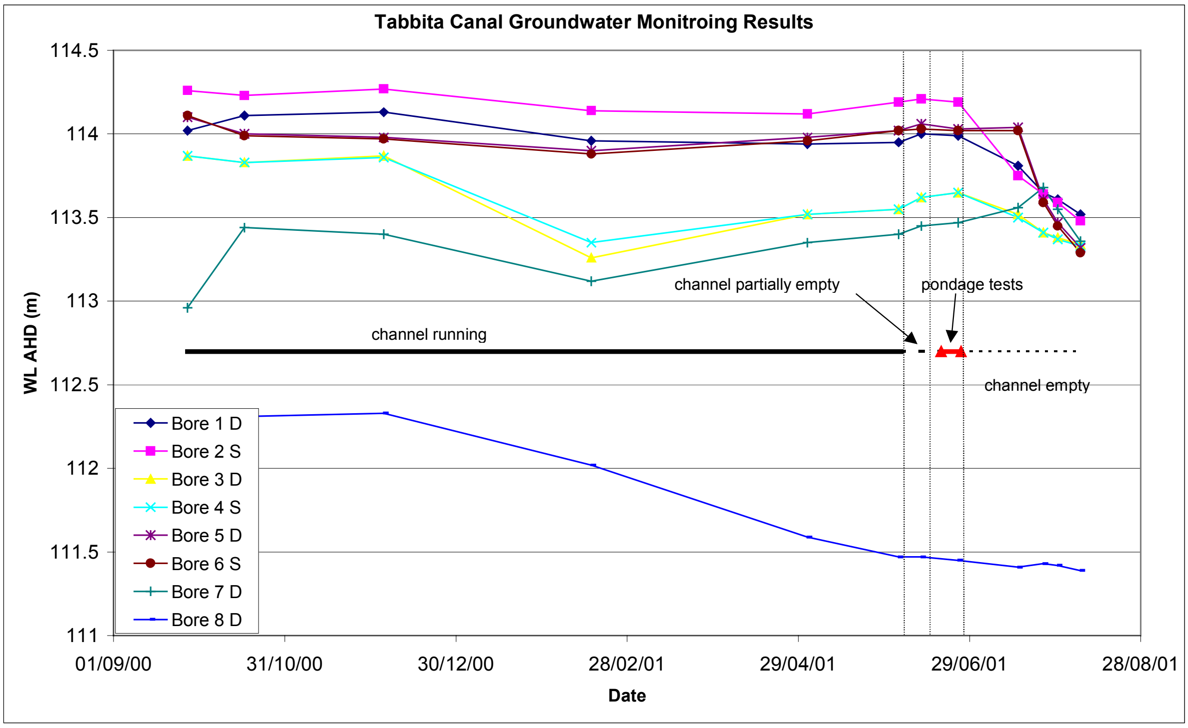
Bores which are a moderate distance (10-15m) away from the channel (nested site 3&4 and bore 7) display greater fluctuation in water levels during the period of channel operation. The gradual fall of these hydrographs from the start of monitoring until end of February and then the gradual rise again is probably due to annual seasonal variation in the groundwater levels. These bores also drop appreciably following the shut down of the channel, but generally only by approximately 0.4m. The decreased effect obviously due to the increased distance from the channel. Again there is a delayed effect in the response to the removal of water in the channel in the bores on the west side of the channel (bore 7) compared to the east side (nested bores 3 & 4). The delay is more significant in this instance, with water levels continuing to rise for approximately 1 month (check) after channel shut down.

Bore 8 displayed a continually declining water level throughout the period of monitoring. Given its distance from the channel there is insufficient period of monitoring at this stage to assess whether there is any channel seepage related response in the water levels. The inconsistent response between bore 8 and the intermediate distance bores, may an indicate that either bore 8 is anomalous and the results should be treated with caution, or that other factors are effecting the response of the bores closer to the channel (other than the channel) such as irrigation of the adjacent vines, and causing the variation observed in the groundwater levels. Further information of activities around the site which might influence local groundwater conditions and a greater period of monitoring are required to assess these influences.

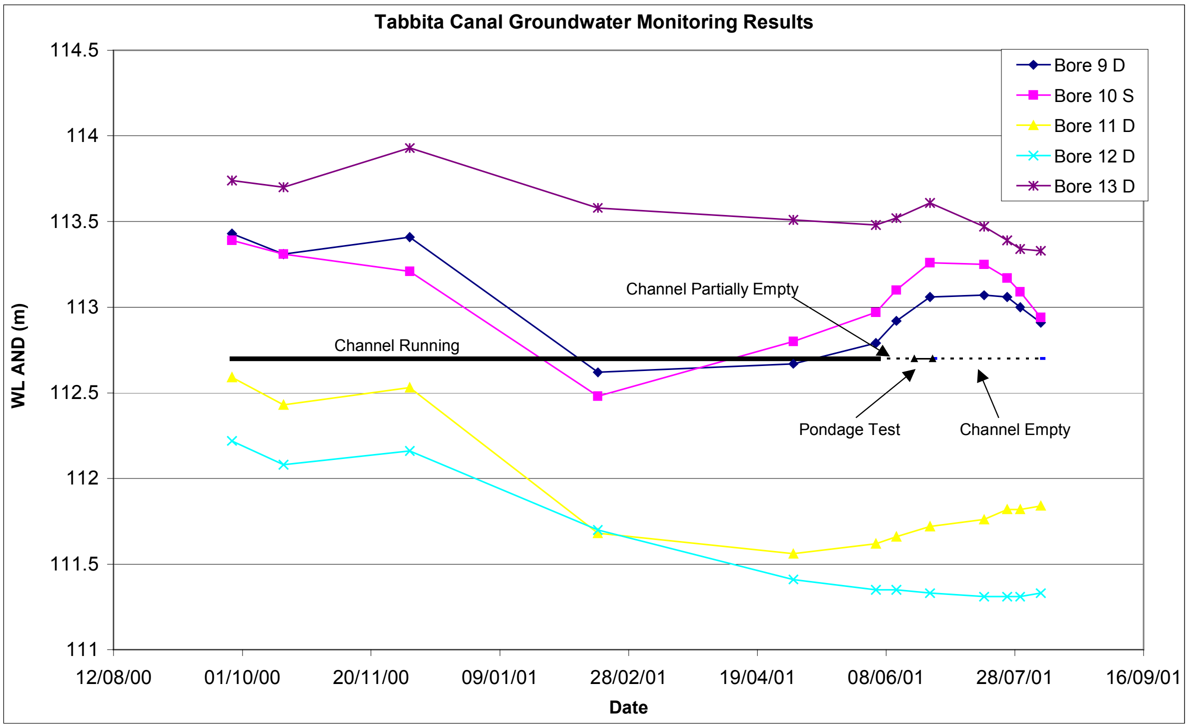
■ **Figure 4-27 Tabbita Groundwater Monitoring Bore Locations**



■ Figure 4-28 Tabbita Groundwater Bore Hydrographs – Transect 1



■ Figure 4-29 Tabbita Groundwater Bore Hydrographs – Transect 2



4.4.4.2 Transect 2

Essentially 2 types of response are observed in the hydrograph behaviour in Transect 2:

1) Bores 10-15m away from the channel (bores 9, 10 and 13); and,
2) Bores 11&12 which is well away from the channel.

These categories of response are briefly discussed below.

The hydrographs from the bores 10-15m from the channel Transect 2 (bores 9, 10 & 13) show that bore 13 had relatively constant water levels between October 2000 and June 2001, with relatively minor fluctuations only observed in this period. This corresponds with the fact that the channel was running throughout this time, largely masking any other influences on groundwater behaviour.

Bores 9 and 10, a similar distance to the channel as bore 13 show a greater fluctuations in groundwater levels during the monitoring period with a gradual fall in groundwater levels from the start of monitoring until end of February and then the gradual rise again. This may be attributed to annual seasonal variation in the levels with groundwater levels from these bores following similar trends to that of bores 11 and 12.

The channel ceased operation (pondage test completed) on 26th June 2001, and groundwater levels in the bores adjacent the channel, bores 9, 10 and 13, dropped sharply, by approximately 0.3m between 25th June 2001 and 7th August 2001.

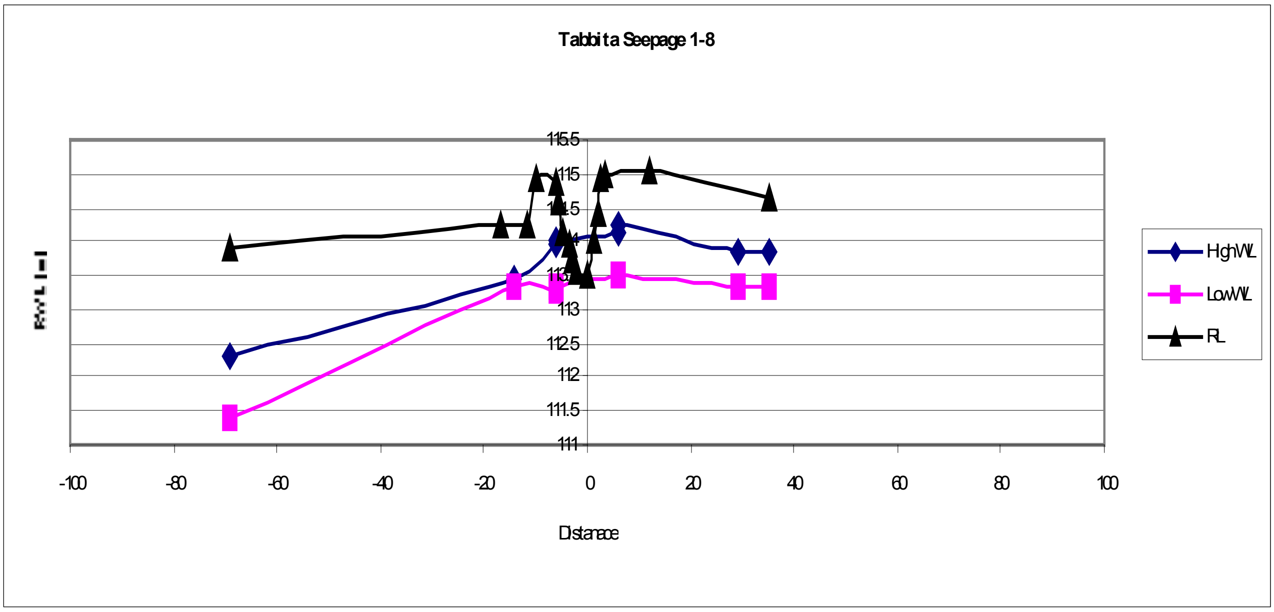
Bores 11&12 are a greater distance from the channel and appear to be influenced more from regional groundwater trends rather than from the channel.

4.4.4.3 Summary

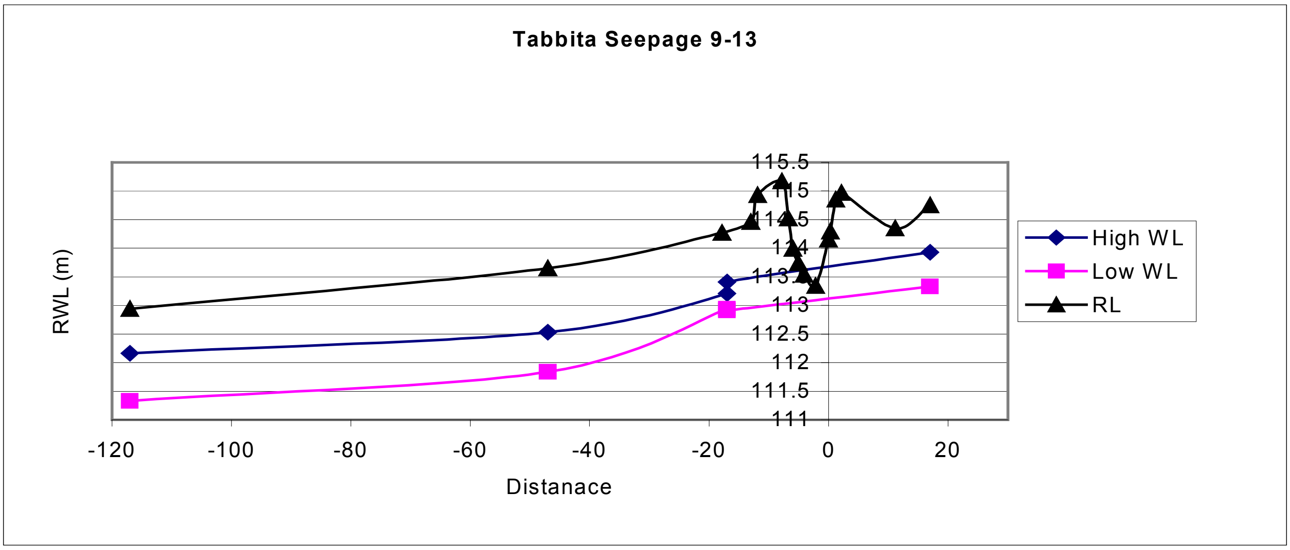
In summary, both transects 1 and 2 indicate significantly declining waterlevels in the bores close to the channel during the channel closure period (June and August 2001). This is almost certainly attributable to the removal of the groundwater recharge source of the seeping channel. Bores at an intermediate distance (10-15m) from the channel displayed a subdued response to seepage and bores at a significant distance from the channel (>50 m) showed little response that may be attributed to channel seepage over the period of monitoring available.

The cross sections displayed in Figure 4-30 and Figure 4-31 display high and low water levels in the two Tabbita bore transects.

■ **Figure 4-30 Tabbita Channel, Bore Transect 1: Groundwater Level Cross-Section**



■ **Figure 4-31 Tabbita Channel, Bore Transect 2: Groundwater Level Cross-Section**



4.4.5 Conclusions

The trials conducted in this investigation suggest that use of groundwater bores for quantitative analysis of seepage rates is not considered an accurate or cost effective means of determining seepage rates for typical Rural Water Authority investigations. In order of increasing importance the method is not considered accurate due to:

- Sensitivity to hydraulic conductivity inputs (eg Tabbita – depending on input hydraulic conductivity, seepage rates of varying orders of magnitude can be obtained) and the cost of obtaining sufficiently reliable estimates.
- Relies on assumptions regarding pre-channel groundwater water levels. These can be estimated from conditions before and after channel filling, but depending on site hydrogeology this assumption may or may not be accurate.
- It is essentially a type of point test and does not answer the question of what area of the channel is seeping. A high density of bore transects would be required for meaningful identification of local areas of channel seepage.
- Relies on an assumption of aquifer thickness (this may be able to be calculated but in a deep aquifer this may be very expensive).

4.5 Remote Sensing

A remote sensing trial was planned for the Wimmera, including the Rocklands, Toolondo and Donald Main Channels as part of the Stage 1 project. However the trial was not undertaken as it could not be accommodated into the RWA budget. However, the project brief for this trial is contained in *Appendix* D. The brief contains information regarding the type of issues that require consideration when developing a methodology for using remote sensing to identify channel seepage.

Prior and separate to the ANCID Stage 1 project, Wimmera Mallee Water arranged for the collection of airborne video multispectral imagery along the Rocklands and Toolondo channels (conducted by Charles Stuart University, CSU). This data was evaluated by Sinclair Knight Merz (with a view to potentially incorporating the results into this project) but unfortunately the data was not in a form suitable for use in the project. The reasons for the unsuitability of this data are briefly documented below:

- Imagery was collected along the Rocklands and Toolondo channels and included data in the red, green, blue and near infrared bands.
- The image pixel size was 2m and the registration accuracy was found to be variable compared to the WMW geographic information system (GIS) channel data. The ground control data provided by WMW consisted of channel outlines and registration accuracy in the channel areas was considered to be 10 – 15 m by CSU.
- There were some concerns with registration of the base GIS data and the pixel size of the imagery.
- The quality of the images was variable for different bands. This has been attributed to the time of year of the imagery (June) which equates to reduced solar irradiation and reflectance, and possibly a light haze above the Toolondo Channel which would affect the shorter wavelengths (bands 1 – 3 rather than band 4, which is longer) as observed.
- The mosaics of the Toolondo Channel were found to be co-registered along the channel within the area of interest, however, the colour matching could be improved. The recent mosaics, displayed in infrared mode appeared to show some correlation with the results of the EM data and may have some potential for seepage detection.
- The re-sampled 8 m mosaics appeared to be acceptable at the upper limit for viewing the channel, its immediate surrounds and location/presence of trees.

The following conclusions were made regarding the available data:

- Further investigation of the registration of one of the bands was required.
- The mosaics need to be improved, particularly with respect to colour matching, co-registration, gaps and duplications before they can be included in the GIS.
- There may be some potential of the infra-red data to contribute to the detection of channel seepage, however, this requires further detailed GIS analysis with other data sets to confirm.
- The use of the imagery for detecting vegetation affects of channel seepage is limited due to the timing of the image acquisition as the optimum time would be during drier periods (ie. late Spring to Autumn).

4.5.1 Summary

Remote sensing trials were not conducted in the Stage 1 investigation. However conclusions regarding remote sensing techniques (are made below) based on knowledge gained through the literature review and preparation of a brief for proposed trials:

- Remote sensing techniques offer considerable potential for rapid identification of seepage zones (but not quantification) of large lengths of a channel system. Remote sensing should primarily be regarded as a seepage identification tool and not a seepage quantification tool. Quantification using remote sensing was to be trialed in this study, however there are currently no documented studies of remote sensing being used to quantify channel seepage.
- The techniques are best suited to investigation where the primary aim is identification of land degradation associated with channel seepage. Remote sensing techniques rely on the detection of differences in soil / moisture properties in the upper surface. Therefore it has significant potential if there are known surface effects of channel seepage. Conversely, they should not be used if it is known that the seepage mechanism is predominantly vertical, such as is likely to occur at sites with a deep watertable.
- Remote sensing will be most useful in environments where lateral seepage is predominant. For example sites with a high watertable, shallow impermeable layer or bank seepage - these environments represent conditions most likely to facilitate lateral seepage and cause the seepage to have a surface expression.
- It offers a promising means of providing a first-cut identification tool for targeting potential seepage sites, although a drawback is that it assumes seepage will have a surface expression as moist soil or associated vegetation adjacent the channel.
- For this method to be cost effective, it needs to be conducted at a suitably large scale. Costs are likely to come down and resolution likely to improve as the technology develops, and will therefore become an increasingly attractive option.
- If remote sensing is proposed it should be well thought out and planned , given the high cost of the resources involved.

5 Geophysical Techniques

5.1 Introduction

Geophysical techniques were identified in the literature review (ANCID, 2000a) as having potential for channel seepage identification and quantification. In addition, geophysical techniques fit well with the type of technique RWAs require for channel seepage assessment. The national RWA survey indicated that RWAs considered cost and speed to be the most important criteria in selecting a channel seepage measurement technique, with accuracy of lower importance (ANCID, 2000b). This suggests that RWAs are looking for a relatively cheap technique that can provide a reasonable estimate of seepage rates, with some margin for error in estimates considered an acceptable trade-off for improvements in cost and speed. The project therefore incorporated trials of geophysics in its program.

5.1.1 Theory of using geophysics to identify and quantify seepage

Seepage of water from channels causes local changes in the physical properties of the areas surrounding the channels. These include an increase in saturation, decrease in groundwater salinity, decrease in stored salts and a rise in the watertable. These changes all have an effect on the terrain electrical conductivity (or its inverse, resistivity) and therefore can be detected using electrical geophysical techniques, which measure resistivity or conductivity.

The overall conductivity / resistivity response is dependent on both soil lithology and the salt content of any contained water. In general it can be assumed that the clays will be more conductive due to their chemical structure. These properties are in contrast to the sands, which generally have a lower conductivity. When both parameters (lithology and groundwater salinity) are varying, interpretation can be difficult. However, in the case of channel seepage, higher permeability soils and low salinity water in areas of high channel seepage will enhance each other to produce a low conductivity / high resistivity response. Therefore conductivity can be used to map areas of high permeability soils and low salinity water emanating from the channel.

The two techniques used in the trials were electromagnetics (Geonics) and resistivity, based on techniques identified as most likely to be successful in the literature review (ANCID, 2000a). These each provide different depth sub-divisions. EM31 and EM34 essentially average the conductivity over a depth (to provide one number representative across that depth) where as the resistivity technique used was multi-channel, which provides a depth distinction (various numbers for different depth intervals are provided).

5.1.2 Methodology

The basic methodology used to assess the accuracy of geophysical techniques was comparison with pondage test seepage rates. Pondage test seepage was compared to the average geophysical response (conductivity or resistivity) along the length of the pond. Usually pondage tests were conducted back to back, to minimise the number of banks required and hence reduce costs. Comparison of the average geophysical response and pondage test seepage involved plotting the two variables against each other, and analysis of the trends.

As the average geophysical response for the section was selected, it was important that the pondage cell covered a length of similar geophysical response. To achieve this the geophysical survey was conducted prior to the pondage tests, and the pondage test bank locations selected based on the results of the geophysical survey (in most cases). Pondage lengths generally varied between 100m - 300m in length.

While the average geophysical response across the pond was used, and is considered suitable for this study due to the method of selecting a length of like response, there is potential for using geo-statistics to improve the effects of spatial variability on geophysical response.

5.1.2.1 Years 1 and 2 Trials

The first two years of geophysical trials were conducted using Geonics electomagnetic systems (EM31 and EM34). EM31 systems 'see' to about 6-7m depth, while EM34 systems 'see' between 7m – 60m, depending on the coil spacing and dipole orientation used. The following variables were tested during the first two years of the trials (with respect to their impact on the accuracy of the technique compared to pondage test seepage rates):

- The location of the survey (eg adjacent the channel versus away from the channel, or down-gradient side of the channel versus up-gradient side of channel);
- On-land versus on-channel (EM31 only);
- Dipole orientation of EM31 and coil spacing of EM34 (which both effect the depth focus of the instrument); and,
- Repeatability of surveys.

In general, the years 1 and 2 trials showed good correlations between pondage test seepage and the average EM conductivity for the pond (statistical evaluation showed EM conductivity values correlated against pondage seepage rates to give correlation coefficients as high as 0.9 for sections of channel). In addition to this primary finding, other key findings from the years 1 and 2 trials were:

- **Mechanism** - The application of the EM technique appears to primarily depend upon a significant contrast in terrain conductivity being attained due to fresh seeped water invading the more saline formations and particularly changing the salinity of the groundwater. Geological effects appear to be of secondary importance. Therefore it was concluded that a key part of conducting an EM survey for detecting channel seepage is the penetration depth of the survey. The survey should concentrate on the zone immediately above and several metres below the natural watertable, in order to detect the displacement of the natural groundwater with fresher channel water. (As discussed in later in this section, 'detection' above the watertable can also be used to infer where seepage is most likely to occur).
- **Channel operation** – The above hypothesis regarding the primary mechanism by which the geophysical survey 'predicts' seepage indicates that it is important that the EM surveys should be carried out when the channel has been in operation for a period long enough to raise the local water table and for seepage to penetrate the surrounding formations. This may be a relatively short period in sandy formations and longer in clays.

- **Survey location** - Best results were obtained close to the channel bank on the down hydraulic gradient side. Further away from the channel the salinity of the groundwater grades to the background groundwater quality and seepage becomes more difficult to identify.
- **On-channel surveys -** (EM31 in both vertical and horizontal dipole) – Results of variable success were returned. Evidence indicates that these on-channel (boat) surveys use a different method of seepage detection to the land surveys which primarily rely on the detection of the displacement of the natural groundwater with fresher seeped water. (eg in the horizontal dipole the EM31 is essentially monitoring the presence, thickness, and clay content of the retarding layer immediately below the channel. In the vertical dipole mode the success seems to be dependent on the degree to which the survey 'sees' below the fresh flushed zone created uniformly beneath the channel.) In summary, the land based survey appeared to be a more accurate means of assessing channel seepage because it relies on the direct detection of the seepage plume, and is largely unaffected by the seepage mechanism (ie through the walls or base of channel), and is not influenced by the flushed zone immediately beneath the channel.

Trials conducted in the first two years of investigation indicated the potential of geophysical techniques to rapidly identify and quantify sections of channel seepage were superior (both technically and economically) to other techniques assessed in the trials. Therefore geophysical techniques became the primary focus of the year three trials, the methodology for which is described below.

5.1.2.2 Year 3 Trials

Based on the successful first two years of trials and the RWA needs identified in the national survey, the focus of the year three trials was on further development of geophysical techniques. The key conclusions drawn from the year two trials required further testing to asses the effectiveness of geophysical techniques to quantify channel seepage. The two key objectives of the third year program were to:

1. *Identify transferability of correlations between seepage rates and conductivity at different locations*.
   At most sites in the first two years of trials a reasonable relationship between pondage test seepage and average EM(31 & 34) conductivity was obtained. For such a technique to be useful at a broad scale, the applicability of these relationships outside of the pondage test area must be known, ie is the relationship transferable beyond the immediate test area? This involved identifying the key factors which determine the validity of extrapolating geophysical results to predict seepage and the development of general rules for extrapolating results from pondage tests.

2. *Trial a system which simultaneously measures conductivity (or resistivity) at a range of depths*.
   Investigations in the first two year of trials using (single channel) electromagnetic techniques (EM31 and EM34), both inside the channels and along the outside toe of the banks, gave results that indicated that these geophysical techniques were superior (technically and economically) to other techniques assessed in the trials.

   The EM techniques:

- Indicated areas of low conductivity that were related to probable seepage;
- Correlated with pondage test seepage at most sites; and
- Were of high resolution and located narrow areas of possible seepage.

Depending upon local and temporal conditions of watertable depth, different EM systems appeared to perform better at different sites and at different times. An important conclusion was that the EM surveys appeared to work best where the conductivity measurement was focused at the depth where addition of seepage water was most significant in diluting groundwater salinity. The limitation of these single channel electromagnetic systems is that the instruments measure a single parameter equivalent to a single depth. Therefore investigation of a system that simultaneously measures at a range of depths was recommended to ensure penetration to the depth where seepage water and groundwater salinity contrasts are greatest. The advantage of this approach would be that it could be applied independent of knowledge of groundwater depths and salinities. Investigation of multi-channel systems that measure at a range of depths to around 15m below surface was recommended.

The following methodology was adopted for the third year trials in order to meet these objectives:

Objective 1 - Identifying the transferability of correlations established at one site to different locations, was addressed by undertaking geophysical trials at sites with a range of different site conditions which might affect the geophysical survey response. To this end the following tasks were undertaken:

a) *Mapping of key factors effecting geophysical survey response* – At one channel within each RWA (where pondage tests had been undertaken) key factors likely to affect conductivity / resistivity response along 10 - 20 kilometres of channel were collated. These factors included:
   - Soils and Geology; and,
   - Groundwater Depth and Quality.

   Field work was not undertaken in development of the maps, but the finest scale and best quality data available was used.

b) *Selection of new trial sites* – Using these maps two new trial areas were selected along each channel. One area was selected where conditions were similar to the original trial area and the second where conditions differed from the original trial area

c) *At new and original sites undertake geophysical surveys and pondage tests*:
   - An EM31 survey was undertaken at the two new sites and the original site;
   - A new geophysical technique (resistivity) was also trialed at the two new sites and the original site; and,
   - Pondage tests were conducted at each of the sites to determine the accuracy of the geophysical surveys. They were relatively short pond lengths and the bank locations were based on the geophysical survey results (covering areas of like conductivity).

d) *Drilling of soil bores* –Soil bores were drilled to assist in interpretation of the geophysical surveys.

e) *Additional analysis of data using a statistical approach* – A more rigorous statistical evaluation of the data was conducted in the third year of the trials, including conducting a multi-variate analysis to determine potential impacts of other variables on the geophysical response and pondage test relationship.

Objective 2 - To meet the second objective of trialing a system which simultaneously measures conductivity (or resistivity) at a range of depths, a multi-channel system operating from within the channel was deemed to be the most appropriate set-up. This would allow seepage zones to be tracked from the channel base into the groundwater. Various systems and techniques to achieve this simultaneous range of depth penetrations were explored and the most appropriate technique was considered to be a resistivity array towed behind a boat. This system was chosen for the trials reported here. The system was custom designed for the project by Zonge Engineering and Research Organisation, in consultation with a Sinclair Knight Merz senior geophysicist. A paper describing the application of a similar system for canal seepage assessment in the US was recently published (Hotchkiss et al, 2001).

5.1.3 Description of Trial Sites

Figure 5.1 presents the location of all geophysical trials used in the final year's analysis. The trials were conducted within the areas controlled by Wimmera Mallee Water, Murray Irrigation and Murrumbidgee Irrigation. Goulburn Murray Water were also able to contribute useful data to the project, due to seepage investigation work associated with the upgrade of the Waranga Western Channel. Data inputs from this project included an EM31 survey along a significant length of the channel. The data was in a suitable form to incorporate into this study. In addition to the Waranga Western Channel, the Rocklands and Donald Main Channel in the Wimmera were also used in the EM31 analysis, using data collected in year 1 and 2 of the trials. At remaining sites both EM31 and resistivity survey data were collected.

■ **Figure 5.1 Year Three Geophysical Trials Regional Location Map**

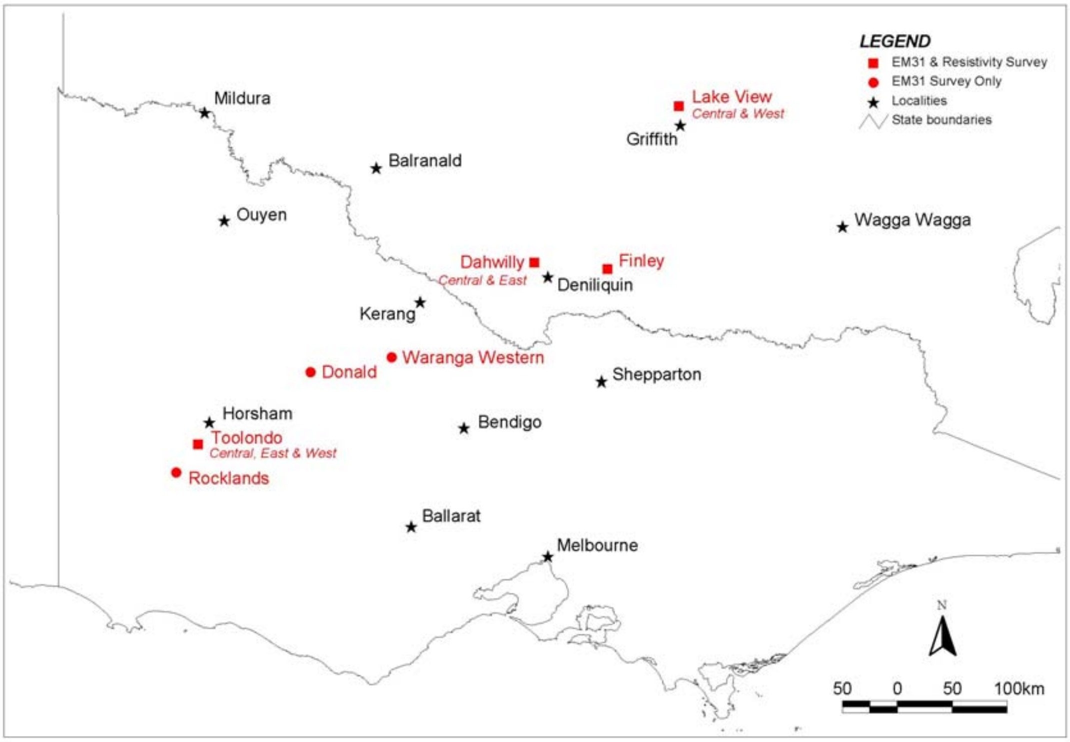


Table 5-1 Year Three Geophysical Channel Seepage Measurement Trial Sites

Rural Water Authority	Channel And Site	Summary of Lithology	Background Groundwater Salinity (µS/cm, EC) / Depth to Groundwater (m)	No. pondage tests / seepage range (mm/d)	Geophysical Techniques Trialed
Wimmera Mallee Water	Toolondo – Central (original site)	Predominantly clay to sandy clay overlying sandstone @ 3 – 9m depth. Fine to medium grained sand 1-2m deep located sporadically across site	❑ ≈ 5,000 EC ❑ ≈ 9 m	6 cells 1 – 12 mm/d	Resistivity & EM31
	Toolondo – West	Surface layer (0.5 - 1m) of weakly cemented fine sand overlying 1-2m of sandy clay, overlying medium clay to 7m, with underlying sandstone	❑ ≈ 5,400 EC ❑ ≈ 9 m	4 cells 1 – 5 mm/d	Resistivity & EM31
	Toolondo – East	Heavy – medium clay to 3-4m, overlying shallow sandstone	❑ ≈ 4,200 EC ❑ ≈ 9 m	4 cells 0 – 1 mm/d	Resistivity & EM31
Murrumbidgee Irrigation	Lake View – Central (original site)	Sandy clay – sand clay loam overlying medium to heavy clay starting from 2-6m below surface	❑ ≈ 6,700 EC ❑ ≈ 1.5 m	4 cells 5 – 7 mm/d	Resistivity & EM31
	Lake View – West	Surface layer (approx 1m) of sandy clay overlying 3-4m of gravelly clay, overlying medium clay	❑ ≈ 5,400 EC ❑ ≈ 0.5 m	4 cells 20 – 25 mm/d	Resistivity & EM31
Murray Irrigation	Dahwilly – Central (original site)	Medium to coarse grained sand to at least 10m depth. Sandy clay to clay loam in top metre along most of channel length	❑ ≈ 5000 EC ❑ ≈ 5 m	7 cells 1 – 10 mm/d	Resistivity & EM31
	Dahwilly – East (Pretty Pine)	Medium to coarse grained sand to approx 6-8m depth, underlain by clayey sand. Sandy clay to clay to 1-2 m at surface	❑ ≈ 2,500 EC ❑ ≈ 5 m	3 cells 9 – 10 mm/d	Resistivity & EM31
	Finley	Heavy clay to 8-9m, overlying sandy clay.	❑ ≈ 17,500 EC ❑ ≈ 1.5 m	3 cells 5 – 7 mm/d	Resistivity & EM31
Additional Sites Used in EM31 Analysis					
Wimmera Mallee Water	Donald Main Channel	Surface layer (approx 0.5-1m) of clayey sand overlying predominantly clay, but replaced by fine-med. grained sand in southern half of trial site, starting near surface and dropping to 2-3m below surface in section centre	❑ ≈ 30,000 EC ❑ ≈ 2 m	6 cells 9 – 48 mm/d	EM31 only
	Rocklands	Predominantly sandy clay in southern half of site overlying sandstone at depth. Sand at 1-2m rising to surface, also in south. Sandstone rises to near surface in northern part of site, underlying shallow clay soils.	❑ ≈ 11,000 EC ❑ ≈ 5 m	6 cells 4 – 13 mm/d	EM31 only
Goulburn Murray Water	Waranga Western Channel	Predominantly clay to sandy clay overlying sandstone at varying depths. Fine to medium grained sand intersect channel and at depth at various intervals along the channel	❑ ≈ 25,000 EC ❑ ≈ 8 m	11 cells 1 – 13 mm/d	EM31 only

Table 5-1 provides an overview of the key characteristics of each of the year three trial sites, including:

- ❑ A summary of lithology;
- ❑ Background groundwater salinity and depth to groundwater; and,
- ❑ The number of pondage tests conducted at the site and the range of seepage rates obtained during the tests.

This table illustrates that the seepage sites encompass a wide range of site conditions, in terms of lithology, groundwater depth and salinity, and seepage rates. Further details of the lithology at each of the sites are contained in *Appendix* A, which presents a geological long section of each of the sites.

5.2 EM34 Trial Results

5.2.1 Introduction

5.2.1.1 EM34 Systems

Frequency domain electromagnetic (FEM) systems can measure the electromagnetic properties of the soil profile up to a depth of 100m, with the penetration depth dependent on the frequency and coil spacing. These studies used the Geonics style FEM units which utilise the concept of low induction numbers to give an output in conductivity. For a given coil spacing, Geonics EM systems can be used in horizontal dipole or vertical dipole mode. The dipole mode effects the relative contribution of the profile at different depths to the overall response. In general, near surface features tend to dominate in the horizontal mode while the vertical mode is more influenced by the ‘mid’ part of its depth range (McNeil, 1980).

Geonics EM34 systems can be used at various intercoil spacings so as to vary the effective depth of exploration, in contrast to Geonics EM31 systems which have a fixed coil spacing. Table 5-2 presents maximum exploration depths for Geonics EM34 systems at various coil spacings and dipole orientations. Figure 5-2 shows an EM34 unit in operation. It is a slower technique than EM31, as the required coil spacing means that the coils must be carried by hand.

■ **Table 5-2 Exploration Depths for EM34 at Various Intercoil Spacings (after McNeil, 1980)**

Intercoil Spacing (m)	Exploration Depth (m)	
	Horizontal Dipoles	Vertical Dipoles
10	7.5	15
20	15	30
40	30	60

- **Figure 5-2 EM34 In Operation**

5.2.1.2 Methodology

A horizontal dipole orientation was used in all of the EM34 trials, usually at a coil spacing of 10m, with 20m also trialed at some sites. Based on previous experience with EM34 channel seepage assessment (SKM, 1998) and on results emerging from the initial EM31 trials, only one survey line on each side of the channel was conducted (compared to EM31 where 3-4 lines were conducted). Each line was located immediately adjacent the outside toe of the channel. The surveys were conducted by subcontractors with experience in EM34 operation.

As described above (refer Section 5.1.2), the basic assessment methodology consisted of comparison of the pondage test results to the average EM34 conductivity for the corresponding pond length.

5.2.2 Results

The following EM34 surveys were conducted during the three years of trials and are reported on in this section:

- Rocklands – November 1999 and August 2001;
- Donald Main – October 1999 and September 2001;
- Toolondo Central – August 2001; and,
- Dahwilly Central – *February* 2002.

5.2.2.1 Rocklands – November 1999 and August 2001

November 1999

An EM34 conductivity survey was conducted from 1st – 4th November 1999 (by sub-contractor Michael Murphy), along the down gradient outside channel toe along 30km of the Rocklands channel. The survey was conducted using a coil spacing of 10m (horizontal dipole) and the channel was running at the time of the survey. Depth to watertable at the site is around 5m, therefore the technique measures the conductivity of the profile above and several metres below the watertable. The section of interest from the survey (ie where the pondage tests were conducted) and the associated conductivities are shown in Figure 5-3.

The EM34 data were plotted against the pondage tests results (average down gradient channel toe EM34 conductivity for the pondage section verses the steady state pondage test seepage rate). This analysis shows a consistent relationship between seepage and conductivity as shown in Figure 5-4, (R^2 = 0.79) which indicates a reasonable correlation between the two variables. Despite a fairly narrow range of seepage rates (4 – 13 mm/d), there is a general pattern that the lower conductivity results relate to higher seepage.

The most significant deviation from the line is Pond 4, which according to the line of best fit, would be expected to record a higher conductivity than was actually detected in the survey (33 mS/m). There is no obvious explanation for this divergence. The Rocklands geological section (refer *Appendix* A) does not indicate anything anomalous with the geology beneath Pond 4.

However, the deviation is not highly significant and the overall correlation is reasonable. The relationship established at the Rocklands site between seepage and EM34 conductivity, as indicated by the regression equation is:

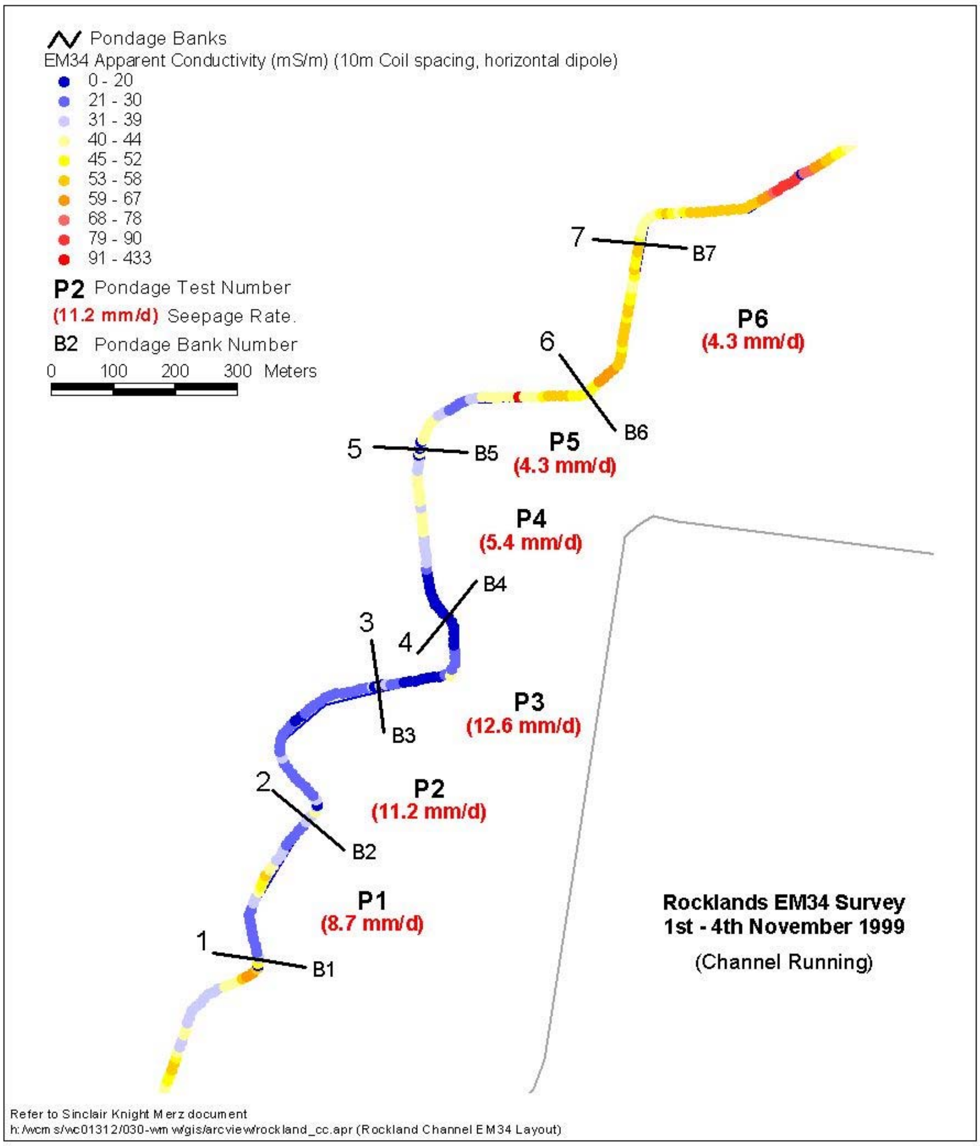
$$\text{Seepage (mm/d)} = 19.5 - 0.34\ EM34_{Cond.}\ \text{(mS/m)}$$

It can be concluded that the average EM34 conductivity correlates reasonably well with pondage test seepage rates at this Rocklands site. The analysis suggests that the relationship established can be used to predict seepage rates along the Rocklands channel, in areas of like geology and hydrogeology.

August 2001

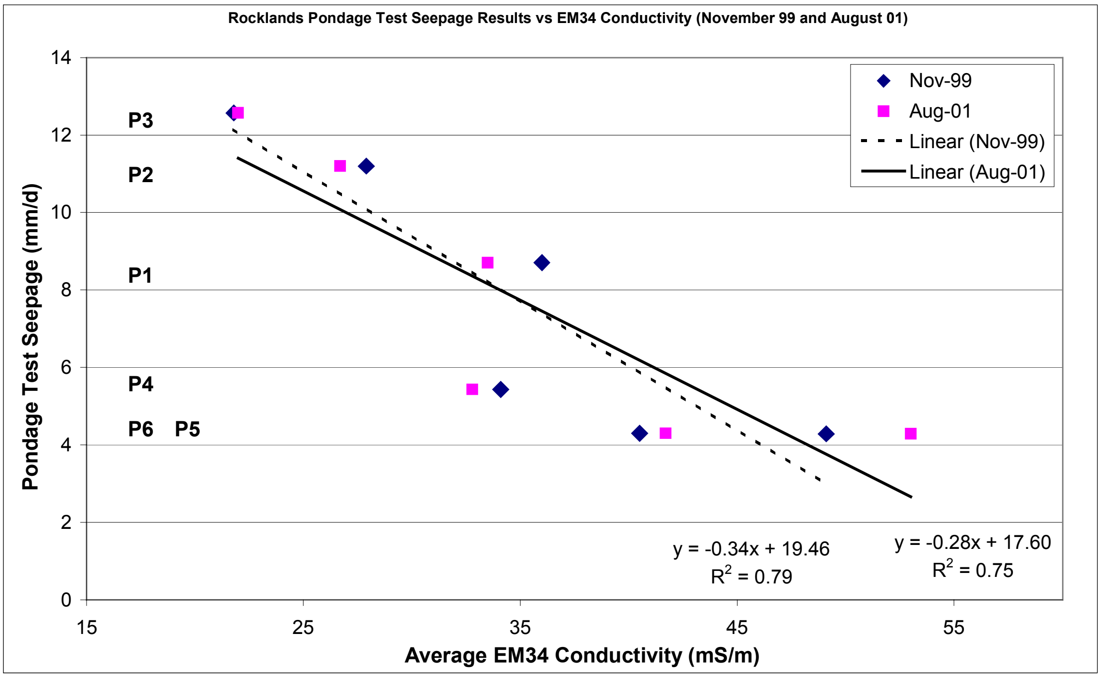
To test the repeatability of the results obtained in the November 1999 EM34 survey, the survey was repeated on 11th August 2001 along the pondage test sections of the Rocklands Channel. The same contractor, coil separation, dipole orientation (horizontal) and location (along the down gradient outside channel toe) were used, and again the channel was in operation at the time of the survey. The mapped results of this survey have not been presented in this report as they are virtually identical to those obtained in the November 1999 survey (Figure 5-3). In addition to the November 1999 data, Figure 5-4 also plots the August 2001 data. This figure shows the high degree of similarity between the two surveys, with again a high correlation coefficient of 0.75 obtained and a very similar line of best fit equation.

■ **Figure 5-3 Rocklands EM34 Survey – November, 1999**



The EM34 surveys at Rocklands demonstrate the repeatability of the method. It also indicates that conditions between the two surveys were reasonably constant (particularly seepage rates and groundwater levels). Not only were the average conductivity results across the pondage tests virtually identical, the individual results along the channel compared very well to each other in terms of magnitude and the coincidence of peaks and troughs in conductivity (graphs not presented in this report).

■ **Figure 5-4 Rocklands EM34 (Nov 1999) verses Pondage Test Seepage**



5.2.2.2 Donald Main – October 1999 and September 2001

<u>*October 1999*</u>

An EM34 survey (10m coil spacing, horizontal dipole) was conducted from 20th - 25th October 1999, along the down gradient outside channel toe along a 43km section the Donald Main channel, east of Lake Buloke. The survey coincided with the shut down of the channel, which had been running for the previous six months (groundwater levels next to the channel were therefore quite high).

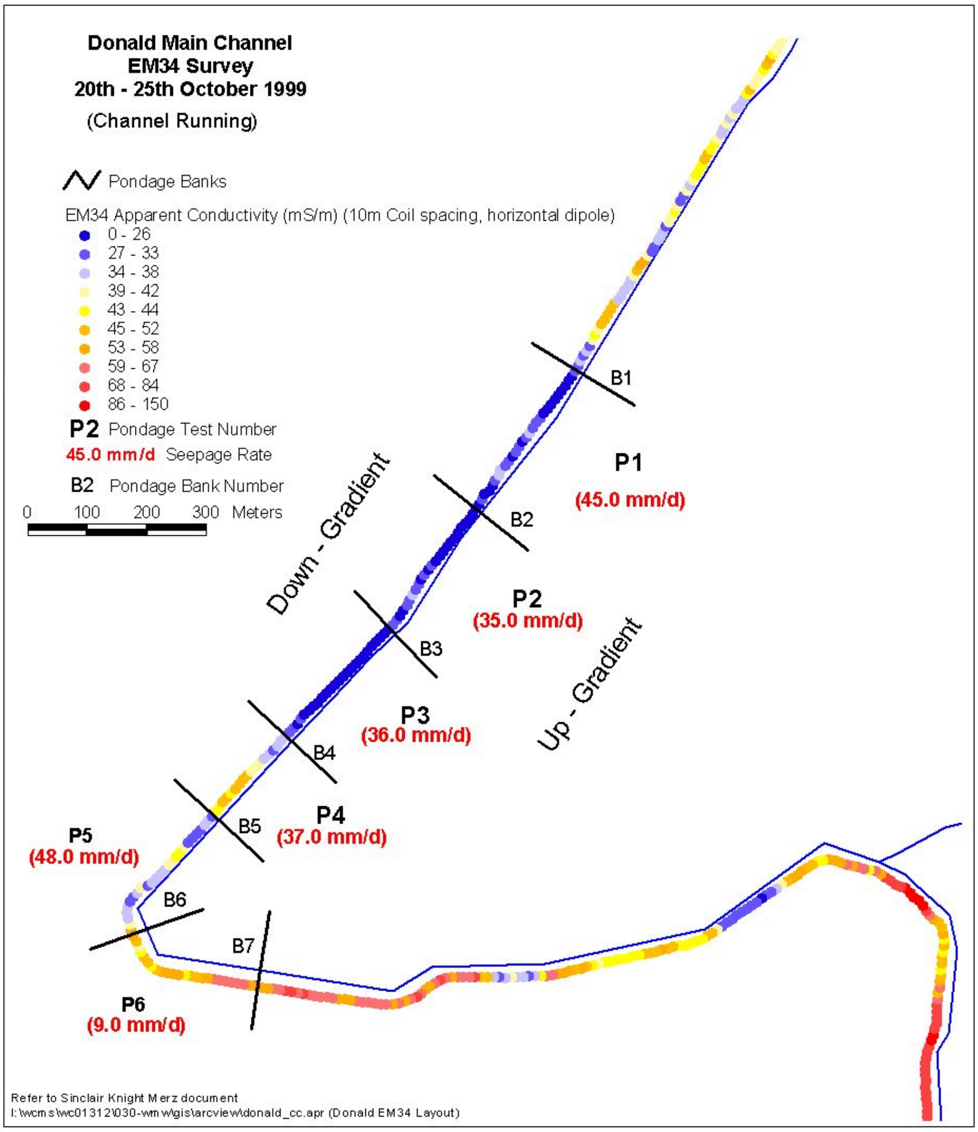
The depth to watertable at the site was about 2m below surface adjacent to the channel at the time of the survey and therefore the EM34 measured the conductivity of the 2m unsaturated interval and up to 5m below the watertable. The EM34 survey results from the section of interest (ie where the pondage tests were carried out) are presented in Figure 5-5.

The EM34 conductivity data along this section were plotted against the pondage test results as presented in Figure 5-6. The pondage test seepage rates indicate that except for one pond (Pond 6 with 9 mm/d), the seepage rates are in a fairly tight band ranging between 35 mm/d and 48 mm/d. The first half of the pondage test results were used in preference to the steady state results (which was the method used in analysis of other channels) due to the relatively low initial water levels in the Donald pondage tests.

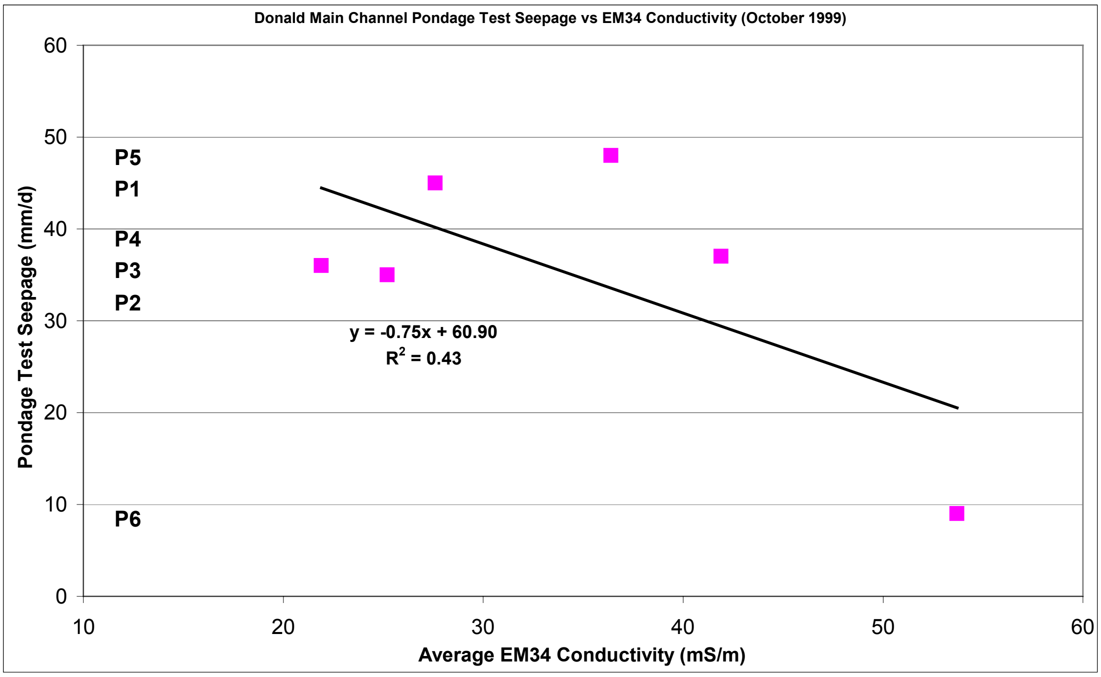
This analysis produced a poor correlation as shown in Figure 5-6, with a correlation coefficient of 0.43. However, the general relationship of higher seepage relating to lower conductivity is clear. The bulk of the results are clustered around the five higher seepage rate ponds (22-42 mS/m) with the low seepage pond containing a higher average conductivity of 54 mS/m. The results indicate that the EM34 survey has distinguished between areas of high (35-50 mm/d) and low seepage (< 10 mm/d). The EM34 survey has not been able to distinguish between various degrees of high seepage (eg 35 mm/d cf 48 mm/d). The Donald Main Channel Geological Long Section, (refer *Appendix* A), confirms the above interpretation of the EM34 results. As the long section shows, Pond 6 is the only area to display a completely clayey profile on both sides of the channel. This concurs with the highest conductivity and the lowest measured seepage rate. Ponds 2, 3, 4 and 5 have a large sand unit 1-2m below the channel base on the down gradient side of the channel, and Ponds 1-3 have a sand unit virtually intersecting the channel on the up-gradient side of the channel.

Ponds 4 and 5 contribute significantly to the poor correlation and display higher conductivities than would be expected for the magnitude of seepage losses detected in the pondage tests (compared to ponds 1 - 3). The possible cause of the higher conductivity results in ponds 4 and 5 is discussed in the following section, under the September 2001 survey results.

- **Figure 5-5 Donald Main Channel EM34 Survey – October, 1999**



■ **Figure 5-6 Donald Main Channel Pondage Test Seepage verses EM34 Conductivity (October 1999)**



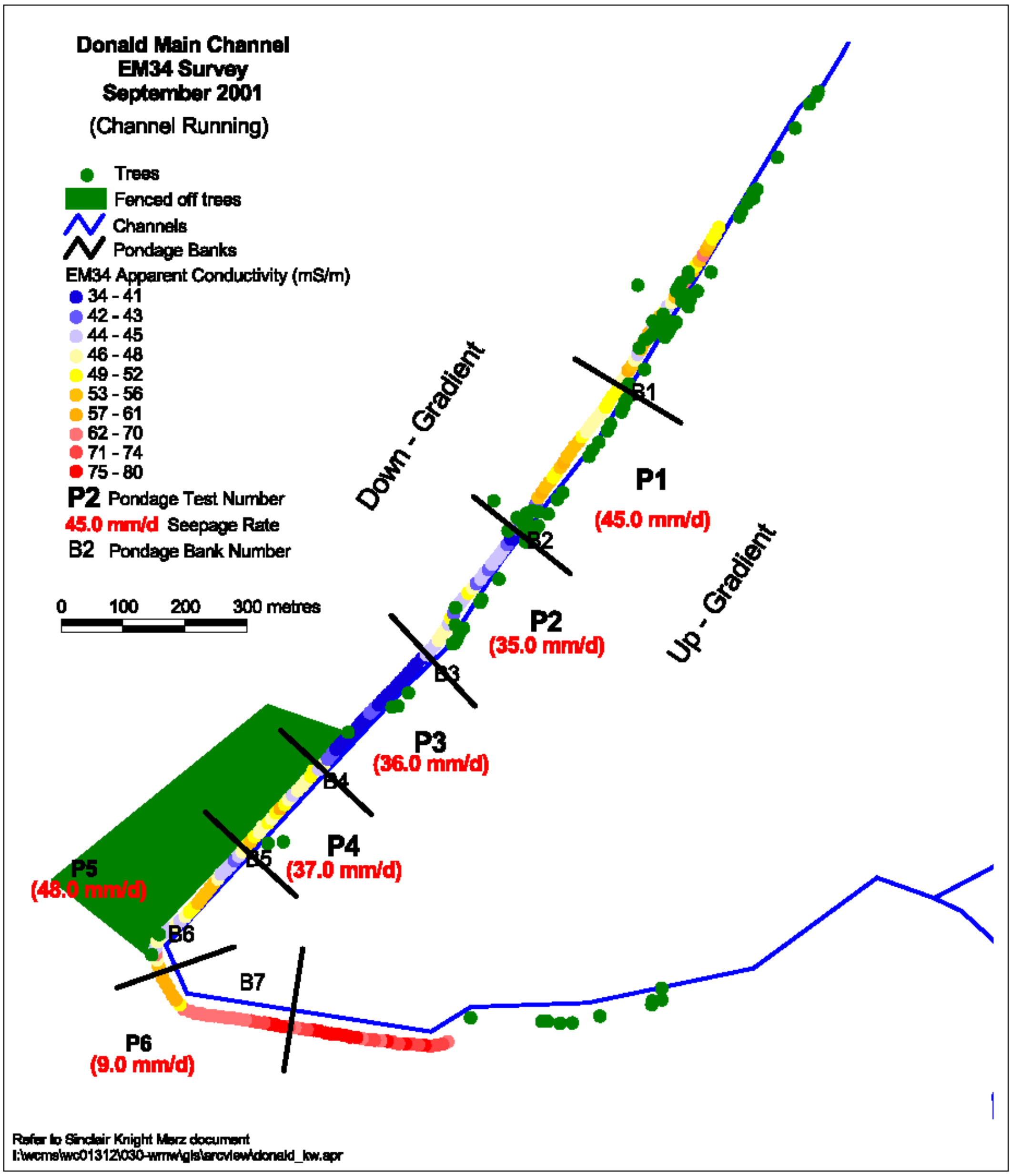
September 2001
Based on previous results at the Donald Main Channel which indicated that EM34 could be used to identify relatively low and high seepage rate sites, the pondage test sections of the Donald Main Channel were re-surveyed using EM34 (10m coil spacing, horizontal dipole) on 21st September 2001. The same contractor and technique were employed in this follow up survey. The channel had been flowing at levels below full supply level for a little over one month (commencing 16/8/01), prior to which it had not operated since December 2000. Depth to watertable was approximately 3m adjacent the channel, approximately 1 - 1.5m lower, and 0.5 - 1m lower away from the channel than compared to the October 1999 survey.

The results are presented in Figure 5-7 and a graph of these results as well as the October 1999 results are plotted against pondage test seepage in Figure 5-8. As per the 1999 EM34 survey, this analysis produced a poor correlation (R^2 of 0.50). However, again the general relationship of higher seepage relating to lower conductivity is clearly evident.

Figure 5-7 also plots tree locations along the channel. It is worth noting the potential effects of the trees on the results. In the October 1999 EM34 survey (described above), it was observed that the two main ponds deviating from expected trends were ponds 4 and 5, and that the conductivities were higher than expected. In the September 2001 survey the two main ponds deviating from 'expected' are Pond 1 and 5, which again recorded higher conductivities than expected. Ponds 4 and 5, and to a lesser degree Pond 1, are adjacent significant tree plantations. The trees adjacent Ponds 4 and 5 were planted in order to control visible seepage and waterlogging in the area (SKM, 1999). It is possible that the trees have taken up much of the seeped channel water along these sections, concentrating salt in the profile and resulting in overall higher conductivities than the corresponding sections of Ponds 2 and 3.

Alternatively, and perhaps in addition to the above mechanism, the trees may be increasing seepage above what would naturally occur in the absence of the trees. Correcting these ponds by lowering seepage rates, or reducing conductivities would improve the correlation for this section of channel. This brief analysis indicates that there is a need to consider the potential effects of trees adjacent the channel on interpreting geophysical survey results. The effect is only likely to be significant when there are significant numbers of trees involved (very close to the channel), and where the sub-surface profile is sufficiently permeable to allow significant up-take of the seeped water by the trees.

■ **Figure 5-7 Donald Main Channel EM34 Survey – September 2001**



■ Figure 5-8 Donald Main Channel Pondage Test Seepage vs EM34 Conductivity (October 1999 & September 2001)

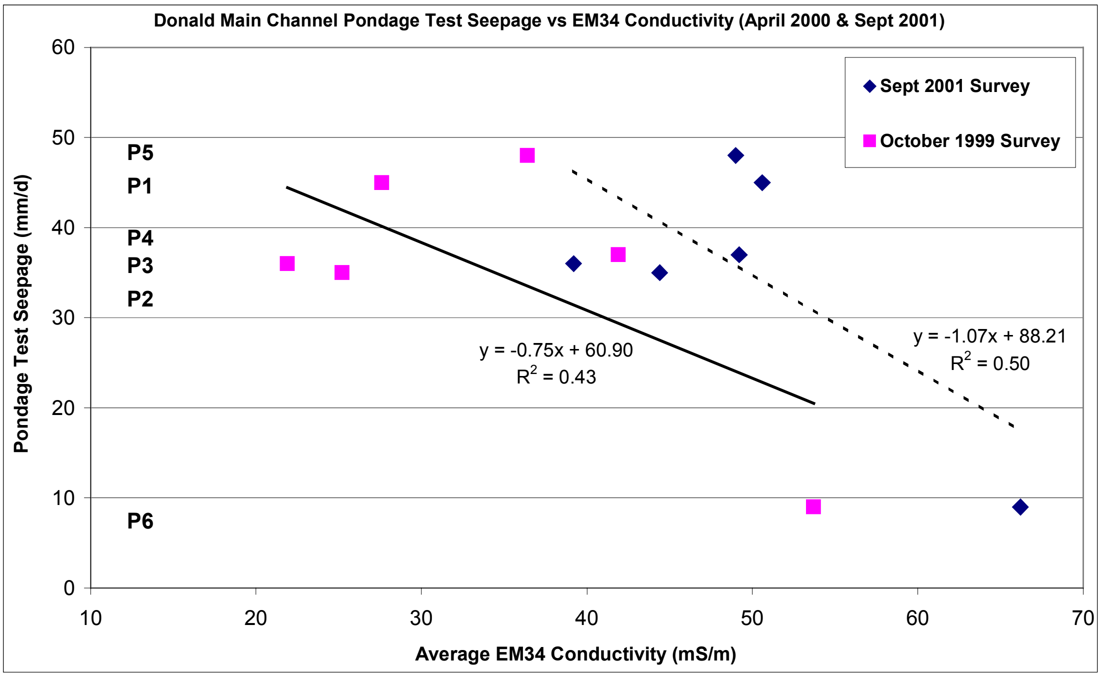


Table 5-3 compares the average conductivities in each pondage section between the two surveys. The September 2001 results consistently returned higher conductivities than the October 1999 survey, with an overall average increase of 15 mS/m. This is primarily due to the elevated and fresh groundwater levels in the October 1999 survey due to 6 months of prior channel operation. The channel had only been running four weeks (at reduced capacity) at the time of the September 2001 survey, possibly only enough to flush some of the accumulated surficial salts down into the profile. The October 1999 survey was therefore conducted under a sub-surface environment dominated by seeped water and a flushed (ie relatively salt free) profile, while the September 2001 survey was conducted in a environment probably only just beginning to flush salts through the profile (ie relatively salt rich). Although groundwater levels were lower in the September 2001 survey, the channel had been running for sufficient time to ensure that the unsaturated zone was sufficiently moist to be conductive.

■ Table 5-3 Comparison of Donald Main Channel EM34 Results: October 1999 and September 2001

Pondage	Av. Sept 2001 Conductivity (mS/m)	Av. October 1999 Conductivity (mS/m)	Difference between Sept 01 & Oct 99 (mS/m)	Percentage increase from Oct 99 to Sept 01
P1	51	28	23	83%
P2	44	25	19	76%
P3	39	22	17	79%
P4	49	42	7	17%
P5	49	36	13	35%
P6	66	54	13	23%

5.2.2.3 Toolondo Central – August 2001

An EM34 survey was conducted on 11th August 2001, along the down gradient outside channel toe along 4 km of the Toolondo channel. The survey was conducted using a coil spacing of 10m (horizontal dipole) and the channel was running at the time of the survey. The results, plotted against pondage test seepage, are presented in Figure 5-9. Only a moderate correlation is produced (R^2 = 0.50), however the EM34 conductivities have distinguished between low (1 – 5 mm/d) and moderate seepage rates (10 – 12 mm/d). The relationship is largely deteriorated by the high conductivity recorded in Pond 1.

■ **Figure 5-9 Toolondo Channel Pondage Test Seepage Versus EM34 Conductivity (August 2001)**

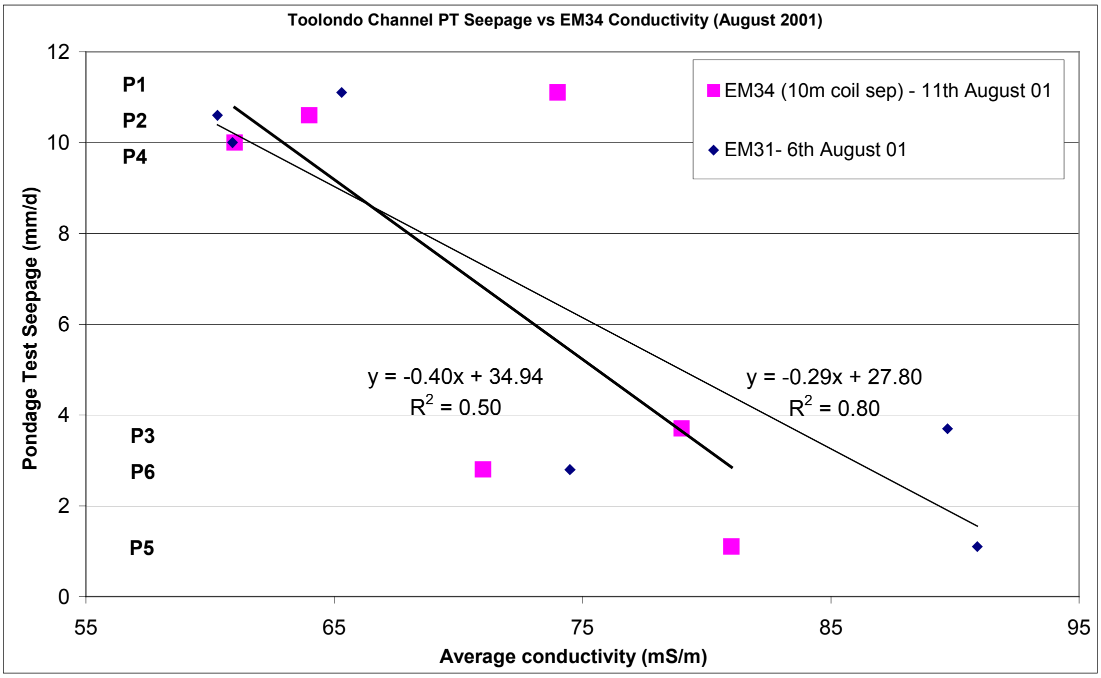


Figure 5-9 also plots the adjacent channel toe EM31 survey results (vertical dipole), which returned a good correlation coefficient for the adjacent channel toe data of 0.80 (refer Section 5.3.3.1 for further discussion). The EM31 survey was conducted only five days before the EM34, so it can be assumed groundwater conditions were essentially identical. Understanding the differences between the EM31 (vertical dipole) and the EM34 (horizontal dipole, 10m coil spacing) surveys is important.

Figure 5-9 shows an interesting difference between the two surveys. The EM31 conductivities were consistently higher than the EM34 results for the low seepage ponds, whereas the EM34 conductivities were higher than the EM31 in the three higher seepage rate ponds. This is probably explained by the deeper penetration depth of the EM34. Depth to groundwater at the site is around 8-10m, therefore only the EM34 with an effective exploration depth of around 8m may just 'see' into the capillary fringe and the groundwater. In the sandy sections (Ponds 1, 2 and 4) the EM34 is 'seeing' into the natural groundwater (ie more salty) and therefore returning a higher conductivity. However in the clayey sections, the lithology, not the groundwater salinity effect is the dominant feature of the response. Therefore in these sections, the EM31 is detecting the higher conductivity of the clays compared to the underlying sandstone, and consequently the reversal of the relationship between the EM31 and EM34 survey results is observed in the high seepage and low seepage areas. A possible counter to this interpretation is that while the EM34 (horizontal dipole) may 'see' slightly deeper than EM31 (vertical), its depth focus is shallower.

5.2.2.4 Dahwilly Central and Dahwilly East – February 2002.

<u>*Dahwilly Central*</u>

A 2km length EM34 survey (10m and 20m coil spacing, horizontal dipole) was conducted in February 2002, adjacent the outside toe of both sides of the Dahwilly channel. The 10m coil spacing results (EM34-10m) are presented in Figure 5-10 (along with the Dahwilly East results).

The depth to groundwater at the time of the survey was approximately 5m. The EM34(10m) configuration measures the conductivity of the 5m of unsaturated interval and up to a couple of metres below the watertable. However, recall from the introductory comments to this section that in horizontal dipole mode the focus of the measurements is from the upper part of the profile. Therefore the relative contribution from below the watertable is less than from above. At a 20m coil spacing, the bulk of the measurement will be from below the watertable, with an effective penetration depth of approximately 15m.

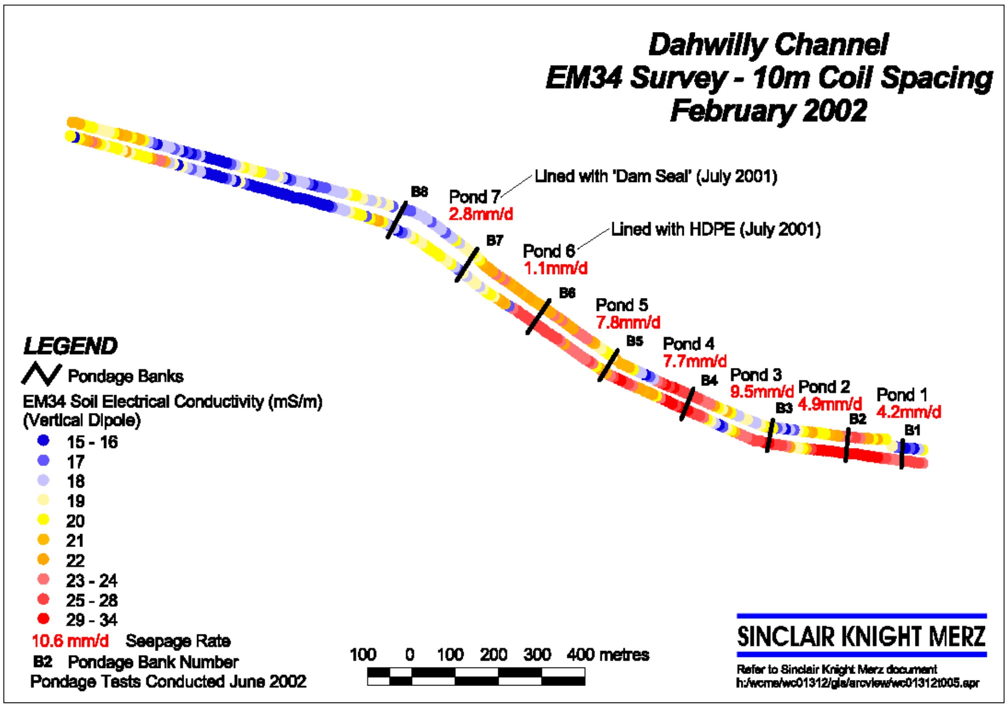
The average EM34 response per pond, plotted against pondage test seepage rates, is presented in Figure 5-11. The pondage test seepage rates range from 1 to 10 mm/d (the two low seepage rate ponds represent two ponds lined in July 2001). The following comments are made regarding the results:

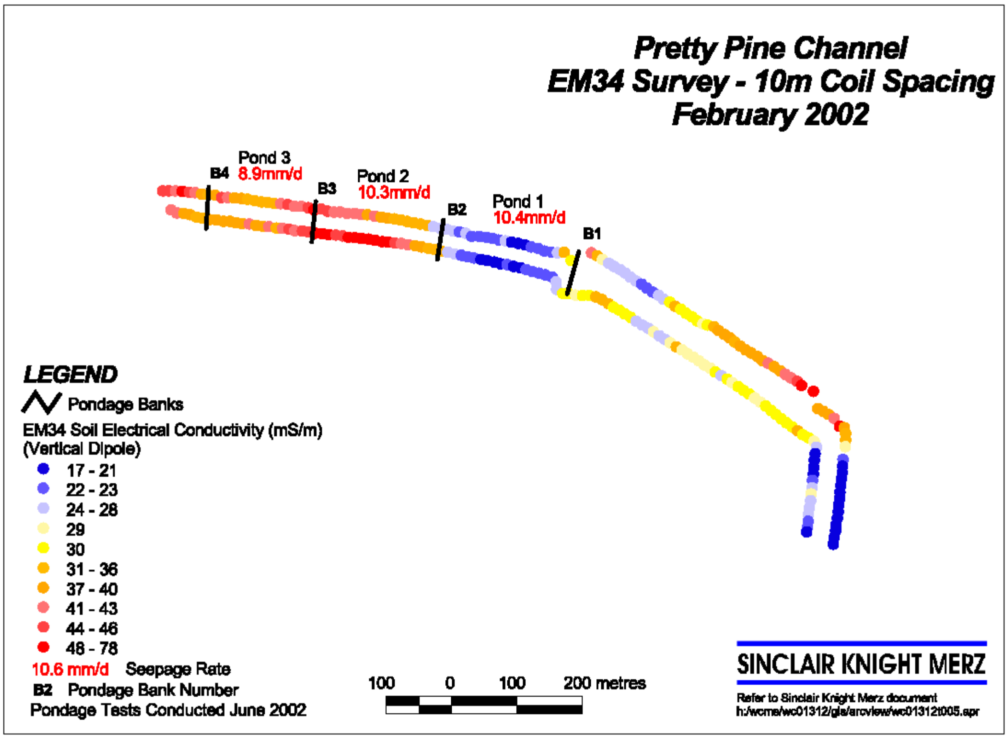
- The EM34(20m) data displayed a consistently higher conductivity than the EM34(10m) data. This is due to the deeper penetration depth of the 20m configuration, and reflects the increased influence of (salty) groundwater at depth.
- Both the 10m and 20m coil spacing conductivities lie in a narrow seepage rate range: 18 – 25 mS/m for 10m, and 32 – 44 mS/m for the 20 m coil spacing, ie there is little differentiation between the ponds in terms of conductivity. Excluding the lined ponds, the conductivity range is even narrower;
- The most important comment is regarding the effect of the lined ponds, which appear to be skewing the results away from the 'expected' trend. The dark line for both the 10m and 20m data sets is the regression line when the lined ponds are excluded from the analysis, and the thinner lines are the regression lines for all points including the lined ponds.

  Higher conductivities were 'expected' beneath the lined ponds - given that they have relatively low seepage rates, it was anticipated that they would contain a greater proportion of (salty) groundwater compared to the unlined ponds. However, it is apparent from these results that there may not have been sufficient time between the pond lining (July 2001) and the EM34 survey (February 2002) for the seepage water (prior to pond lining) to have migrated from beneath these ponds. Over time it is anticipated that conductivities beneath the lined ponds will increase as the lower salinity water originating from pre-lining seepage is removed via advection and diffusion processes.

Therefore, the two lined ponds have been removed from the regression analysis.

■ **Figure 5-10 Dahwilly Channel EM34 Survey – February 2002**



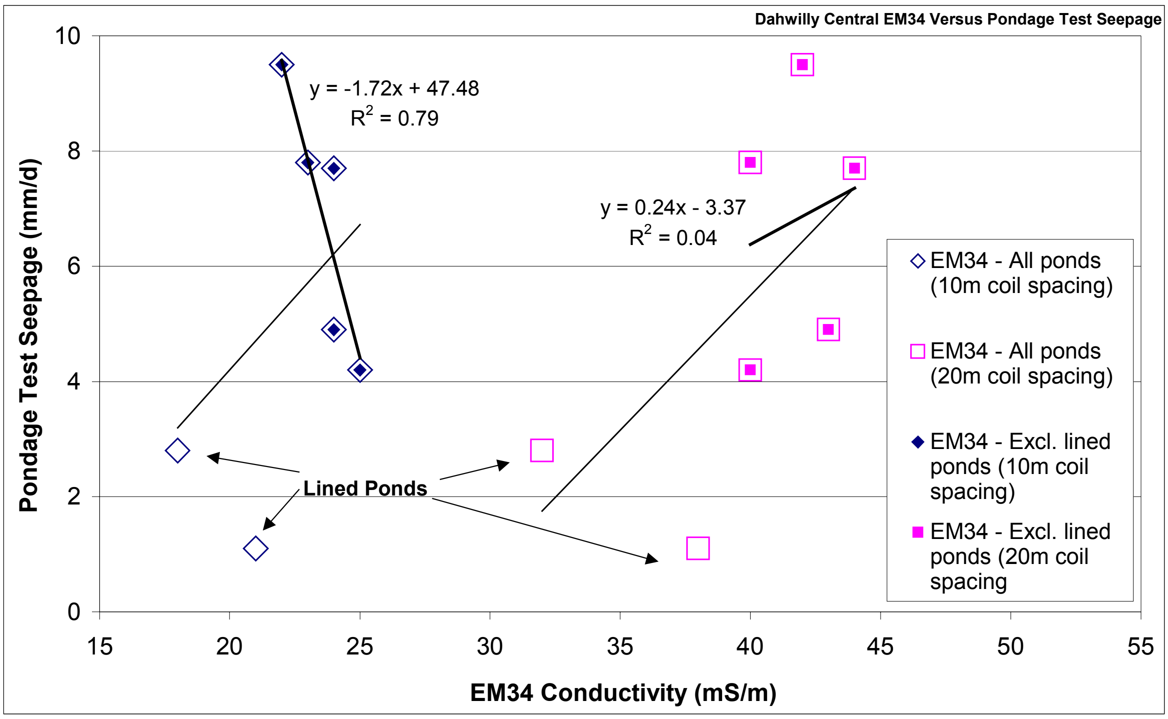


- The regression line for the EM34(10m) data, for the unlined ponds, displays a good correlation coefficient (0.79) for the inverse relationship between seepage and EM34 conductivity. This fits with the expected model for EM response – that is that low conductivity equates to high seepage and high conductivity to low seepage. However the average conductivity range for each pond over which the relationship is derived is very narrow (22-25 mS/m) and therefore confidence in this relationship is lessened. Two potential causes of the very narrow range are suggested:
    i) The very sandy nature and high transmissivity of the aquifer could result in substantial mixing of the fresh water to adjacent pond, thus blurring the identity of the pond from which the water originated and creating a relatively uniform EM response in the saturated zone. The problem with this explanation is that it runs contrary to the rationale for leaving the lined ponds out of the analysis – that there has been insufficient dilution of pre-lining seepage water beneath lined ponds.
    ii) The 10m coil spacing and horizontal dipole orientation are largely affected by surface response and are not highly influenced by the unsaturated zone. Therefore the observed response for the 10m coil spacing is largely dominated by the unsaturated zone. The geological logging at the site (refer *Appendix* A) indicates that the unsaturated zone is relatively uniform at this site which explains the very consistent response and narrow range of results in the EM34(10m) data. This is considered the more feasible explanation of the very narrow range observed. (Detection of unsaturated zone differences to measure the likelihood of seepage has been demonstrated to be successful at sites where there are significant differences in the unsaturated zone, eg Rocklands, Toolondo. However at this site it is apparent that the clogging layer is probably the controlling influence on seepage, and therefore seepage differences must be detected in terms of their impact on the groundwater salinity and not on soil differences within the unsaturated zone);
- The 20m coil spacing data displays no trend, as confirmed by the fitted regression line and resulting correlation coefficient (0.04). This is largely attributable to the very narrow range over which the EM34(20m) response is spread (39 – 44 mS/m). Given the comments in the above dot point (that the narrow range in the EM34(10m) data was due to a lack of penetration into the saturated zone) it would be anticipated that the deeper penetration provided by the EM34(20m) configuration should detect differences between high and low seepage ponds, as caused by the varying volumes of fresh seepage water causing dilution of the salty groundwater. This does not appear to be observed however. The response is relative uniform across the five ponds. It is apparent that the EM34(20m) configuration may have penetrated *too deeply* into the saturated zone, beneath the area at and immediately below the watertable where the effects of seepage on groundwater salinity are most dominant.

  The potential of going too deep and missing the ideal zone in which to detect seepage is well illustrated by the resistivity surveying conducted at this site (refer *Section 5.4.4.4* and *Figure 5.96 Correlations of average resistivity values of sections under ponds for Dahwilly Central*). Figure 5.96 plots seepage versus resistivity for different depth slices, and clearly shows that the ideal zone for detecting seepage differences at the Dahwilly Central site is at and just below the watertable. Therefore the best correlations are observed for the 6m, 8m and 10m depth slices, while below this depth the results become more uniform across ponds and reflect background groundwater salinities.

In summary it is apparent that the EM34(10m) configuration has not penetrated to sufficient depth to detect changes in the saturated zone and was largely measuring differences in the unsaturated zone, of which there are very little at the Dahwilly site. In contrast the EM34(20m) configuration appears to have penetrated too deeply, below the critical zone of seepage influence, and therefore tends to reflect background groundwater salinities and displays a correspondingly uniform response. The resistivity surveying (refer Section 5.4.4.4) which collects depth slices through the profile confirms the above interpretation of the EM34 results, and shows that the critical zone in which to detect seepage effects is at and immediately below the watertable (approximately 5-8m at this site).

■ **Figure 5-11 Dahwilly Central EM34 Versus Pondage Test Seepage**



Dahwilly East

A 2km, EM34 survey (10m and 20m coil spacing, horizontal dipole) was conducted in February 2002, adjacent the outside toe of both sides of the Dahwilly channel, approximately 4 to 5km east of the original Dahwilly site (described above). The 10m coil spacing results are presented in Figure 5-10.

Depth to groundwater at this site was estimated to be around 5-6m at the time of the survey. The EM34(10m) configuration measures the conductivity of the 5m of unsaturated interval and up to a couple of metres below the watertable. However, recall from the introductory comments to this section that in horizontal dipole mode the focus of the measurements is from the upper part of the profile. Therefore the relative contribution from below the watertable is less than from above. At a 20m coil spacing, the bulk of the measurement will be from below the watertable, with an effective penetration depth of approximately 15m.

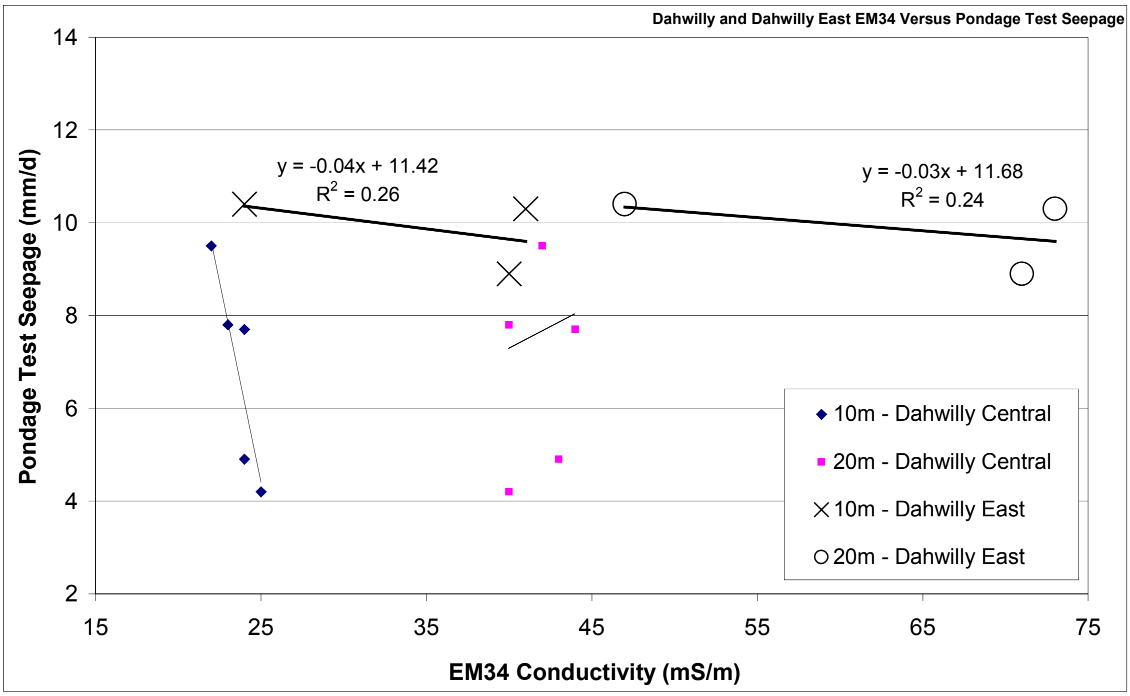
The EM34 plotted against the pondage test seepage are presented in Figure 5-12. As this figure shows, only three pondage test cells were conducted at the Dahwilly East site. The Dahwilly Central results are also plotted in this figure for comparison purposes. A much wider range of conductivities is observed at the Dahwilly East site, with 24 – 40 mS/m for 10m, and 47 – 71 mS/m for the 20 m coil spacing.

The pondage test seepage rates for the three ponds is very narrow (8.9 mm/d – 10.4 mm/d) which limits the statistical significance of the results. However, the highest seepage rate pond did record the lowest conductivity, suggesting that at this site the inverse relationship between conductivity and seepage (observed at most sites) is applicable. The EM34(10m) trend line is very much flatter than the steep trend line observed at the Dahwilly East site.

The geology of the site also suggests that the ‘normal’ inverse relationship could be expected at this site. While the unsaturated zone is quite similar to Dahwilly Central (high permeability sands), the saturated zone is comprised of a clayey sand (refer Dahwilly East Geological Long Section, *Appendix* A). This would slow the lateral mixing of seeped channel water within the upper part of the aquifer and increase the potential for detecting seepage water from beneath the pond from which it was sourced.

Additional pondage tests across a wider seepage rate range would be required to confirm the observed relationships at this site between pondage tests and conductivity at other sites.

■ **Figure 5-12 Dahwilly East EM34 Versus Pondage Test Seepage**



5.2.3 Conclusions

Good to moderate relationships were obtained between average EM34 conductivity and the corresponding pondage test seepage at most sites. For EM34 at a 10m coil spacing in horizontal mode, the effective depth of penetration is around 6-7m, with a shallow depth focus at around 1-3m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is predominantly via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

- **Rocklands** – A good relationship was recorded in both surveys. A high degree of repeatability was demonstrated between the two EM34 surveys conducted.
- **Donald Main** – A moderate relationship was recorded in both surveys. Further points are required in the mid-seepage range to appropriately test the relationship. The technique distinguished between high and low seepage but not within the high seepage results range. Possible interference by adjacent trees may have effected results in some ponds. A generally consistent increase in conductivity was observed between repeat surveys. The difference was caused by the higher watertable and reduced channel running time prior to the survey.
- **Toolondo Central** – A moderate relationship was observed but largely skewed by the result in one pond. The relationship distinguished between high and low seepage rates.
- **Dahwilly Central** - Moderate relationship for 10m coil separation but a very low range of conductivity response was recorded across the five ponds used in the analysis. This is because the EM34(10m) configuration does not penetrate to sufficient depth to significantly detect changes in the groundwater and was therefore mainly measuring differences in the unsaturated zone, which is largely uniform at the Dahwilly site. The EM34(20m) configuration penetrated too deeply below the watertable and therefore a uniform response was observed reflecting native groundwater conditions.
- **Dahwilly East** – No relationship was observed. The seepage rate range was too narrow for a meaningful relationship to be derived.

In summary, the only site where no relationship was observed was at Dahwilly East, which was largely due to the narrow seepage rate range. At the Toolondo central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence a reasonable trend was observed (a fact reinforced by the success of EM31 at the site). Significantly, the resistivity surveying showed improved correlations compared to the EM34, for the depth slices focussed immediately below the watertable.

The Donald site survey was focussed on the saturated zone, however the EM31 survey at the site demonstrated a slightly better relationship with pondage test seepage compared to the EM34 (R^2=0.73 compared to R^2=0.50), but neither survey differentiated between the higher seeping ponds. The improved correlation is probably attributable to the deeper depth focus of the EM31 compared to the EM34 (10m, vertical dipole configuration).

At the Rocklands and Dahwilly sites, where the penetration depth (EM34 - 10m coil separation, vertical dipole) was just sufficient to reach the watertable (but the focus was above the watertable), the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone worked to provide a reasonable indicator of seepage. However it is significant that at Dahwilly, where resistivity surveying was conducted, an improved relationship was obtained when the depth slice was focussed immediately below the watertable, where seepage impacts are most discernible.

5.3 EM31 Trials

5.3.1 Introduction

This section is presented in the following sub-sections:

- Background – This section describes the functioning of EM31 systems (their typical response curves etc) as well as the specific methodology as to how they were used in the trials (eg location, dipole orientation etc);
- Year 1 and 2 Trials - This presents the results of the year 1 and 2 EM31 trials, across seven sites;
- Regional Assessment of Key Relationships – For all of the year 3 sites (plus some year 1 and 2 sites) an attempt was made to look for potential correlations between seepage rates across all sites and EM31 response. This was conducted applying multiple linear regression using a number of key explanatory variables and simple linear regression, using EM31 as the only explanatory variable.
- Channel Specific Assessment EM31 Assessment and Extrapolation of Relationships - This section examines the EM31 - seepage relationship at each channel and assesses this relationship compared to the regional relationship. This section also assesses the success of extrapolation of seepage-EM31 relationships from the 'original' site to other sites along the channel.

5.3.2 Background

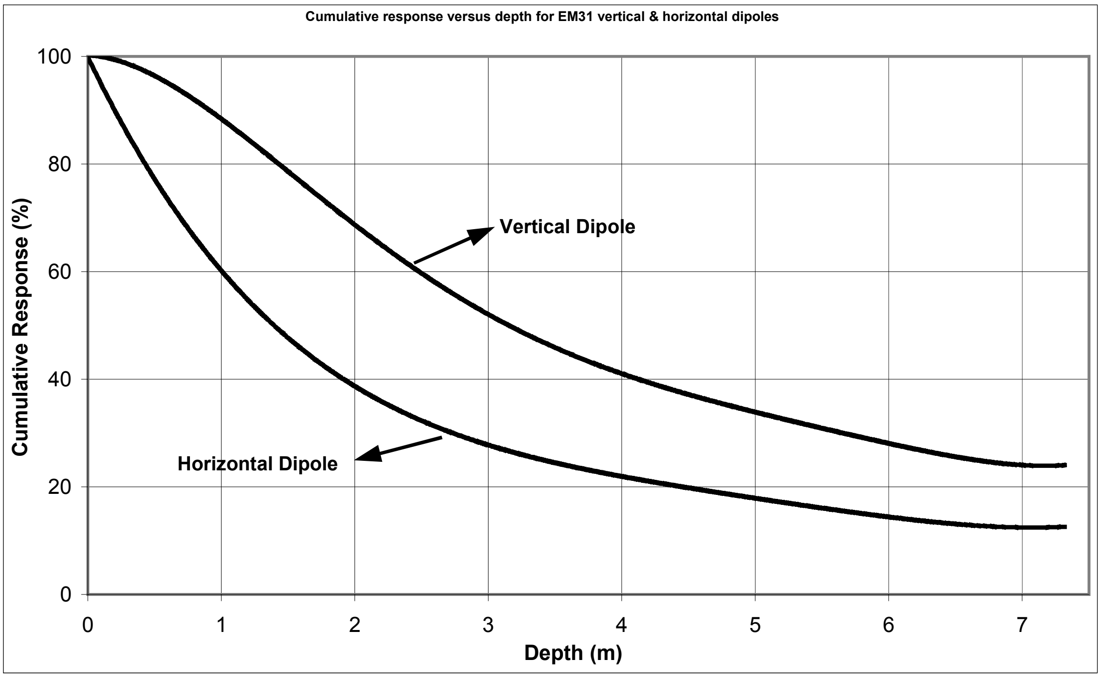
5.3.2.1 EM31 Systems

Frequency domain electromagnetic systems can measure the electromagnetic properties of the soil profile up to a depth of 100m, with the penetration depth dependent on the frequency and coil spacing. This investigation used the Geonics style Frequency Domain Electromagnetics (FEM) units which utilise the concept of low induction numbers to give an output in conductivity. For a given coil spacing, Geonics EM systems can be used in horizontal dipole or vertical dipole mode. The dipole mode effects the relative contribution of the profile at different depths to the overall response.

An EM31 system has a fixed coil spacing of 3.66m. This coil spacing, in the vertical dipole orientation, provides an effective penetration depth of around 6m with the dominant effect in the 1 – 3m range. Figure 5-13 presents the cumulative response for Geonics EM31 systems for vertical and horizontal dipole orientations. It can be seen from these curves that near surface features will tend to dominate in the horizontal mode while the vertical mode is more influenced by the 'mid' part of its depth range (where the gradient of these curves is steepest indicates from where the greatest proportion of response emanates). For example, in horizontal mode about 40% of the response comes from the top 1m of the profile, whereas approximately only 10% of response is attributable to the upper 1m in vertical dipole mode.

EM31 and EM34 systems were used in years 1 and 2 of the trials, and both with reasonable success. The attraction of an EM31 over an EM34 system (and the reason it was adopted as the preferred EM system in the year 3 trials) is that it can be mounted on a four wheeled motorbike and therefore represents a more rapid and cheaper method of assessment. On the four-wheeled motorbike, readings were taken at approximately 5m intervals. Surveys were usually conducted while the channel was in operation.

■ **Figure 5-13 Cumulative Response Versus Depth For EM31 Horizontal and Vertical Dipoles (after McNeil, 1980)**



5.3.2.2 Methodology

Generally the EM31 survey was conducted in eight traverses, four on each side of the channel, except where surface features prevented access. The inner line was located immediately adjacent the channel bank and the outer line up to 50-60m from the channel. In the second year of trials, EM31 was also conducted on the channel (in a boat) but the land based surveys consistently returned better results (ie better correlations with pondage tests). Therefore land based surveys adjacent the outside toe of the channel were the preferred survey method in the third year trials. Figure 5.14 illustrates the EM31 set up, both as conventionally used on land and the on-channel boat system.

As described in Section 5.1.2, the basic assessment methodology consisted of comparison of the pondage test results to the average EM34 conductivity for the corresponding pond length. In addition, multi-variate analysis was conducted on the data collected in the third year trials, in order to identify other parameters which may have a significant impact on seepage rate and / or EM conductivity.

■ **Figure 5.14 EM31 Set-up on Land and On-channel (Toolondo Channel August 2002)**

5.3.3 Year 1 and 2 – EM31

This section presents the results of the year 1 and 2, EM31 trials,involving:

- ❑ Toolondo Central – December 2000, August 2001;
- ❑ Rocklands – August 2001;
- ❑ Donald Main – August 2001;
- ❑ Dahwilly Central – June 2000;
- ❑ Finley – July 2000;
- ❑ Lake View – June 2000; and,
- ❑ Tabbita – July 2000.

5.3.3.1 Toolondo Central – December 2000, August 2001

December 2000

An EM31 resistivity survey (vertical dipole) was conducted by Ken Bates Soil Surveying on 13th and 14th December 2000 along a 4km section of the Toolondo channel. The survey was carried out soon after the channel ceased flowing. In total nine traverses were conducted, four on each side of the channel up to 50m from each channel bank, and one in the channel (where possible). The base of the channel was wet in places and an in-channel run could only be conducted in part. Survey results are presented in Figure 5-15. (For analysis purposes, values were interpolated for a 75m section on the right hand side of Pond 2 to correct for missing data in this location). Depth to groundwater at the site is approximately 9-10m, therefore EM31 surveys are measuring unsaturated zone properties.

Figure 5-15 shows a dominant response in the higher conductivity end of the range with most of the channel and surrounds returning responses above 60 mS/m. The areas around Pond 1, Pond 2, Pond 4 and the far southern area surveyed displayed the lowest conductivities. The conductivities displayed in Ponds 1 and 2 suggest that seepage is predominantly to the south, but also to the east in Pond 2. Pond 4 appears to be seeping to both the east and west. The conductivities of Ponds 5 and 6 would suggest low seepage in these areas and Pond 3 would appear to be seeping at the southern end of the pond only. The areas of lowest conductivity on the plan, generally coincide with the ponds where highest seepage rates were recorded.

The assessment shown by mapping is supported by plots of pondage test seepage against the average EM31 results (refer Figure 5-16 and Figure 5-17). Figure 5-16 shows three averages of the survey data: all traverses, traverses on the LHS of the channel and traverses on the RHS of the channel. Figure 5-17 shows two averages: the in-channel traverse only and the channel sides (ie both sides excluding the in-channel traverse). For each pond the average conductivity of these different traverses was plotted against the corresponding (pondage test) seepage rate.

All combinations of the traverses except for the *in-channel* traverse produced a strong (inverse) correlation. That is, there is a strong relationship between the average electrical conductivity in the top four to six metres adjacent the channel and (pondage test) seepage rates. Data from all traverses, including the in-channel run, produced a correlation co-efficient of 0.72.

The results on the up-gradient side of the channel (RHS), produced a stronger correlation (R^2 of 0.78) than the down-gradient (LHS) side (R^2 of 0.33). This is attributable to the fact that the Toolondo trial site does not slope steeply however, and therefore there is not a strong gravity driven preferential flow direction. The nature of the geology at the site has a stronger influence on seepage. It appears that water is preferentially being lost via the sandy up-slope sides of Ponds 1 and 2, rather than the clayey down slope sides (shown on cross section in *Appendix* A). It can be concluded that the average EM31 response for all data along the channel provides a reasonable correlation with the pondage test results, while detailed breakdown of data is less conclusive. This is largely a reflection of the gross characteristics of the EM31 averaging process and pondage test procedures.

■ **Figure 5-15 Toolondo EM31 Land Survey – December 2000**

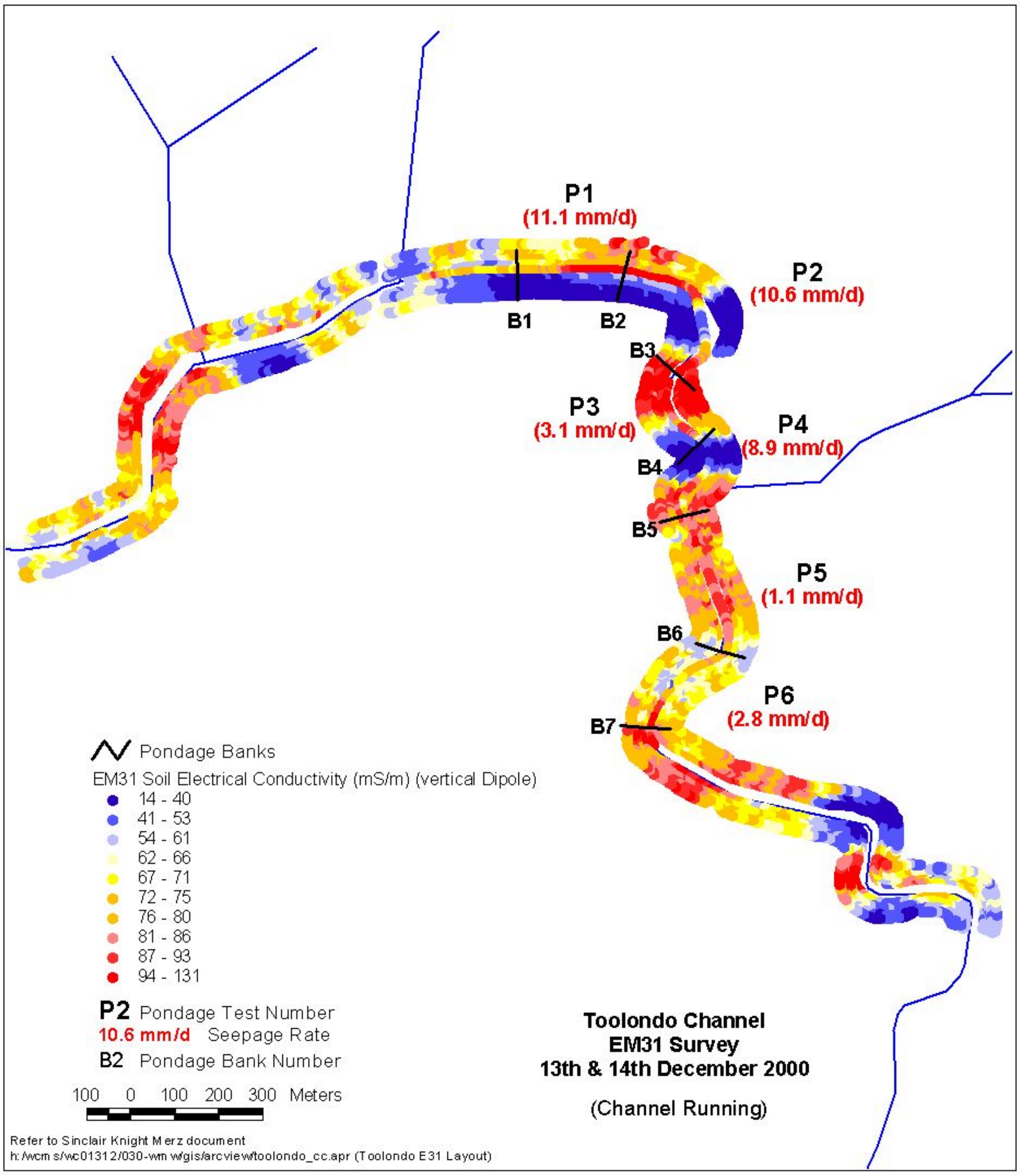
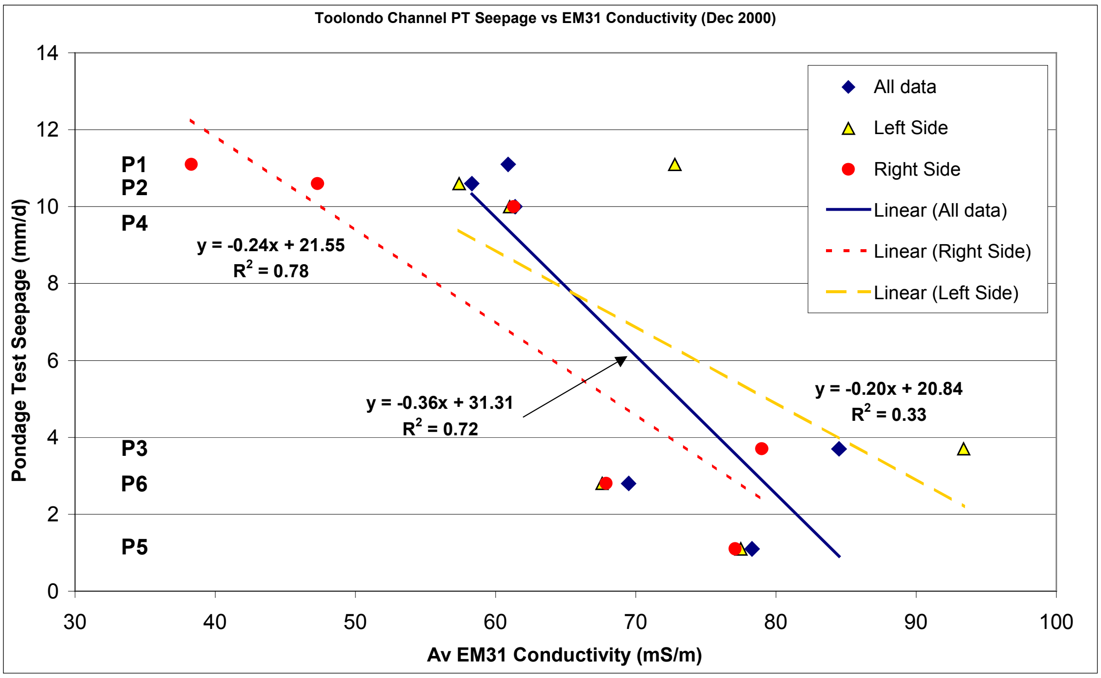
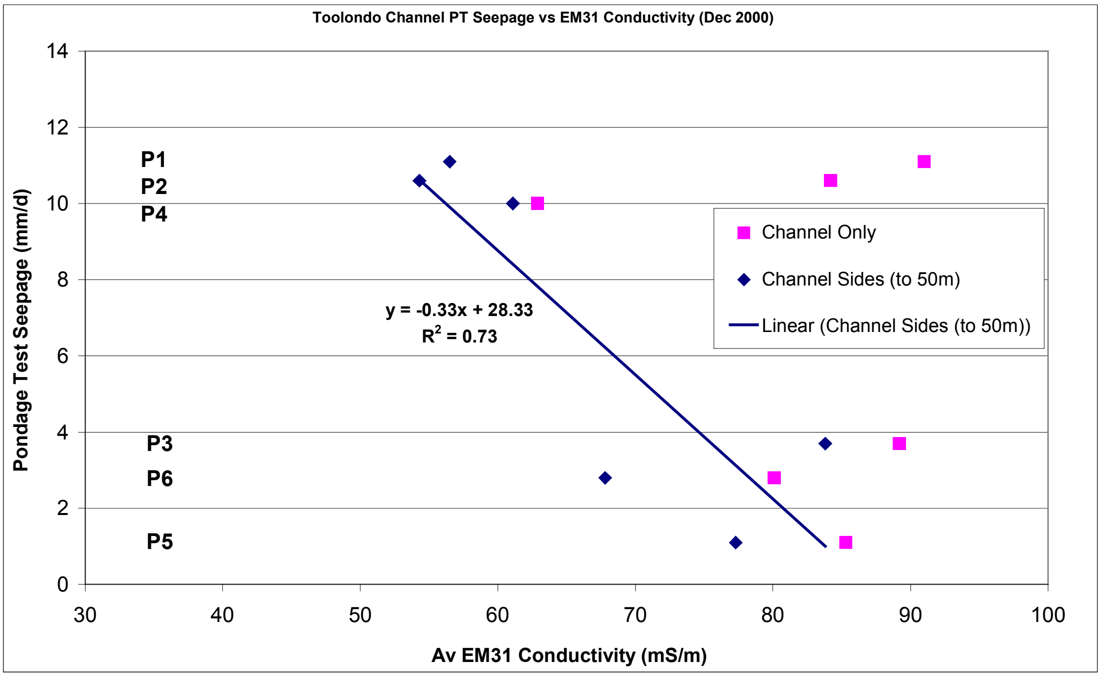


Figure 5-17 shows that using only the traverses outside of the channel (both LHS and RHS) a strong correlation is obtained, comparable to the coefficient for all traverses, of $R^2 = 0.73$. The line of best fit for the in-channel data is poor, (and therefore not plotted) due to the high conductivities in the high seepage ponds (Ponds 1 and 2, and to a lesser in extent Pond 3). These high conductivities are explained by the fact that immediately beneath the channel all the pores contain fresh water, and are effectively saturated, even beneath low seepage ponds. This will tend towards a uniform conductivity response, dominated by seepage water rather than lithology. In contrast, the outside channel toe results infer the likelihood of seepage based on unsaturated zone lithology (watertable at 10m) but are not effected by seepage water.

■ Figure 5-16 EM31 Survey Results (Dec 2000)



■ Figure 5-17 EM31 Survey Results cont' (Dec 2000) – Toolondo Channel



permeable sections of channel (as indicated by the pondage test results) the fresh water contained in the pore spaces from the recently running channel may have seeped away quickly vertically (compared to the clayey sections). However, due to slower lateral movement this fresh water was still present adjacent the channel and was therefore able to be picked up in the traverse outside of the channel. (Evaporation and subsequent salt build up of water ponded in the channel may also have caused higher conductivities and led to inaccurate readings.) The significant aspect of these results is the good correlations between the conductivity adjacent the channel and the channel seepage.

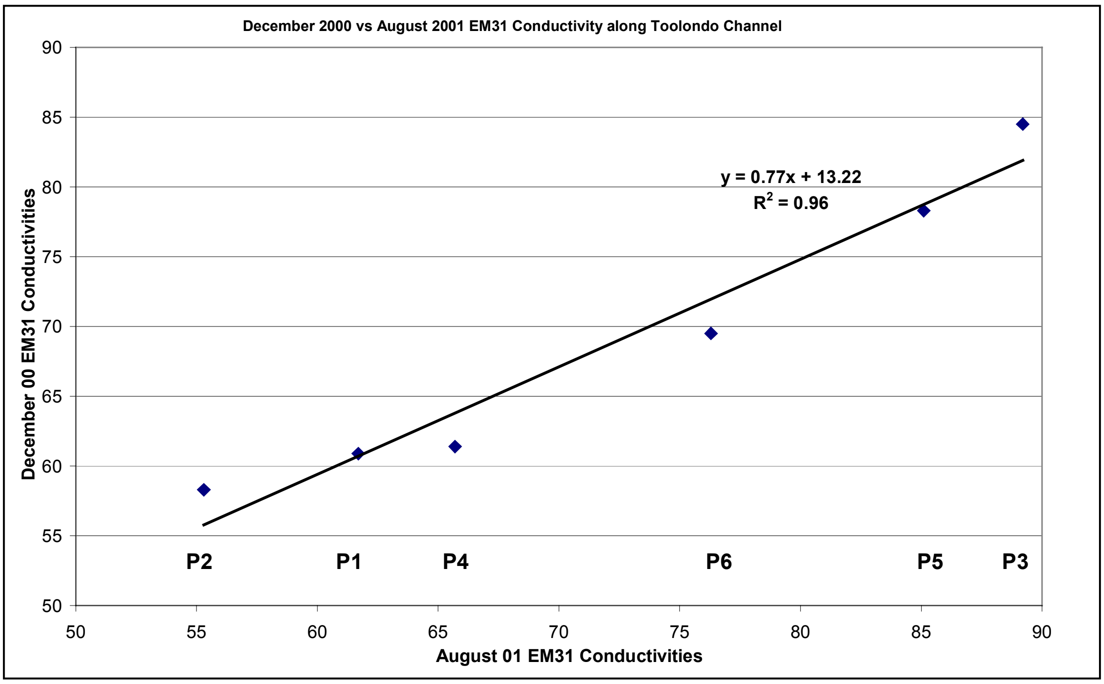
August 2001

Land Based Survey

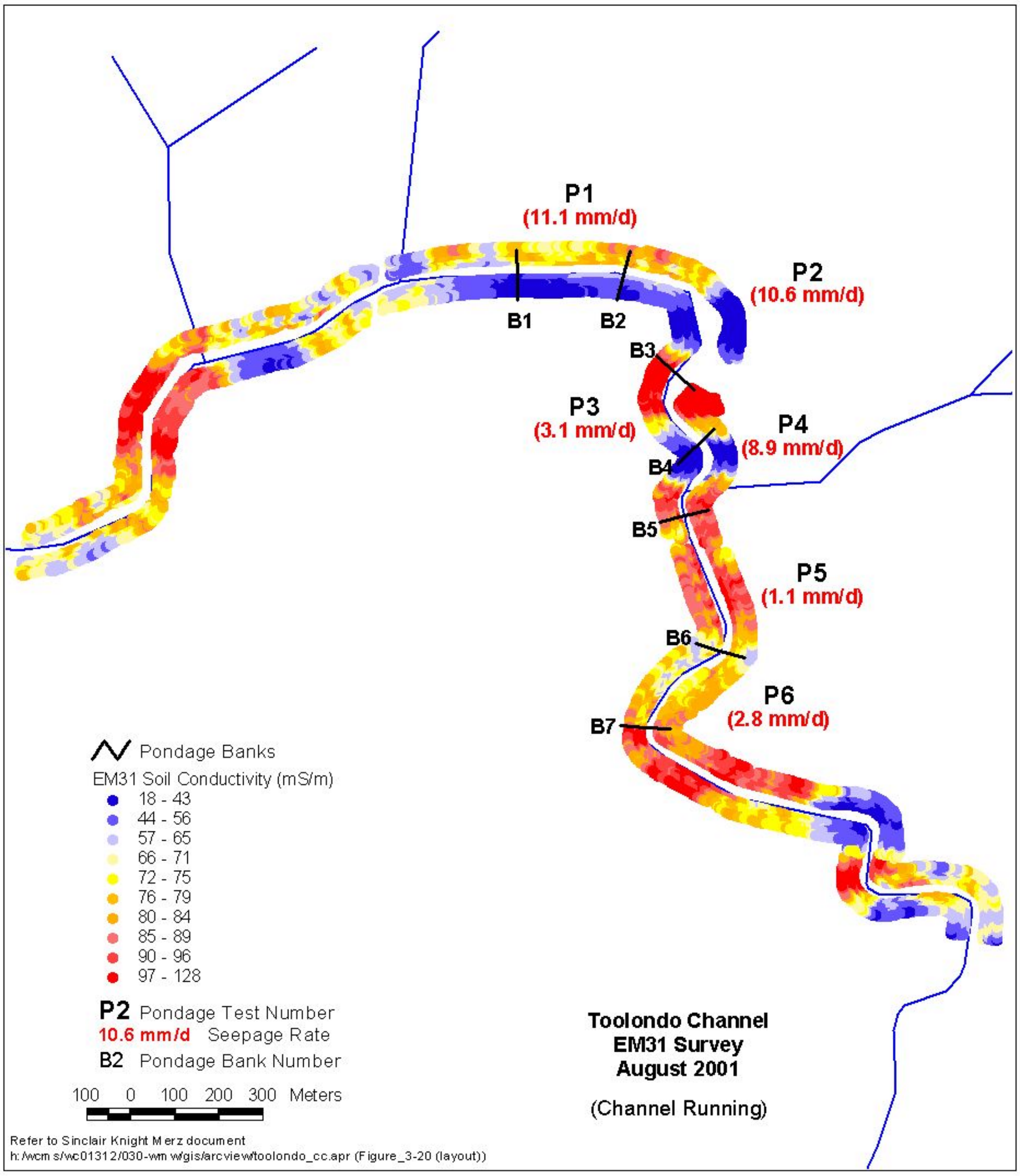
The repeatability of the good results obtained during the EM31 survey of the Toolondo channel in December 2000 was tested by conducting another EM31 survey in August 2001. In contrast to the December 2000 survey, the channel was flowing at the time of the August 2001 EM31 survey. The same contractor was employed for the task (Ken Bates Soil Surveying), and the same dipole orientation (vertical) was used. The survey was undertaken on the 6th August 2001 along a 2km section of the Toolondo channel, incorporating the pondage test sections. In total eight traverses were conducted, four on each side of the channel up to 50m from each channel bank. (As per the December 2000 survey, for analysis purposes values were interpolated for a 75m section on the right hand side of Pondage 2 to correct for missing data in this location). On-channel traverses were also undertaken in a boat and the results are discussed in the following section.

A comparison between the EM31 (land-based) survey results of December 2000 and August 2001 are presented in Figure 5-18 and a graphical presentation of the survey is shown in Figure 5-19. Figure 5-18 shows that correlation between the two surveys was strong (R^2=0.96). There was a slight difference between the results of the surveys

■ **Figure 5-18 Comparison between December 2000 and August 2001 EM31 Surveys along Toolondo Channel**



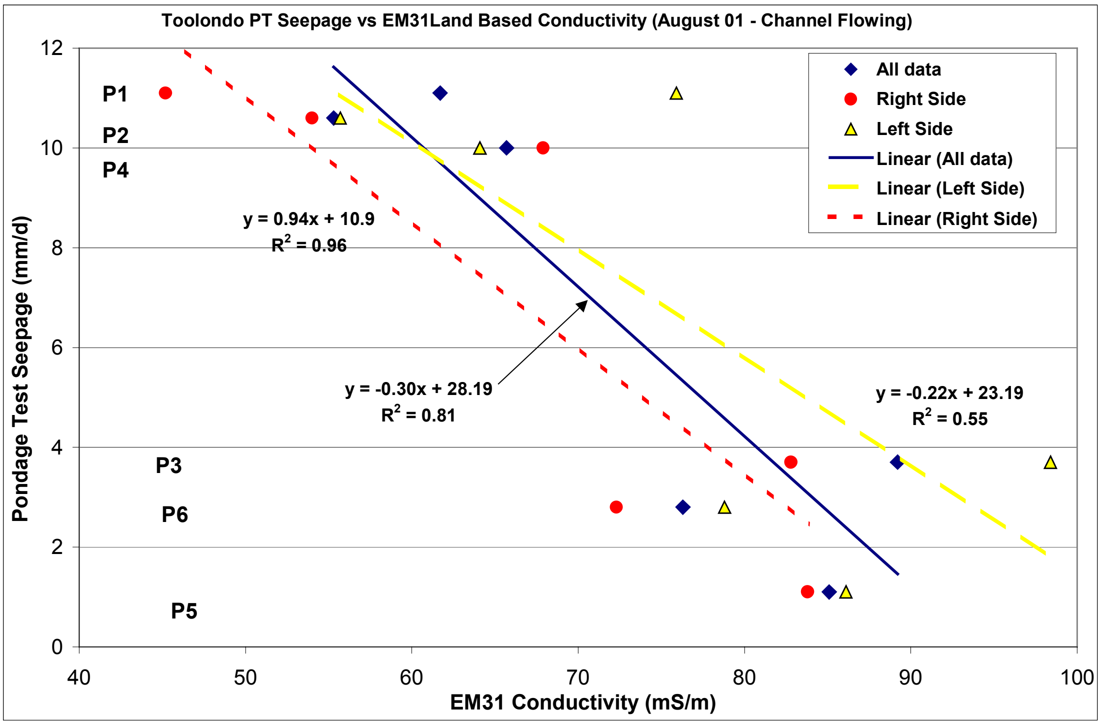
■ **Figure 5-19 Toolondo EM31 Land Survey – August, 2001**



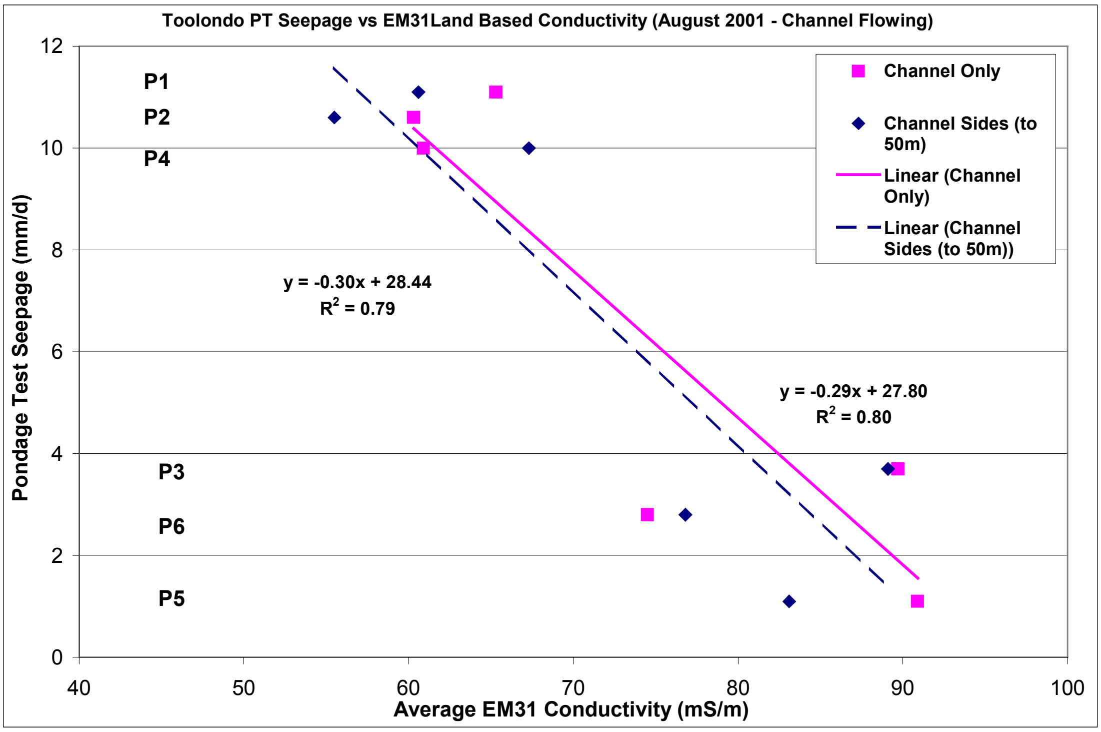
but the difference was generally consistent, with the August survey returning higher conductivities than the January survey (average of 3.4 mS/m higher for each pond). This difference is not considered significant and demonstrates the repeatability of the technique.

Figure 5-20 and Figure 5-21 present the results of the Toolondo August EM31 land based survey compared to the pondage test results. These figures should be compared with Figure 5-16 and Figure 5-17 which are the corresponding results for the December survey. The differences are small, and it is concluded that the good correlations between EM31 surveys along the outside of the channel and pondage tests were successfully repeated and appear to be marginally better under channel flowing conditions. As per the January results, significantly better correlations were obtained on the right hand (up-gradient) side of the channel than on the left.

■ **Figure 5-20 EM31 Land Based Survey Results (August, 2001) – Toolondo Channel**



■ **Figure 5-21 EM31 Land Based Survey Results cont' (August, 2001) – Toolondo Channel**



On-Channel Survey

In addition to the land-based survey at Toolondo on 6th August 2001, an on-channel survey was conducted on the same day using a small boat to house the EM31 equipment. The on-channel survey was conducted in both vertical and horizontal dipole arrangements to provide different penetration depths beneath the channel. The results of the surveys for the vertical and horizontal modes are presented in Figure 5-22 and Figure 5-23 respectively. The influence of the metre column of water above the instrument will affect the results in a uniform manner, provided the water depth along the section of interest is approximately constant.

It is worth comparing Figure 5-22 and 5-23 with Figure 5-19, the land based survey taken on the same day as the boat survey. The low conductivity areas (usually interpreted as higher seepage) generally match with each other in the two figures. Within the pondage test area, however, there are two exceptions. The eastern half of Pond 1 and the northern half of Pond 2 are displayed as high conductivity in the on-channel (boat) results, but in the land-based survey are mapped as low conductivity on the right hand side. The reason for these differences is explored below.

Table 5-4 presents the land (vertical) and boat (horizontal dipole) data and illustrates the difference between the two surveys. As the final column illustrates, there is generally a 15-20 mS/m increase in conductivity for the land based data over the same pondage test section compared to the boat data (horizontal dipole). The reason for this difference is that the on-channel based survey is measuring the conductivity of the completely flushed profile immediately beneath the channel (flushed of salts etc), whereas the land based survey adjacent the channel is measuring a non-flushed profile, which still contains salts and therefore higher conductivities. The reason that this difference in conductivity does not exist in Ponds 1 and 2, is due to their sandy profile (refer to Toolondo long section in *Appendix* A), which results in a wider flushed zone (evidently at least to the edge of the outside channel toe) compared to other ponds and thus lower conductivities.

- **Table 5-4 Comparison of Land and On-Channel EM31 Results, August 2001**

Pondage	Average Land Conductivity: Vertical Dipole (mS/m)	Average Boat Conductivity: Horizontal Dipole (mS/m)	Land Data – Boat Data
P1	62	65	-3
P2	55	63	-8
P3	89	67	23
P4	66	52	14
P5	85	66	19
P6	76	62	14
Average	**72**	**62**	**10**

■ **Figure 5-22 Toolondo On-Channel EM31 Survey, August 2001 – Vertical Dipole**

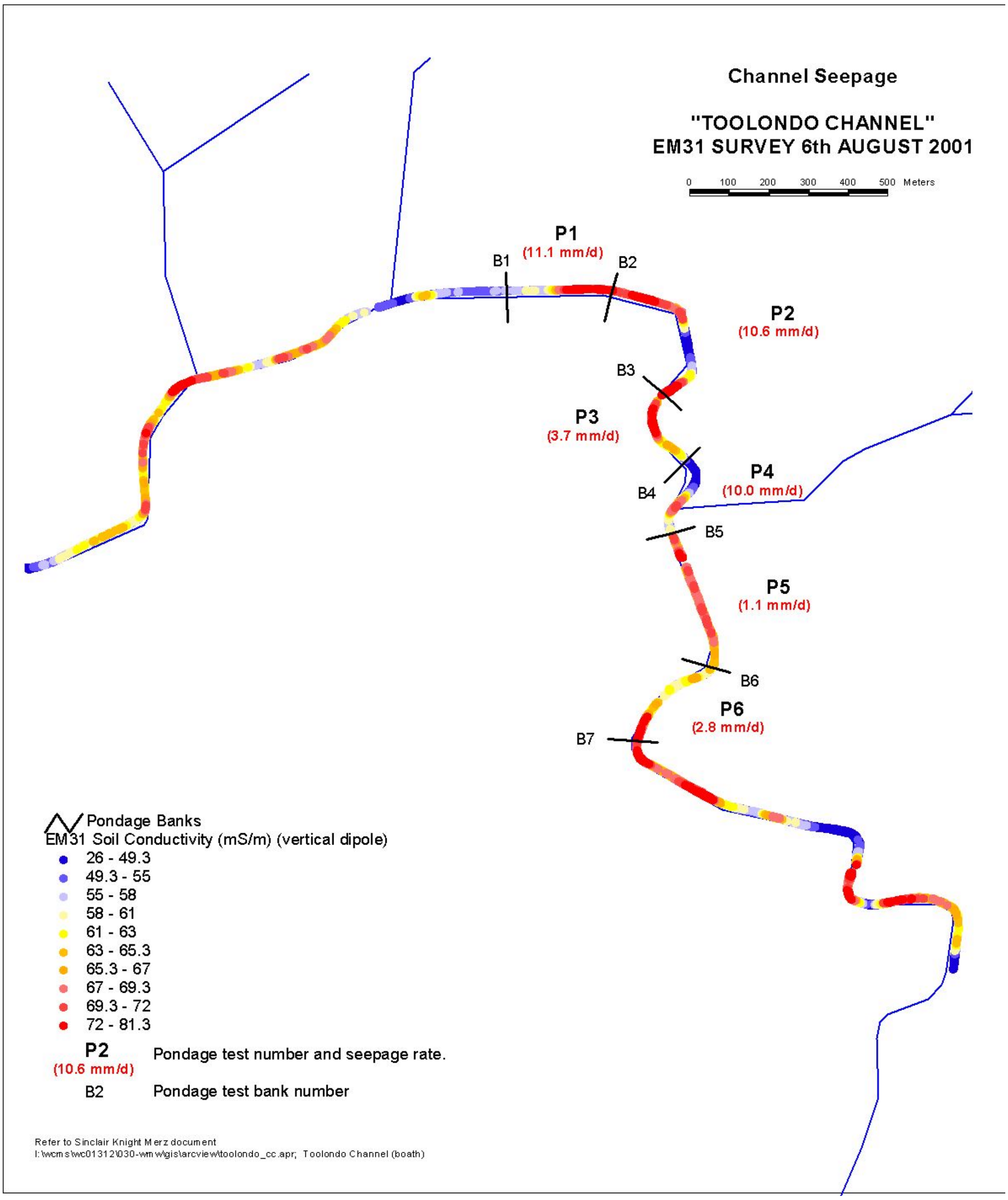
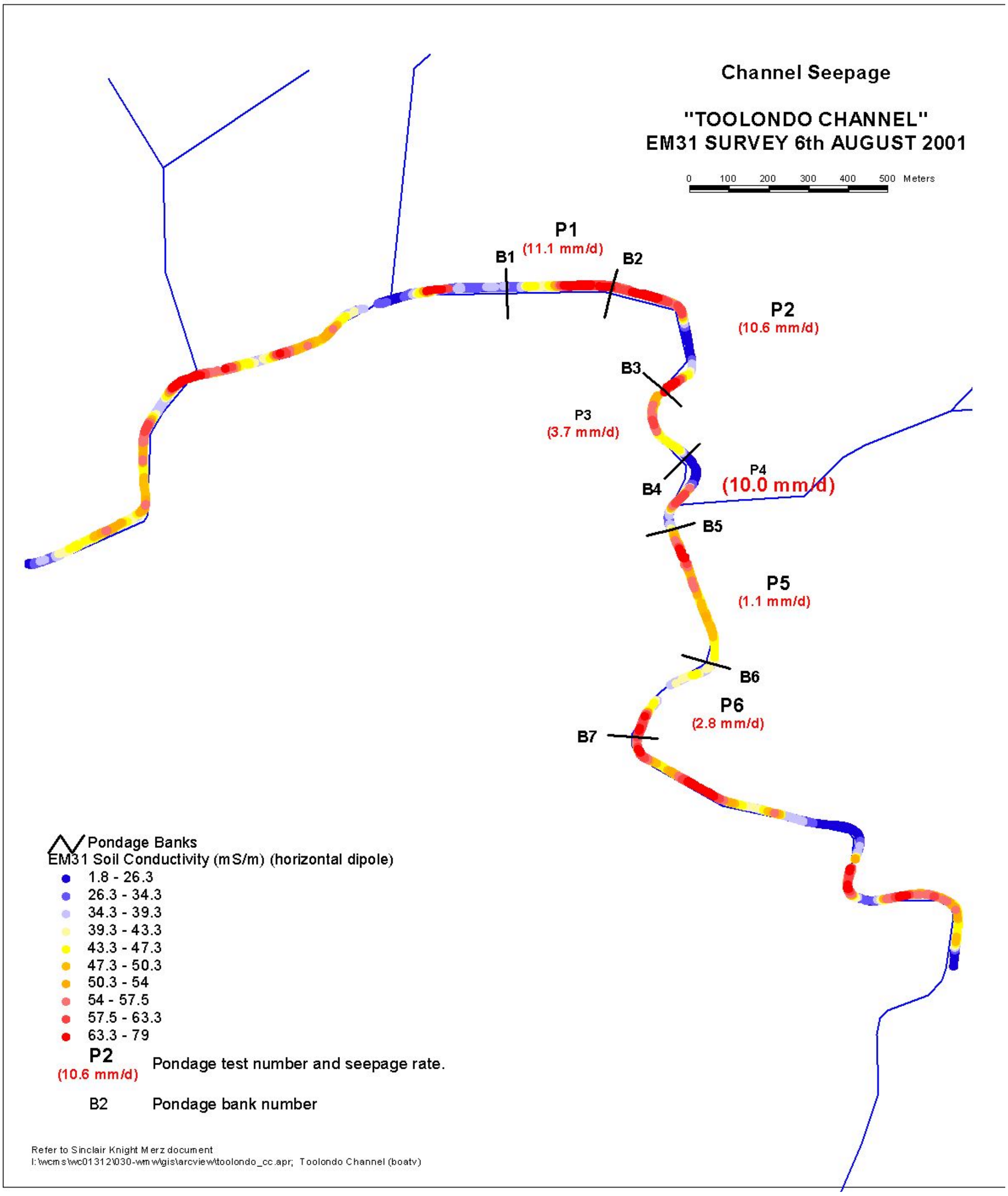


Figure 5-24 presents the results of the on-channel survey for both vertical and horizontal dipole modes, against the pondage test seepage data. The following comments are made regarding this graph:

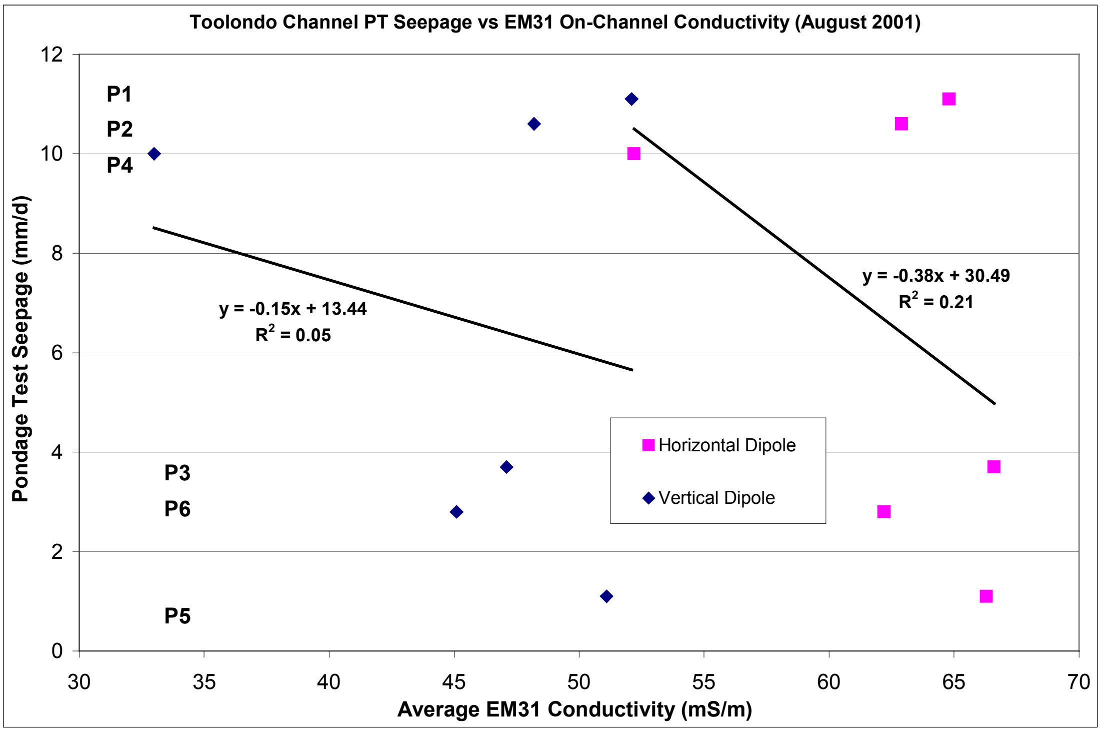
- There is no trend at all in the vertical dipole data, and the correlation for the horizontal dipole is also very poor. The reason for the uniformity of the conductivities (with the exception of pond 4) and hence the lack of correlation, is attributed to the flushing mechanism described above. Even for low seepage rate ponds, the profile immediately beneath the channel is essentially saturated with seeped water. This uniform saturation produces a uniform conductivity response. It is apparent that the effect of the seepage saturation largely masks other influences on response such as lithology.

- The horizontal dipole returns higher conductivities than the vertical configuration, as it more influenced by the upper part of the profile. The upper part of the profile consists of the channel water, a higher degree of saturation and generally more clay than deeper in the profile, all of which will produce higher conductivity results.

■ Figure 5-23 Toolondo On-Channel EM31 Survey, August 2001 – Horizontal Dipole



■ **Figure 5-24 EM31 On-Channel Survey Results (August 2000) – Toolondo Channel**



5.3.3.2 Rocklands – August 2001

A land based and on-channel EM31 survey was conducted by Ken Bates Soil Surveying on 7th - 8th August 2001 along the pondage test sections of the Rocklands channel. Approximately 20 mm of rain was received the night before the survey (according to the local farmer), however given that the rain did not occur during the survey, the most important prerequisite of uniform conditions throughout the test were satisfied. The contractor reported that the ground was not wet during the survey. The channel was also in operation at the time of the survey.

The groundwater depth at the site is approximately 5m, therefore the vertical dipole EM31 survey would be just 'penetrating' into the top of the watertable.

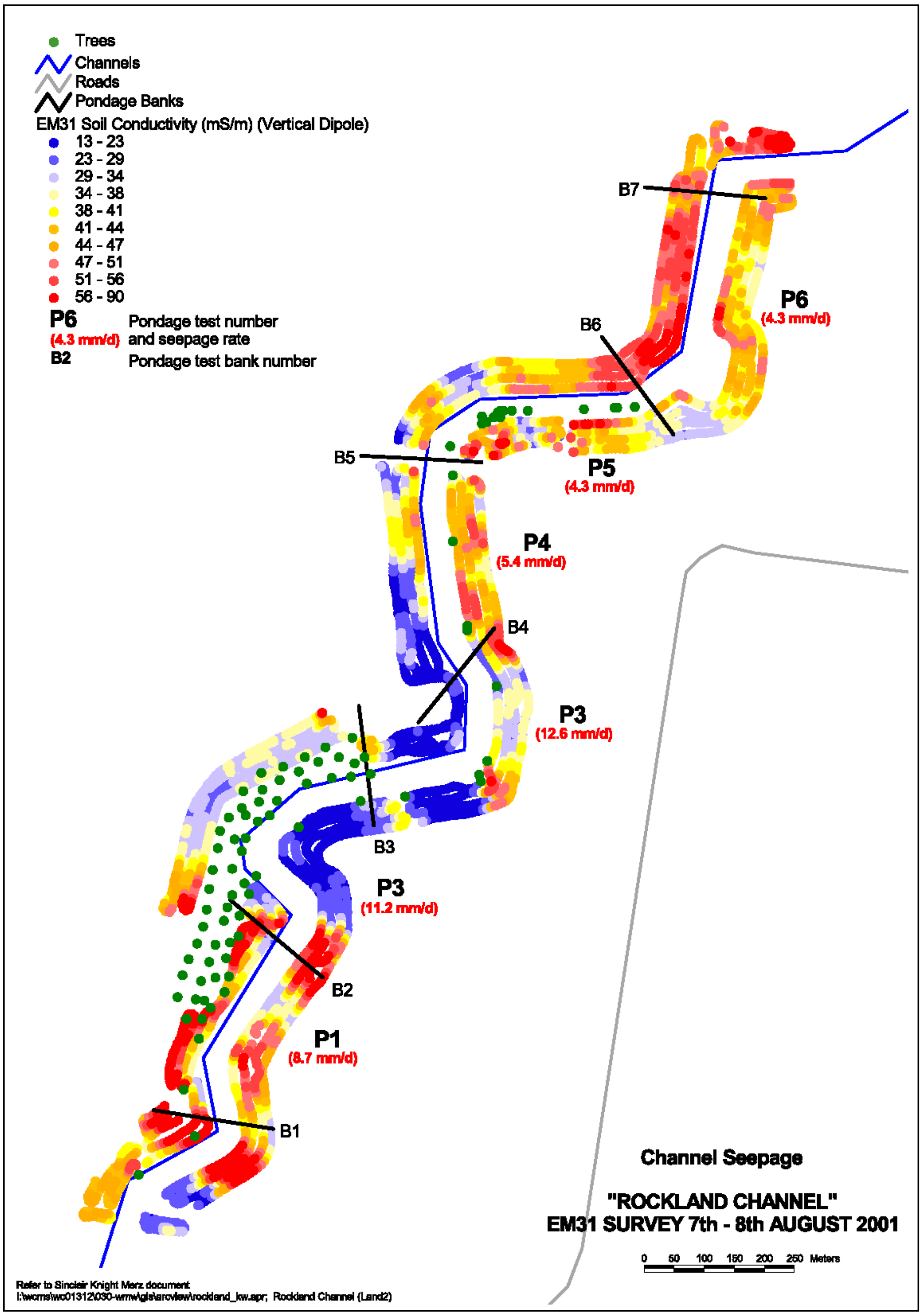
Land-Based Survey

The land based survey results are presented in Figure 5-25. (The tree plantation shown in this figure, west of Ponds 1 and 2, forced the western runs adjacent to Pond 1 to be squashed between the plantation and the channel and adjacent to Pond 2 prevented the traverses being conducted immediately adjacent to the pond). As this figure illustrates, the most dominant response was in the middle part of the conductivity range with most of the channel and surrounds returning responses of between 30 - 45 mS/m. Ponds 2 and 3 displayed the lowest conductivity, while Pond 1 returned the highest response.

Figure 5-26 and Figure 5-27 plot the pondage test seepage results against the average EM31 results. Figure 5-26 shows three combinations of data: all traverses, traverses on the LHS of the channel and traverses on the RHS of the channel. Figure 5-27 shows two combinations: the traverses adjacent to the channel only and the channel sides (ie both sides excluding the adjacent channel traverse). For the length of channel over which each pondage test was conducted, for each of these combinations of traverses, the average conductivity over the distance is plotted against the corresponding (pondage test) seepage rate.

All combinations of the traverses produce a moderately strong inverse correlation between EM31 conductivity and pondage test seepage rate. That is, there appears to be a clear inverse relationship between the average electrical conductivity in the top four to six metres adjacent to the channel and (pondage test) seepage rates. Using data from all traverses, a correlation co-efficient of 0.33 was produced. The correlation coefficient for traverses on the right hand side of the channel was stronger at 0.56 and weaker on the left at 0.26. As clearly seen in Figure 5-26 the two points weakening this relationship were Pond 1, which returned a higher than expected conductivity, and Pond 4 which returned a lower than expected conductivity.

■ **Figure 5-25 Rocklands EM31 Survey – August, 2001**



Pond 1 actually returned a much lower conductivity response in the EM34 survey of around 35 mS/m compared to 51 mS/m, (LHS) in the EM31 survey. This points towards the fact that the Pond 1 results for the August 2001 EM31 survey (LHS) might be anomalous, as there was better correlation between the EM31 and EM34 for the remaining ponds. The higher than expected response in Pond 1 may be due to the increased seasonal influence of the adjacent tree plantation (LHS Pond 2) which also extends on the outside of the survey results in Pond 1. The removal of water by the trees would cause a higher conductivity response than normal due to the absence of the fresh water which relatively acts as a resistor compared to the saltier soil and groundwater.

The cause of the lower than expected response in Pond 4 is a matter requiring further investigation (the low response is largely attributable to the low response on the LHS of the channel). For example, the area on the LHS of the channel may sit in a topographic low and therefore be receiving significantly more run-off, simulating channel seepage.

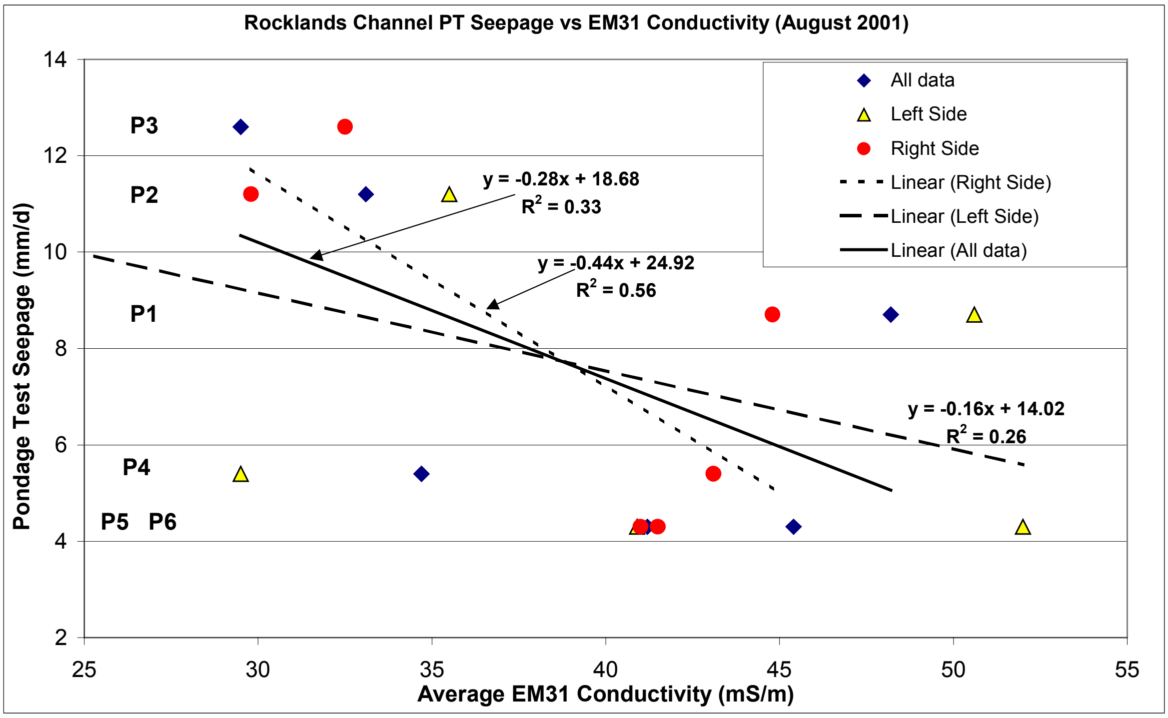
The reason why the best trend is clearly produced by the line adjacent the channel (R^2 = 0.82 in Figure 5-27) is largely due to the reduction in the conductivity immediately adjacent Pond 1 compared to the average across the 50m away from the channel. As discussed above, the increase in conductivity away from the channel (particularly noticeable on the LHS) is apparently due to other non-channel influences (probably trees). The more accurate traverse in terms of representing channel seepage, is therefore that which is least effected by these external influences.

The geological cross section for the Rocklands channel (refer *Appendix* A) generally concurs with the results of the EM31 survey. The clay and shallow sandstone underlying ponds 4 to six corresponds with the generally high conductivity response in these areas and the low measured seepage. The sandstone is apparently of fairly low permeability, given that the base of pondage four appears to intercept sandstone along most of its length and that the pondage test returned a relatively low seepage rate (5.4 mm/d).

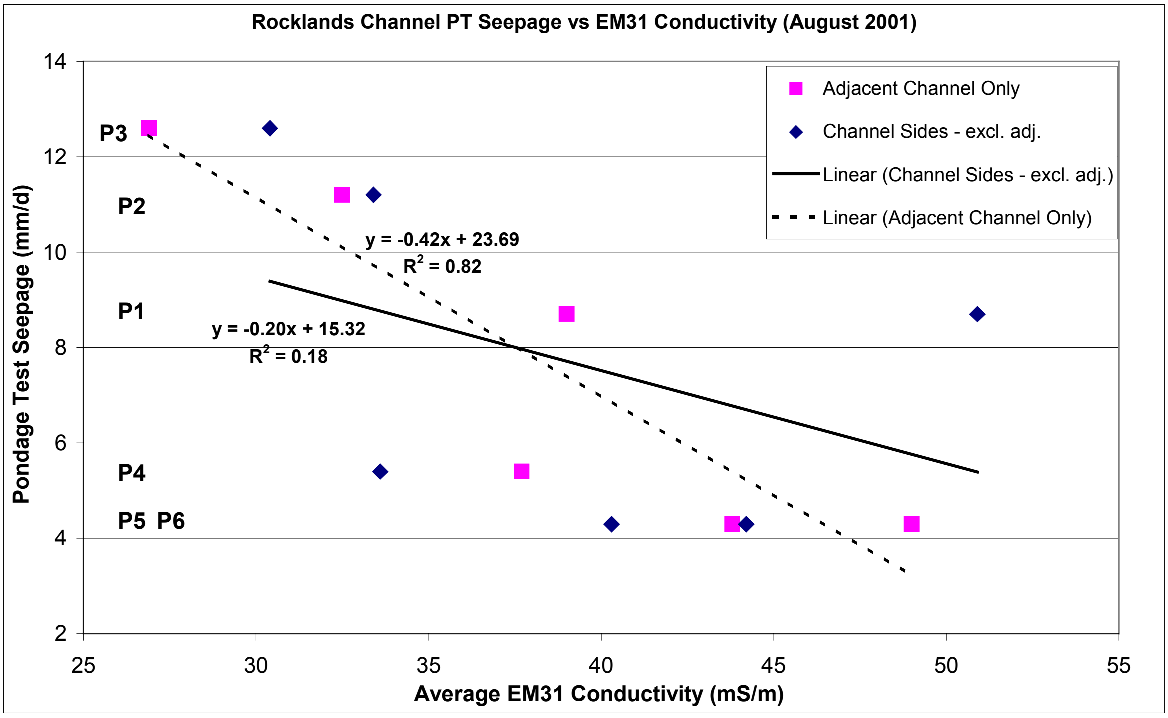
The generally lower conductivity response in ponds 1 to 3 also agrees with relatively more permeable sandy clay and fine sands underlying this area. Slightly higher conductivities in Pond 1 are again consistent with sandy clays and rock, although there is some sand beneath the channel centre line. The seepage rate is 8.7 mm/d, consistent with a mixed lithology in the channel bed.

In summary, the best correlation between the EM31 survey and pondage seepage rates are obtained with data from adjacent the toe of channel.

■ **Figure 5-26 EM31 Survey Results (August 2001) – Rocklands Channel**



■ **Figure 5-27 EM31 Survey Results cont' (August 2001) – Rocklands Channel**



The correlation decreases with distance from the channel, due in part to the mixing effect of the seeped channel water with the native groundwater, and also due to the interference effects of the trees adjacent Pond 1 and 2.

On-Channel Survey
In addition to the land-based survey at Rocklands in August 2001, an on-channel survey was conducted on the same day. The survey was conducted in both vertical and horizontal dipole arrangements to provide different penetration depths beneath the channel. The results of the surveys for the vertical and horizontal modes are presented in Figure 5-28 and Figure 5-29 respectively.

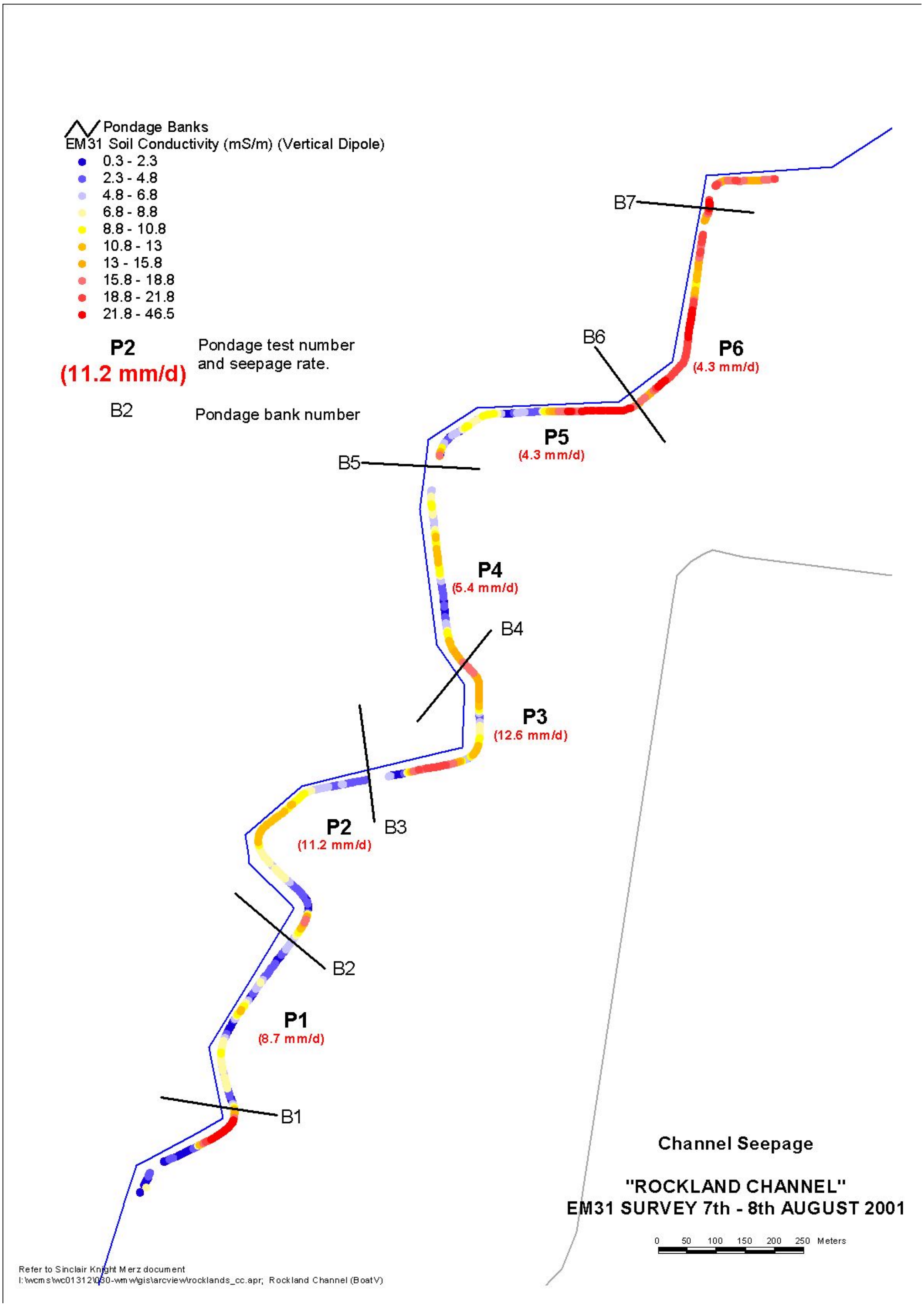
During the survey, the boat sits on about one metre of water, which will affect the results. However the results will be affected in a uniform manner, provided the water depth along the section of interest is approximately consistent. The difference between the relatively high and low seeping areas is most clearly evident in the horizontal dipole mode (Figure 5-29). The red sections of Ponds 1-3 are in sharp contrast to the blue sections of Ponds 4-6.

Figure 5-30 presents the results of the on-channel (boat) EM31 survey at Rocklands verses the pondage test seepage results. The following comments are applicable to these results:

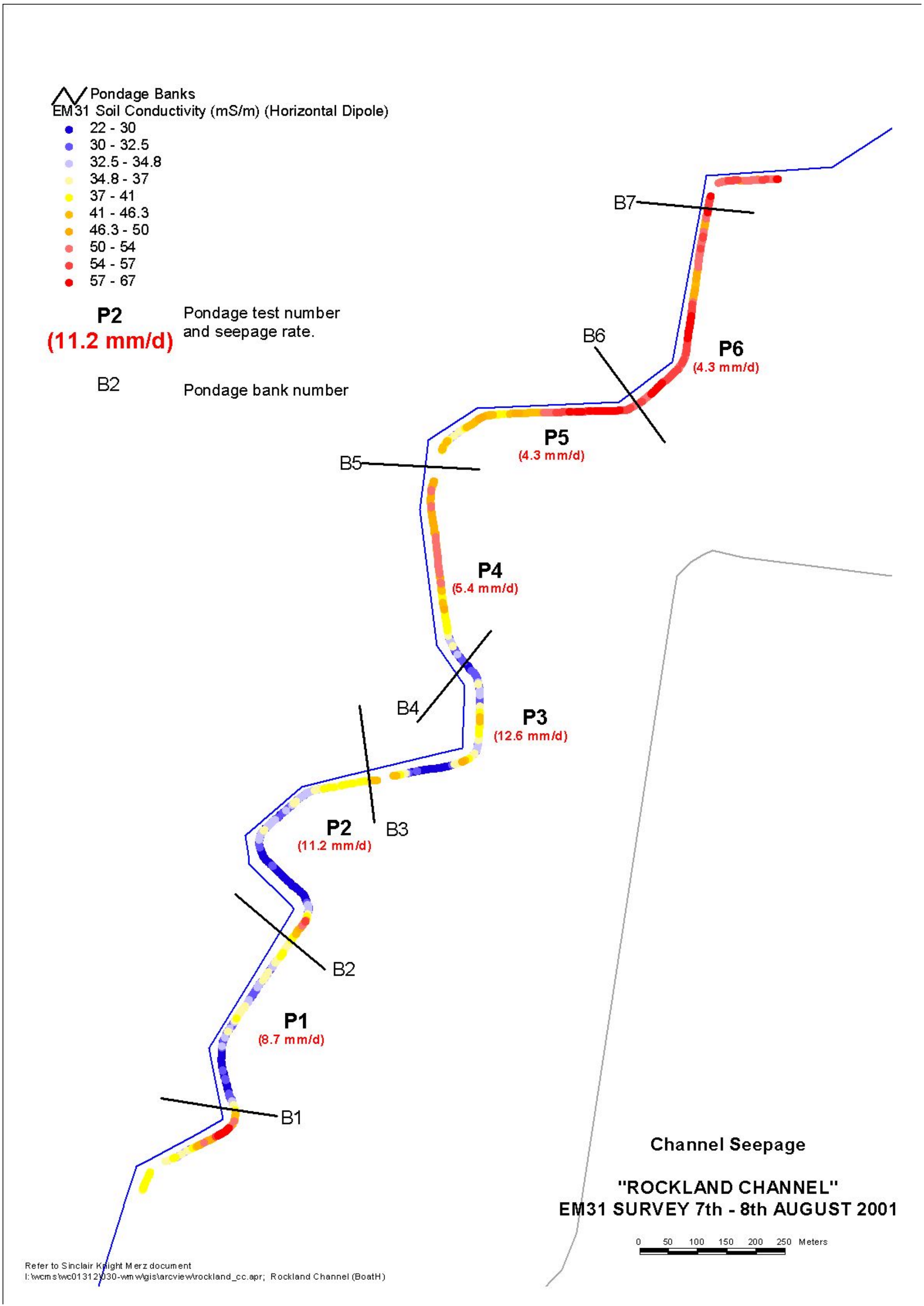
- The conductivities in the vertical mode are much lower than the horizontal mode (all < 20 mS/m). This is predominantly due to the effect of the metre (or greater) depth of water in the channel which is very much more influential on the horizontal than the vertical dipole results. Of secondary importance is the generally more clayey nature of the 1-2 metres immediately beneath the channel base (due to clay infilling during channel construction and natural sedimentation etc) which will cause a higher conductivity response. Therefore, apart from the water conductivity, in the horizontal dipole mode, the EM31 is essentially measuring the percentage of clay in the layer immediately beneath the channel bed. This is an important difference compared to the land based surveys outside the channel which are primarily detecting the seepage itself where it has displaced the more saline groundwater.
- There is a good correlation of the horizontal dipole results with the pondage test data. The contrast between the lower conductivity and higher seeping ponds (P1-P3: 32-34 mS/m) and the high conductivity and lower seeping ponds (P4-P6: 43-53 mS/m) is clearly evident. The mechanism for detecting this difference was described above: in the horizontal dipole mode the main property which is detected is the clay content in the metre or so below the channel bed. The good correlation between the horizontal dipole mode at Rocklands suggests that the efficiency of this clay 'liner' beneath the channel has a very important influence on seepage *at this site*. It is important to note that this method will only work if the depth of water in the channel is reasonably constant, as even fairly small variations in depth could lead to false interpretation (eg an increase in depth of water will appear as in increase in conductivity and will be interpreted as an increased clay presence and therefore decrease seepage, and vice-versa).
- The Rocklands geological cross-section (refer *Appendix* A) assists with interpretation of the results. This figure shows that Ponds 1 and 2 are the only ponds to contain sand deposits in the top 1-2 metres beneath the channel base. The geophysical data suggests that the sand layer beneath Pond 2 may well extend into Pond 3. However there were no bores in the section to help confirm

this theory. In contrast, the upper profile of Ponds 4-6 is dominated by clay and sandstone.

■ **Figure 5-28 Rocklands On-Channel EM31 Survey, August 2001 – Vertical Dipole**



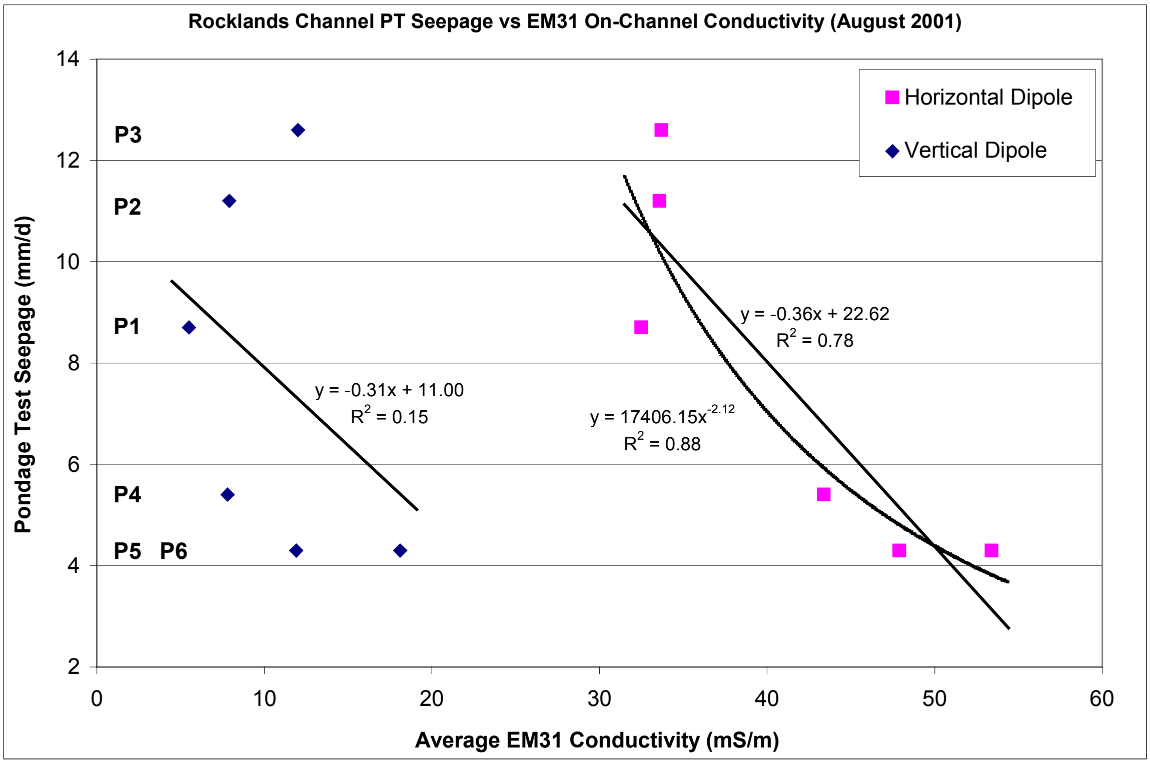
■ **Figure 5-29 Rocklands On-Channel EM31 Survey, August 2001 – Horizontal Dipole**



- A trend line using a power function has also been fitted to the horizontal dipole data, to suggest that, in the horizontal dipole mode, a linear relationship may not be the most accurate formula for describing the conductivity – seepage relationship.
- There is a poor correlation between vertical dipole data and seepage. This is partly because of low conductivity readings. The vertical data is mostly less than 15 mS/m which is approaching the reading resolution limits of the meter. An error of at least +/- 2 mS/m can be expected at low conductivities. In addition, at low conductivities small changes in other physical properties such as porosity, cation exchange capacity and salt storage will have a large influence on the total reading. The very low conductivities immediately beneath the channel (below one metre or so beneath the base) reflect a flushed zone. This zone appears to have been flushed of all salt, regardless of lithology and primarily represents the conductivity of the fresh water and the porosity of the sediment). The absence or presence of clay at this depth would obviously not control seepage as much as clay closer to the channel, which is why the correlation breaks down in this instance.

In summary, the in-channel EM31 in the horizontal dipole mode produced good correlations between pondage test seepage rates by identifying clay content immediately beneath the channel. The EM31 in the vertical dipole mode produced poor correlations due in part to the poor resolution of the meter at low conductivities, and in part due to the flushed zone beneath the channel, where clays and sands alike have been completed filled with fresh water.

■ **Figure 5-30 Rocklands On-Channel EM31 Survey Results (August 2001) vs Pondage Test Seepage**



5.3.3.3 Donald Main – September 2001

An EM31 survey was conducted by Ken Bates Soil Surveying on 6th September 2001 along a 2 km section of the Donald Main Channel. The channel had recently commenced operation at reduced capacity (16/8/01) at the time of the survey, after being out of operation for approximately 9 months. Both a land based and an on-channel based survey were conducted. Depth to watertable at the time of the survey was approximately 1.5m on the down slope side of the channel and approximately 3m on the up slope side.

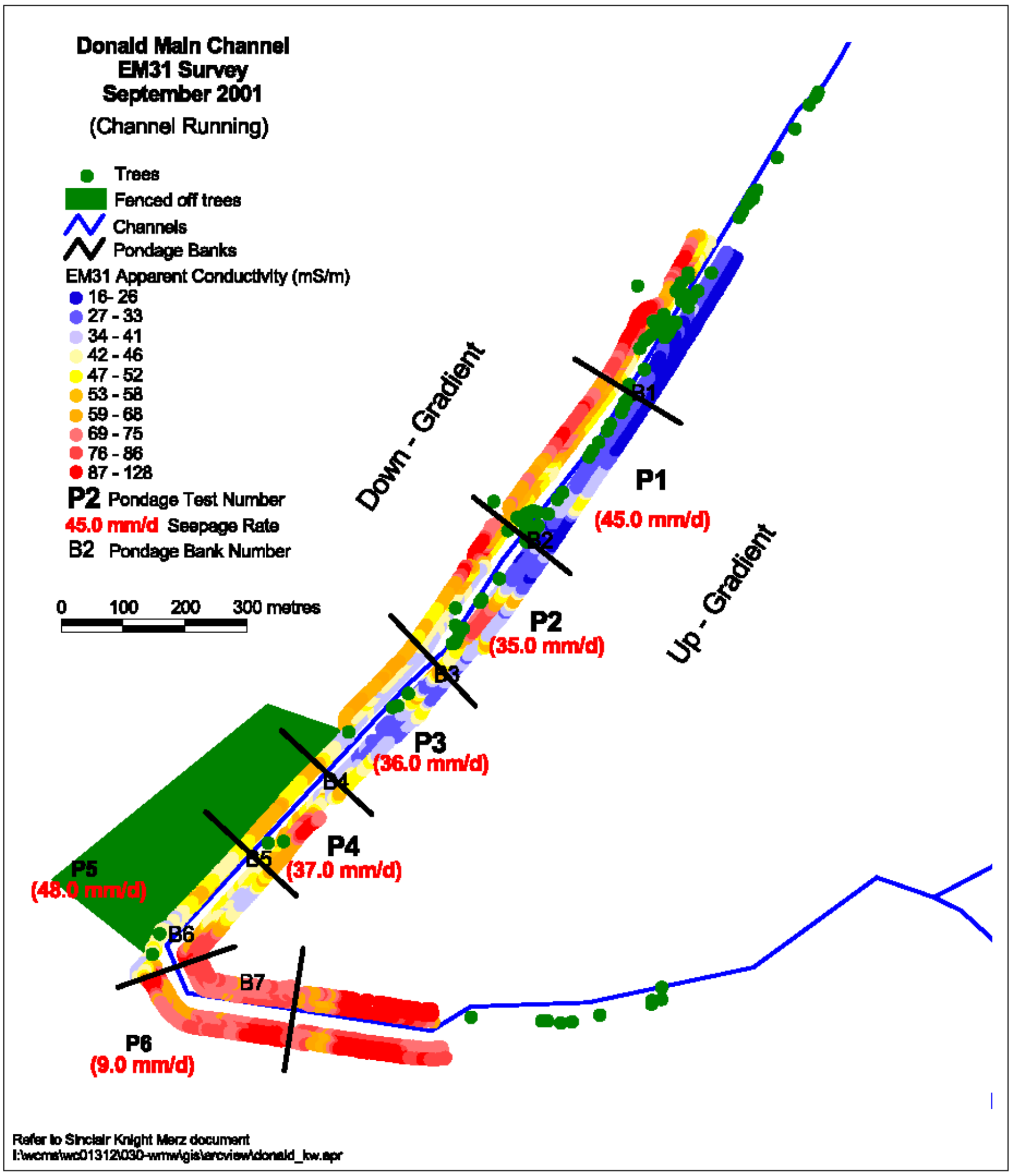
Land-Based EM31 Survey
The land-based survey was conducted with the EM31 in the vertical dipole orientation. In total eight traverses were conducted, four on each side of the channel up to around 50 m from each channel bank. The land based survey results are presented in Figure 5-30. As this figure illustrates, the most dominant response was in the 40 - 60 mS/m conductivity range, with the exception of Pond 6 which clearly returned the highest response in the 70 - 80 mS/m range. Close examination of this figure (particularly in Ponds 1-3) indicates lower conductivity readings closer to the channel, and increasing away from the channel.

Figure 5-32 and Figure 5-33 plot the pondage test seepage results against the EM31 results for various combinations of the average conductivities from the survey runs. Figure 5-32 shows three combinations of averages from the EM31 data: all traverses, traverses on the LHS of the channel and traverses on the RHS of the channel. Figure 5-33 shows two combinations of averages from the EM31 data: the traverses adjacent the channel only and the channel sides (ie both sides excluding the adjacent channel traverse). The following observations are made from these plots:

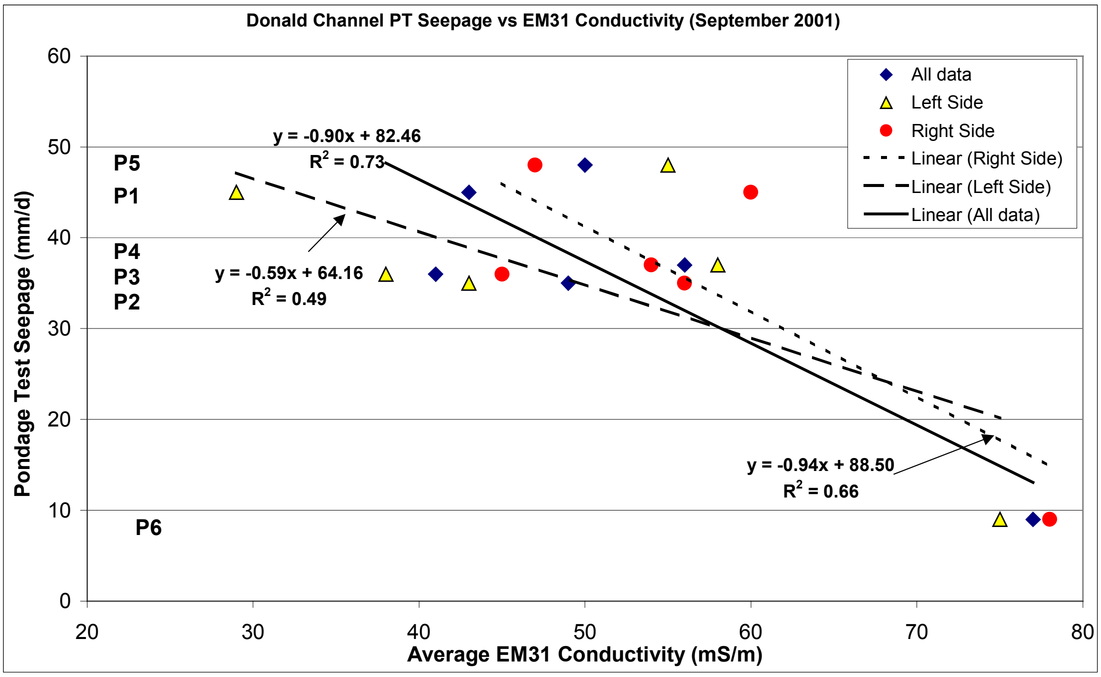
- There is an inverse relationship between the average EM31 conductivity adjacent the channel and (pondage test) seepage rates. Using data from all traverses produced a correlation coefficient of 0.73. The correlation coefficient for traverses on the right hand side and left hand of the channel produced weaker correlations of 0.66 and 0.49 respectively, reflecting the 'averaging' of seepage across the length and width of the pond section.
- There was little distinction between the seepage rates in the 35-50 mm/d range. The correlation would be more useful if there was pondage test data in the middle and lower seepage rate ranges.
- Figure 5-33 confirms the visual observation in Figure 5-31, that lower conductivity readings occur adjacent the channel and increase away from the channel. Figure 5-33 shows lower average conductivities near the channel in Ponds 1, 3, 4 and 6. This is attributable to the greater influence of the low salinity seepage water near the channel which is increasingly diluted by the high salinity native groundwater away from the channel.
- The relationship between the EM31 land survey and the pondage tests is better than the EM34 relationships. This is attributed to the deeper depth focus of EM31 in vertical dipole (2-4m), which targets the watertable, compared to the shallow depth focus of EM34 which is largely affected by the unsaturated zone.

  EM34 surveys have been more successful in the past at Donald however, due to the fact that the channel had been running longer prior to survey. The watertable was therefore more elevated and the profile dominated to a greater degree by seepage water. This highlights the importance of the channel running time on the correct selection of EM survey equipment. There is an optimum time after commencement of channel operation for surveying with a particular EM configuration, depending on the hydraulic conductivity of the surrounding formation and depth to watertable. For example, an EM configuration with a shallow depth focus might be appropriate if the channel has been in operation for a period of several months or more. However an EM configuration with a deeper depth focus would be required if conducted soon after the channel begins operation to ensure targeting of the watertable. If the channel has not been in operation for a long period then the EM response will reflect local geological/soil type changes and should be interpreted as such for zones of potential seepage.

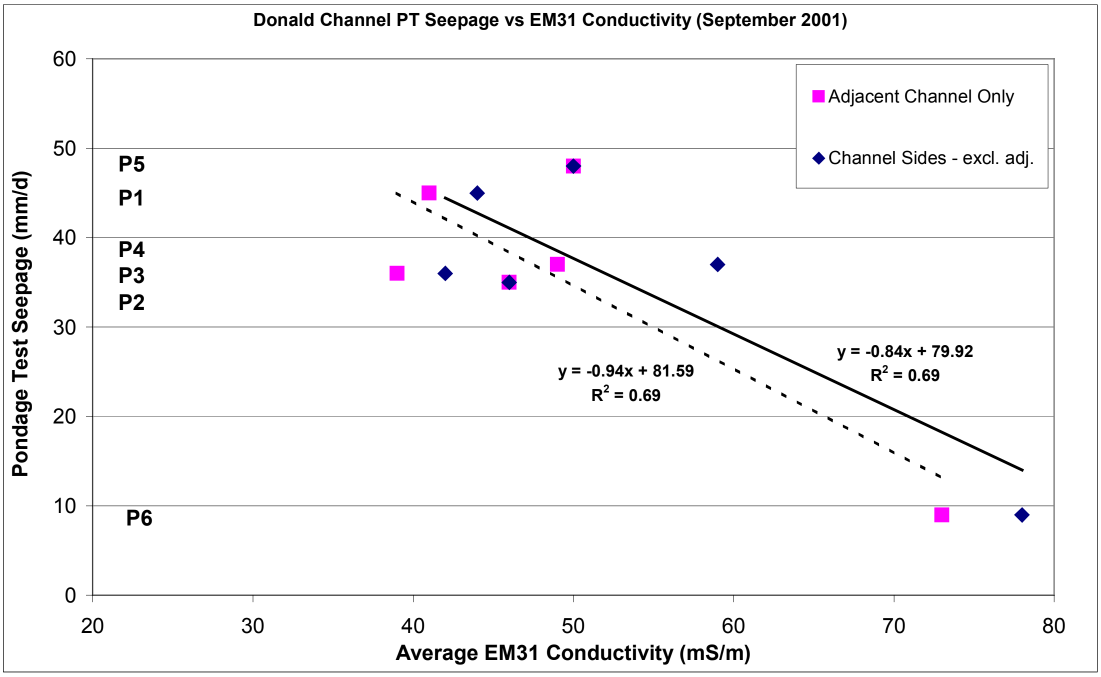
- **Figure 5-31 Donald Main Channel EM31 Land Based Survey – September 2001**



■ **Figure 5-32 Donald Main Channel Pondage Test Seepage vs EM31 Land Based Conductivity (September 2001)**



■ **Figure 5-33 Donald Main Channel Pondage Test Seepage vs EM31 Land Based Conductivity, Continued (September 2001)**



On-Channel EM31 Survey

In addition to the land-based survey at Donald Main in September 2001, an on-channel survey was conducted on the same day. The survey was conducted in both vertical and horizontal dipole arrangements to provide different penetration depths beneath the channel. The results of the surveys for the vertical and horizontal modes are presented in Figure 5-34 and Figure 5-35 respectively. The influence of the metre column of water above the instrument will affect the results in a uniform manner, provided the water depth along the section of interest is fairly constant.

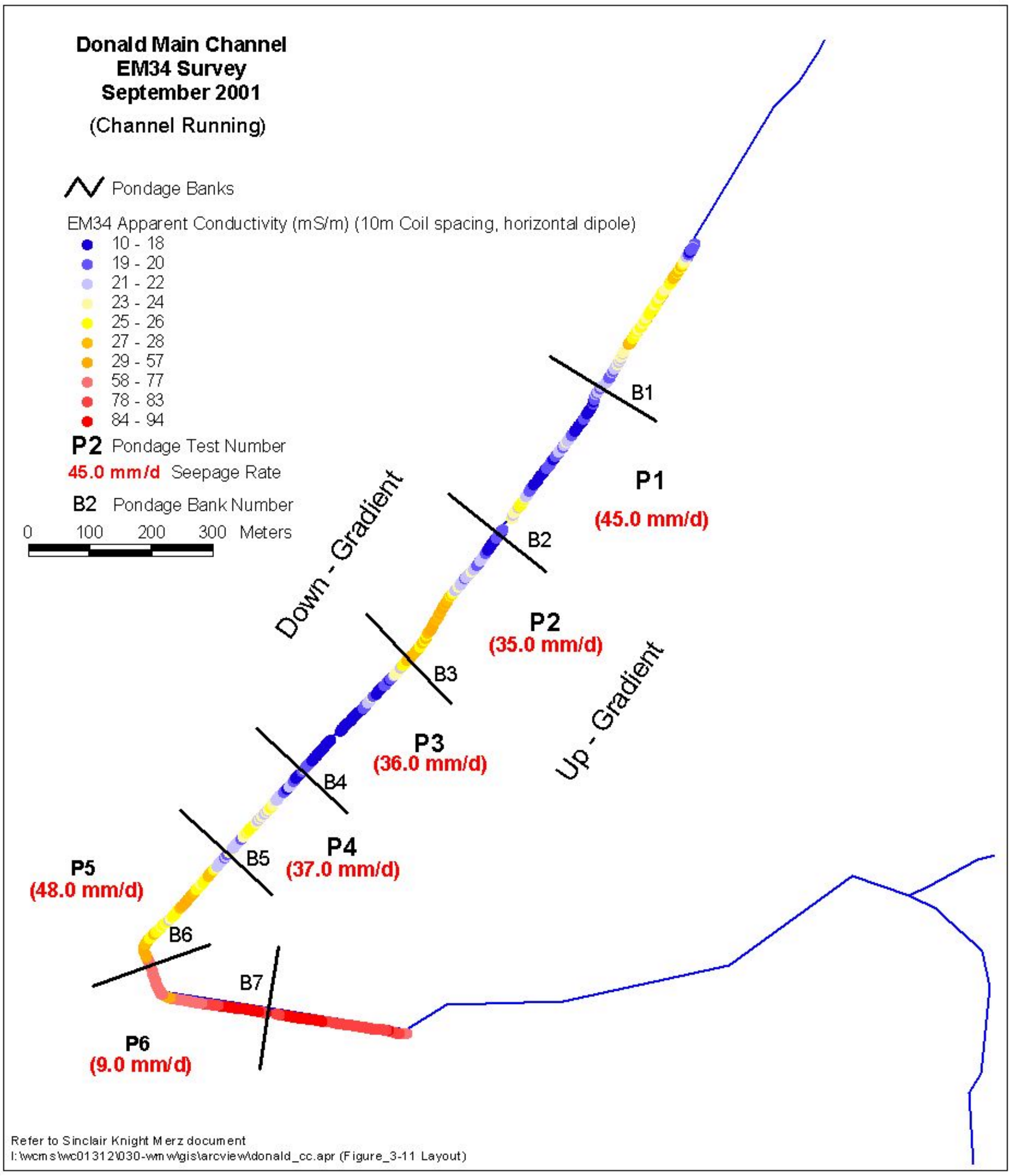
The difference between the relatively high and low seeping areas can be seen in both the dipole modes. It is worth comparing Figure 5-34 and Figure 5-35 with Figure 5-31, the land based survey taken on the same day as the boat survey. The low conductivity areas (usually interpreted as higher seepage) generally match with each other in the two figures, however the horizontal dipole mode consistently records a higher conductivity than the vertical dipole, as can be seen by the greater dominance of blue and yellow. The one exception to this is Pond 6, where a consistently high conductivity response (red in Figures) is recorded for both ponds.

Table 5-5 presents the difference between the average land and boat data and between the average horizontal and vertical dipole on the boat. The last columns of the table compare the two dipole results on the water with the land results. The horizontal dipole on the boat and the land based survey returned results of similar magnitude, with the land survey displaying conductivities approximately 20% higher on average. The land vertical dipole however returned much lower conductivities, with the land survey generally equal to or greater than 100% of the boat survey in the vertical dipole. The exception to this was Pond 6 where the results were almost the same magnitude for the land and the boat (vertical dipole). The V/H column illustrates the relationship between the vertical and horizontal dipoles. With the exception of Pond 6, the average vertical dipole response for each pondage section ranged between 48-70% of the horizontal dipole response for the same pond. For Pond 6, the vertical dipole response was actually marginally higher than the horizontal response.

- **Table 5-5 Donald Main Channel - Comparison of Average Land and On-Channel EM31 Results, September 2001**

Pondage	Land (Vertical Dipole)	Boat (Horizontal Dipole)	Boat (Vertical Dipole)	Boat V / Boat H	Land – Horiz / Horiz	Land – Vert / Vert
	(mS/m)	(mS/m)	(mS/m)			
1	43	37	20	54 %	16%	117%
2	49	41	24	60%	20%	100%
3	41	38	18	48%	9%	129%
4	56	39	22	56%	44%	159%
5	50	41	29	70%	22%	74%
6	77	68	73	107%	12%	5%
Average	53	44	31	66%	21%	97%

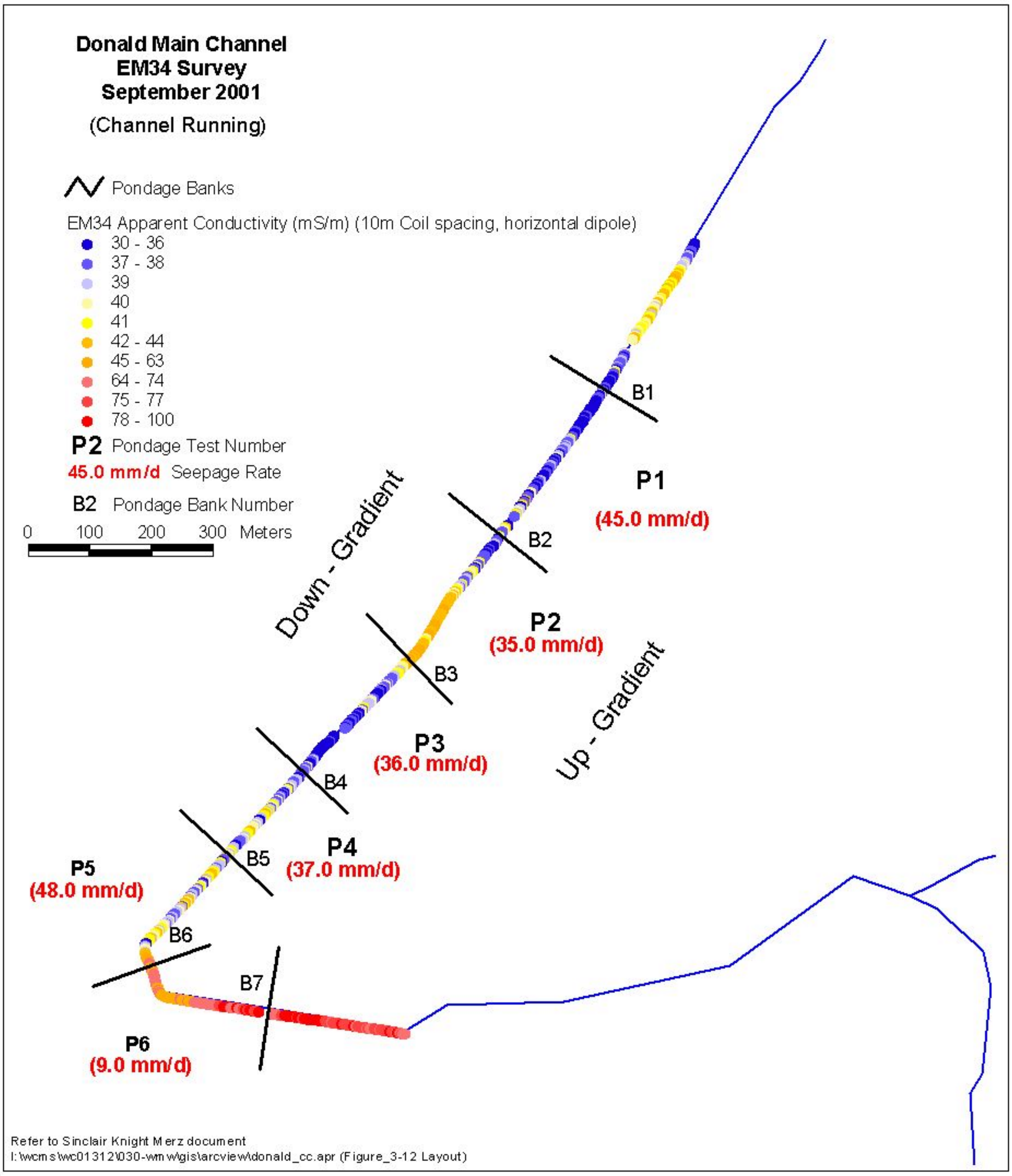
■ **Figure 5-34 Donald Main Channel EM31 On-Channel Survey Results – Vertical Dipole**



The reason for the lower conductivity response in the surveys directly over the channel (boat) is explained by the increased volume of fresh pore water immediately below the channel, causing a reduction in the conductivity of the profile, compared to the saltier pore water in sediments away from the channel.

The difference between the horizontal and vertical dipole response of the boat survey is primarily controlled by the water in the channel which will dominate the horizontal response. However an important secondary governing factor is the soils. This is best understood by examining the Donald Main Channel Geological Long-Section (refer *Appendix* A). This figure illustrates that generally the upper two metres along the channel is comprised of clay, before more sandy and permeable sediments are encountered. The shallower penetration depth of the horizontal dipole

■ **Figure 5-35 Donald Main Channel EM31 On-Channel Survey Results – Horizontal Dipole**



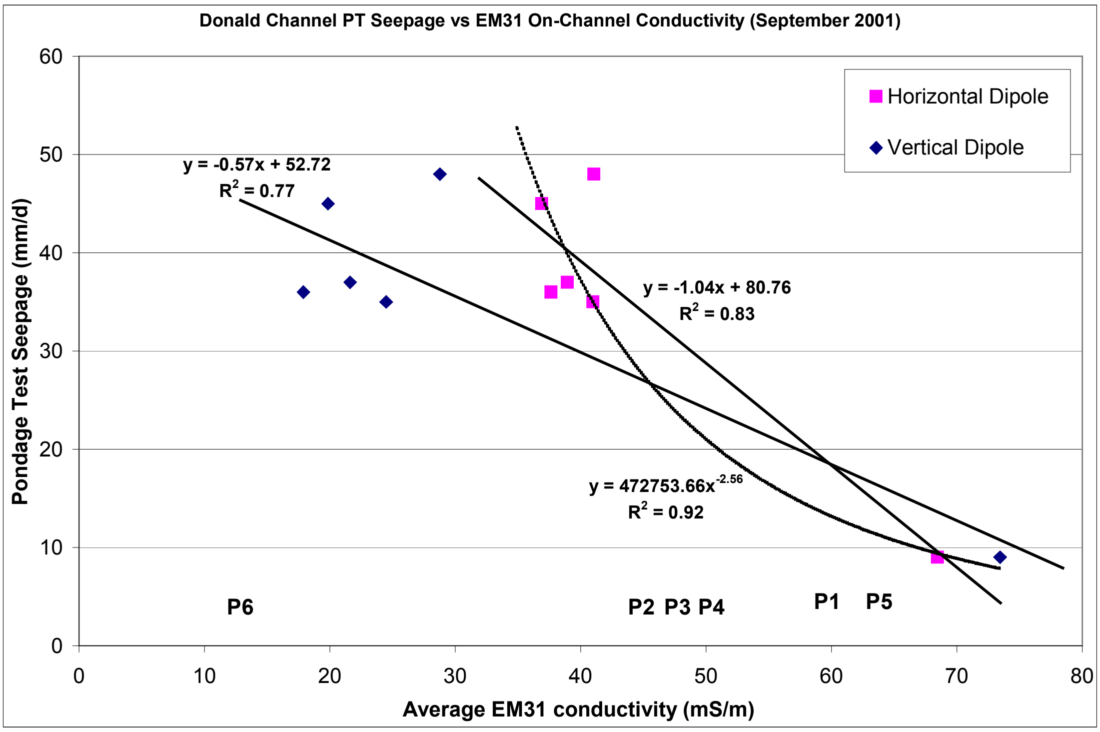
arrangement primarily targets the clays near the surface and therefore returns a higher conductivity than the vertical dipole which has a response predominantly from the deeper, sandier and less conductive sediments. The exception is Pond 6, where as the geological section illustrates, this part of the channel is underlain by clay to at least 4m depth below surface. Saturation of sand will result in low conductivity at depth, whereas saturation of clay will result in higher conductivity at depth due to higher porosity, cation exchange capacity and salt storage. Therefore there is essentially no difference observed between the average responses in Pond 6 for the two dipole configurations.

Figure 5-36 plots the results of the EM31 boat survey against the pondage test seepage results. The correlation coefficient for the linear line of best fit was similar for the vertical and horizontal dipoles, at 0.77 and 0.83 respectively. Similarly to the land based EM31 results at the site, this figure illustrates that the survey did not distinguish between seepage rates at the higher end of the range. For example in the horizontal dipole mode Ponds 1 – 5 were in a tight band between 37 – 41 mS/m. For this reason, the power function line of best with its flatter gradient through the higher seepage results fits the data more closely. As with the land based data, the low seepage rate Pond 6 is clearly distinct in its high conductivity response.

In summary, the relationship between the EM31 boat survey and the pondage tests is comparable than the EM31 land based survey, which was in turn better the EM34 survey. To properly test this relationship however, more data points in the middle and lower seepage rate ranges are required. The current trend line is heavily dependent on the single low seepage rate result of Pond 6.

To summarise the results of the on-channel surveys, they did not work at sites where the watertable was beyond the range of the EM31 (Toolondo), did work at sites with a shallow watertable (Donald) and were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31 (Rocklands). Further work is required in this area, but the evidence collected in this investigation suggests on-channel surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

- **Figure 5-36 Donald Main Channel EM31**



5.3.3.4 Dahwilly Central – June 2000

An EM31 survey (vertical dipole) was conducted by Ken Bates Soil Surveying on 13th June 2000 along a 5 km section of the Dahwilly channel. The channel was not running at the time of the survey (and had ceased to run several weeks prior to the survey). Depth to watertable at the time of the survey was around 5 to 6m. In total eight traverses were conducted, four on each side of the channel up to 50m from each channel bank. The survey results are presented in Figure 5-37. This figure shows that the dominant response is in the low conductivity range. Virtually all of the pondage test sections display average conductivities below 26 mS/m.

The low conductivities are primarily due to the sandy profile along the channel. The geological long section at the site (refer Dahwilly Central Geological Long Section A, *Appendix* A) shows that along the entire extent of the pondage sections a medium to coarse sand layer is present from 1m to at least 4m below surface (Geological Long Section B at the Dahwilly site shows that the sand extends to at least 10m depth). Approximately one metre of sandy clay overlies this sand layer, but as the geological section depicts, the elevation of the channel bed is approximately one metre below surface and close to the top of the sand layer.

This geological profile is consistent with the long history of seepage problems reported on this section of the channel. The geophysical response is also relatively uniform and with the exception of Pond 6, the conductivities fall within a fairly narrow band between 14-17 mS/m (for all data). However, despite the relative uniformity of high permeability materials along the section, seepage rates in the channel are not uniformly high across all ponds. It is noted that the seepage rates in ponds one and two are very low (< 5 mm/d). It is understood that seepage is low in these ponds due to the deposition of sediment upstream of the check at bank 3 (as discussed in the pondage test section, 4.1.3), so that a low permeability layer overlies the more permeable sandy interval.

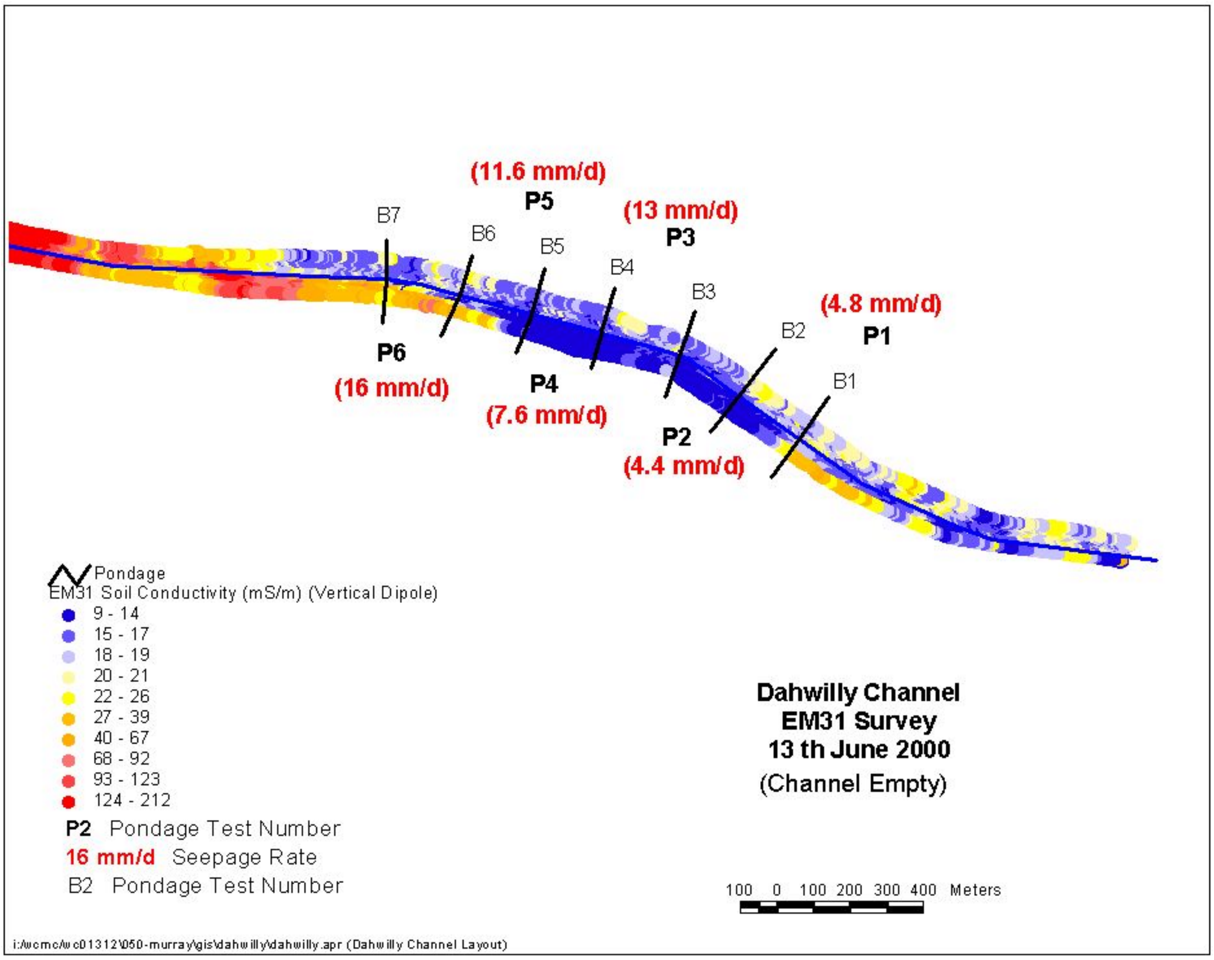
Within the narrow conductivity range, there is no apparent trend of conductivity with seepage rate, and if any trend at all, there appears to be an opposite trend to that observed at other sites (ie increasing conductivity relates to increasing seepage). Several factors may explain these results:

- The channel was not running at the time of the survey and previously seeped water (ie from the previous irrigation season) is likely to have thoroughly mixed with native groundwater. Therefore there is no seepage plume to detect.
- The main depth focus of EM31 is in the unsaturated zone. At some sites the measurement of unsaturated zone soil properties with EM31 successfully correlates with seepage based on the inferred likelihood of seepage, as indicated by lithology (eg Toolondo, Rocklands). At these sites, however, a significant difference between unsaturated zone soil properties is observed between ponds. At the Dahwilly site the unsaturated zone is very uniform, and seepage rates are actually controlled by the clogging layer, not the unsaturated zone. Therefore seepage detection mechanisms must target impacts on the groundwater, not the unsaturated zone. This is supported by the good correlations with resistivity at this site, where the watertable is targeted (refer 5.4.4.4).
- The very high permeability of the aquifer at this site may be contributing to the lack of distinction between seepage rates. At a 'normal' site the fresh seeped water is detectable beneath the pond from which it has originated. However at

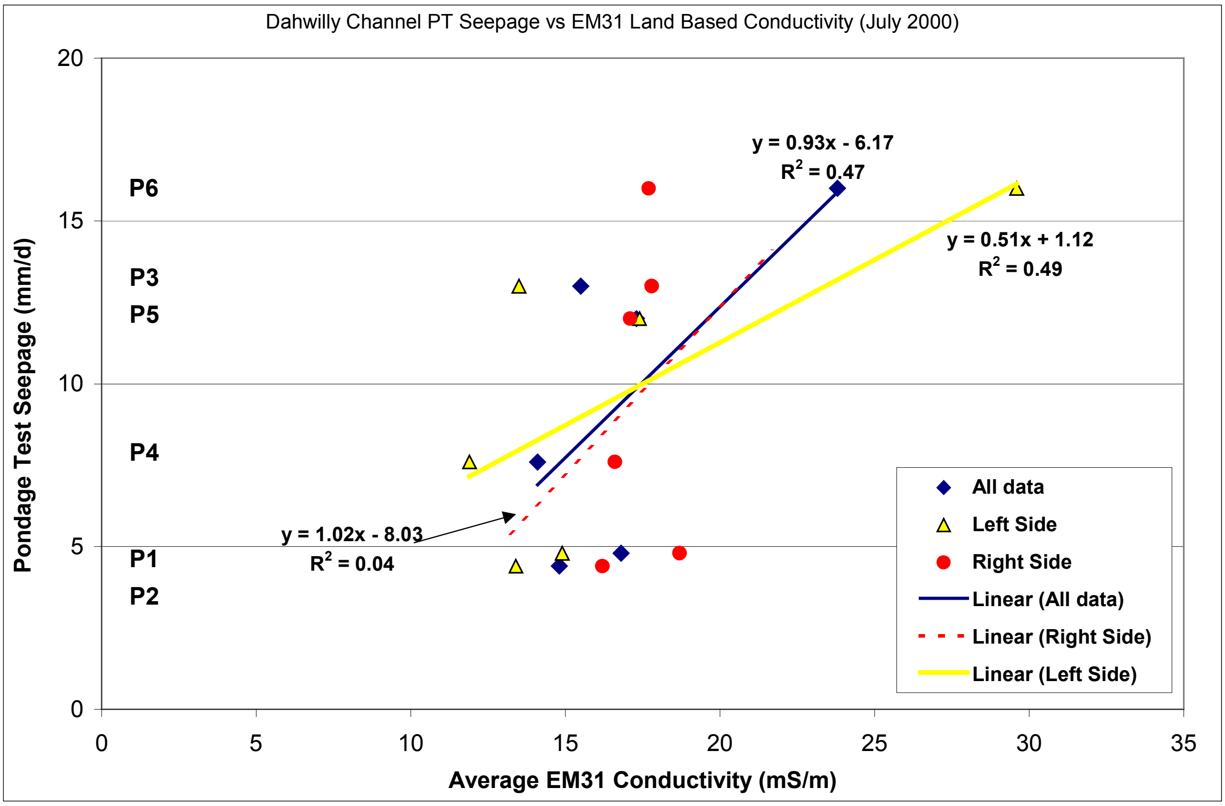
this site the very high permeability of the aquifer may be causing mixing of the fresh water adjacent the ponds (by advection and dispersion), thus blurring the identity of the pond from which the water emanated, and creating a relatively uniform response in the saturated zone. (This is considered the least likely explanation and the first two points are considered more feasible explanations).

- The high conductivity in pond 6 is due entirely to the high conductivity on the LHS of the channel and is considered somewhat anomalous. This may be due to clayey sand on this side of the channel, and also the resulting retained moisture. Given the very high permeability of the unsaturated zone, seepage is still controlled by the clogging layer in the channel and therefore the clay in the unsaturated zone does not effect seepage rates.

Figure 5-37 Dahwilly EM31 Survey Results, June 2000



■ **Figure 5-38 Dahwilly Pondage Test Seepage vs EM31 (July 2000) Results**



5.3.3.5 Lake View – June 2000

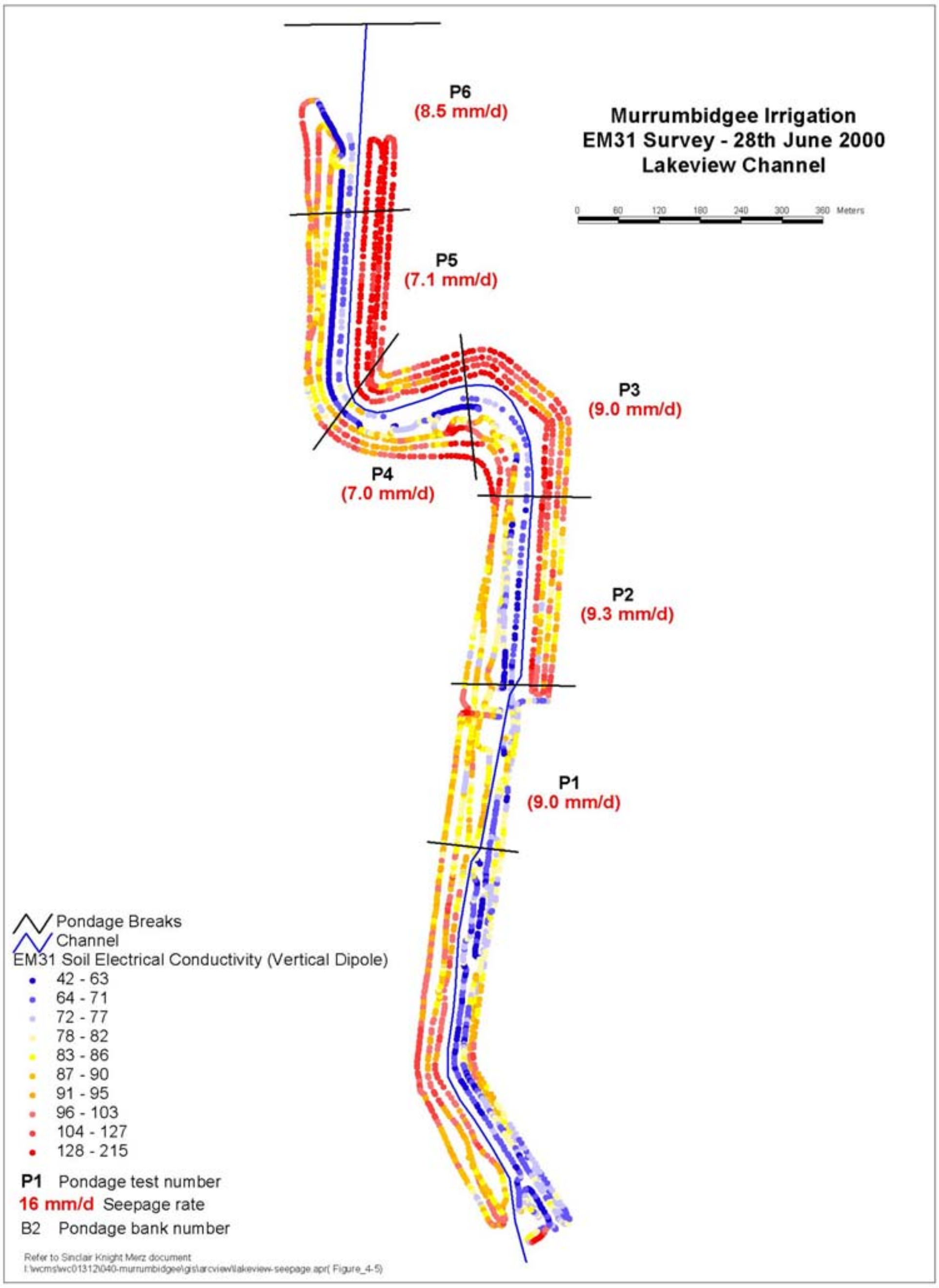
An EM31 survey (vertical dipole) was conducted by Lloyd Angove Soil Surveying and Drilling Pty Ltd on 28th June 2000 along a 2 km section of the Lake View channel. In total 8 traverses were conducted, 4 on each side of the channel, up to 50m from each channel bank. The channel was running at full supply level at the time of the survey and had been running for the previous 9 months. Depth to watertable at the site is approximately 1.5m. The survey results are presented in Figure 5-39. The conductivities at the site are relatively high (median conductivity is approximately 90 mS/m), which is consistent with the overall clayey geological profile and shallow depth to (saline) groundwater.

The lowest conductivities shown in this plan are on the left hand side of the channel (for ponds 2-6), suggesting that there could be a fresh water plume and the grading of this plume into the more saline background groundwater on the left hand side of the ponds. The generally high conductivities, coupled with the relatively uniform clayey profile, are consistent with uniform seepage rates as shown by the narrow range of measured seepage rates (7.1 – 9.3 mm/d). However it is worth noting that these seepage rates are higher than those obtained at other sites with clayey profiles (eg Toolondo East).

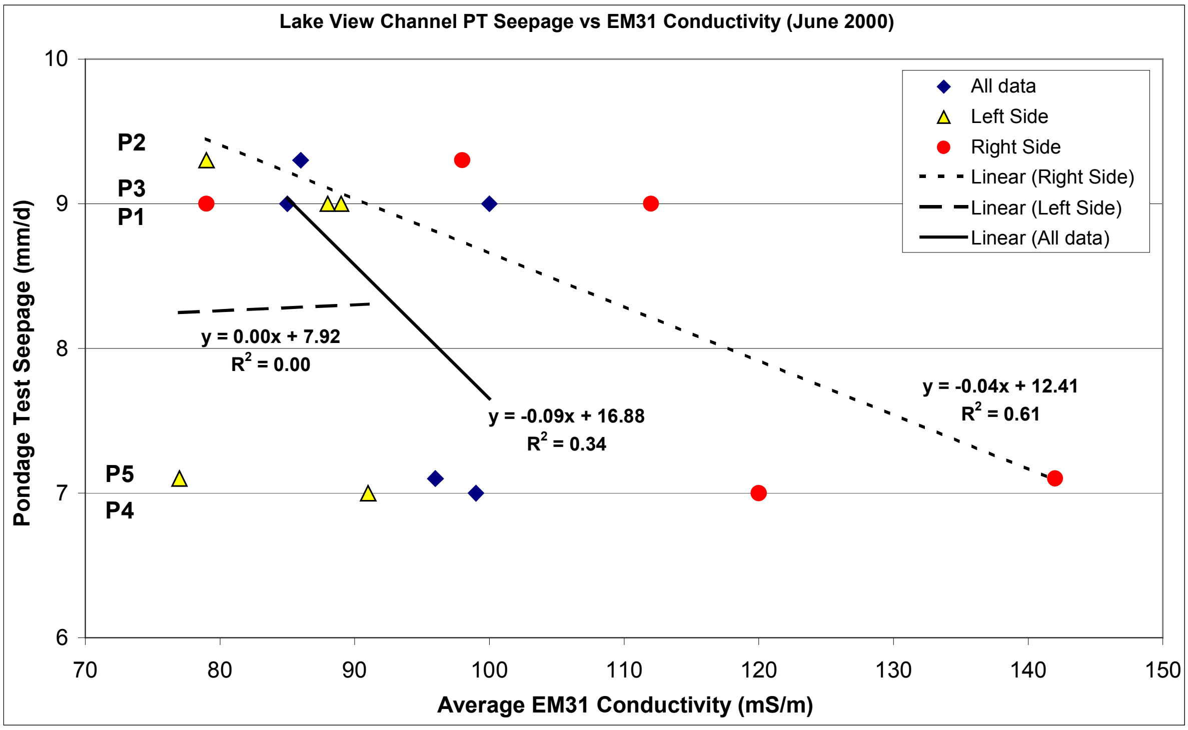
Figure 5-40 and Figure 5-41 plot the pondage test results at Lake View against average EM31 conductivity for the corresponding pondage section. (Note that Pond 6 was removed from the analysis as the EM31 survey only covered half of this pondage section). Conclusions which can be drawn from these results are limited by the very narrow range of seepage rates over which the correlation has been established (approximately 2 mm/day). Further confidence in the results could be obtained by conducting pondage tests across a wider range of seepage rates. With this in mind the following conclusions can be drawn from the plots:

- There is little distinction between the conductivities across the ponds using all data. This is apparently due to the fairly rapid mixing of the seeped plume back into the native groundwater once away from the channel.
- The correlation of the adjacent channel results in Figure 5-41 is reasonable (R^2=0.58). In terms of predicting channel seepage, this result is more useful than the correlation of one particular side of the channel, because without the pondage test results, selecting which side of the channel to use for predictive purposes will not always be obvious. However the lines adjacent the channel have consistently returned good correlations with the pondage test data across most of the site examined in this study.
- Overall the EM results at Lake View are positive and confirm the potential of EM to map seepage plumes with a reasonable degree of accuracy compared to pondage test data. These results suggest that EM31 (vertical dipole) is the correct arrangement for (this section) of the Lake View channel to provide the depth penetration required to pick up the diffusion of the seepage plume into the groundwater.
- Most importantly these results show that at sites where a seepage plume is quickly mixed back into the native groundwater, it is important that the adjacent channel EM data is used in preference to all of the data, in order to adequately distinguish between relatively high and low seepage sites.

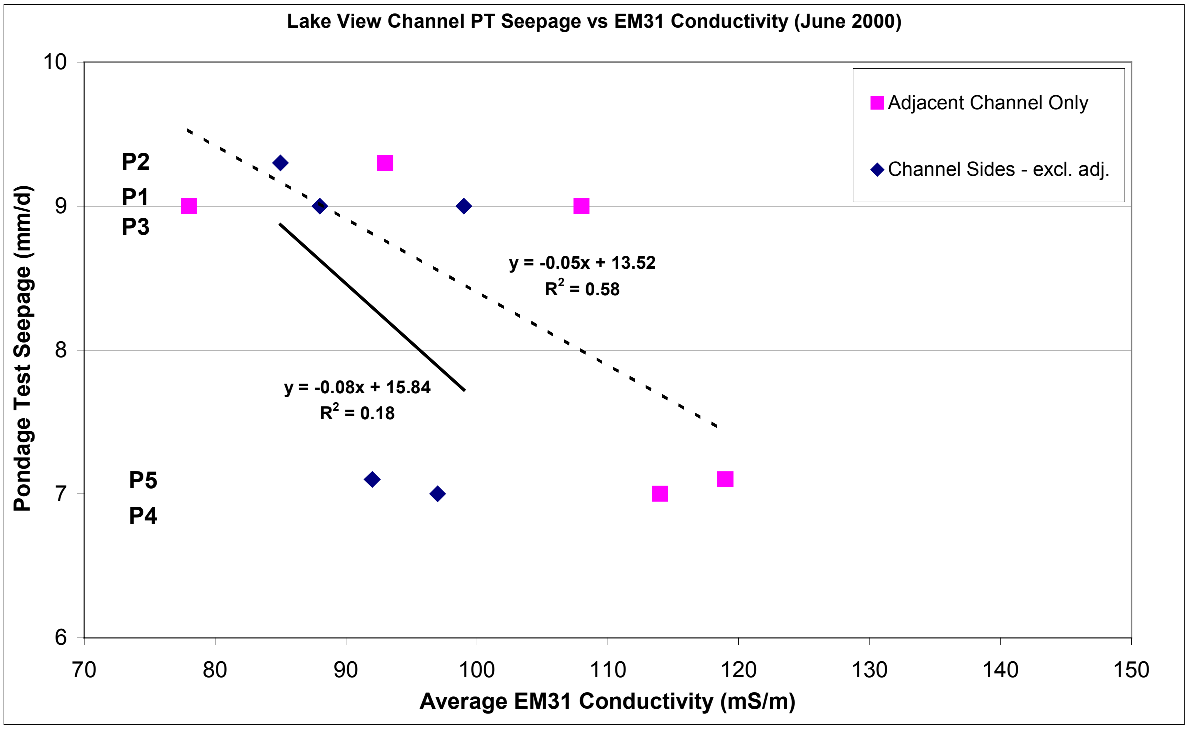
■ **Figure 5-39 Lake View EM31 Survey Results, June 2000**



■ **Figure 5-40 Lake View Pondage Test Results vs EM31 (June 2000) Results**



■ **Figure 5-41 Lake View Pondage Test Results vs EM31 (June 2000) Results (cont')**



5.3.3.6 Tabbita – June 2000

An EM31 survey (vertical dipole) was conducted by Lloyd Angove Soil Surveying and Drilling Pty Ltd on 28th June 2000 along a 3 km section of the Tabbita channel. The survey results are presented in Figure 5-42. The channel was running at full supply level at the time of the survey. Groundwater levels at the time of the survey were approximately 1-1.5m below the natural surface adjacent the channel. In total eight traverses were conducted, four on each side of the channel up to 50m from each channel bank. On the eastern side of the channel access was limited in part due to adjacent vineyards and in some sections only 2-3 traverses were possible.

As Figure 5-42 illustrates, the dominant response was in the high conductivity end of the range with most of the channel and surrounds returning responses above 65 mS/m. The left hand side, (which is also the down-slope side of the channel), of Ponds 1 and 5 are the only sections where significantly lower conductivities were detected. It is apparent that water has migrated down-gradient, and is the probable cause of the lower conductivity responses on the left hand side of the channel. Overall, the high conductivities are primarily due to the clayey soil profile and shallow saline watertable at the site (refer *Appendix* A Tabbita Geological Long Section). This logging of the soil indicates most of the soils adjacent the channel section are comprised of light – medium clays and sandy clays.

Figure 5-43 presents the results of the pondage tests plotted against the average conductivities for the corresponding pondage section and shows no particular trend. Pond 3 is perhaps the best example of the difference in these results compared to the inverse conductivity-seepage relationship observed at other sites. Despite having the highest seepage rate at nearly 10 mm/day, the overall conductivity response was the second highest at 80 mS/m.

Several possible reasons are proposed for the lack of a meaningful seepage – EM31 relationship at this site:

1) The very narrow range of the seepage rates (difference between maximum and minimum) detected in the pondage tests (approximately 4mm) suggests it is difficult to find statistical correlations between variables when the range on the control variable is very low. Essentially on average the ponds are seeping at a constant rate across the pondage test area, and therefore trying to detect differences compared to another variable may not be possible, as there are no practical differences in the seepage rates.

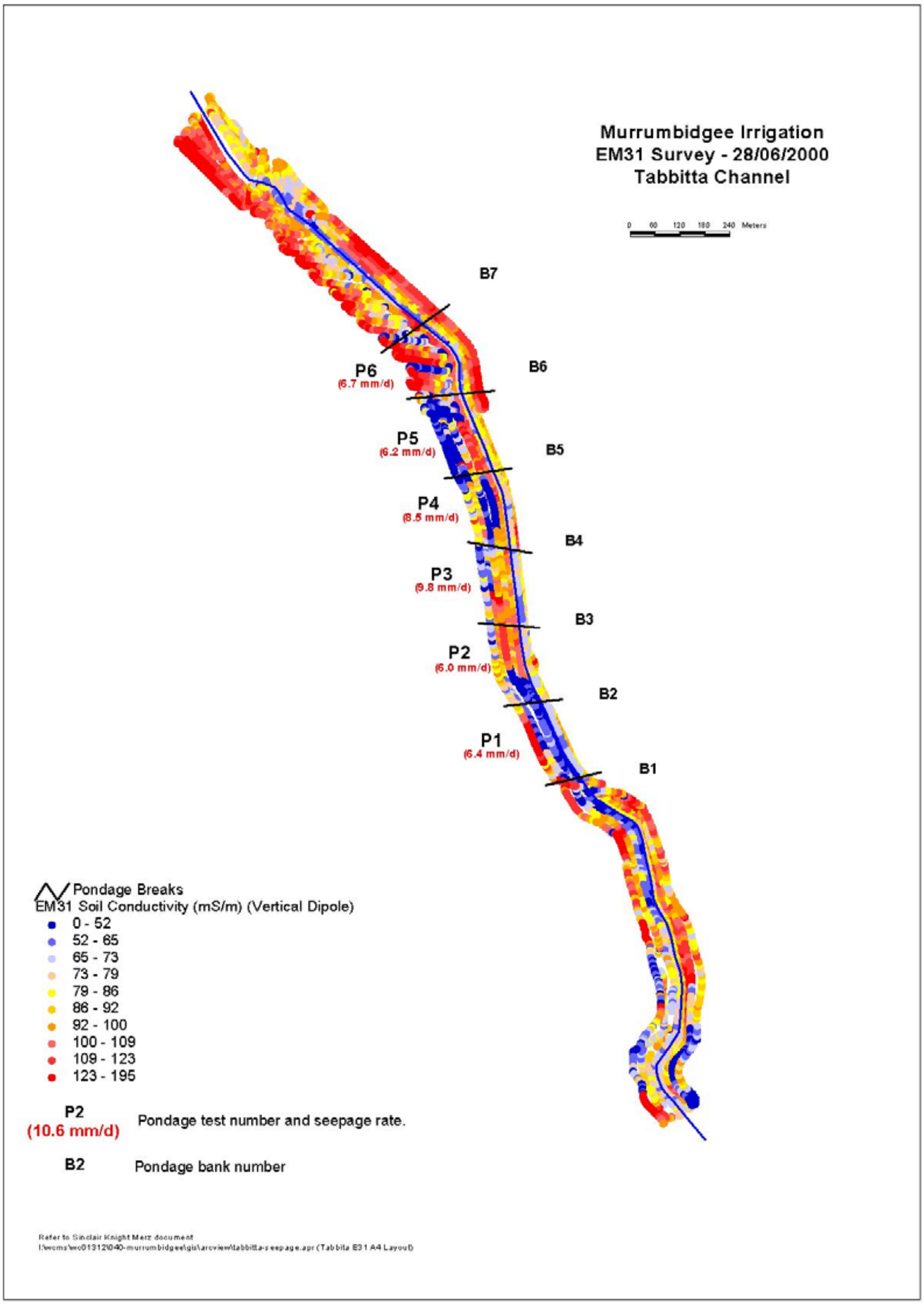
2) The EM31 in vertical dipole mode may be seeing a little too deeply into the aquifer, ie into native groundwater rather than seepage affected groundwater. EM31 in horizontal mode may be a more appropriate configuration.

3) With such a low seepage rate range, the method of averaging conductivity over ponds may be inappropriate. It may be more appropriate to map local conductivity lows. Seepage cannot be considered to be occurring uniformly across each pondage section, ie when there is high seepage over part of the pond, then it is enough to sufficiently bias the conductivity results. However if seepage is low then there might be the same amount of seepage from small sections in what appears to be (in the conductivity survey) an otherwise non-seeping channel section. Better placement of pond banks may over come some of these issues.

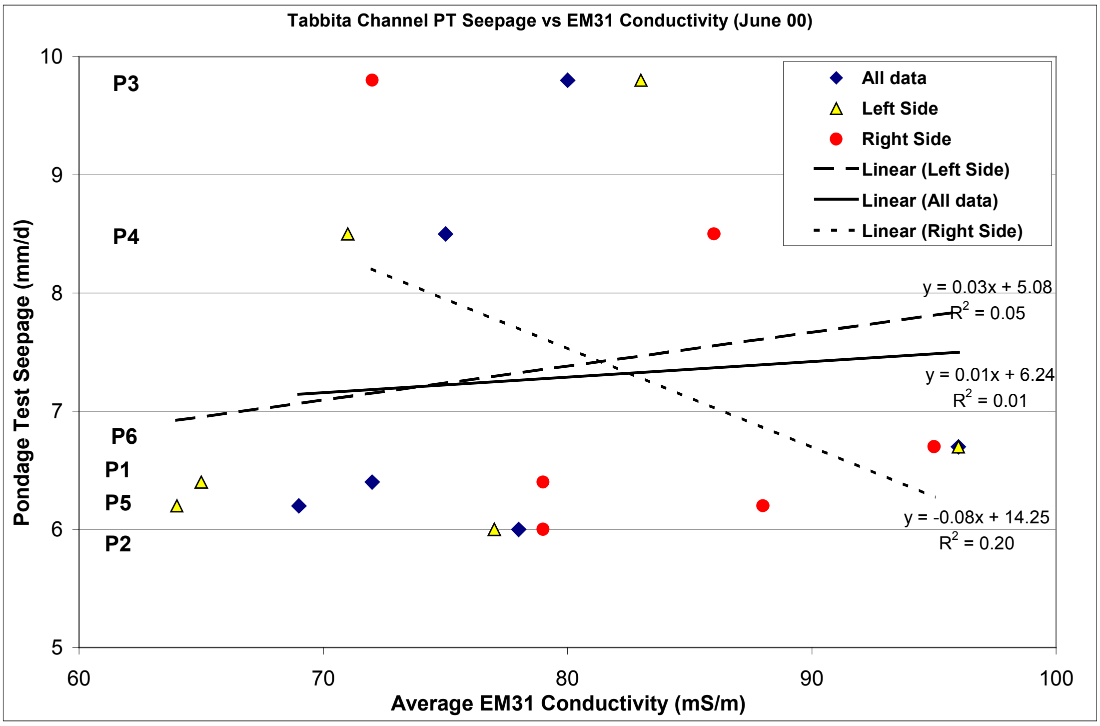
4) The primary seepage mechanism at this section of the Tabbita channel may be such that the majority of seeped water does not reach the groundwater. The

geological long section of the Tabbita Channel (refer *Appendix* A) shows half a metre of clayey sand along the surface of the site, intersecting the walls of the channel. This suggests that the primary seepage mechanism is lateral seepage via the upper clayey sand layer, through the walls of the channel and discharge onto the outer channel toe. Reported problems with water logging and salinisation along this stretch of the Tabbita Channel support this seepage mechanism theory.

- **Figure 5-42 Tabbita EM31 Survey Results, June 2000**



■ **Figure 5-43 Tabbita Pondage Test Seepage Versus Average EM31 Conductivity**



If this is correct, the majority of seeped water would not reach the watertable and the key means by which seepage is detected using geophysics is not possible (ie a relatively fresh water plume imposed on more saline native groundwater). However, section 4.4.4 casts some doubt over this theory. This section details groundwater response to seepage at the site, and suggests a reasonable connection between the channel and the groundwater.

5.3.3.7 Conclusions

Good relationships were obtained between average EM31 conductivity and the corresponding pondage test seepage at most sites. At only one site (Tabbita) was there no significant relationship identified. For EM31 in vertical dipole mode, the effective depth of penetration is around 6-7m, with a mid-range depth focus of about 2 – 4.5m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is largely via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

Toolondo

- Good relationships between EM31 conductivity and pondage tests seepage were recorded in all three surveys at Toolondo Central. This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties.
- A high degree of repeatability between the surveys was observed.

- In-channel (shortly after channel shut down) and on-channel EM31 surveys returned poor results. This is attributed to the fact that an EM31 survey above the watertable 'works' by inferring seepage based on soil properties. However immediately beneath the channel, even for low seepage rate ponds the profile beneath the channel is saturated (or near saturated) with seeped water. This uniform saturation produces a uniform conductivity response, and tends to mask changes in lithology resulting in little differentiation between low and high seepage sites. Significantly however the on-channel resistivity survey recorded good correlations between seepage and resistivity (10m and 12m depth slices). The EM31 on-channel however could not 'see' into the watertable.

- Better results were obtained with the EM31 compared to the EM34(10m) at this site, possibly due to the greater number of EM31 traverses conducted (ie away from the channel).

- <u>Three Toolondo Sites (Central, East and West)</u> - The relationship established for all sites was moderately strong. Local correlations at Toolondo Central and Toolondo West were stronger than the combination of sites. The Toolondo East site displayed an opposite correlation, but the very narrow range of seepage rates & the flat regression line indicates this is not a meaningful trend. Confidence bands for the overall regression relationship are wide but indicate that the relationship can be used to differentiate between high and low seepage sites. The data most contributing to the low R^2 and wide confidence bands is the four ponds with sandy banks at Toolondo Central. It is apparent the shallow depth of the sand causing the seepage (largely through channel banks) is largely missed by the EM31(vertical) with a depth focus of around 2 - 4.5m.

- If the Toolondo Central site had been used to predict seepage at Toolondo West, predicted seepage would have been 2-3 times too high. At Toolondo East it would have been essentially accurate (0 mm/d), except in one pond seepage would have been predicted at 4 mm/d when actual seepage is practically zero.

Rocklands

- A good relationship was observed between EM31 response and pondage test seepage at the Rocklands channel trial site (for the adjacent channel EM31 data). This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties. However, with a depth to watertable of around five metres, the EM31 survey may also have been detecting some seepage induced salinity changes in the watertable.

- A poor response was observed when all survey runs were used, largely due to the effect of trees adjacent one pond. The adjacent channel run was less affected and accordingly better results were returned.

- The on-channel results recorded mixed results. In vertical dipole mode no trend was observed. The configuration is focussed on the flushed zone beneath the channel where uniform saturation from seepage appears to be masking lithology response. In horizontal dipole a reasonable correlation was observed, apparently through identification of lithology changes (clay content) immediately beneath the channel. This was the only case observed where on-channel measurement above the watertable successfully correlated with seepage. At other sites the uniform saturation appeared to dominate the response over changes in lithology, however at this site it is apparent that the changes in lithology close to the channel surface are sufficiently contrasting to distinguish between high and low seepage areas.

Donald Main

- A good relationship was observed between EM31 conductivity and pondage test seepage but there is a poor spread of seepage data at the site (1 point of low and 5 of high seepage). With a relatively shallow watertable (2m), the EM31 detects seepage at this site in terms of its impacts on the watertable. The EM31 survey did not distinguish between higher seepage ponds (35 - 48mm/d). Confidence bands are fairly wide for the regression line, particularly at the high conductivity range, but indicate that the relationship can differentiate between high and low seepage sites. Additional data points are required to tighten confidence bands.
- A better relationship was established with EM31 (R^2=0.71) adjacent the channel compared to EM34 (R^2=0.50) but there was still no differentiation observed between the higher seeping ponds. The improved relationship is probably due to the greater depth focus of EM31, particularly on the up-slope side of the channel, allowing deeper penetration into the watertable
- Moderate to good relationships were also observed for the on-channel surveys in both horizontal and vertical dipole. With a shallow depth to watertable the EM31 on-channel survey detects seepage as it impacts the watertable.

Dahwilly

- For a survey conducted when the channel was not running, no relationship was observed between EM31 conductivity and pondage test seepage. The technique failed because the channel was not running and previously seeped water was therefore likely to have thoroughly mixed with native groundwater. Unsaturated zone lithology is a good indicator of seepage at some sites. However at Dahwilly it is not the unsaturated zone controlling seepage rates, but the clogging layer at the channel surface and therefore seepage must be detected directly (ie in terms of impact on watertable) which means the channel must be in operation.
- In a repeat survey conducted when the channel was operating, a good relationship was observed (at Dahwilly Central), confirming the importance of identifying the seepage plume as the primary seepage detection mechanism at this site.
- Two Dahwilly Sites (Central and East) - The relationship established for both sites is moderately strong. Local correlation at the Central site is slightly stronger than the two sites combined. The East site displays a very weak correlation, but this is due to the very narrow seepage range and few data points at this site. Confidence bands are relatively wide, suggesting the regression relationship for both sites can only be used to broadly indicate the likelihood of low or moderate seepage. The slightly deeper depth to watertable at the East site appears to have put the watertable largely beyond the range of EM31 and hence very different results are obtained at the East site. Using the Central site regression relationship to predict seepage at the East site would have resulted in over prediction of 1.5 - 2 times actual seepage.
- Better correlations at both sites were obtained using the resistivity compared to EM31 due to better targeting of the top of the watertable.

Lake View

- A poor relationship between pondage test seepage (July 2001) and EM31 conductivity (June 2000) was obtained at Lake View Central for all data due to rapid mixing of the seepage plume away from the channel. However for adjacent channel data a significantly improved relationship (to moderate) was observed as seepage impacts are less diluted. Interpretation is limited at this site due to the very narrow seepage rate range. Seepage is detected at this site in terms of its impact on watertable salinity.

- No sensible trend was observed at the Lake View Central site using the same EM31 survey data (all lines) and the June 2002 pondage tests. It is anticipated however that a better response could be obtained using the adjacent channel data, as was the case for the July 2001 pondage tests. In addition, the 2002 pondage tests may not have been properly placed over sections of like conductivity.

- Both Sites (Central and West) - The relationship established for both sites is moderately strong with a high correlation coefficient but the two data sets creating the regression line have small conductivity and seepage rate ranges. It is desirable to obtain data in the mid range to improve confidence in the relationship. The Central site could not have been used to predict seepage at the West site. However using Central data from adjacent the channel is likely to improve this correlation.

Tabbita

- No relationship was observed between EM31 conductivity and pondage test seepage. Possible reasons for the failure of the technique at this site include:

  i) Narrow range of seepage rates (little differentiation in rates along section of interest);

  ii) Seepage mechanism may be such that majority of seeped water does not reach watertable but move laterally (evaporating and causing salinisation as evidence adjacent the channel);

  iii) EM31 vertical dipole orientation may penetrate too deeply into the native groundwater, below the zone most effected by seepage; and,

  iv) The method of averaging conductivity may not be appropriate at this site (or the ponds may need to be placed more carefully, ie over shorter sections of high/low conductivity)

Finley

- While a moderate correlation coefficient was obtained for the pondage test – EM31 conductivity relationship at this site (and the highest seeping pond did record the lowest conductivity), the statistics are not meaningful due to the fact that only three data points make up the relationship. The width of the prediction intervals indicate that the regression relationship cannot be used to predict seepage at this site. Additional data points across a wider seepage range are required to improve the relationship.

In summary, the only site where no relationship was observed was at Tabbita. A number of possible causes for this were identified, but the predominant contributing factor is not known. At two sites (Rocklands and Lake View Central), the adjacent channel data was used instead of all survey run data. This was required to obtain the best relationship, due to the interference effects of trees and rapid mixing of seepage water away from the channel.

At the Toolondo central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence good trends were observed.

The Donald and Lake View site surveys were focussed on the saturated zone, and seepage was detected as it created a conductivity low against higher background conductivity groundwater.

At the Rocklands and Dahwilly sites, where the penetration depth of the EM31 (in vertical dipole) was just sufficient to reach the watertable, the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone combined to provide a reasonable indicator of seepage. However it is significant to note that at Dahwilly, when the channel was not running, no relationship was observed. This suggests seepage impacts in the watertable are the primary detection mechanism at this site, a fact reinforced by the uniform nature of the unsaturated zone lithology at the site. Seepage at Dahwilly is not controlled by the unsaturated zone but by a clogging layer at the base of the channel. Techniques which purely infer seepage from unsaturated zone soil properties will not work at such sites (including remediated or lined channels).

At Waranga a reasonable relationship was observed, considering the distance over which the data forming the relationship was spread. Improvements might be expected using a technique targeting the top of the watertable at this site.

On-channel surveys did not work at sites where the watertable was beyond the range of the EM31 (Toolondo), did work at sites with a shallow watertable (Donald) and were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31 (Rocklands). Further work is required in this area, but the evidence collected in this investigation suggests on-channel surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

5.3.4 Regional Assessment of Key Relationships

For all of the sites described in Section 5.1.3 (site's used in final year analysis), an attempt was made to look for potential correlations between seepage rates across all sites and EM31 response. This was conducted in two ways:

- Multiple linear regression, ie looking for correlation between seepage rate and average EM31 response and other important variables which might effect seepage (or EM31 response); and,
- Simple linear regression, ie looking for a direct correlation between seepage rate and average EM31 response.

5.3.4.1 Multiple Linear Regression

Introduction

Multiple linear regression is a statistical technique that allows one response (or dependent) variable to be predicted from a number of explanatory (or independent) variables. In this study the response variable is seepage, as measured in pondage tests. The explanatory variables which were included in the multiple linear regression analysis included:

- EM31 conductivity;
- Soil permeability;
- Depth to watertable; and,
- Groundwater salinity.

The most important independent variable is EM31 conductivity. Previous work (years 1 and 2 trials) demonstrated that this is the most easily collected variable with a generally strong correlation to seepage. The main aim of conducting multiple regression analysis was therefore to determine which other variables could account for variations in seepage apart from EM31. Groundwater salinity and depth to watertable were included as independent variables because they will affect EM31 response.

The coefficients of the prediction equation are determined using a method of least squares, that is, the coefficients are selected so that the sum of the squared residuals are minimised. A residual is the difference between an observation and its predicted value.

Data Sources

The response variable is observed seepage as measured in pondage tests (averaged over the life of pondage tests, excluding outliers). This is the variable we want to be able to explain. The explanatory variables and their method of collection is described below:

- EM31 - Spatially this is the most reliable data source, with a high density of readings over the pond length. EM31 response is measured at approximately 5m intervals (using the EM31 set-up described in 5.3.2) and averaged over the length of the pond.
- Soil Permeability - Average soil permeability was determined based on geological cross sections constructed for each site (refer *Appendix* A). Four different vertical hydraulic conductivities for each pondage cell were calculated, and each tested in the multi-variate analysis as potential explanatory variables.

These are described below and graphically presented in Figure 4-4 (refer Section 4.2 - Sub-surface Characterisation):

i) Weighted according to typical EM31 (vertical dipole) response - most heavily weighted around 1 – 3m depth and terminated at 7m [generally the effective depth of EM31 (vertical) penetration];
ii) Representative of surface permeability and evenly weighted over the top 2m of the profile;
iii) An average across the entire profile but giving more weight to upper surface layers and less to layers at depth (to 10m); and,
iv) Evenly weighted across 10m.

For each of the four scenarios, hydraulic conductivity was based on text book vertical hydraulic conductivities for the given soil texture. The average across multiple layers was calculated based on the method described in Freeze and Cherry (1979). Details of these calculations, and an example to clarify the process used, are provided in *Appendix* C.

- Groundwater salinities were obtained from regional hydrogeological maps (MDBC 1:250,000 scale maps), or in the case of Dahwilly Channel at Murray Irrigation using more detailed groundwater salinity information supplied by the RWA. It is important to note that groundwater salinities based on adjacent channel sampling (which are affected by mixing with fresher channel water) were not used in this analysis, but rather groundwater salinities away from the effects of channel seepage were adopted;
- Depth to watertable was obtained from near channel groundwater bores drilled specifically for the project, or based on moisture and groundwater observations recorded during drilling of the soil bores. At sites where soil bores did not intersect groundwater, nearby groundwater bores were used to estimate the depth to watertable.

Methodology

All of the variables described above were available for inclusion in the regression. Stepwise multiple regression was used to select appropriate variables (using the software program: *SYSTAT, 1998*). The process was interactive, allowing variables to be added or removed from the model one at a time. Foremost the variables were selected based on an understanding of the important seepage processes and the F statistic. The F statistic is a measure of the amount of remaining variation (ie the variation not explained by variables already in the model) explained by the variables. Variables with an F-statistic less than 4 were not included in the model. Multi-collinearly, the correlation of independent variables, was avoided.

Two measures were used to assess the accuracy, or 'goodness'of fit of the regression. These were the coefficient of determination (R^2) and the standard error (SEE). The R^2 measures the proportion of the total variation explained by the model. A large R^2 is associated with a good model or prediction equation. The standard error is a measure of the degree of scatter of the observed data points around the regression line. Hence a small standard error is associated with a good model. The standard error has been expressed as a percentage of the mean of the observed dependent variable (ie pondage test seepage).

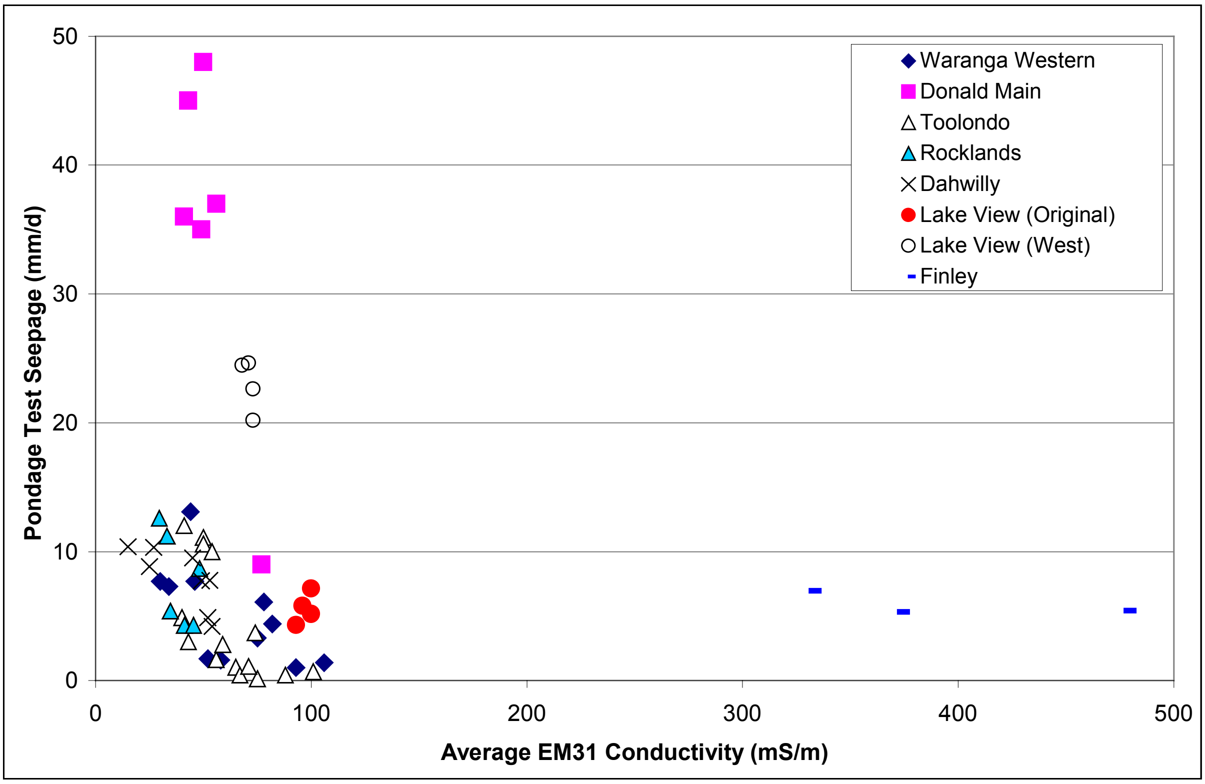
Removal of Outliers

Meaningful regression modelling involves the removal of any significant outliers. Figure 5.44 presents average EM31 conductivity plotted against pondage test seepage for all sites where trials were conducted, representing a total of 57 ponds. Each of the sites is plotted with a different symbol to assist with identification of possible trends between sites. Several outliers appear obvious in this data, including Donald Main Channel, the Lake View West site and Finley channel.

The three Finley ponds, with conductivities three to five times higher than the next highest response, are extreme outliers on the x-axis. Observation of the Finley geological long section (refer *Appendix* A) indicates a heavy clayey profile to about 9m below the channel. In addition the groundwater at the site is highly saline (approximately 17,000 EC) and the watertable at the site is quite shallow. All of these factors combine to produce a very high conductivity response. The dominantly clay profile suggests very low permeability and that the seepage mechanism is other than vertical leakage through the profile. The seepage mechanism is most likely horizontal bank seepage, associated with poor bank construction / compaction.

On this basis the Finley data was excluded from the overall analysis. It is apparent that correlations specific to these type of environments would need to be established. In this study there was insufficient data (three data points) to determine a meaningful correlation in such a conductivity range. However, even within these three points the lowest conductivity pond also had the highest seepage rate (ie the trend was in the 'right', or expected direction).

■ **Figure 5.44 EM31 Conductivity Versus Pondage Test Seepage at All Sites**



Results and Discussion

Multi-variate regression analysis was initially conducted on the entire data set (excluding Finley), (refer *Appendix* E for statistical details). This indicated that the following variables were significant explanatory variables:

- Average EM31 conductivity;
- Depth to watertable; and
- Upper K_v (permeability of the top 2m of the profile).

However, the standard error of estimate for the regression was very high (82%). In an attempt to improve the accuracy of the fitted regression model, the sites were split into two data sets on the basis of one of the key explanatory variables, depth to watertable, as described below:

The data (with Finley removed) are plotted in Figure 5.45. This plot shows three potentially 'outlying sites' (Donald Main, Lake View West and Lake View Original). All of these sites are characterised by watertables close to the surface (0.5-2m). The remaining sites have watertables of between 5 – 10m below surface. Given that the dominant EM31 response (in vertical mode) is concentrated in the 1-3m range, the elevated watertable appears to significantly affects the results, and produces two distinctly different trends. This is made more clear in Figure 5.46, which divides the data into two categories: watertable less than 2m and watertable 5 – 10m.

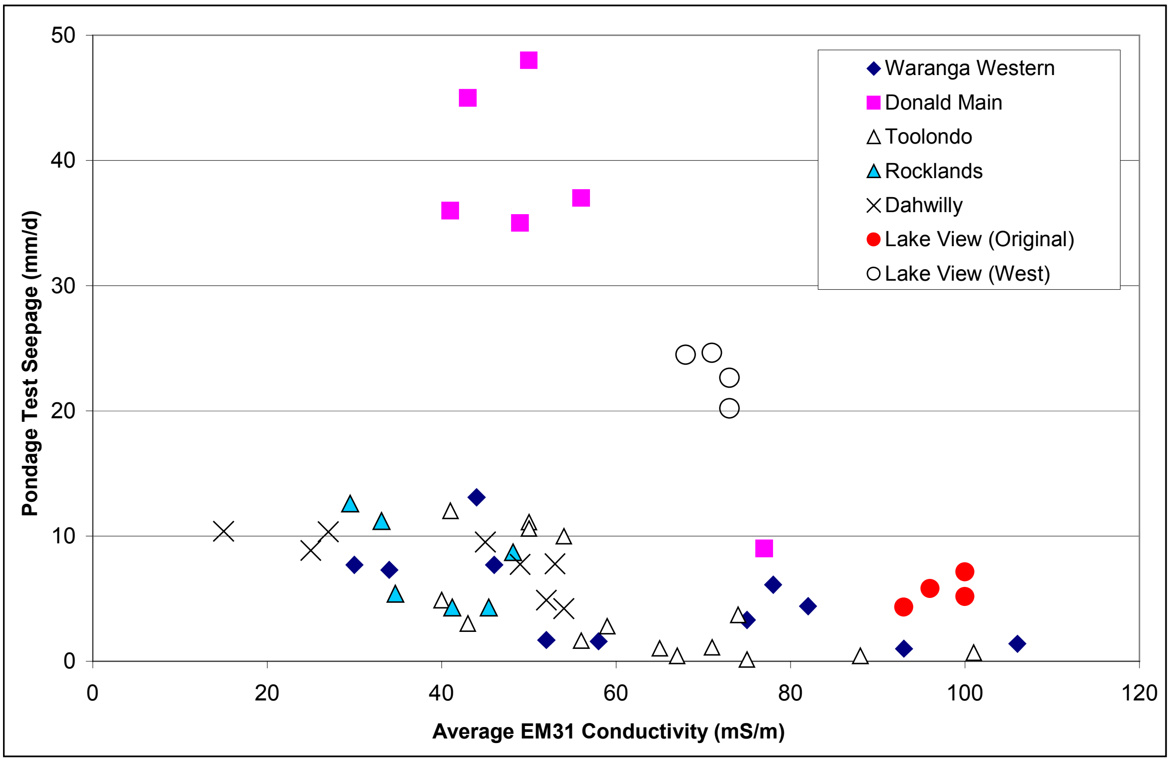
The difference in EM31 response between a high and low watertable site is due to the shallow and saline groundwater. For example, the high seepage sites at Donald (seepage > 30 mm/d) range in EM31 conductivity between 40-60 mS/m. Based on the lower trend line (greater than 5 m depth to watertable) it would be expected that ponds of such high seepage would have extremely low conductivities. However the shallow, saline groundwater has a strong influence on the EM31 response, which is concentrated in the 1-3m range, where the groundwater is absent at the sites producing the lower trend line. Unsaturated conditions will clearly return lower conductivities than in a saturated environment.

It might be expected that for high seepage sites such as Donald and Lake View West, the high seepage rates would result in greater volumes of fresh water mixing with the native groundwater, reducing overall conductivity. While this effect is occurring, it is apparent that this diluting effect is much less significant than the effect of an elevated (saline) watertable, and that the average salinity of groundwater in the 1-3m range is more affected by the native groundwater salinity than the seepage plume.

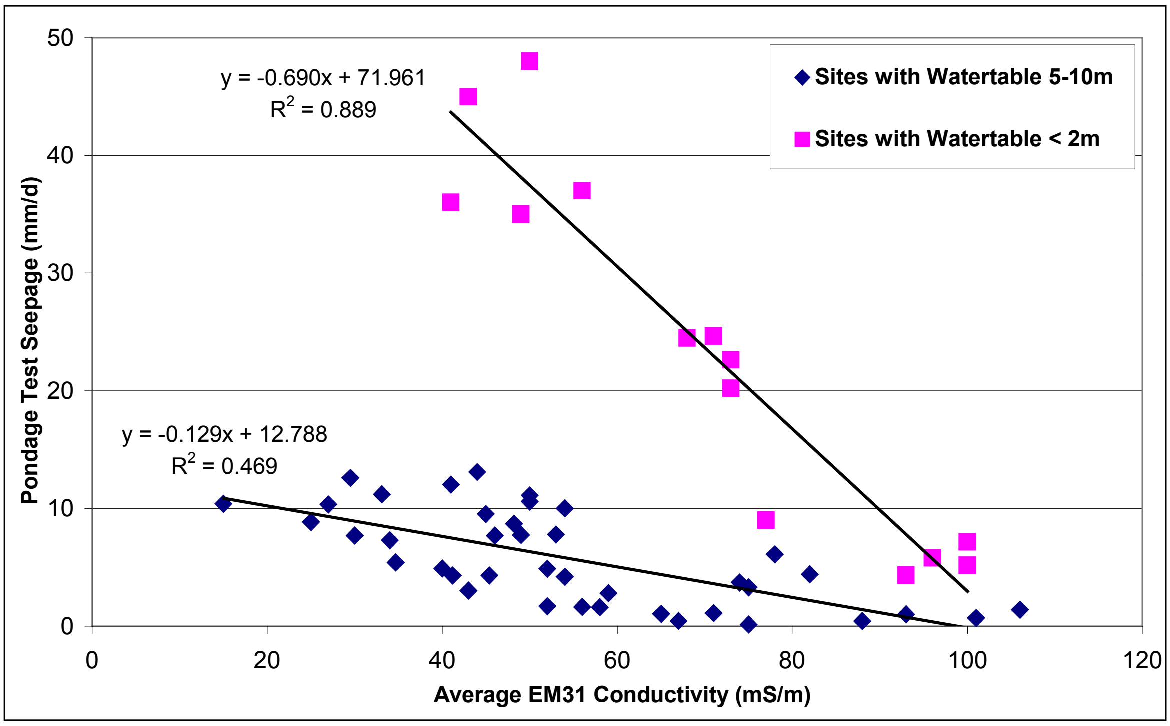
This effect should be more pronounced at sites with high natural groundwater salinities, such as at the Donald Main Channel. However, the data does not appear to indicate a significant difference between the high salinity Donald site (30,000 EC) and the moderately saline Lake View site (5,000 – 7,000 EC). This is most likely due to other factors that contribute to the overall conductivity response, such as the more clayey profile at Lake View.

The deep watertable sites in Figure 5.46 all have groundwater depths between 5-10m below surface. Note that there were no sites in the study with watertables in the intermediate (2-5m) range. It is considered likely that sites with a watertable in the 2-5m range would lie between the two trend lines.

■ **Figure 5.45 EM 31 Conductivity Versus Pondage Test Seepage at All Sites (Finley removed)**



■ **Figure 5.46 EM 31 Conductivity Versus Pondage Test Seepage: Categorised by Depth to Watertable**



The key difference between the two categories can be understood when considering the EM31 focus and depth range. For the 0-2m sites EM31 is directly measuring seepage in terms of its impact on the watertable zone. In contrast, for the 5-10m category, the watertable is almost out of range of the EM31, and is therefore largely measuring unsaturated zone properties. In this case, seepage is not directly being detected, but rather the likelihood of seepage is being inferred based on unsaturated zone properties. (Sites with a watertable at 5-6m are just in the range of EM31, but outside of the focal part of the range).

In summary, it was found that division of the data into two sets based on depth to watertable improved the regression characteristics of the two separate data sets compared to the entire data set. Therefore the following discussion is divided into two categories: watertable less than 2m and watertable 5 to 10m. Once the data was split into these two categories, depth to watertable was not found to be a significant explanatory variable, as would be expected.

Watertable Depth Five to Ten Metres

For sites where the watertable is 5-10m below surface, the equation found to provide the best prediction of channel seepage was:

$$\text{Seepage} = 11.6 - 0.12\,EM31 + 4.4\,\text{UK}_v \qquad \textit{(Equation 1)}$$

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

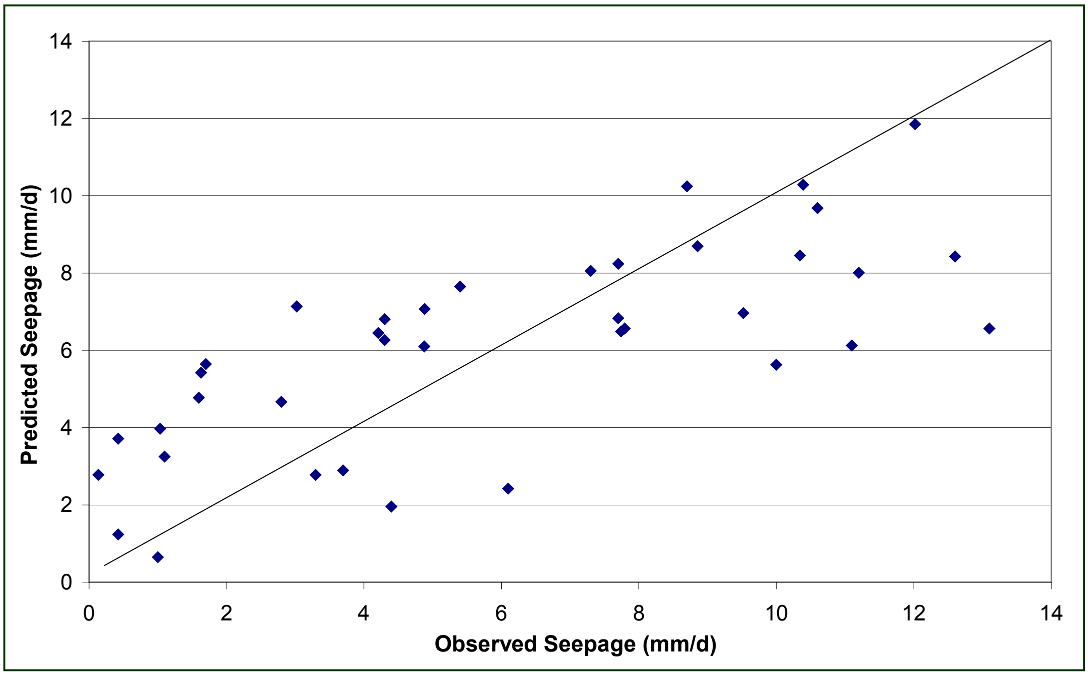
The equation was established with 40 data points. The coefficient of determination for the relationship was $R^2 = 0.55$ and the standard error of estimate was 48% of the mean observed seepage rate. This standard error indicates that on average estimated seepage is approximately 50% above or below the actual seepage rate.

Figure 5.47 provides a visual presentation of the degree of scatter in the prediction equation. The equation appears to over-estimate seepage for low seepage rates (less than 5 mm/d) and underestimate for high seepage rates.

EM31 was found to be the dominant explanatory variable with soil hydraulic conductivity of secondary importance. This is probably more a reflection of the accuracy of the collection technique of the variable, than the actual contribution of the variable to seepage. If soil permeability could be accurately assessed along the length of the channel via very high density and accurate testing, soil permeability would probably be a more significant variable than this analysis indicates. However, the method of estimating hydraulic conductivity and the density of sampling conducted in these investigations is typical of RWA priorities. Therefore for the purposes of this study soil hydraulic conductivity as an explanatory variable of seepage is considered to be of less importance that EM31 conductivity.

Groundwater salinity and depth to groundwater were not found to be significant explanatory variables in the analysis. The fact that depth to groundwater was not significant is not surprising, as the data set had already been divided based on depth to groundwater, largely removing the influence of this variable on the relationship.

■ **Figure 5.47 Predicted Versus Observed Seepage for Multiple Linear Regression, Based on EM31 Conductivity and Upper Soil Profile Hydraulic Conductivity (Sites with watertable 5- 10m)**



<u>Watertable Less Than Two Metres</u>
For sites with watertables within two metres of the surface (Lake View, Lake View West and Donald), multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond EM31. Therefore multiple linear regression analysis was not possible. The best fitting equation that can be derived based on available data is the linear equation with EM31 as the only explanatory variable. This analysis is presented in section 5.3.4.2.

5.3.4.2 Simple Linear Regression

Simple linear regression, using EM31 only as the explanatory variable, was conducted to determine how much of an improvement the multiple linear regression actually represents. As for the multiple regression analysis, the data was divided based on depth to watertable.

<u>Watertable Depth Five to Ten Metres</u>
For the data category representing sites with a watertable between 5 – 10m below surface, established with 40 points (refer Figure 5.46), the best fitting linear regression equation is:

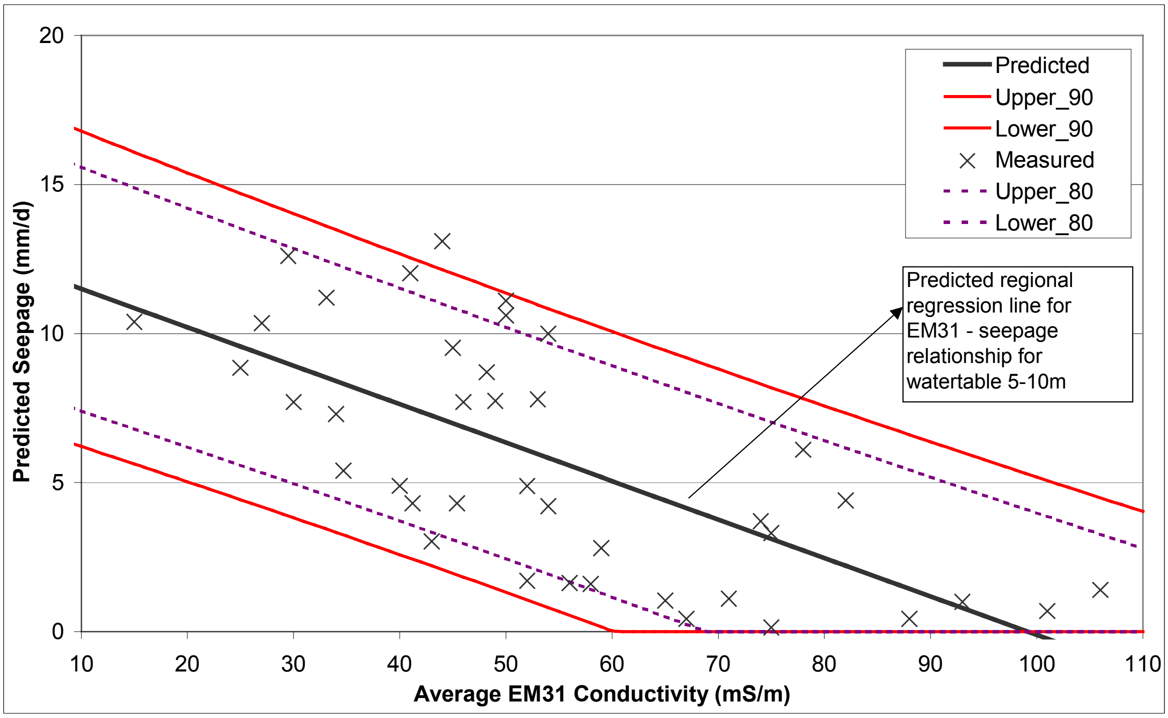
$$\text{Seepage} = 12.8 - 0.13\ EM31 \qquad \textit{(Equation 2)}$$

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

This relationship is proposed as the equation on which prediction of the likely seepage for an average EM31 measurement can be based (for depth to watertable 5-10m). The coefficient of determination for the relationship was $R^2 = 0.47$ and the standard error of estimate was 51% of the mean observed seepage rate. This standard error indicates that on average estimated seepage is approximately 50% above or below the actual seepage rate.

Figure 5.48 provides prediction bands for estimating seepage based on EM31 response when the watertable depth is 5-10m. Confidence intervals at 80% and 90% confidence are presented. For example, for the 80% confidence intervals, these bands indicate that if EM31 was used to predict seepage rates in a certain stretch of channel (covering an area of similar EM31 response), we would be 80% certain that the seepage rate in that section would lie within the confidence bands at that average EM31 value. The 80% intervals are narrower than the 90% intervals, as there is less certainty in pinning the value down to its 'true' seepage rate. This figure shows that the prediction equation is accompanied by quite broad prediction intervals.

- **Figure 5.48 Regional Prediction Intervals: Predicting Seepage from EM31 (watertable 5-10m)**

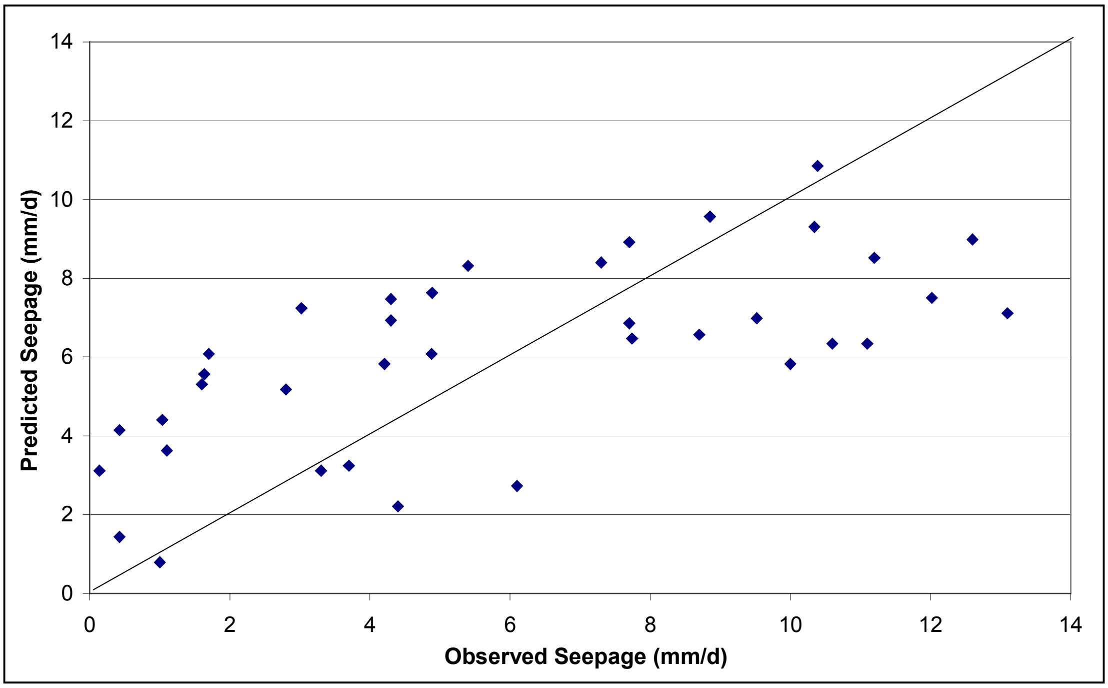


Using this prediction equation, an EM31 survey with an average response (within a like section of channel) of 30 mS/m, would suggest a seepage value of 10 mm/d. The prediction bands indicate we would be 80% confident that the real seepage value in that section would be between 5 – 13 mm/d and 90% confident that that it was between 4 – 14 mm/d. These bands are quite wide, however they indicate that the prediction equation can be usefully applied to broadly classify seepage rates (eg into low, medium and high categories).

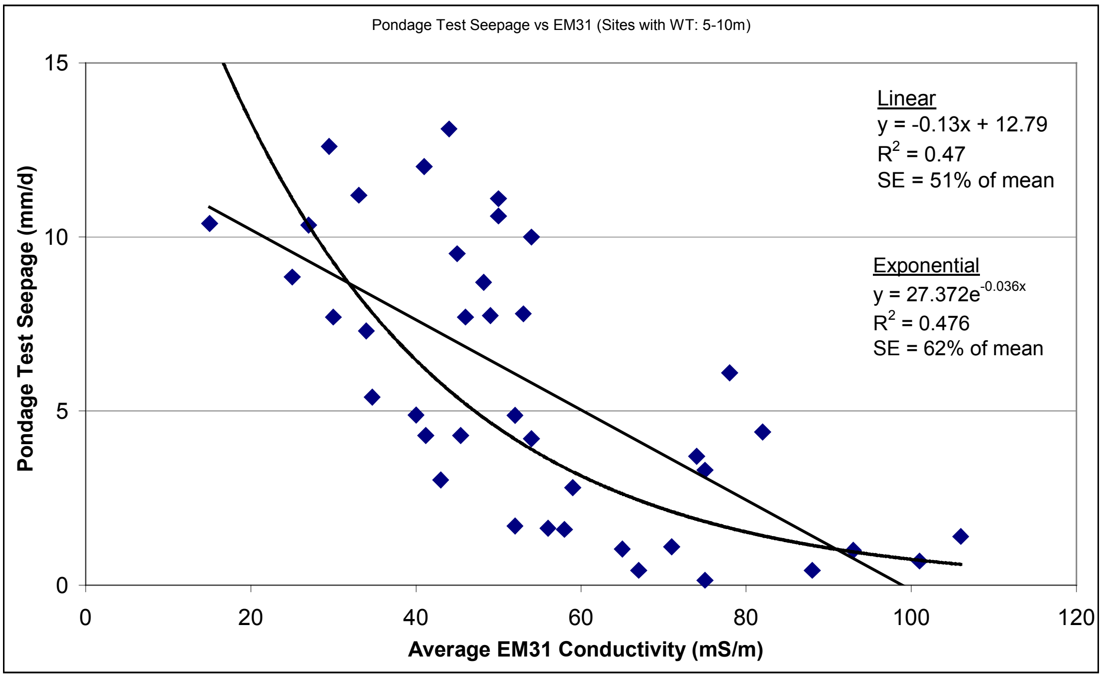
Figure 5.49 graphs the actual seepage versus the predicted seepage (using the regression equation) and provides a visual presentation of the degree of scatter in the prediction equation. The equation appears to over-estimate seepage for low seepage rates (less than 5 mm/d) and under-estimate for high seepage rates, implying a non-linear equation may provide a better fit. An exponential regression equation was applied to the data and is shown along with the linear regression line in Figure 5-50. The predicted versus observed seepage for the exponential fit is shown in Figure 5.54.

The statistics for these equations are shown in the figure. They reveal that while there is a only a marginal improvement in the correlation coefficient for the exponential fit (from R^2 = 0.47 to 0.48), the standard error actual worsens (from 51 % to 62%). Therefore, overall a less accurate is obtained using the non-linear equation, even though it may visually appear to fit the data better.

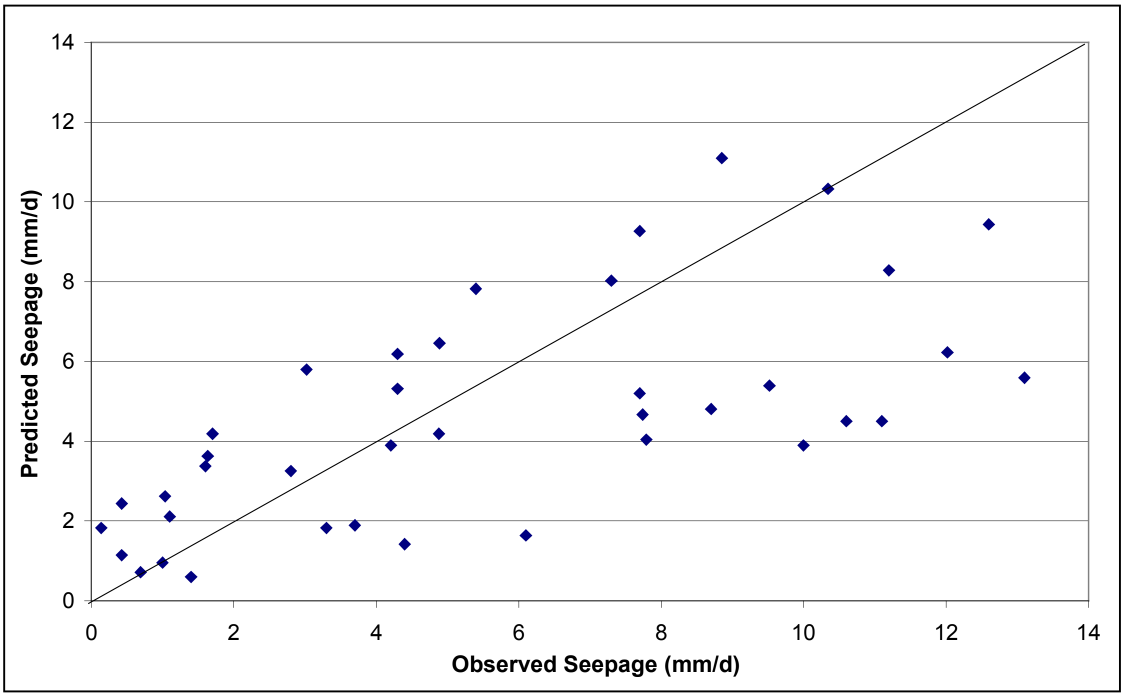
- **Figure 5.49 Predicted Versus Observed Seepage for Linear Regression (watertable 5 –10 m)**



■ **Figure 5-50 Linear Compared to Exponential Prediction Equations (watertable 5-10m)**



■ **Figure 5-51 Predicted Versus Observed for Exponential Regression (watertable 5 – 10m)**



However there are several advantages to the exponential fit over the linear fit. The first is that there is less of a pattern displayed in the observed versus predicted seepage plots (ie Figure 5-51 compared to Figure 5.49), which suggests that the more realistic model may in fact be the exponential model. The second is that the linear model places a maximum limit on the seepage of about 12 mm/d, whereas the exponential model appears to be more realistic, allowing for higher seepage rates in the very low conductivity range (up to around 20-25 mm/d).

Comparing the linear regression to the multiple regression, the statistics indicate that only a marginal improvement is made to the accuracy of the regression fit in the multiple linear regression analysis (*Equation 1*), compared to the simple regression fit (*Equation 2*). The R^2 for *Equation 1* was 0.55 and the standard error of estimate was 48%. Therefore a relatively modest improvement of 0.08 in the correlation coefficient and 3% in the standard error of estimate is the only improvement gained in adding soil permeability to the equation. The predicted versus observed seepage plots for the two equations are also very similar.

<u>Watertable Less Than Two Metres</u>

The best fitting linear equation for sites with a watertable less than 2m (based on only 14 data points) is:

$$\text{Seepage} = 72 - 0.69\, EM31 \qquad \textit{(Equation 3)}$$

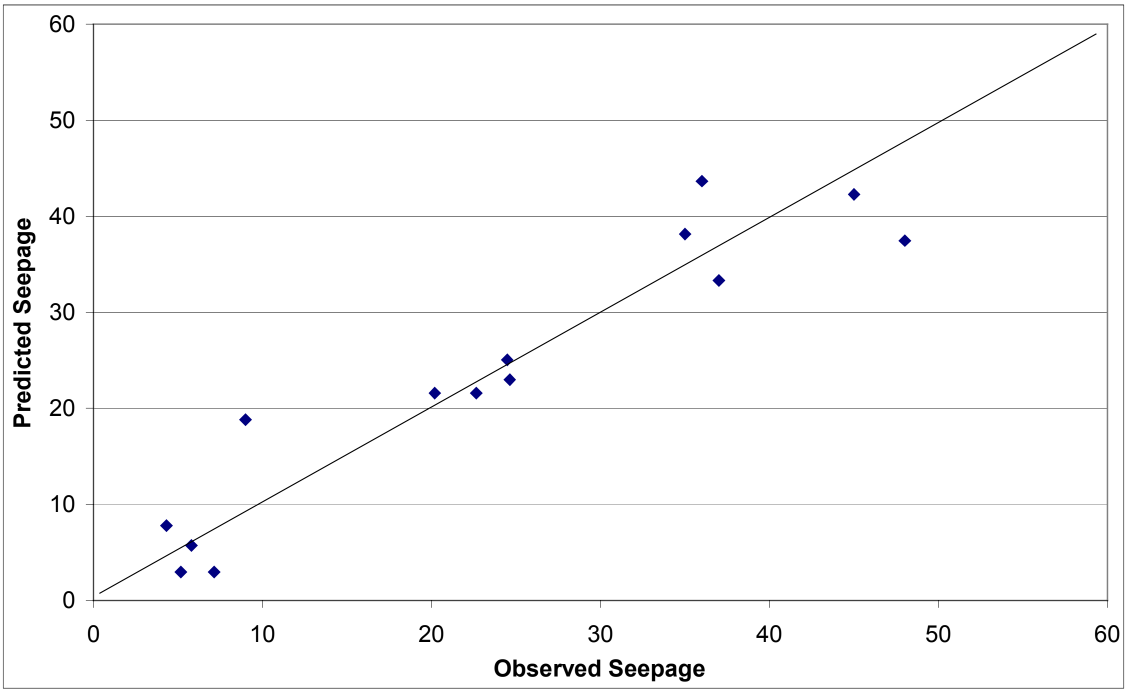
Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

The coefficient of determination for the relationship was $R^2 = 0.89$ and the standard error of estimate was 23% of the mean observed seepage rate. This standard error indicates that on average observed seepage was approximately 23% above or below the predicted seepage rate. Figure 5.52 plots actual seepage versus predicted seepage (using the regression equation) and provides a visual presentation of the degree of scatter in the prediction equation.

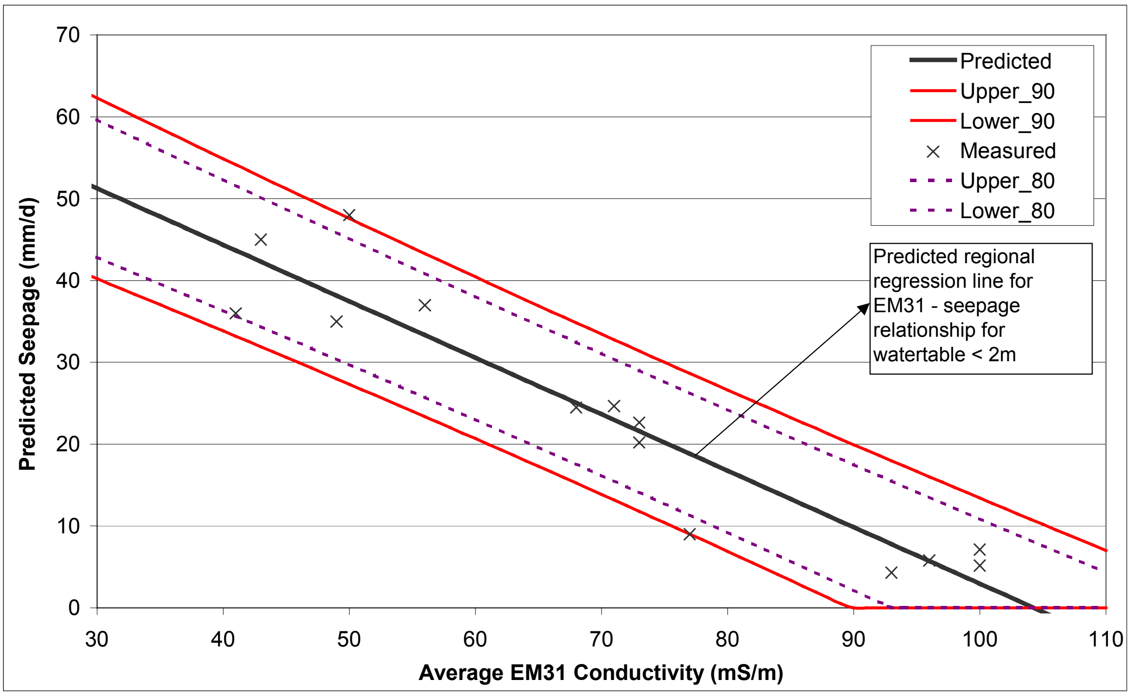
The high R^2 value and the relatively low standard estimate of error suggest a good correlation for the variables. However the results should be tempered by the fact that relatively few data points have been used to form the relationship. This is best illustrated by the example of a data set comprising only two points. This will return a correlation coefficient of 1 and a standard estimate of error of 0, but obviously there would be little confidence in the accuracy of the resulting regression equation. To improve confidence in the regression equation for the watertable less than two metres scenario, additional points are required in the data set.

Figure 5.53 presents prediction bands (80% and 90%) for estimating seepage based on EM31 response when the watertable is less than 2m, based on *Equation 3*. While the prediction intervals are broader in magnitude (approximately 20 mS/m and 15 mS/m for the 90% and 80% intervals respectively) than for the prediction bands for the deeper watertable scenario, as a percentage of the overall seepage range covered by each of the equations, they are narrower.

■ **Figure 5.52 Predicted Versus Observed Seepage for Linear Regression (sites with watertable less than 2m)**



■ **Figure 5.53 Prediction Intervals: Predicting Seepage from EM31 (watertable less than 2m)**



5.3.5 Channel Specific EM31 Statistical Assessment and Extrapolation of EM31 Relationships

5.3.5.1 Introduction

In contrast to the regional assessment, the aim of examining the EM31 - seepage relationship at each channel was to find if better relationships existed between EM31 and seepage at a local level. In particular, for those channels specifically targeted in the year 3 program to conduct pondage tests and geophysical surveys in similar and dissimilar environments, this section discusses the success of the extrapolation from the 'original' site (refer section 5.1.2.2 for discussion of methodology). The channels where this was conducted included:

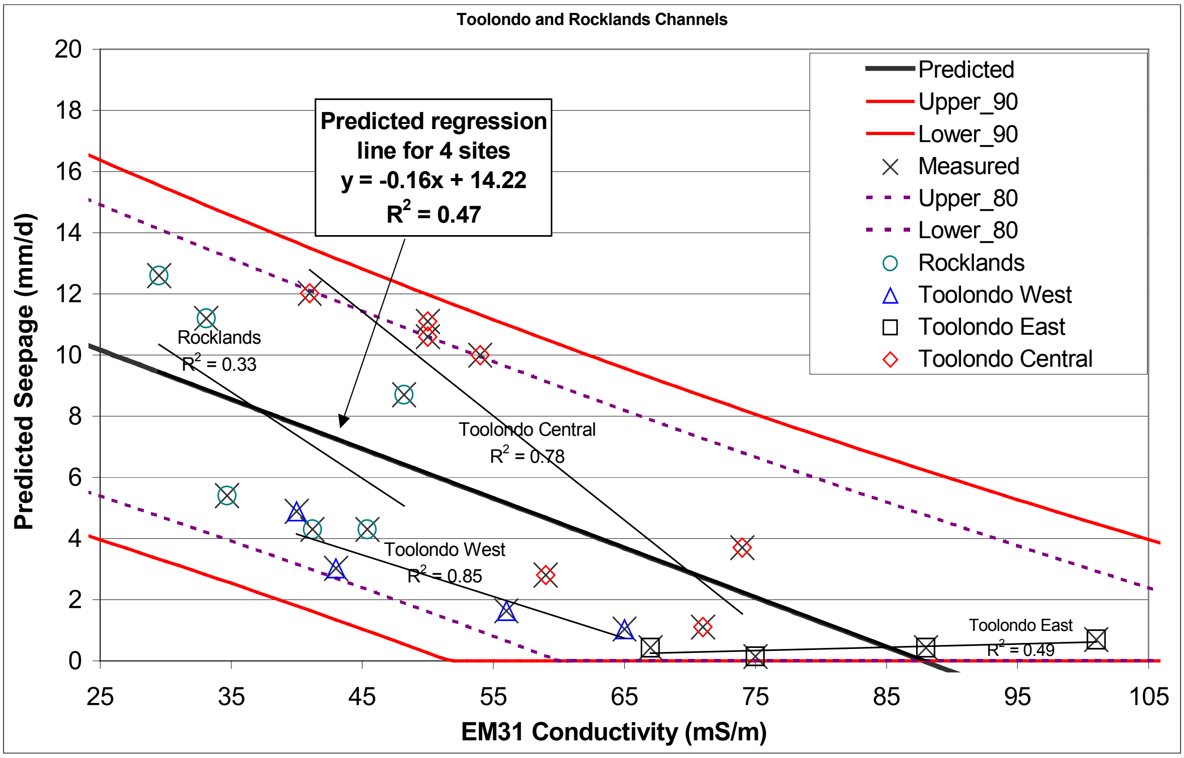
- Toolondo;
- Dahwilly; and,
- Lake View.

Note that the Rocklands site was included in the Toolondo analysis as the site is relatively close to the Toolondo channel and site characteristics are similar.

5.3.5.2 Toolondo and Rocklands

Figure 5.54 presents EM31 results against pondage test seepage for the Rocklands and Toolondo Channels. The Toolondo results are comprised of three sites as depicted in the figure: Toolondo Central (original site), Toolondo East and Toolondo West. The EM31 surveys were conducted at these sites in March 2002.

■ Figure 5.54 Toolondo and Rocklands Pondage Test Seepage Versus EM31 Conductivity



The Toolondo Central site is the original site where pondage tests and EM31 surveys were conducted in years 1 and 2 (refer section 5.3.3.1). The Toolondo East and West sites are several kilometres from the Central (original) sites and represent the sites which were selected to be different and similar to the original site. The Toolondo West site is similar to the Central site, while the East site differs in terms of lithology, with very heavy clay to approximately 3.5 - 4m depth. Rocklands data collected in August 2001 was included in the analysis as the site is relatively close to the Toolondo channel, and the site characteristics are reasonably similar to the Toolondo Central site.

Figure 5.55, Figure 5.56, and Figure 5.57 present the EM31 results at each of the Toolondo sites. (Figure 5-25 presents the results at the Rocklands sites). Note that different scales are used in each of these figures for presenting the EM31 conductivity.

A reasonable correlation coefficient for the fitted regression line of 0.47 was obtained. The standard estimate of error for the data is moderate to poor, at 61%. Confidence bands are wide but indicate the equation can differentiate (at 80% confidence) between high and low seepage sites.

The data decreasing the correlation coefficient and increasing the width of the confidence bands are the four ponds of high seepage at the Toolondo Central site, which contain relatively very high proportions of fine to medium grained sand in the upper 1-2m of the profile (as shown in the Toolondo Geological Long Section in *Appendix* A). It is apparent that while the sand is causing relatively high seepage rates, the EM31 conductivity is not as low as expected adjacent these ponds compared to the remainder of the channel. A potential cause of this is that the shallow depth of the sand layer through which most of this seepage occurs (via channel walls) is not in the primary focus range of the EM31 in vertical dipole mode, and therefore does not influence the results as much as a sand layer immediately below the channel base (eg at 2-3 metres depth).

Extrapolation from Toolondo Central Site

The regression line based on the Toolondo Central ponds is presented in Figure 5.54. This trend line has almost double the gradient of the combined Rocklands/Toolondo sites regression line. If the Toolondo Central regression relationship had been used to predict seepage at:

- Toolondo West ('similar' site): Predicted seepage rates would have been 2-3 times greater than actual rates due to the steeper Toolondo Central regression line
- Toolondo East ('different' site): Predicted seepage rates would have been accurate (essentially predicting 0 mm/d) except at Pond 2, where predicted seepage would have been approximately 4 mm/d (actual 0.4 mm/d). However the Rocklands/Toolondo trend line would also over predict the rate at this pond at approximately 3 mm/d.

Regression lines were fitted through each of the sites individually (Toolondo Central line only is plotted in Figure 5.54). The correlation coefficients for each of the sites when plotted individually are:

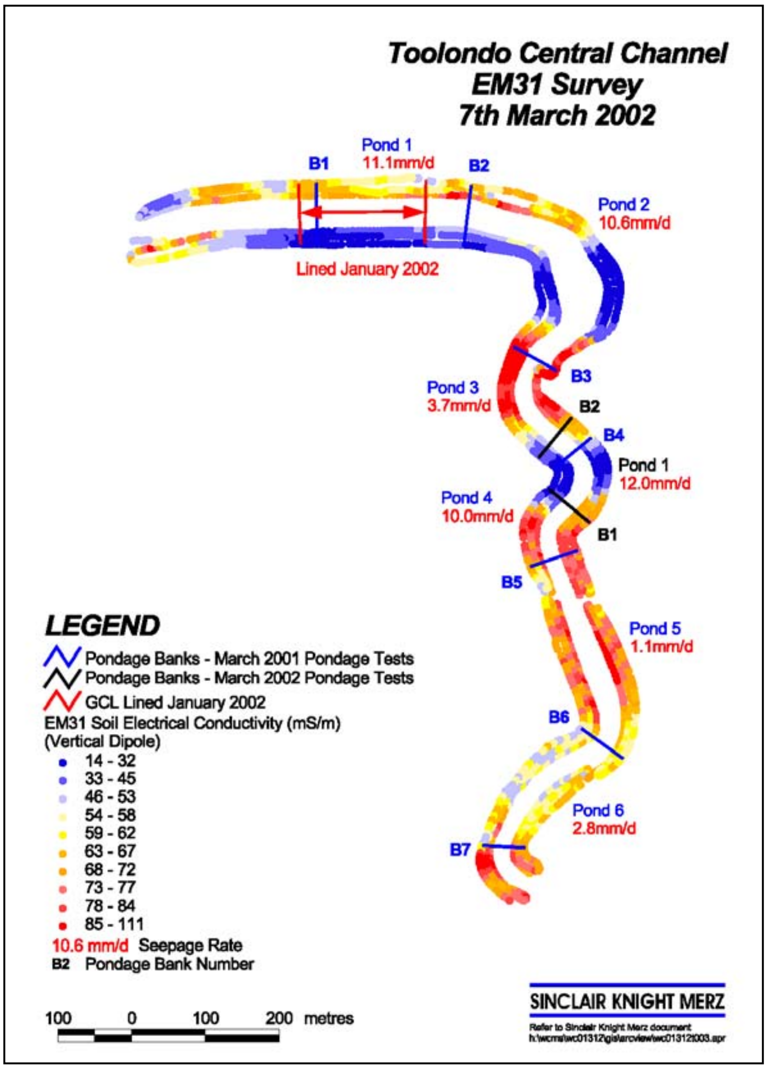
- Toolondo Central: 0.78
- Toolondo West: 0.86
- Toolondo East: NA – slight trend in reverse direction
- Rocklands: 0.33 (adjacent the channel: 0.82)

These results concur with soil types at the sites. The Toolondo East site was selected due to its change in soil type from a sandy clay to a very heavy clay profile and no trend was discernible within this site. However, as a data group, the site still fits within the broader regression trend, even though at a site specific level the trend line is reversed (the slope of the reverse trend line is almost flat compared to slopes of the other Toolondo and Rocklands sites, and therefore not highly significant).

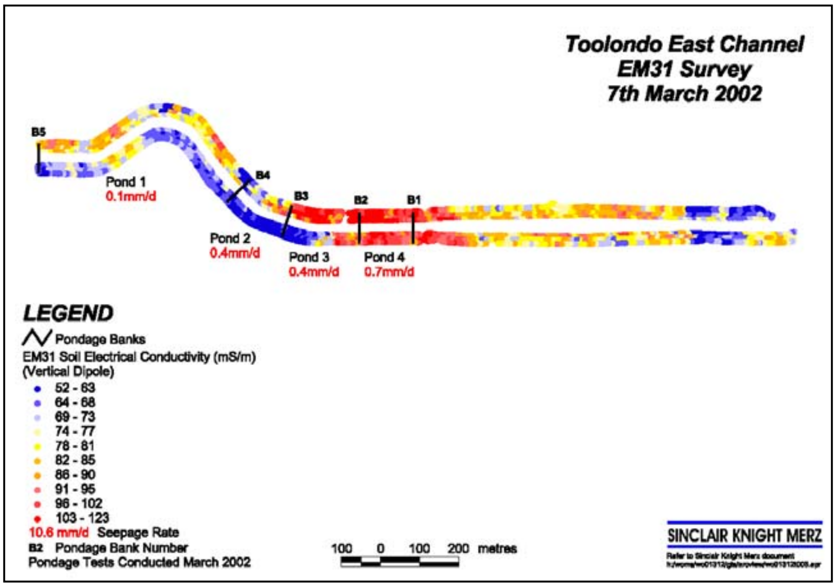
These results, along with examination of the channel specific data points in Figure 5.54 suggest that within the individual pondage test sites, better correlations can be obtained, with R^2 values of around 0.8 at Toolondo Central and West.

As would be suspected, this analysis shows that local correlations are more accurate for local predictions. However the regression line ('*Predicted*') presented in Figure 5.54 is a more useful tool for water managers as it allows prediction over longer sections of channel and across varying conditions.

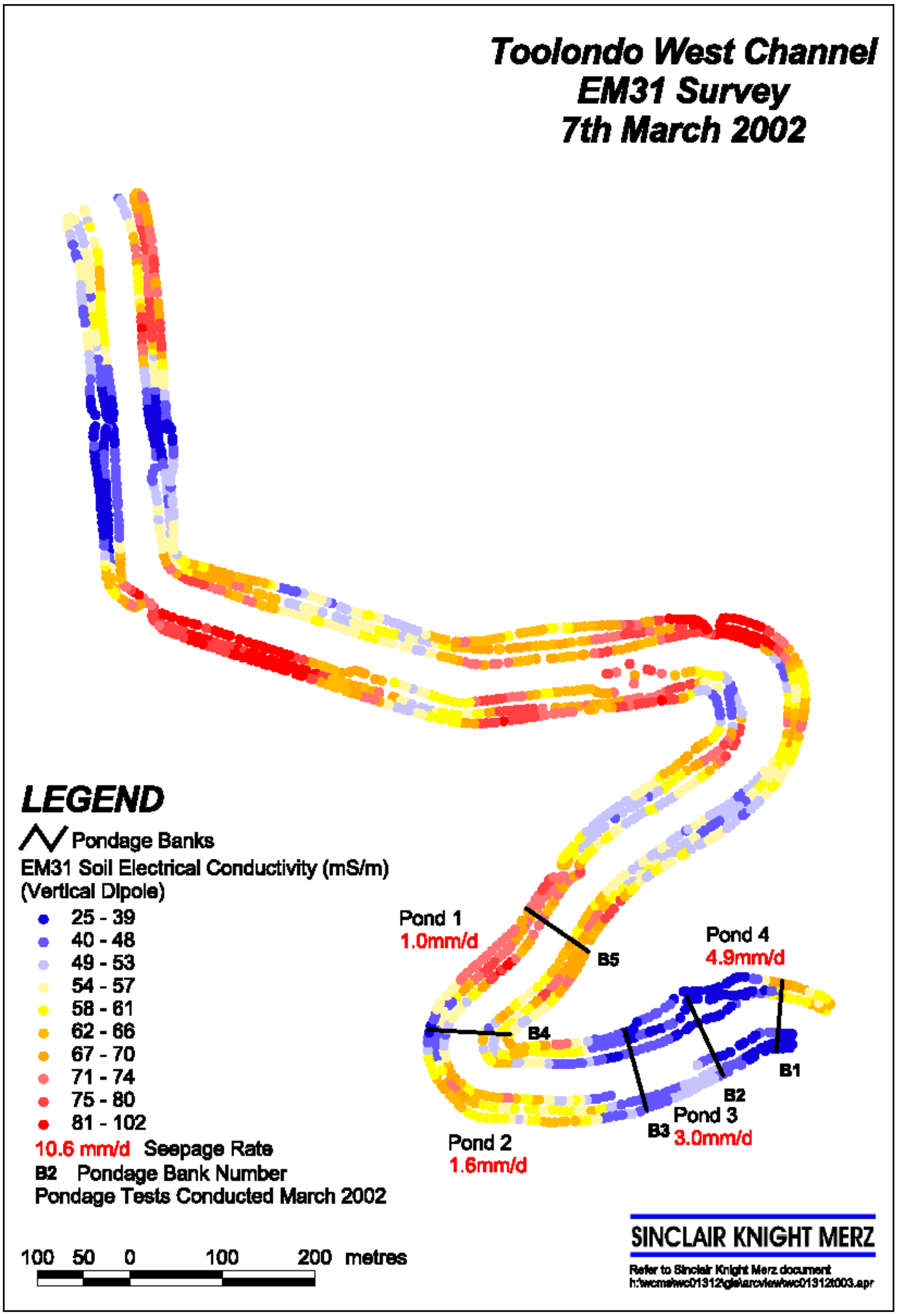
■ **Figure 5.55 Toolondo Central EM31 Survey, March 2002**



■ **Figure 5.56 Toolondo East EM31 Survey, March 2002**



■ **Figure 5.57 Toolondo West EM31 Survey, March 2002**

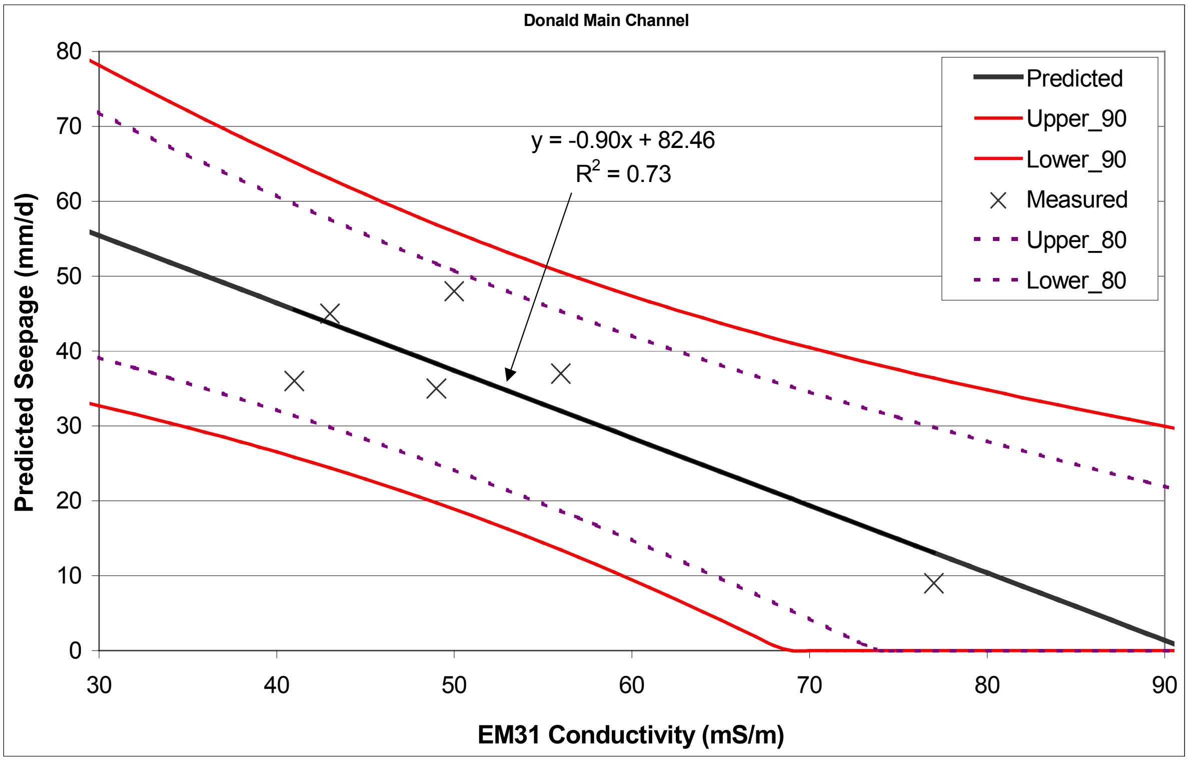


5.3.5.3 Donald

Figure 5.58 presents EM31 results (conducted September 2001) against pondage test seepage at the Donald Main channel. This survey is reported on in detail in Section 5.3.3.3 and the results are graphically presented in this section in Figure 5-31. This site is now briefly re-visited to apply a more rigorous statistical evaluation.

A correlation coefficient of 0.73 was obtained and the standard estimate of error was also good at 23% of the mean. Confidence bands are wide but indicate the equation can differentiate between high and low seepage sites. For example, if the EM31 survey result is 45 mS/m, with 80% confidence it can be concluded that seepage is between 30-55 mm/d. While this range is still wide, it indicates with a reasonable degree of confidence that seepage at the site is high. The bands widen at the higher conductivity range, which is a reflection of the small number of data points contributing to the construction of the regression equation. If a 75 mS/m (or greater) conductivity is recorded, it can be concluded with 80% confidence that seepage is less than 30mm/d.

■ **Figure 5.58 Donald Main Channel Pondage Test Seepage Versus EM31 Conductivity**

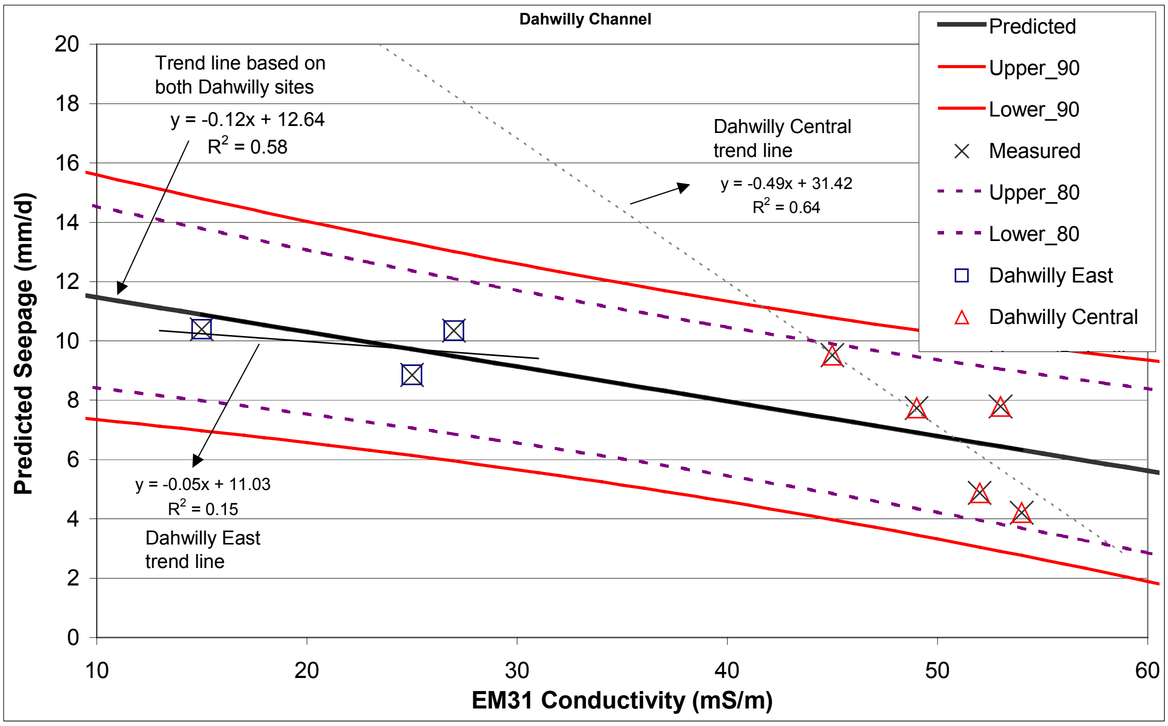


5.3.5.4 Dahwilly Channel

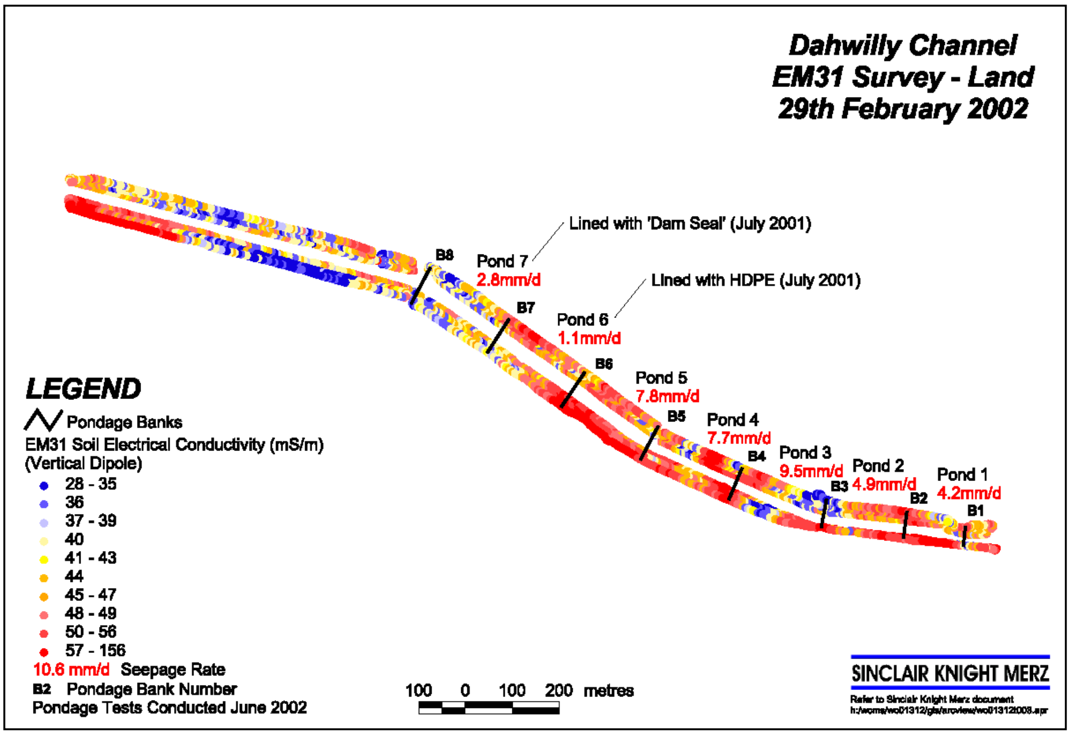
Figure 5.59 presents EM31 results against pondage test seepage at the Dahwilly channel, comprising surveys at the Dahwilly Central and Dahwilly East (Pretty Pine) sites. The two sites are approximately four to five kilometres apart. The Dahwilly East site represents the site which was selected with similarities to the original site. Pondage tests at the ‘different’ sites selected along the Dahwilly channel were not conducted due to operational constraints, and thus analysis could not be undertaken. The geology at the Dahwilly Central and Dahwilly East sites are reasonably similar (refer *Appendix* A for geological sections of both sites). Figure 5.60 and Figure 5.61 show maps of the EM31 results at Dahwilly and Dahwilly East (Pretty Pine). The EM31 surveys were conducted in February 2002.

It should be noted that the Dahwilly Central site examined here is slightly different in location to the Dahwilly site referred to earlier in the report (refer section 5.3.3.4). The pondage tests conducted here (2002) bordered the six pondage tests conducted in 2001. In fact, ponds 1 and 2 from the June 2001 pondage tests were pond 6 and 7 in the June 2002 pondage tests. [Theses two cells were remediated in July 2001. The two lined cells were removed from the analysis however, due to insufficient time between the pond lining and the EM31 survey (February 2002)]. It is important to note the significant difference between these results and the June 2000 EM31 survey. In the 2000 survey, no trend was detected in the data as the channel was not running, and therefore there was no seepage impacts on the watertable to detect. Further, the unsaturated zone at this site is relatively uniform and therefore unlike at other sites seepage cannot be inferred from unsaturated zone properties. At this site seepage is controlled by a clogging layer in the channel and not the unsaturated zone.

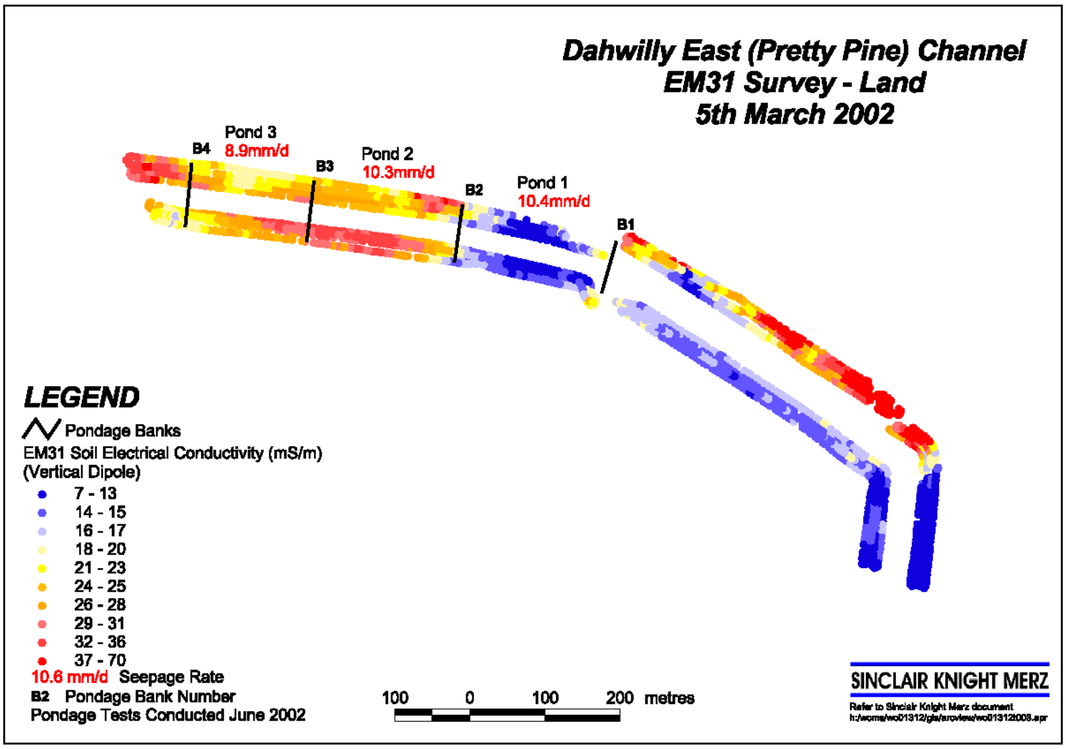
■ **Figure 5.59 Dahwilly Pondage Test Seepage Versus EM31 Conductivity**



■ Figure 5.60 Dahwilly Central EM31 Survey, February 2002



■ Figure 5.61 Dahwillly East (Pretty Pine) EM31 Survey, March 2002



The fitted regression line for the Dahwilly site had a correlation coefficient of 0.58 and a relatively low standard estimate of error of 21% of the mean. The 80% prediction interval bands are 5-6 mm/d wide, which are quite wide as a percentage of the range covered by the regression equation. This suggests the equation can only be confidently used in a broad sense to indicate the likelihood of low (< 5 mm/d) or moderate seepage (> 5 mm/d).

Extrapolation from Dahwilly Central Site

The regression line fitted through the Dahwilly central site (plotted in Figure 5.59 as a lighter colour line) has a slightly improved correlation coefficient compared to the line for both sites, but most notably is much steeper than the overall trend line. (A trend line was not fitted through the Dahwilly East site as there are insufficient points for this to be meaningful). If the Dahwilly Central trend line had been used to predict seepage at the Dahwilly East site, predicted seepage rates would have been 1.5 to 2 times greater than the actual rates recorded in the pondage tests.

The cause of the lower conductivity response at the Dahwilly East site (and thus the reason that the Dahwilly East EM31 conductivities do not plot on the Dahwilly Central trend line) compared to the Dahwilly Central site may be due to the fresher salinity native groundwater (approximately 2,500 EC compared to the 5,000 EC). However a more likely explanation is that the watertable is probably slightly deeper at this site, which would effectively remove the watertable from the penetration depth of the EM31 and lower conductivities. The resistivity survey conducted at Dahwilly East (refer section 5.4.4) suggests the watertable is around 6-7m. Bores at the Dahwilly central site indicate the watertable is approximately 5m below surface.

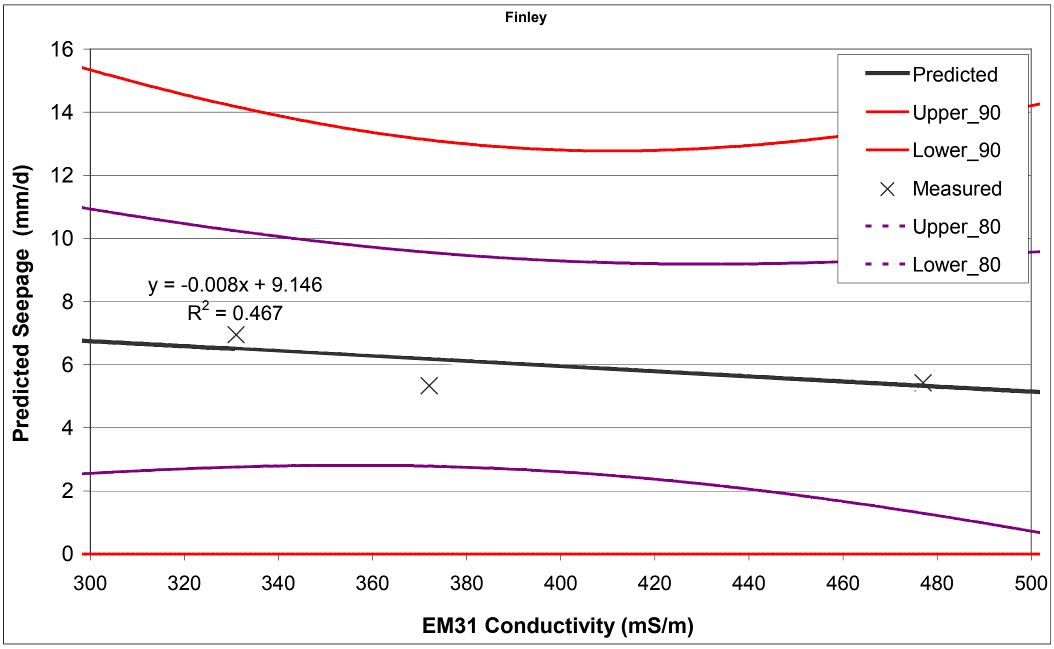
This analysis confirms what was illustrated from the extrapolations at the Toolondo site: local correlations will generally produce more accurate predictions. Even though the Dahwilly East site is only 4-5 km from the Central site, the slightly deeper watertable (and possibly change in groundwater salinity) is sufficient to produce a different trend line. However the regional prediction equation is a more useful tool as it allows prediction over longer sections of channel and across varying conditions.

5.3.5.5 Finley

Figure 5.62 presents pondage test seepage against EM31 conductivity for the Finley channel. The fact that only three ponds were used to establish the regression line means that the correlation coefficient (0.47) and the standard estimate of error (18% of the mean) are essentially meaningless. It is a reminder of the danger of relying on statistics outside of an understanding of the data and the context in which they are used. The prediction interval bands reveal the inadequacies of the data to produce any meaningful conclusions, with intervals of 14 mm across the displayed range (300 – 500 mS/m). Additional data points are required to improve the prediction interval.

The Finley site is an extremely clayey site (refer to the Finley Geological Long Section in *Appendix* A), with a high and salty watertable which produces the very high EM31 conductivities recorded at this site. There were no other sites in the investigation approaching conductivities of this magnitude. Given the moderate seepage rates and yet the very clayey profile, it was concluded in the regional assessment that the probable mechanism of seepage at this site is not vertical seepage through the base of the channel (ie due to in-situ soil permeability) but lateral seepage through the channel banks due to poor bank construction techniques or materials.

■ **Figure 5.62 Finley Pondage Test Seepage Versus EM31 Conductivity**



■ **Figure 5.63 Finley EM31 Survey, February 2002**

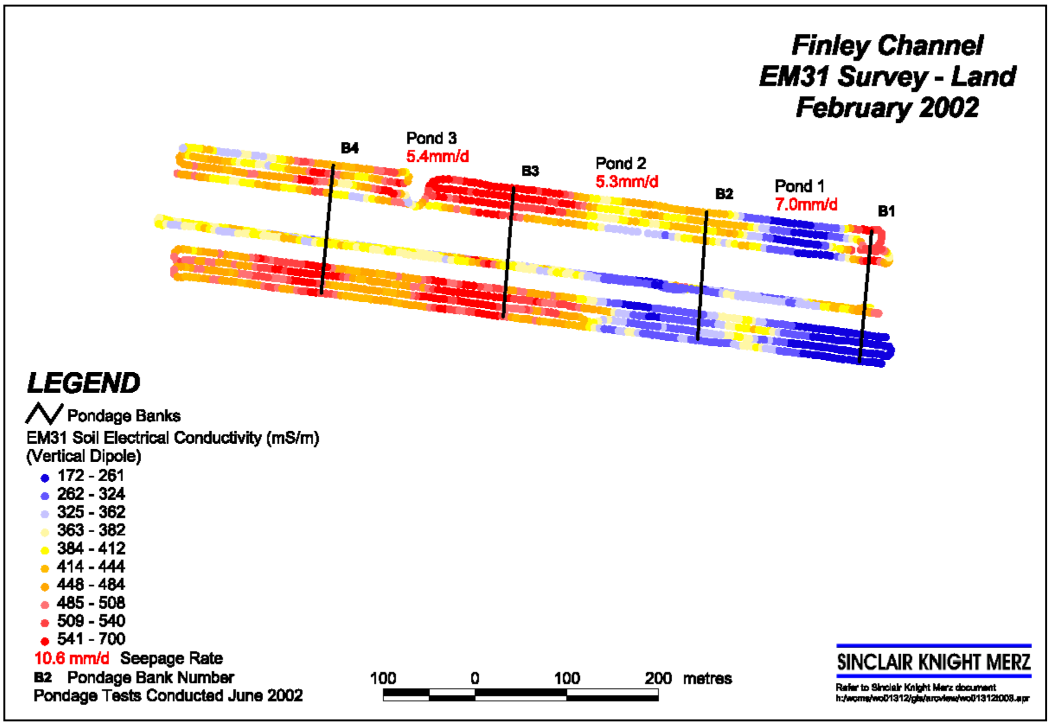


Figure 5.63 presents a map of the EM31 results at the Finley site. Notwithstanding the discussion above, (that the data cannot be used to make meaningful statistical conclusions), this figure does highlight that the fact that the technique appears to have detected an area of relatively higher seepage in the eastern half of pond one, which is supported by the fact that this pond has the highest seepage rate.

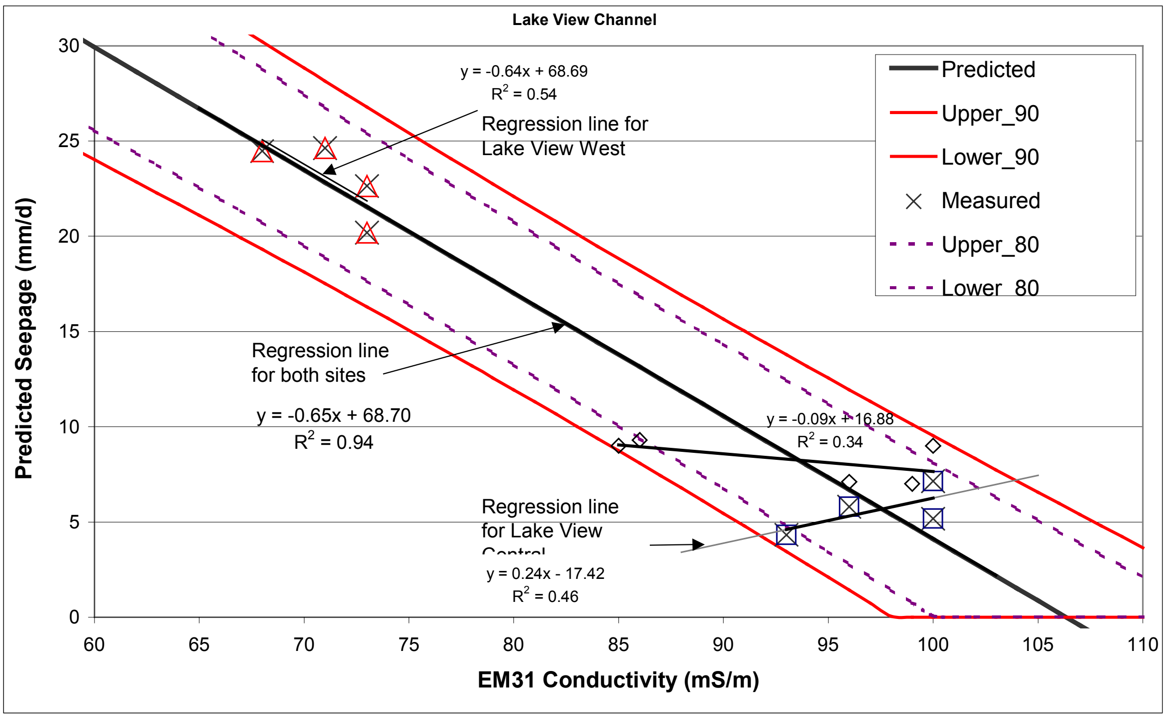
5.3.5.6 Lake View

Figure 5.64 presents pondage test seepage plotted against EM31 conductivity at the Lake View channel, for both the Lake View Original and the Lake View West site. Figure 5.65 and Figure 5.66 show maps of the EM31 results at the two sites. The Lake View central EM31 data was collected in June 2000, whereas the Lake View West data was collected in May 2002. In both cases data collected from pondage tests conducted in 2002 are used in the analysis.

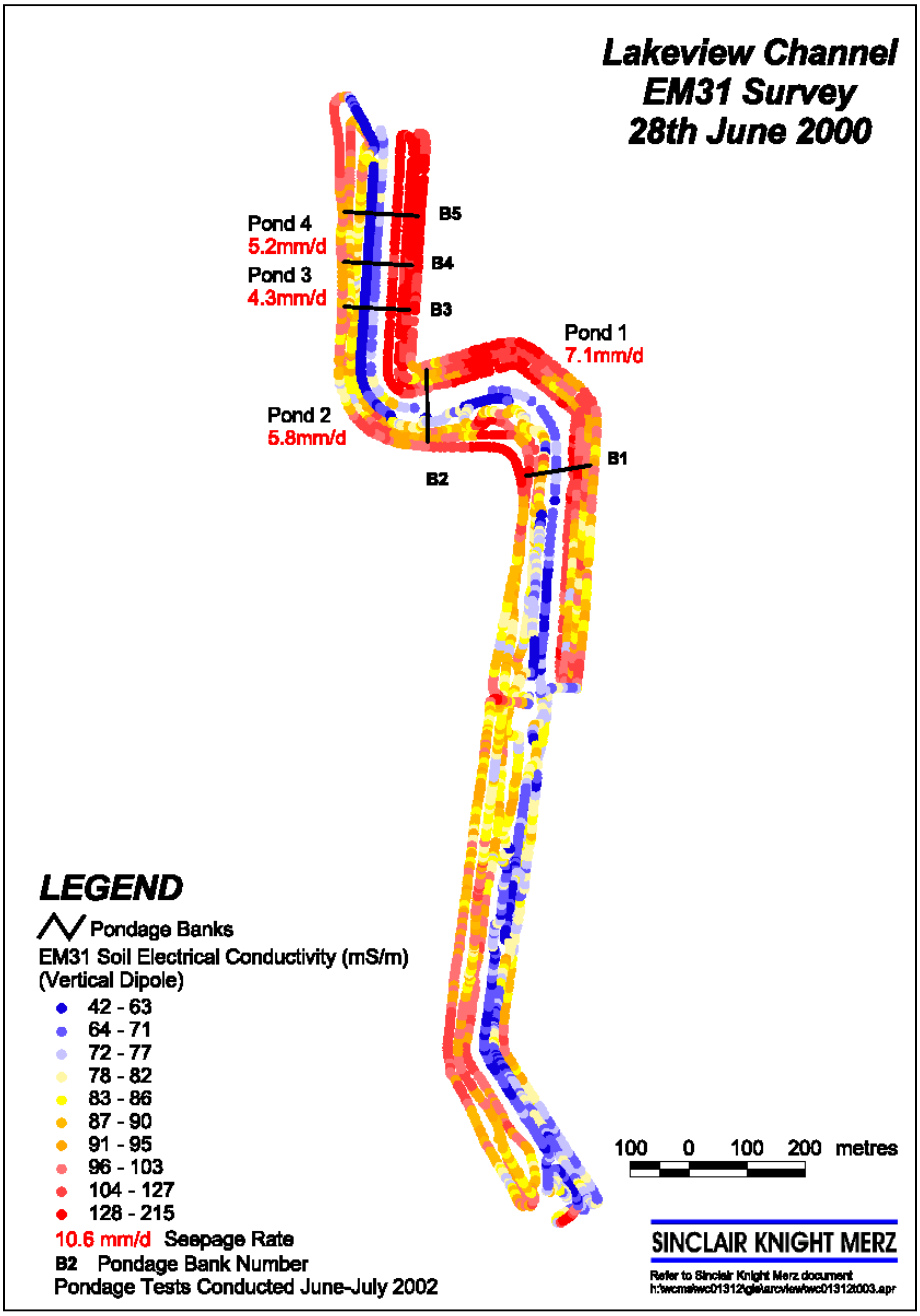
A high correlation coefficient of 0.94 was obtained for the relationship between EM31 and seepage between the two sites and the standard estimate of error was also good, at 17% of the mean. Confidence bands are moderately wide at about 8 mm/d (at 80% confidence level) and 10 mm/d (90% confidence level). However they suggest that the equation is suitable for differentiating between low, medium and high seepage rate sites.

Some warning is necessary however regarding the spread of the data. Both of the sites are clustered around a relatively small seepage rate and average conductivity range – the danger of this is best illustrated again by the example that only two data points will return a correlation coefficient of 1, but obviously there would be little confidence in the accuracy of the resulting regression equation. To improve confidence in the regression equation at this site, data is required in the mid conductivity range.

■ **Figure 5.64 Lake View Pondage Test Seepage Versus EM31 Conductivity**



■ **Figure 5.65 Lake View Central EM31 Survey, June 2000**

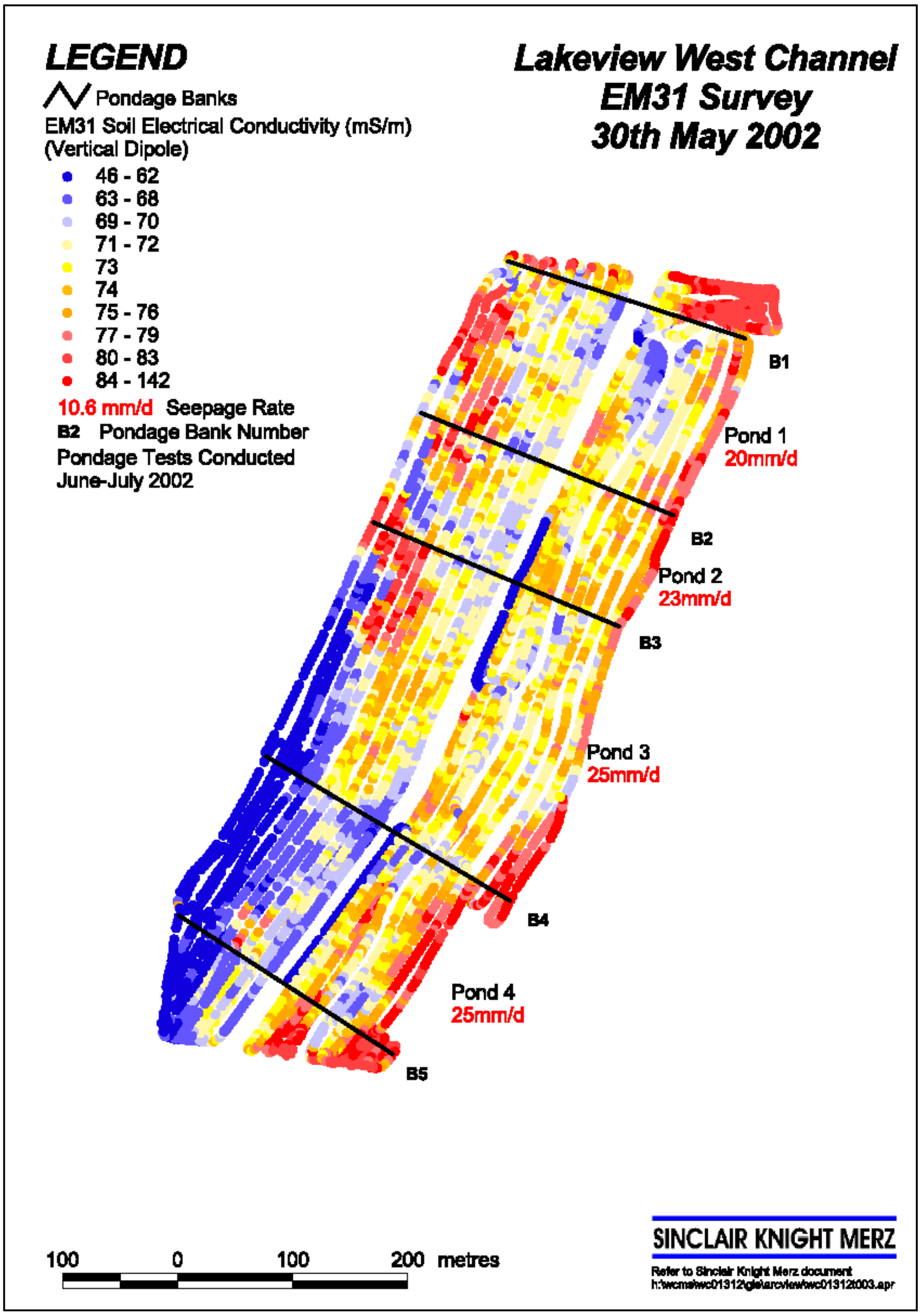


Extrapolation from Lake View Central Site

The Lake View West site was selected to test the ability to extrapolate from one site to another. In Figure 5.64 the line of best fit has been added through the Lake View Central data. This regression line actually has the opposite gradient to that theoretically expected (and to that observed in most of the sites examined in this study). This illustrates that local trends cannot necessarily be assumed to be reliable, particularly when the range of the data is quite small. In this case the pondage test range was only 4.3 – 7.1 mm/d, and the (average) conductivity range very small at 96

- 100 mS/m. However, it should be noted that good correlations were obtained using this same EM31 data but the old pond locations (refer section 5.3.3.5). In particular improved correlations were obtained using the survey line immediately adjacent the channel, rather than all survey lines, due to the mixing that occurred away from the channel. This suggests that improved results could be obtained with the new pondage test locations if the adjacent channel data was used in this analysis. However, for consistency purposes (ie, for comparison with other channels) all the data was used.

■ **Figure 5.66 Lake View West EM31 Survey, May 2002**



5.3.5.7 Summary

Table 5-6 summarises the main conclusions and findings of the EM31 analysis of each channel.

■ **Table 5-6 Summary of Channel Specific EM31 Surveys to Pondage Test Relationships**

Region (channels comprising region)	**Number of Ponds**	**Correlation coefficient (R^2)**	**Standard Estimate of Error (as % of mean)**	**Comment**
Rocklands / Toolondo (Rocklands, Toolondo East, Central & West)	21	0.47	63%	❑ Improved correlations are obtained at each of the individual sites (R^2 approx 0.7-0.8) ❑ Using the Central site to predict seepage at the West site would have caused over prediction of 2-3 times actual seepage rate (due to high surface sands content at Toolondo central) ❑ Prediction interval range of 8 mm/d (80% confidence) fairly wide but considered acceptable given data spans 4 diff. Sites
Donald	6	0.73	23%	❑ Good R^2 & SEE but based on small no. data points, especially at high cond. / low seepage end of range ❑ Prediction interval range of 25 mm/d (80% confidence) but still useful for low risk – high risk assessment. Additional data points likely to tighten confidence intervals
Waranga	11	0.40	61%	❑ R^2 improved to 0.60 when two outliers removed ❑ High SEE reflects high scatter and fairly broad confidence intervals (8mm/d at 80%). Typical of what would be expected given the spatial range of the pondage tests ❑ Useful for high / low risk seepage assessment
Dahwilly (Dahwilly Central & East)	8	0.58	21%	❑ Reasonable R^2, SEE ❑ Prediction intervals relatively wide (5-6 mm) ❑ Using the central site to predict seepage at the east site would have caused over prediction of 1.5 -2 times actual seepage, due to differences in gw salinities (and potentially depth to watertable) between the two sites
Finley	3	0.47	18%	❑ Statistics not meaningful due to low no. data points ❑ Confidence intervals indicate this relationship cannot be used to predict seepage at site ❑ Extremely high conductivity site – very clayey profile suggests bank leakage rather than soil seepage is the dominant seepage mechanism
Lake View (Lake View Central & East)	8	0.94	17%	❑ Good R^2, SEE & prediction interval but 2 data sets creating the regression line have small conductivity and seepage rate ranges – Desirable to obtain some data in mid range to improve confidence ❑ No sensible trend at the Lake View original site – could not have been used to predict Lake View West seepage. However improvement likely if adjacent channel only data used (due to rapid mixing), as per yr 1 & 2 analysis

From examination of the above table it is apparent that the more data points that are added to generate the regression line, the greater the scatter about the regression line. This can be seen in the high standard error of estimates for the Rocklands/Toolondo and Waranga sites. This is a reflection of the fact that the ponds in these sites covered a wide area and range of sub-surface conditions. However, while there is more scatter about these lines, these relationships are probably more useful to RWAs as they encompass a wider spatial range and wider range of conditions, and can therefore be used with greater confidence over a broader area.

5.4 Resistivity Trials

5.4.1 Introduction

This section is divided into the following sub-sections:

- Background – This section describes the functioning of resistivity systems as well as the specific methodology as to how they were used in the trials;
- Regional Assessment of Key Relationships – For all of the year three sites an attempt was made to look for potential correlations between seepage rates across all sites and resistivity response. This was conducted applying multiple linear regression using a number of key explanatory variables and simple linear regression, where resistivity was the only explanatory variable.
- Channel Specific Resistivity Assessment - This section examines the resistivity - seepage relationship at each channel. Variations with resistivity and depth are discussed and various combinations of seepage relationships explored for different depth slices within the profile.

5.4.2 Background

5.4.2.1 Channel Specific Resistivity Systems

Resistivity can be measured using grounded (or immersed) current electrodes to impress an applied voltage across a section of the ground. Differences in voltage distribution can be used to calculate apparent ground resistivity. The method depends on good electrode connection and hence can be slow where extensive electrode preparation is necessary. Thus rates of acquisition are usually only around 5 km/ depending upon conditions. The exception to this is when the electrodes can be immersed in water thus overcoming the need for electrode preparation. Systems also can be linked with a recording device and GPS positioning for rapid survey procedure. In such circumstances continuous recording can be achieved at rates of greater than 5 kph or 40km/d. Hotchkiss et.al. (2001) employed such a device for measuring seepage from irrigation channels in Nebraska, USA. Similar devices are commonly used down bore holes to measure formation resistivity.

The advantage of resistivity systems is that a single transmitting dipole can be used with a number of receiving dipoles. These dipoles positioned at increasing distance from the transmitting electrodes can be used to calculate the depth and conductivity relationships of the sub-surface. This allows a conductivity profile to be established, as opposed to conventional frequency domain EM systems which provide only a single average conductivity for the profile.

5.4.2.2 Methodology

For the year 3 trials, a multi-electrode array was built in what is commonly referred to as a dipole-dipole configuration. A pair of current electrodes separated by a distance *x* are followed by a series of receiver electrodes all separated by the same distance. The closest receiver electrodes sample the resistivity in the near surface (around one third to half *x*) and the more distant electrodes 'see' deeper into the ground. Using an array of receiver dipoles allows the possibility for a resistivity section to be created.

Such arrays have been in common use in mineral exploration for the past 50 years. However data is normally collected while the whole array is stationary, partly because good contact between electrodes and the ground must be obtained. This may be difficult on dry land. In the present study however the array was immersed (floating) on the channel. Contact of electrodes in the water and thus to the underlying ground was good and the array could be towed at speeds of around 5 to 8 kph while data was collected. This allowed data collection of 2 km sections in around 20 minutes. Figure 5.67 shows the resistivity array being used at the Toolondo East site. All resistivity surveys were conducted in mid-March 2002.

In these trials the sites were surveyed in all cases with a five metre dipole array of 6 dipoles. The same section of channel was then re-surveyed with a 10m dipole array in all sites except Toolondo Central which was the first site and Toolondo West where water levels were very low. Time did not allow analysis of the 10m dipole data in this study.

- **Figure 5.67 Resistivity Array Deployed in Year 3 Trials (in operation at the Toolondo East site)**

5.4.3 Regional Assessment of Key Relationships

As was conducted in Section 5.3.4 for the EM31 analysis, this section explores potential correlations between seepage rates across all sites and resistivity response, at sites where resistivity surveying was conducted (refer section 5.1.3). In comparison to the EM31 assessment, this excluded Rocklands, Donald and Waranga channels from the analysis, and reduced the data set to 23 ponds, across eight sites. This regional assessment was conducted in two ways:

- Multiple linear regression, ie looking for correlation between seepage rate and average resistivity response and other important variables which might affect seepage (or the resistivity response); and,
- Simple linear regression, ie looking for a direct correlation between seepage rate and average resistivity response.

5.4.3.1 Multiple Linear Regression

Introduction

As described in Section 5.3.4, multiple linear regression is a statistical technique that allows one response (or dependent) variable to be predicted from a number of explanatory (or independent) variables. In this study the response variable is seepage, as measured in pondage tests. The explanatory variables which were included in the multiple linear regression analysis included:

- Resistivity;
- Soil permeability;
- Depth to watertable; and,
- Groundwater salinity.

The most important independent variable is resistivity. The main aim of conducting multiple regression analysis was therefore to determine which other variables could account for variations in seepage apart from resistivity. Groundwater salinity and depth to watertable were included as independent variables because they will affect the resistivity response.

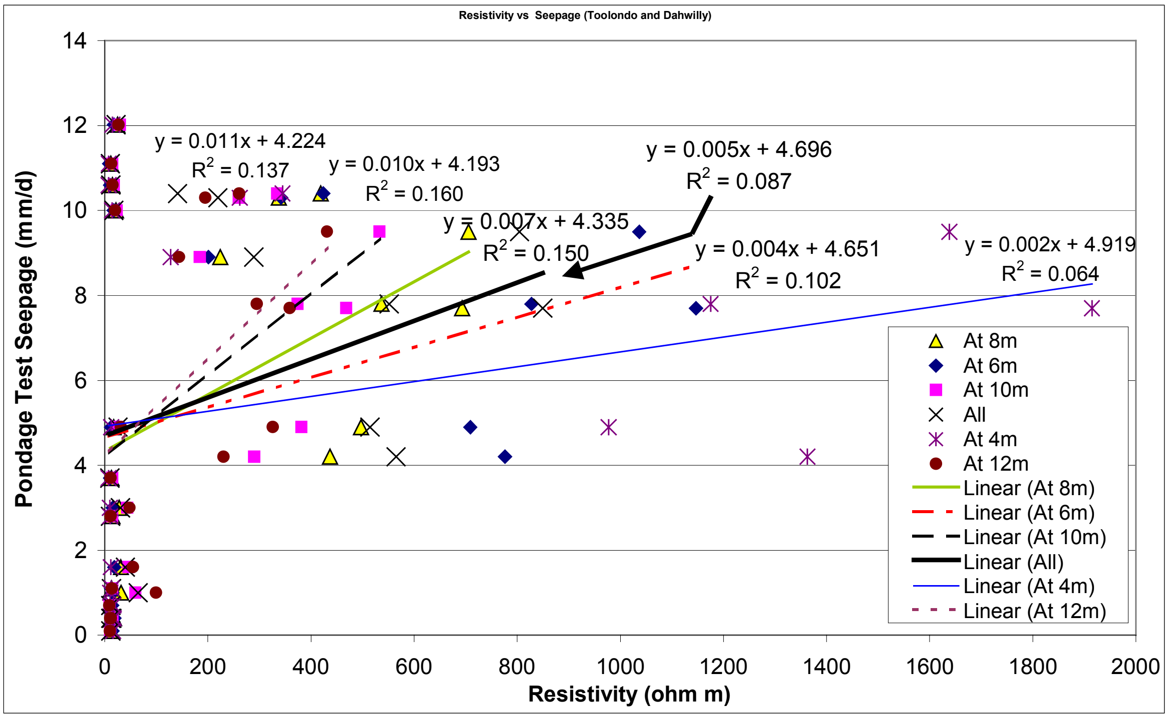
Data Sources

The response variable is observed seepage as measured in pondage tests (averaged over the life of pondage tests, excluding outliers). The explanatory variables of soil permeability, depth to watertable and groundwater salinity and their method of collection is described in Section 5.3.4.1. Resistivity is considered to be the most reliable data source, as spatially this contains the highest density of readings over the pond length. Resistivity was measured using the on-channel set-up described in section 5.4.2 and averaged over the length of the pond.

A further consideration with the resistivity analysis compared to the EM analysis is that data is collected at a number of depths within the profile for the resistivity survey. The whole profile average may not be the most appropriate or the best fitting data to use in the regression analysis. Therefore the most appropriate resistivity depth slice must be selected. Figure 5.68 shows seepage rates versus average resistivity at various depths for sites with watertable between 5 – 10 metres (Toolondo and Dahwilly). This figure shows the progressively improving correlation coefficient obtained for the deeper sections within the profile, with 10 m returning the strongest correlation. The 8 m average was also relatively strong, but the 12 m relationship is weaker, indicating that around 10 m appears to be the optimum measurement depth for this data set. Based on this analysis, the linear and multiple linear regression analysis uses the ten metre section resistivity data for regression modelling.

Using the one depth slice across all sites has limitations. As the channel specific resistivity assessment indicates (refer section 5.4.4), often the depth interval correlating best with seepage is at and immediately below the watertable. Therefore this approach may be appropriate for sites with a watertable in the 5 - 10m range, but may not be best for sites with a shallower watertable. However, for the purpose of applying a consistent approach a single depth slice was used across all sites.

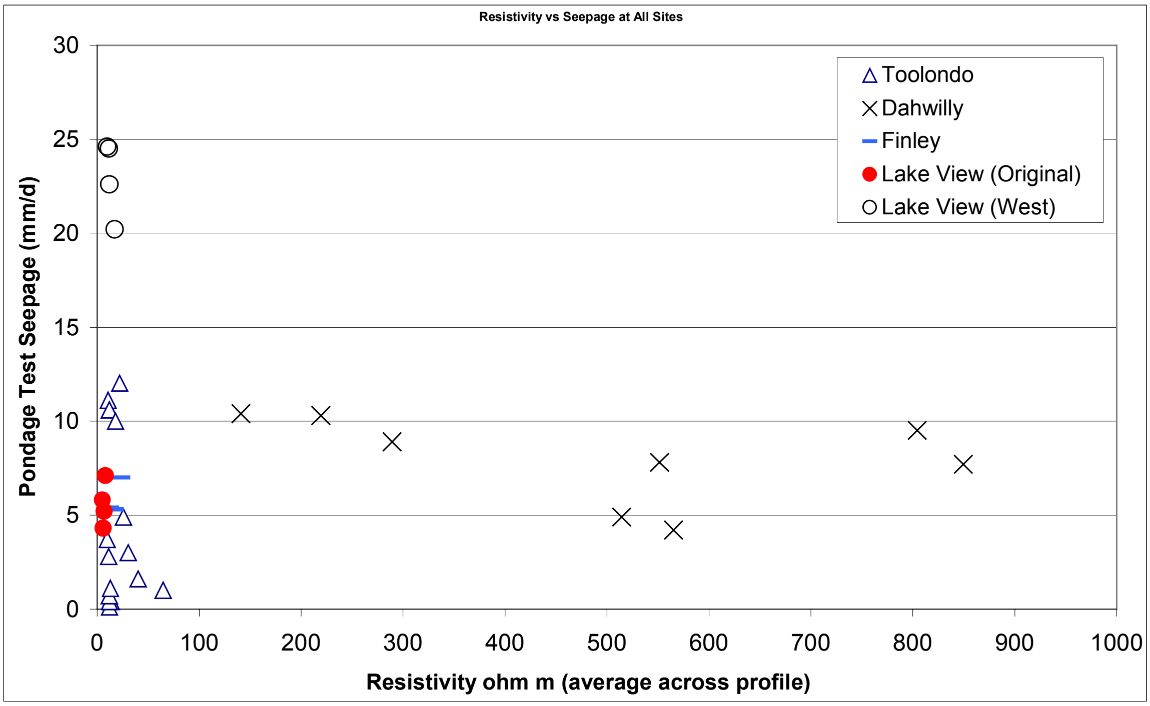
■ Figure 5.68 Pondage Test Seepage Versus Resistivity Average For Various Depths at Toolondo and Dahwilly Channels



Methodology
The methodology used in the analysis was the same as that undertaken for the EM31 multiple regression analysis and is also described in Section 5.3.4.1. Two measures were used to assess the accuracy, or 'goodness' of the regression. These were the coefficient of determination (R^2) and the standard error (SEE). The R^2 measures the proportion of the total variation explained by the model. A large R^2 is associated with a good model or prediction equation. The standard error is a measure of the degree of scatter of the observed data points around the regression line. Hence a small standard error is associated with a good model. The standard error has been expressed as a percentage of the mean of the observed dependent variable (ie pondage test seepage).

Results and Discussion
Figure 5.69 presents the resistivity at 10m depth within the profile at each pondage cell versus pondage test seepage. At first glance there does not appear to be any relationship between the two variables, with the Dahwilly channel returning resistivities many times higher than all other sites. The first cut statistical analysis indicated that depth to watertable was a significant variable across the sites and therefore to improve correlations and allow a more meaningful regional analysis to be conducted, the data was divided based on watertable depth (as was conducted for the EM31 analysis).

- **Figure 5.69 Resistivity (Whole Profile Average) Versus Pondage Test Seepage at All Sites**



<u>Watertable Depth Five to Ten Metres</u>
For sites where the watertable was 5 to 10 m below surface (Toolondo and Dahwilly), resistivity and the hydraulic conductivity of the upper two metres of the soil profile were found to be significant variables. Groundwater salinity was not found to be significant. Depth to watertable was also found not to be significant, however this was expected as the original data set was split into two based on depth to watertable. The regression equation found to provide the best prediction of channel seepage was:

$$\text{Seepage} = 3 + 0.01\,\text{Resistivity}_{10m} + 7.46\,\text{UK}_v \qquad (\textit{Equation 4})$$

Where,
Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Average resistivity at 10m depth recorded on channel (ohm m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

The equation was established with 23 data points. The coefficient of determination for the relationship was $R^2 = 0.44$ and the standard error of estimate was 61% of the mean observed seepage rate.

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 19% of the mean observed seepage rate (to the power of 0.2). A marginal reduction in the correlation coefficient was observed, decreasing to $R^2 = 0.42$.

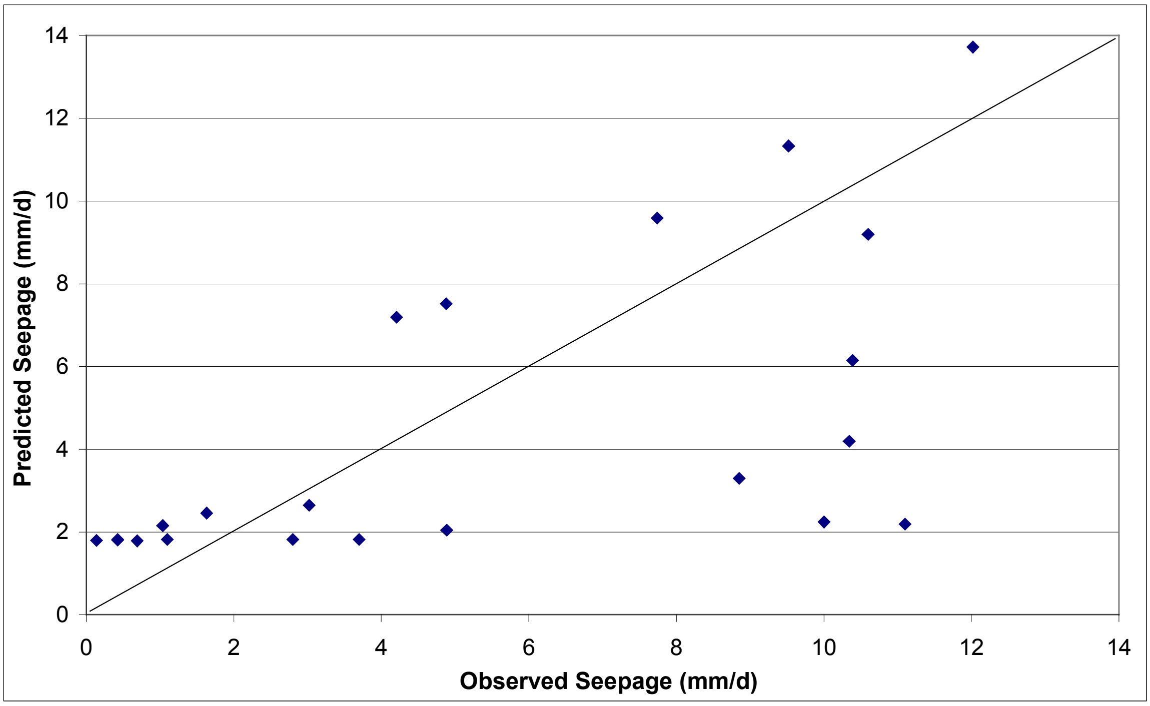
The non-linear multiple regression equation, for predicting channel seepage at sites where the watertable is between 5 - 10m is:

$$\text{Seepage} = [\,1.12 + 0.000825\ \text{Resistivity}_{10m} + 0.47\ UK_v\,]^5 \qquad (\textit{Equation 5})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

Figure 5.70 provides a visual presentation of the degree of scatter in the prediction equation (*Equation 5*).

■ **Figure 5.70 Predicted Versus Observed Seepage for Multiple Non-Linear Regression, Based on Resistivity and Upper Soil Profile Hydraulic Conductivity (Sites with Watertable 5-10m)**



Watertable Less Than Two Metres

For sites with watertables within two metres of the surface (Lake View and Lake View West), multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond the resistivity data. This was also found to be the case for the EM31 regional analysis. It is logical that soils would be a significant variable for the 5-10m watertable sites, but not for the less than 2m watertable sites, as at the shallow groundwater sites the groundwater will tend to mask the impact of soil type on the response. Therefore multiple linear regression analysis was not possible. The best fitting equation that can be derived based on the available data is presented below in Section 5.4.3.2 - Simple Linear Regression.

5.4.3.2 Simple Linear Regression

Watertable Five to Ten Metres

Figure 5.71 graphs pondage test seepage with resistivity (to 10 m) for sites where the watertable is 5 to 10 metres below surface. For the resistivity analysis the number of channels fitting this category was reduced to two (3 sites at Toolondo and 2 sites on the Dahwilly channel). Four points within this data set appear to be outliers. They are the four high seepage ponds at Dahwilly Central. However they were not be removed from the analysis as there was no obvious grounds for their removal.

Therefore the linear regression equation (using resistivity only as an explanatory variable) predicting channel seepage at sites where the watertable is greater than 2m is:

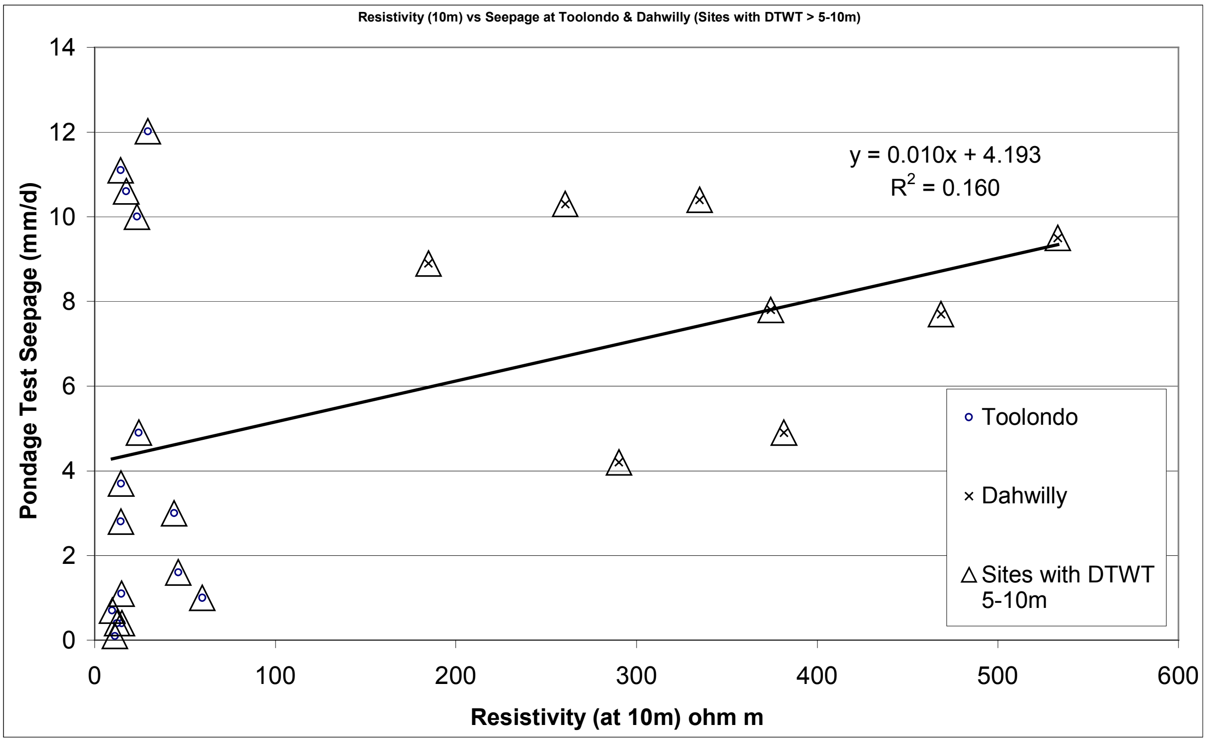
$$\text{Seepage} = 4.2 + 0.01\ \text{Resistivity}_{10m} \qquad (\textit{Equation 6})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

The equation was established with 23 data points. The coefficient of determination for the relationship was $R^2 = 0.16$ and the standard error of estimate was 68% of the mean observed seepage rate. These statistics indicate that the accuracy of the regression is very poor, in large part due to the four high seepage rate ‘outliers’ at the Toolondo Central site. With these outliers excluded the correlation coefficient improves dramatically to $R^2 = 0.63$. However as discussed above there was no obvious basis for their removal, and thus this equation is not presented.

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 20% of the mean observed seepage rate (to the power of 0.2). A marginal improvement in the correlation coefficient was observed, increasing to $R^2 = 0.21$.

■ **Figure 5.71 Pondage Test Seepage Versus Resistivity (av at 10m) for Sites with Depth to Watertable 5 – 10m**



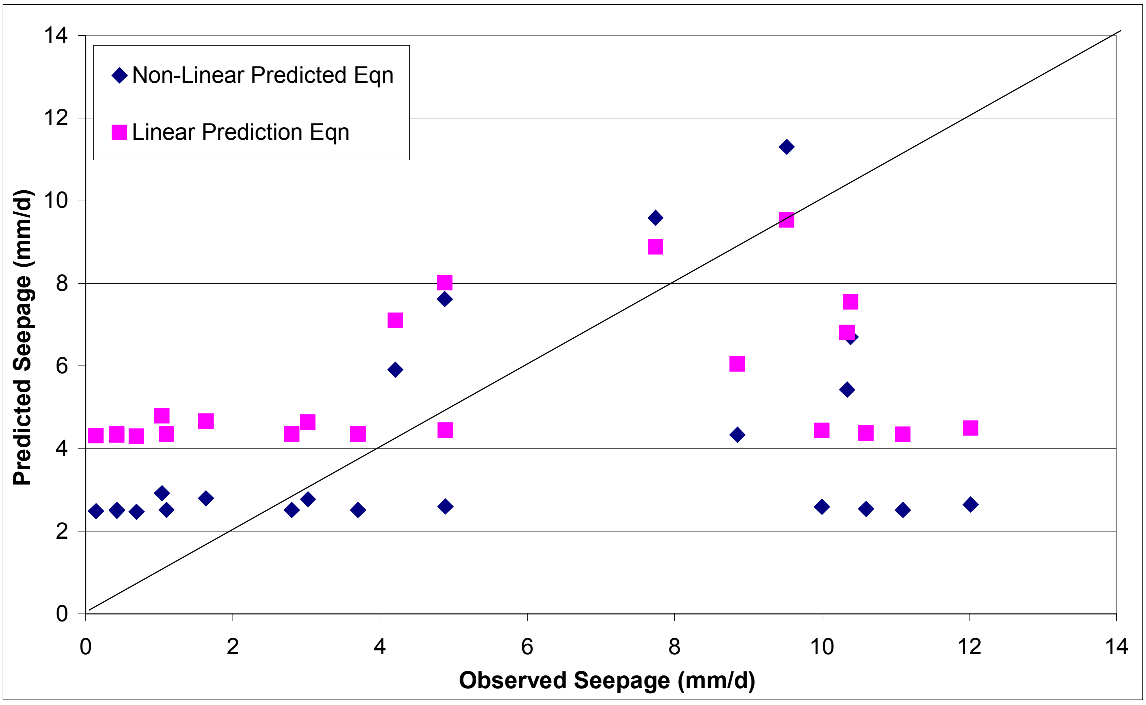
The non-linear regression equation, using resistivity only as an explanatory variable, for predicting channel seepage at sites where the watertable is 5-10m below surface is:

$$\text{Seepage} = [\,1.19 + 0.0008\ \text{Resistivity}_{10m}]^{5} \qquad (\textit{Equation 7})$$

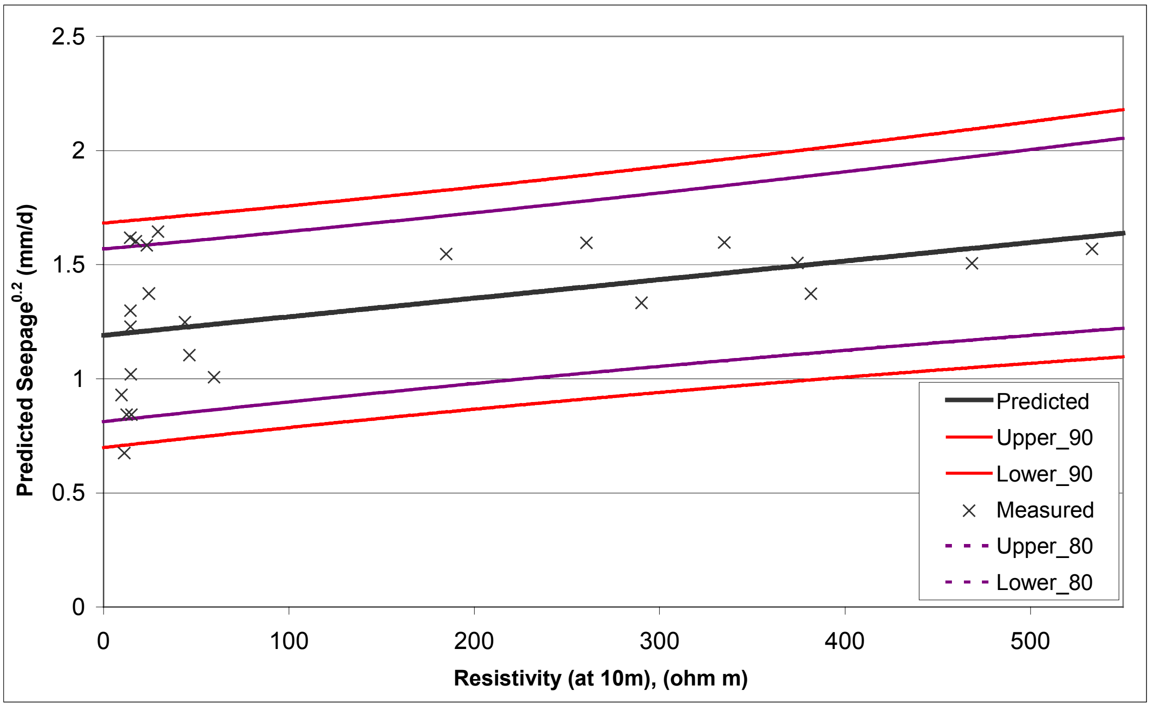
Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

Figure 5-72 presents actual seepage rates versus predicted seepage rates for the resistivity prediction equations, both for the linear prediction equation and the non-linear equation. This figure shows that the standard estimate of error has been improved for the non-linear fit by reducing the predicted seepage at the lower end of the seepage range. However, the non-linear prediction equation increases the error of prediction at the higher end of the seepage range, causing the four outliers to increase in distance from the prediction line. In summary, neither the linear or non-linear simple regression equations are satisfactory predictors of seepage. The very wide prediction bands for the non-linear prediction equation (*Equation 7*) presented in Figure 5.73 confirms this conclusion.

■ **Figure 5.72 Predicted vs Observed Seepage for Simple Linear and Non-Linear Regression (Sites with watertable > 2m: Toolondo and Dahwilly)**



■ **Figure 5.73 Prediction Intervals: Predicting Seepage from Resistivity (average at 10m) For Watertable 5 - 10m**



Watertable Less Than Two Metres

Figure 5.74 presents pondage test seepage versus average resistivity (at ten metres) for sites where the watertable is less than two metres. For the resistivity analysis this data set is comprised of only the Lake View channel (four ponds at the original site and four ponds at the western site). Finley was removed from the data as an outlier, based on the reasoning described in section 5.3.4.2.

The linear equation (using resistivity only as an explanatory variable) predicting channel seepage at sites where the watertable is less than 2m is:

$$\text{Seepage} = 1.7\ \text{Resistivity}_{10m} - 0.66 \qquad (\textit{Equation 8})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

The equation was established with 8 data points. The coefficient of determination for the relationship was R^2 = 0.62 and the standard error of estimate was 6.3, which is 27% of the mean observed seepage rate. These statistics indicate that the accuracy of the regression is reasonable. However, the results must be interpreted based on the fact that only a relatively few number of data points have been used to form the relationship, and all data points were collected on the same channel. Further testing to add different environments to this data set is necessary before a reasonable degree of confidence can be placed in this prediction equation (outside of the immediate area where the relationship was established).

- **Figure 5.74 Pondage Test Seepage Versus Resistivity (at 10m) for Sites with Depth to Watertable Less than Two Metres (Lake View Channel)**

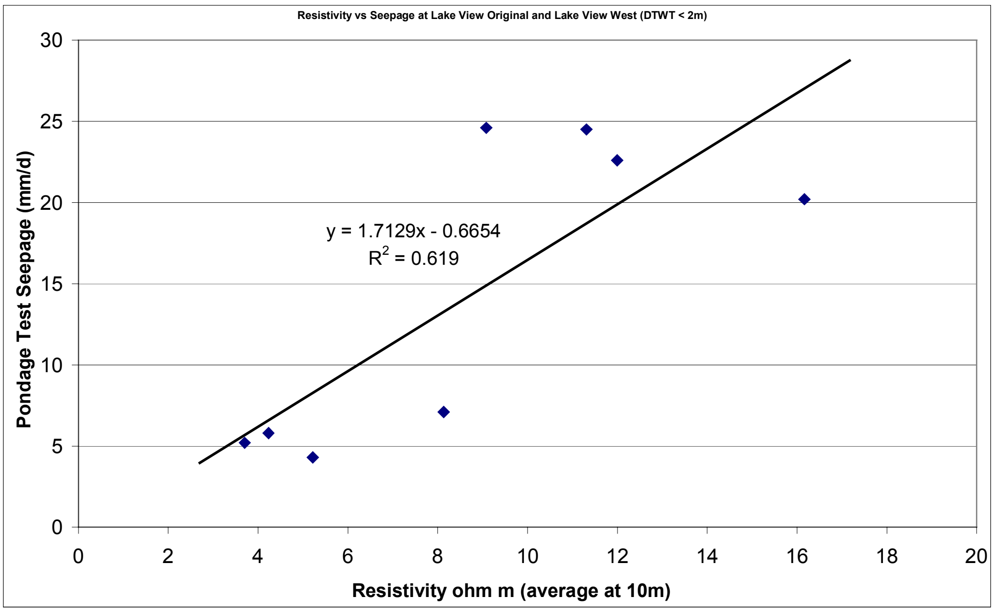
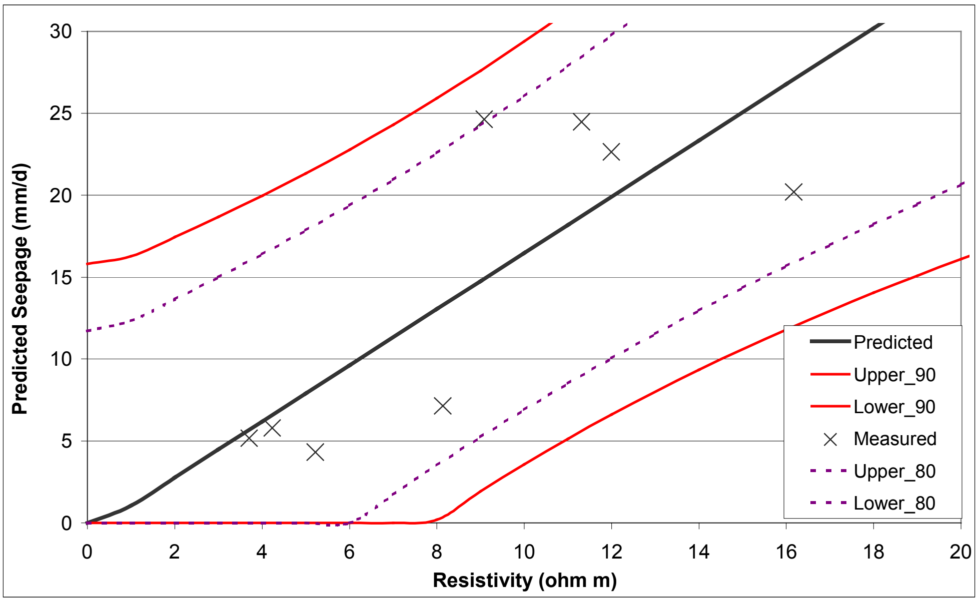


Figure 5.75 presents prediction intervals for *Equation 8*. The large width of the prediction bands is caused by the small number of data points which have been used to generate the regression equation. For example, for a resistivity reading of 8 ohm m, at 90% confidence levels the actual seepage rate could be anywhere in the range of 0 – 25 mm/d, which is not a very helpful guide. The width of these bands does not give a

great deal of confidence in using this equation for prediction, reinforcing the above comments regarding the need for additional data points to improve confidence in the prediction equation. Again it should be noted that the 10m depth slice is probably not the most appropriate depth focus for sites with a shallow watertable. This is also contributing to the uncertainty in the regression equation.

■ **Figure 5.75 Prediction Intervals: Predicting Seepage from Resistivity (average to 10m) For Watertable Less than 2m (Lake View Channel)**



The following summary comments can be made regarding the linear and multiple regression analysis:

- The multiple regression analysis has significantly improved the accuracy of the regression equation compared to the simple regression with only one variable, increasing the coefficient of determination from R^2 = 0.21 to R^2 = 0.42. This improvement can be observed in a comparison between Figure 5-72 and Figure 5-70. However, as was the case for the non-linear simple regression equation, the multiple regression equation still failed to account for the four high seepage rate pond outliers at Toolondo Central.

- As was the case in the EM31 multi-variate analysis, the variable which was found to be most significant in the regression equation was the vertical hydraulic conductivity in the upper two metres (upper K_v). Again this confirms that the upper soil profile is by far the most significant part of the profile controlling seepage (for sites with deep watertable). In terms of significance in the equation (ie the importance of the variable in describing variation) the resistivity and upper K_v variables were both essentially equal in influence as explanatory variables.

- While this analysis indicates a reasonably fitting regression equation, it could not be used with the same degree of confidence as the EM31 based equation due to:
  - The lower correlation coefficient;
  - The few number of data points and small range of environments represented by the data points; and,

- The unexplained outliers in the resistivity analysis that were not present in the EM31 regression equation.

5.4.4 Channel Specific Resistivity Assessment

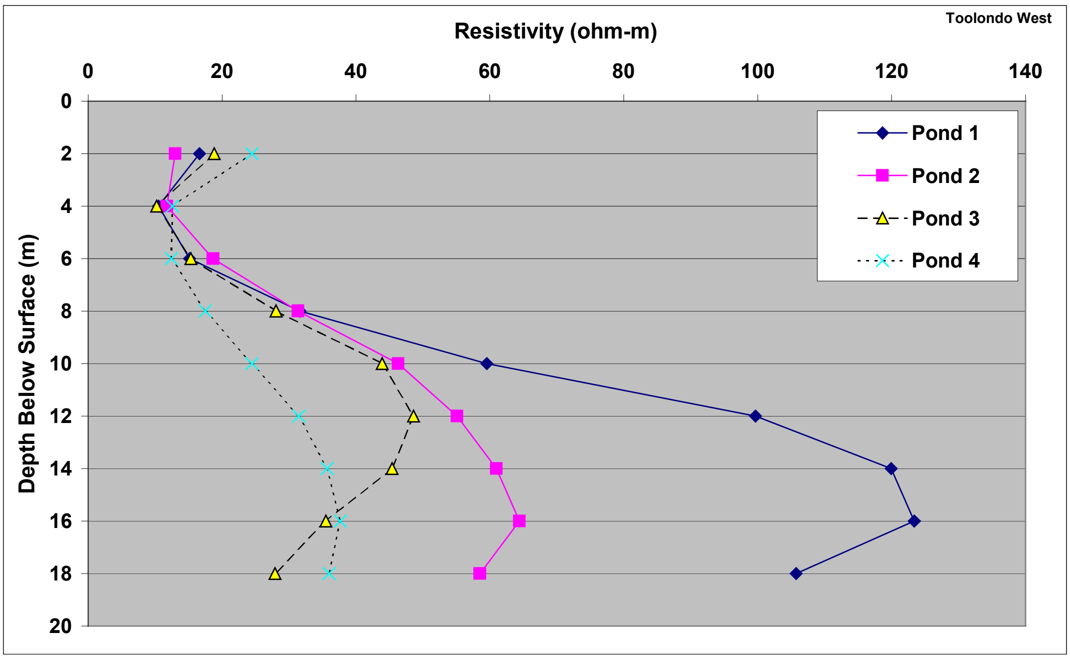
5.4.4.1 Toolondo West

Resistivity surveys were conducted along 2 kilometres of channel at Toolondo West. The water level in the channel was low and the boat had to be dragged at slow speed along the channel bed. This did not appear to affect results.

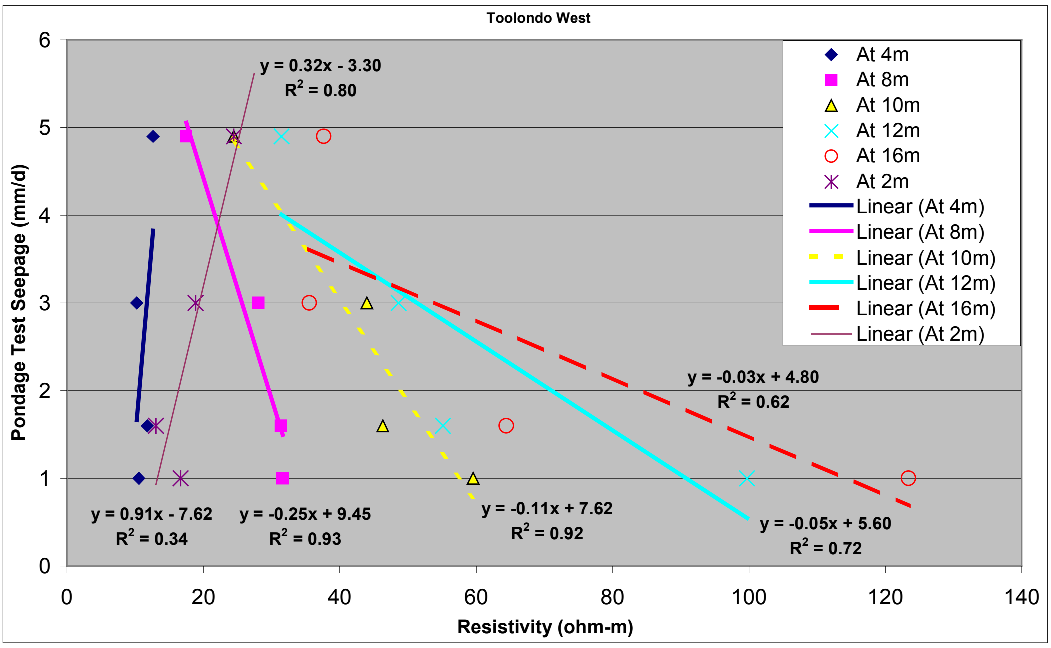
Figure 5-76 presents the change in resistivity with depth at the site (over the pondage test areas). The average resistivity values are much higher than seen at Toolondo Central site some 3 km to the east. This figure shows increasing resistivity with depth, up to the watertable, across all ponds. The watertable appears to be located between 12m to 14m – this is based on the distinct decrease in resistivity (attributed to the saline groundwater) observed between these depths. The sharp increase in resistivity in pond 1 and to a lesser degree in pond 2 at 10-12m is probably attributable to the sandstone at this depth. Sandstone is likely to have a reduced porosity compared to the overlying sediments which will show as an increase in resistivity.

Figure 5.77 presents average resistivity values for the ponds at the Toolondo West site plotted against pondage test seepage rates for each of the ponds. For depths of 8m and below the sandstone appears to be dominating the response. It is apparent that the sandstone is of low permeability and therefore high resistivity may equate to low seepage at this site. Typically (ie, observed at all other sites) high resistivity indicates seepage of fresher water into a saline water table. However at this site it is apparent that the influence of the sandstone resistivity is dominating the response, even below the watertable and effectively masking the effect of the fresher seeped water in the saline groundwater. Either the sandstone is absent beneath ponds 3 & 4 (which the long section in *Appendix* A suggests it may be), or it is less cemented and therefore has a lower resistivity.

- **Figure 5-76 Resistivity Versus Depth At Toolondo West**



■ **Figure 5.77 Resistivity Against Pondage Test Seepage at Toolondo West**



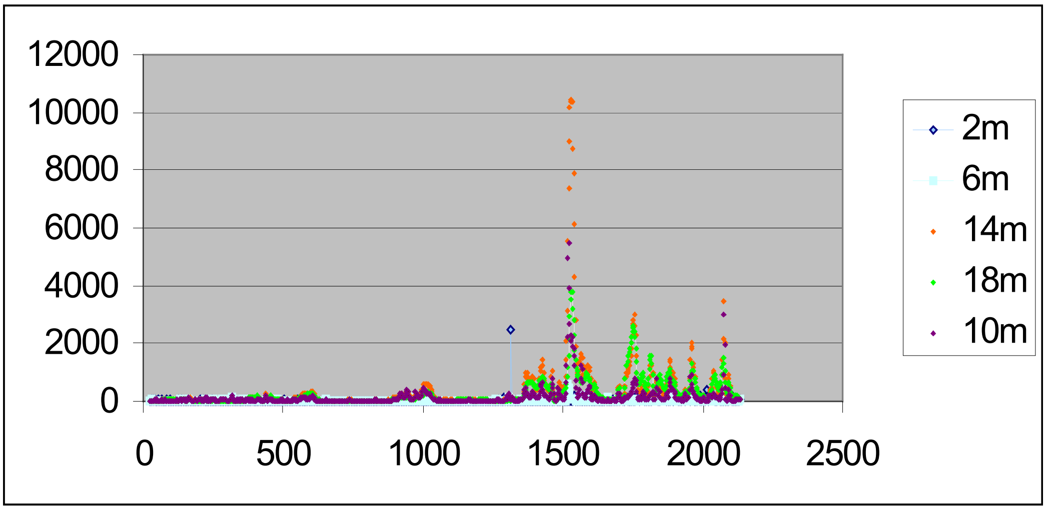
The reasonable correlation observed at shallow depth (2 and 4m) is probably due to difference in clay content immediately below the channel. This method of detection is the same as that of the EM31 (when the watertable is deep). It is not the actual impact of the seepage plume in the groundwater which is detected, but the lithology below the channel. In many cases, the resistivity / conductivity response in the near surface will provide a good indication of the likelihood of seepage, as it has in this case. In some instances this method may break down, for example due to the effect of a channel liner (artificial or natural). In such circumstances the geology in the sub-surface will not provide an indication of the rate of seepage, as seepage is controlled by a thin surface layer.

Figure 5.77 shows that the differences in resistivity are minor in the near surface but the correlation becomes strongly negative at greater depth. It appears that reduced porosity (which will show as an increase in resistivity) may dominate the responses. Porosity will be inversely related to permeability and thus areas with highest resistivity (low porosity) at depth have lowest seepage.

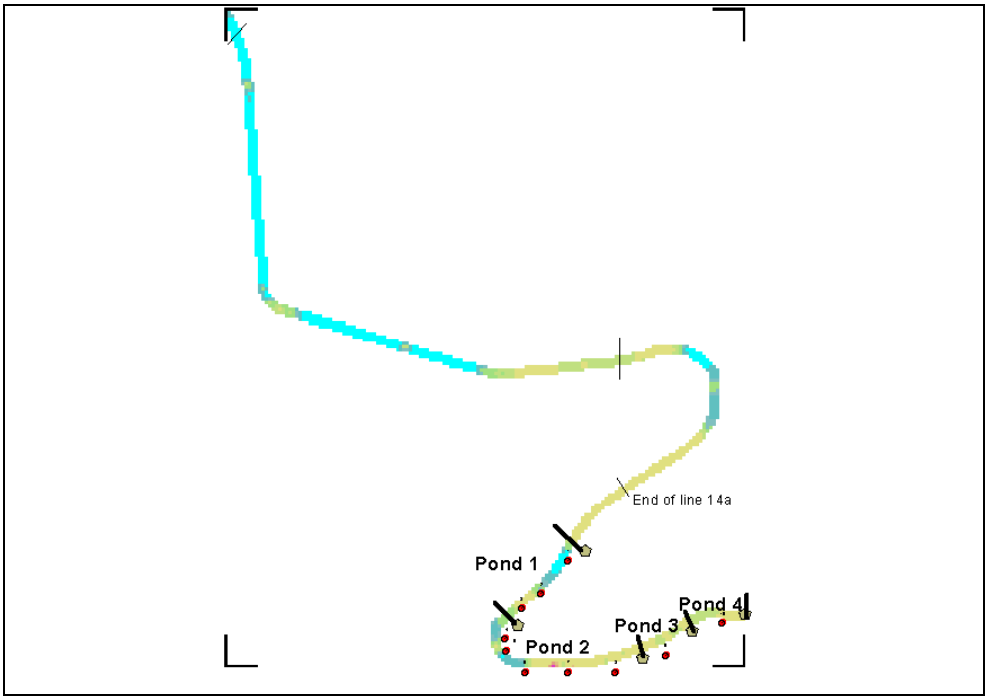
Figure 5.78 shows the relatively low resistivity values for the southern end of the line at Toolondo west. Towards the north the background resistivity values are much higher which possibly reflects sandstone basement rock close to surface but may be due to increased seepage. Individual spikes in the data reflect either better cemented sandstones with low porosity and/or major seepage areas where seepage of the irrigation channel water has significantly diluted the more saline groundwater. This effect appears greatest in the top of the saturated zone between 10 and 14m.

Figure 5.79 shows the resistivity at 18m below surface for the section of channel surveyed at Toolondo West. This reinforces the analysis of Figure 5.78: the northern section shows higher background resistivity compared to the remainder of the surveyed channel. This higher background level may be related to shallower

■ **Figure 5.78 Plot of resistivity values for Toolondo West against distance along the channel [Resistivity (ohm-m) on vertical axis and distance (m) on horizontal axis]**



■ **Figure 5.79 Depth slice from 18m below surface showing lower resistivity (yellow to red) in southern section of surveyed line compared with higher resistivity (blue) in northern section.**



sandstone with low porosity and or increased seepage in this section. The evidence from pondage tests at the site suggests sandstone rather than seepage is the cause, however the depth of drilling at the site is insufficient to confirm this interpretation. Deeper drilling would be required for definitive interpretation of the data.

From the geophysical results it appears the low seepage observed at Toolondo West is occurring over most of the ponds into the unsaturated surface. This seepage plus the presence of sandstone is apparently resulting in elevated resistivities at depth in Ponds 1 and 2. Below the watertable there are narrow zones with low permeability which reduces seepage in some sections. The resistivity of these zones shows a significant increase over background levels. Above the water able there is little difference in resistivity that can be related to seepage. However at 2m and 4m a positive correlation is observed between seepage and attributable to differences in clay content in the upper surface, as EM31 works in the unsaturated zone when the watertable is deep. Below the watertable there is a negative correlation with resistivity (to that expected and observed at other sites) most likely related to the effect of the very resistive nature of sandstone on the response.

5.4.4.2 Toolondo Central

Resistivity traverses were conducted over a 2 km section of the Toolondo Channel from the south (599370mE, 5916042mN) to north (598138mE, 5916840mN). In general the resistivities at this site are much lower than that detected at Toolondo West. This is most likely attributable to differences in lithology, possibly related to variations in the degree of cementing and hence porosity of the sandstone.

Figure 5-80 presents the change in resistivity with depth at the site, over the pondage test areas. This figure appears to show a fresher zone at 2m due to seepage effects immediately beneath the channel, underlain by unsaturated material increasing in resistivity with depth (interpreted as increasingly fresh sandstone) up until the watertable. The watertable appears to be located around 10m to 11m, based on the distinct decrease in resistivity observed between these depths, caused by the relatively high salinity of the groundwater.

■ **Figure 5-80 Resistivity Versus Depth At Toolondo Central**

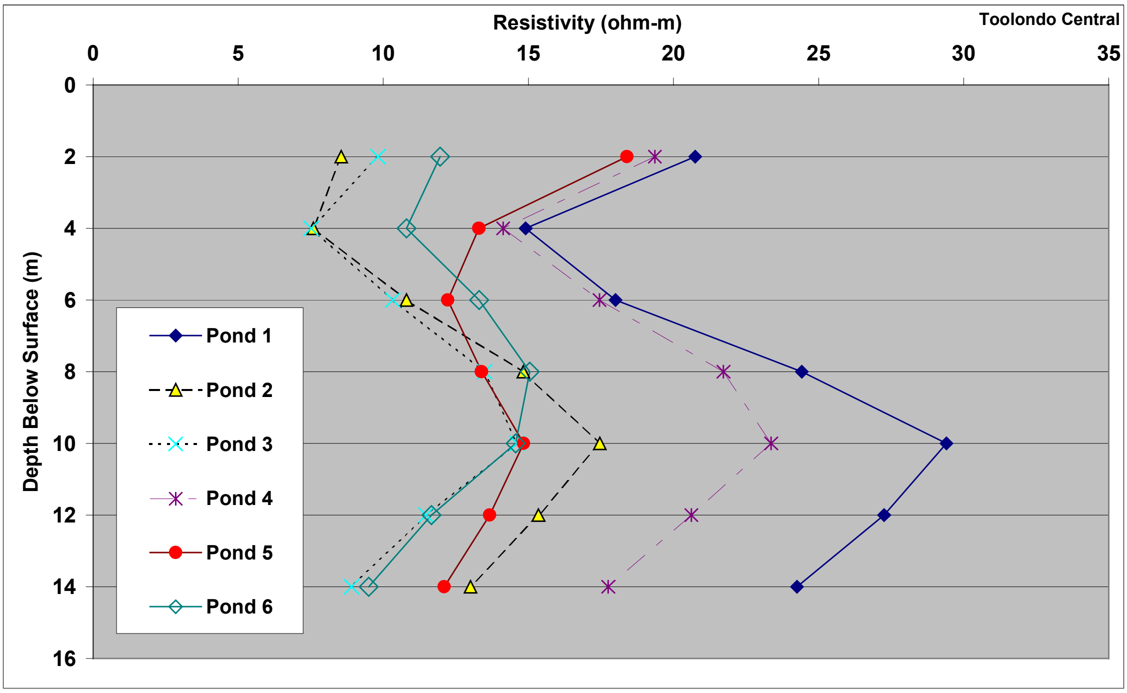


Figure 5.81 shows a series of correlations for different depth slices between seepage rate and average resistivity for the Toolondo Central section. This plot shows the improvement in the correlation using depth slices immediately below the watertable. At 2m there is virtually no correlation and only a poor one at 6m. At 10m and 12m the best correlation is obtained with an R^2 of around 0.6. This fits with the theory that seepage is best detected as it impacts the watertable and creates a fresher plume compared to background conditions.

■ **Figure 5.81 Resistivity Against Pondage Test Seepage at Toolondo Central**

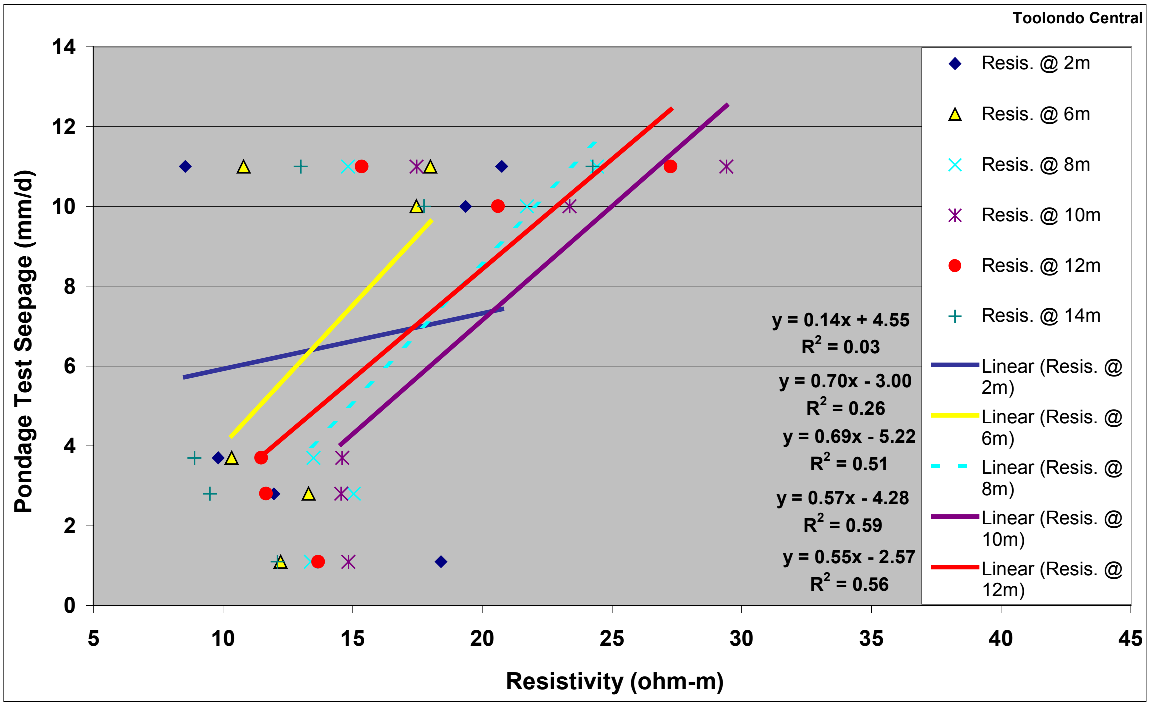
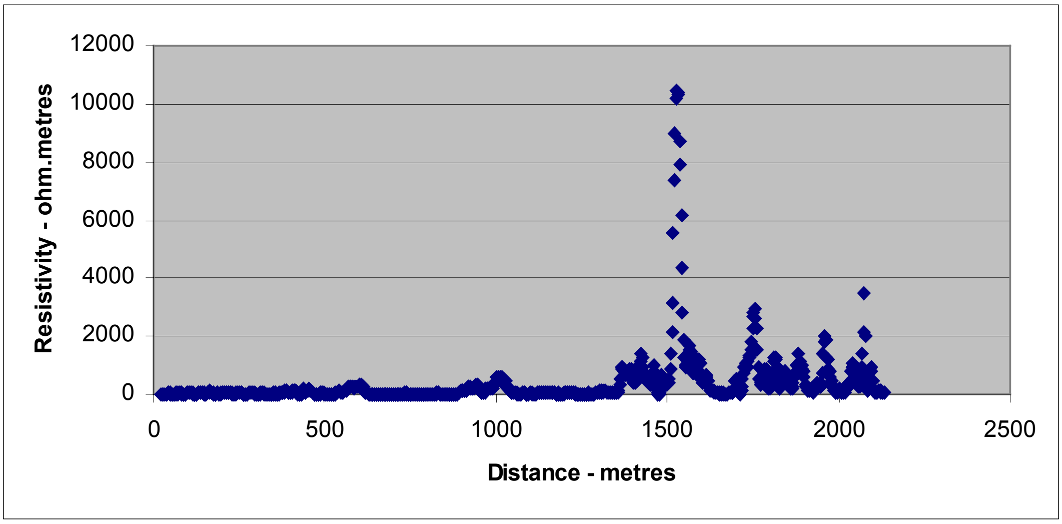


Figure 5.82 shows a plot of the resistivity at 14m below surface. Peaks represent zones of higher resistivity, which are interpreted as major seepage of fresher channel water into the more saline groundwater.

Figure 5.83 shows the resistivity long section beneath Pond 1 (from 2002 pondage tests). The section shows, a conductive surface layer underlain by a more resistive layer and a conductive layer at depth. These interpretations are confirmed by comparison with the geological long section for the site (*Appendix* A), which shows a sand in the top metre over much of the section, underlain by a sandy clay to medium clay to a depth of between 5 and 10m underlain by sandstone with a more saline water table below 10m. The sandstone layer appears irregular in thickness and/or resistivity and the inversion software has not resolved a well-defined layer.

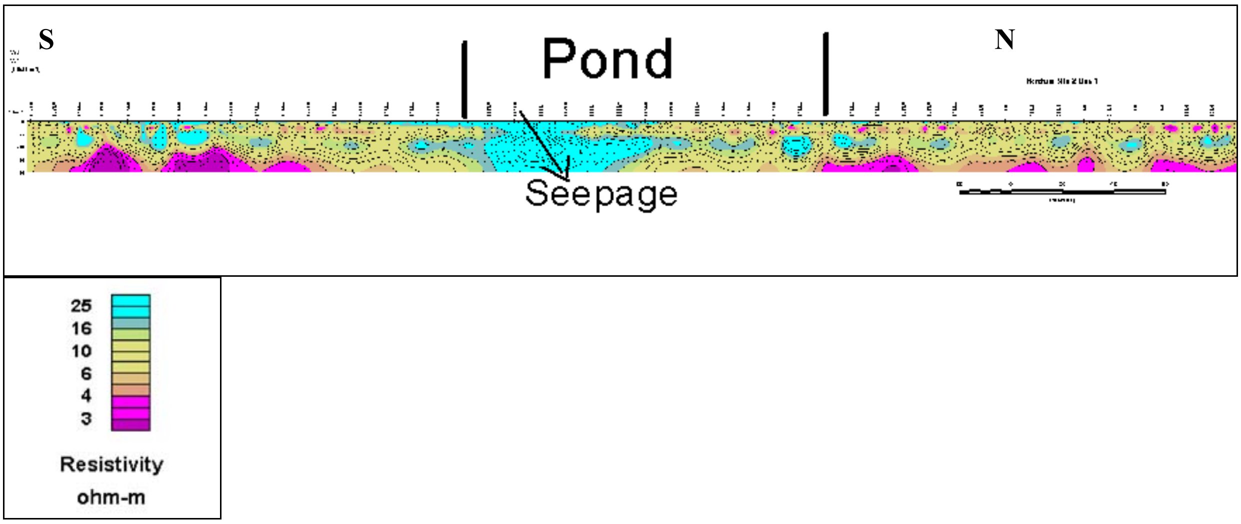
The section (
Figure 5.83) shows a high resistivity zone extending from surface to depth centred in the single 2002 pondage test cell. This pond recorded a relatively high seepage rate, compared to other ponds at the site, of 12 mm/d. A similar feature is present on the

section under pond 1 and 2 from the 2001 pondage tests results, which also recorded high seepage rates (> 10 mm/d).



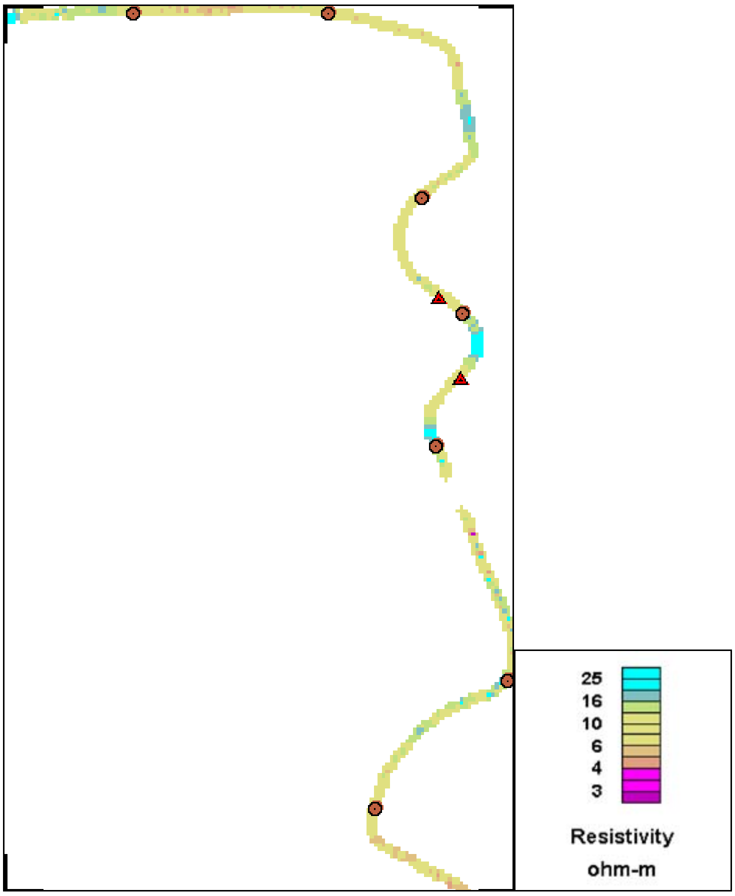
- **Figure 5.82 Plot of resistivity at 14m below surface for section along Toolondo Channel.**

- **Figure 5.83 Resistivity section under Pond 1 (2002 Pondage Tests) at Toolondo Central (Blue = high; red = low). Arrow shows probable seepage zone under pond.**

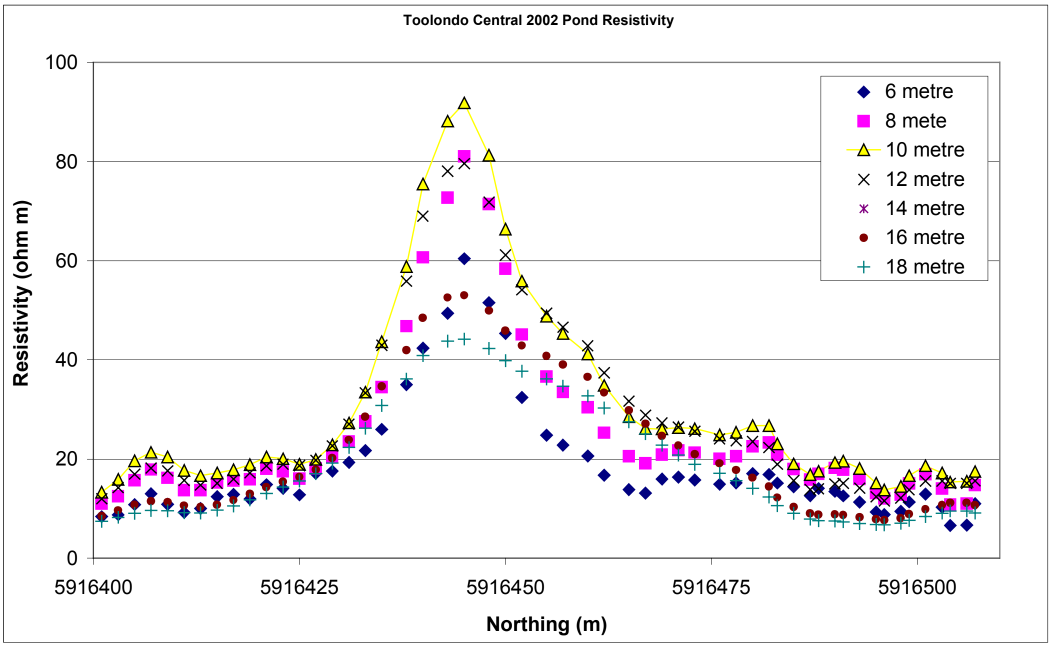


Results from the 6m depth slice are shown in Figure 5-84. These results show a similar pattern of conductivity distribution to the results obtained by the on-channel EM-31 survey conducted in August 2001 (refer 5.3.3.1). The short section of channel sectioned off to form the pond for the 2002 channel seepage test, straddles an area of very high resistivity in the resistivity surveys. This was also detected as a low conductivity feature by the on-channel EM-31 survey in August, 2001 (refer 5.3.3.1). The average resistivity over this section of channel at 14m below surface is 52 ohm metres compared to 11 ohm metres for the whole of the resistivity traverse and 12 ohm metres for the whole traverse section between 6 and 18m depth. Figure 5-85 shows how the resistivity peaks at around 10m below surface which is the top of the saturated zone.

- **Figure 5-84 Depth slice at 6 metres below surface (Toolondo Central)**



■ **Figure 5-85 Resistivity values at various depths beneath the pond created at Toolondo Central in 2002.**



5.4.4.3 Toolondo East

Figure 5-86 presents the change in resistivity with depth at the Toolondo East site, over the pondage test areas. The sandstone which is intersected at 4-5m at this site is actually detected as having a lower resistivity than the overlying clayey sediments. The cause of the low resistivity in the sandstone is not known. The watertable at this site is thought to be greater than ten metres below surface (as per Toolondo West and Central), and therefore cannot explain this decrease. There is very little difference in the resistivity response between the ponds, except for Pond 2, which between 6-10 m is somewhat higher than the other ponds.

Toolondo East site has very low seepage levels and a very narrow range of resistivity values. The differences in both seepage and resistivity values are within the possible error range for both data sets. As such no meaningful correlations were observed between the resistivity and seepage data, as shown in Figure 5.87.

■ **Figure 5-86 Resistivity Versus Depth at Toolondo East**

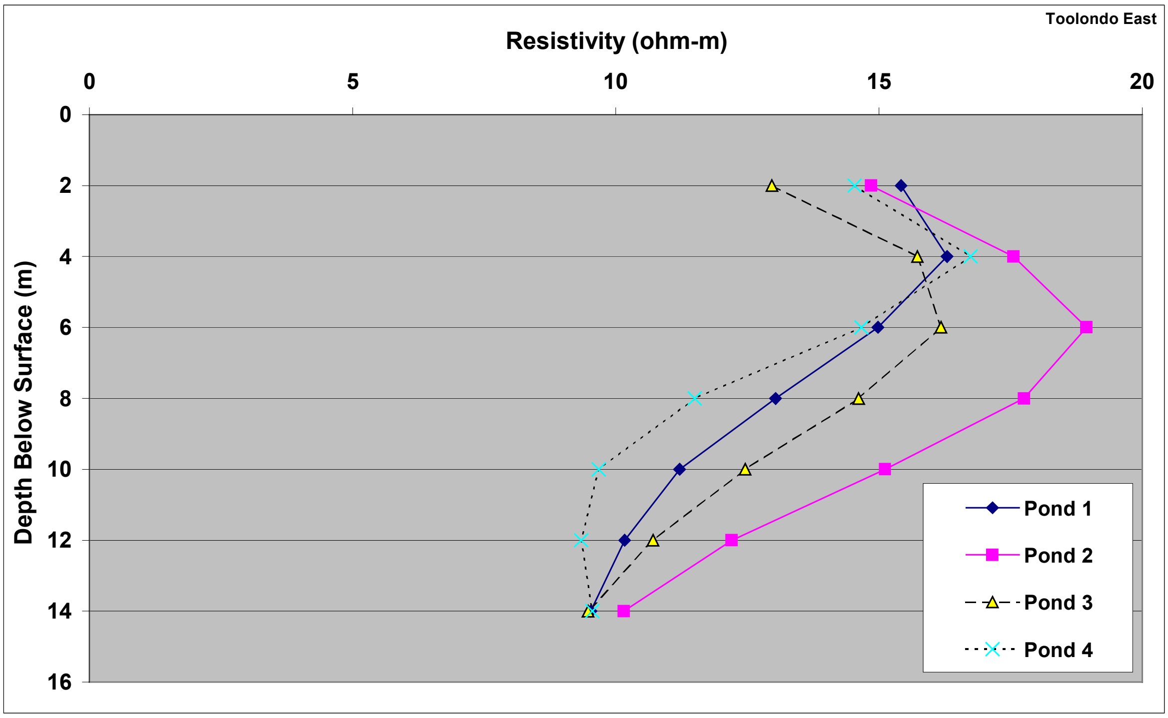
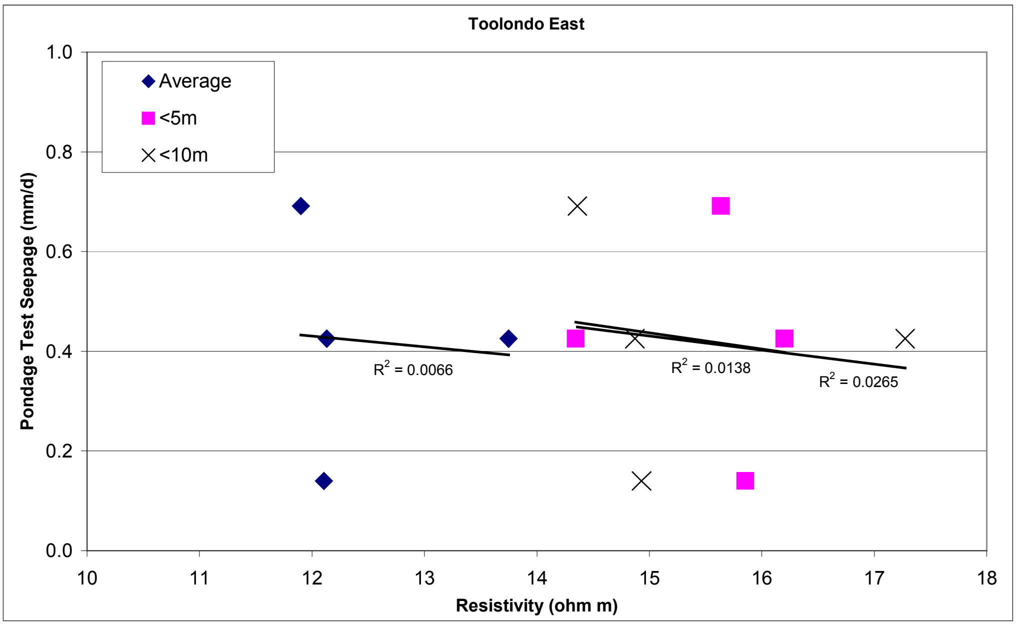
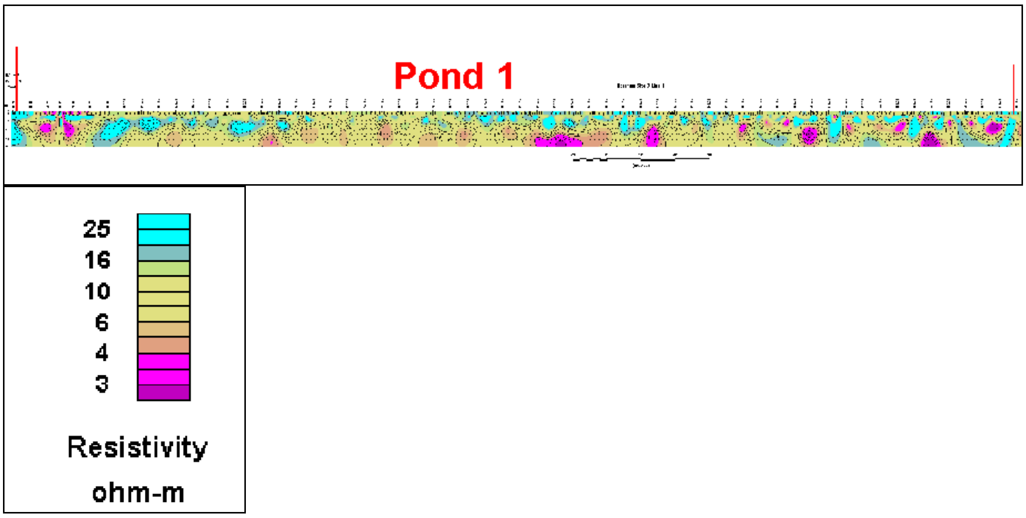


Figure 5.87, Figure 5.88 and Figure 5.89 show the resistivity sections under the channel length corresponding to the pondage sections for Toolondo East. There are no locations that can be immediately interpreted as major seepage zones, such as seen in Figure 5.81 at Toolondo Central. Seepage is minimal at this site, as confirmed by the pondage test results, and from the resistivity sections appears to be relatively evenly distributed within ponds.

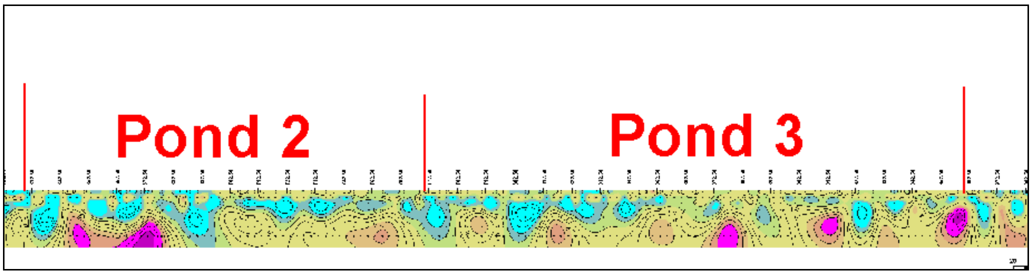
■ **Figure 5.87 Correlation of resistivity and seepage results for Toolondo east.**



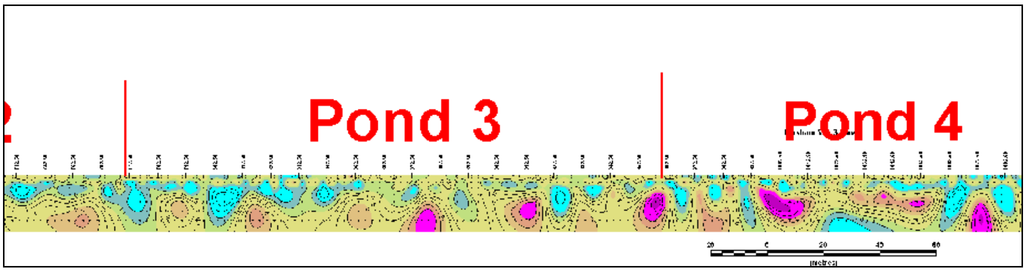
■ **Figure 5.88 Resistivity section for pond 1, Toolondo East.**



■ **Figure 5.89 Resistivity section for ponds 2 and 3 Toolondo east**



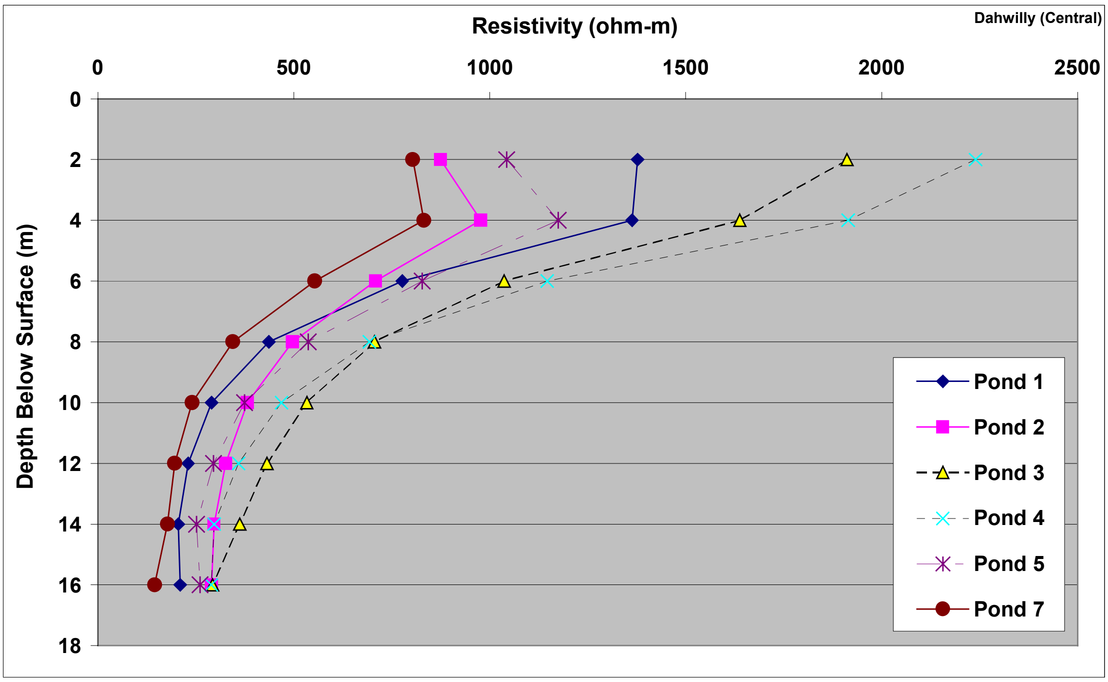
■ **Figure 5.90 Resistivity section for pond 3 and 4 Toolondo East**



5.4.4.4 Dahwilly Central

Resistivity surveys were conducted along 2 km of the Dahwilly Channel (Central site) and pondage tests conducted over approximately the western half of the surveyed channel. Figure 5.92 presents the change in resistivity with depth at the site, over the pondage test areas. This figure shows a highly resistive unsaturated zone beneath the channel, with a sharp drop in resistivity at the watertable, which is located around 5m. With increasing depth below the watertable the resistivity continues to decline as the fresher channel water is increasingly diluted. At around 16m it appears that natural background resistivity conditions are reached (approximately 140 ohm-m). Note that the resistivity values are significantly higher than at the Wimmera sites. This is attributable to the more coarse and 'clean' (ie relatively clay free) sands at the site. These have a much lower conductivity than the clayey sediments at Toolondo.

■ **Figure 5-91 Resistivity Versus Depth at Dahwilly Central**



The Dahwilly Central site includes two sections of channel which were remediated; one section with a plastic liner and the other with a rubber compound. The liners were tested in two separate pondage tests, 2.6 and 2.7. Figure 5.92 shows the resistivity sections from these ponds.

The liner in pond 2.6 is more resistive to electrical current flow. The shape of the resistivity response seen in the section is governed by the shape of the pond liner, with apparently high resistance underlying a thin conductive layer, as all the current is concentrated in the channel water. The ends of the liner area are characterised by conductivity anomalies extending from the surface. These anomalies are caused by the fact that the current is confined to the surface above the liner and by effects related to the asymmetry of the resistivity array. *This pond was therefore removed from the correlation analysis because of these effects on the resistivity*.

In pond 2.7 the liner appears relatively transparent to electrical current and shows a more saline water table at depths of 8 to 10 metres below surface which corresponds with groundwater reported from bores of 6 to 7 metres. The section under pond 2.7 possibly represents more 'natural' (ie, without channel) conditions compared to other parts of the section. Only minor seepage was reported from both the lined ponds (1.1 mm/d for pond 6 and 2.8 mm/d for pond 7). Possible seepage zones are marked by 'S' on the section. These appear to be minor compared to the effects further to east along this channel.

■ **Figure 5.92 Resistivity Sections Below Lined Ponds at Dahwilly Central. Sections over ponds 2.7 and pond 2.6 show different effects due to the pond liners. (The liner beneath pond 6 interfered with the survey and therefore the results were discarded)**

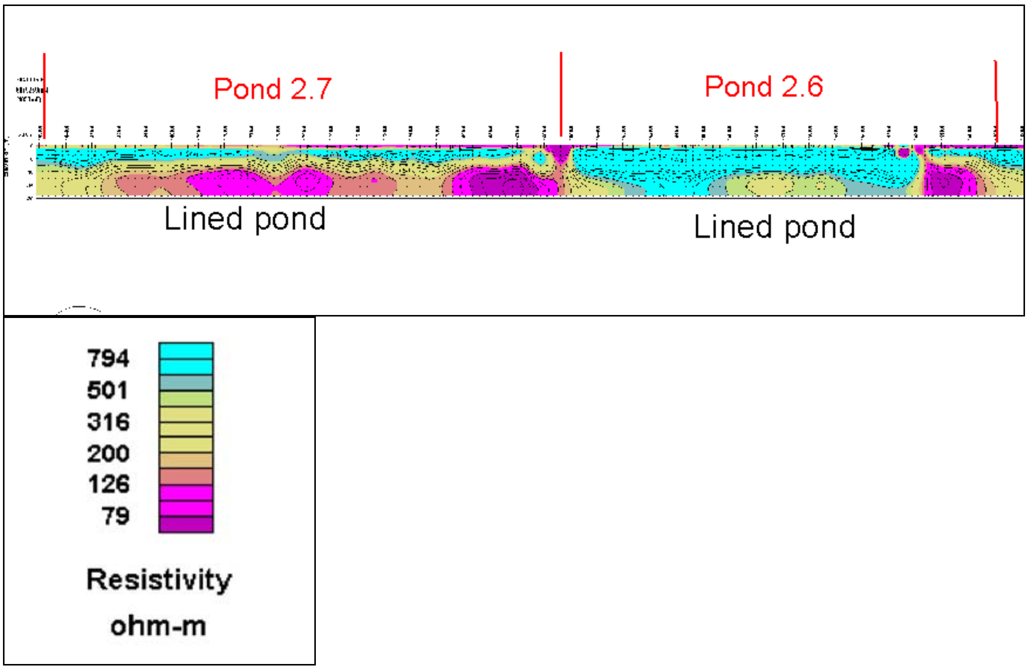
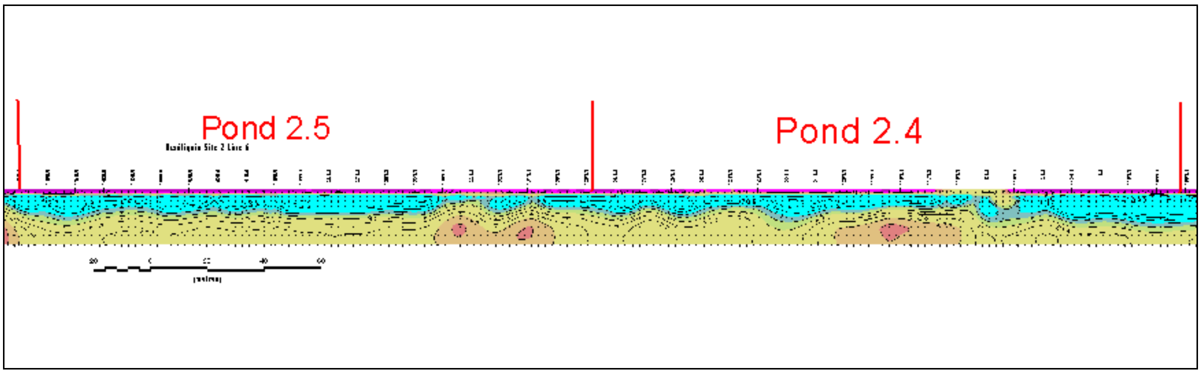


Figure 5.93 shows that the resistivity under ponds 2.5 and 2.4 at Dahwilly Central are significantly higher than under the lined, low-seepage pond 2.7. (This is also clearly illustrated in Figure 5-91). The change in the profile at depth is most obvious in comparing Figure 5.92 and Figure 5.93; note the (pink) low resistance results at depth beneath pond 7 compared to the (yellow-brown) higher resistance results beneath ponds 1-5. This is due to dilution of the more saline groundwater by the seeped

■ **Figure 5.93 Resistivity sections under ponds 2.5 and 2.4 at Dahwilly Central. Refer Figure 5-92 for resistivity legend**



(fresher) channel water which is more resistive. It appears that the seepage mechanism is by relatively continuous diffusion along the channel, in contrast to the more isolated seepage paths observed on the Toolondo channel. This seepage mechanism is also suggested by the lithology at the site, which indicates the entire length of channel surveyed is underlain by approximately 10m of medium to coarse grained sand, and is more likely to result in uniform seepage rather than seepage 'hotspots'. Ponds 1-5 have seepage rates around 4 times that of pond 2.7, with an average resistivity of around 275 +/- 15 ohm metres, compared to 145 ohm metres for pond 2.7.

■ **Figure 5.94 Resistivity sections under Dahwilly Central ponds 2.4 and part of 2.3. See Figure 5.92 for resistivity legend**

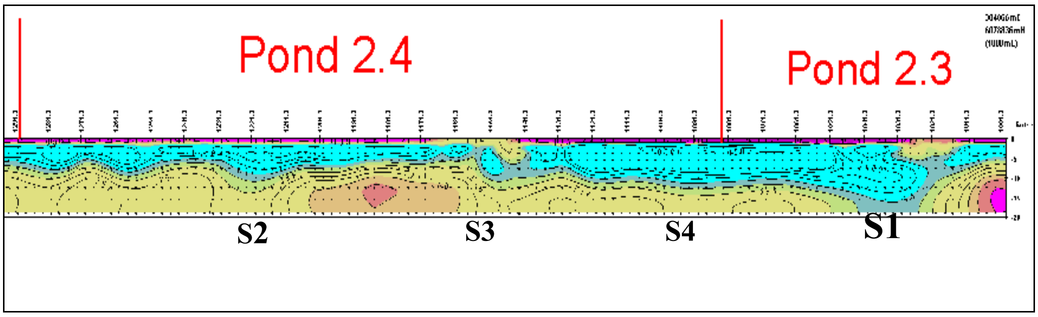


Figure 5.94 shows possible localised seepage zones, as indicated in the resistivity sections under ponds 2.4 and part of 2.3. This site should be compared with pond 7 (Figure 5.92) where there is very low seepage. Overall, resistivity is higher for these ponds. In particular, under pond 2.3 there is a short section where resistivity is significantly higher than the rest of the section (**S1**). This high localised resistivity zone may reflect the higher seepage for this section. Further minor local seepage may be located at **S2**, **S3** and **S4**. The surface and deepest sections are relatively uniform and the greatest deviation is at S1 where the shallow higher resistivity water appears to change the resistivity of the underlying section to a greater depth into the unsaturated zone.

■ **Figure 5.95 Resistivity section under ponds 2.1 to 2.3 at Dahwilly Central. See figure 4.1 for legend of resistivity values.**

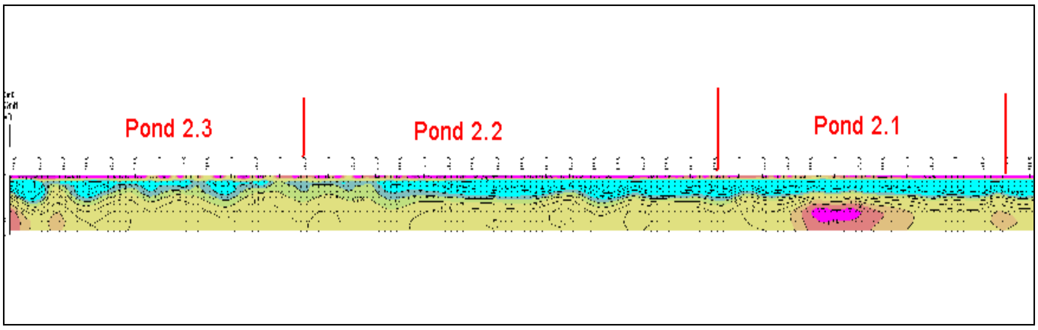
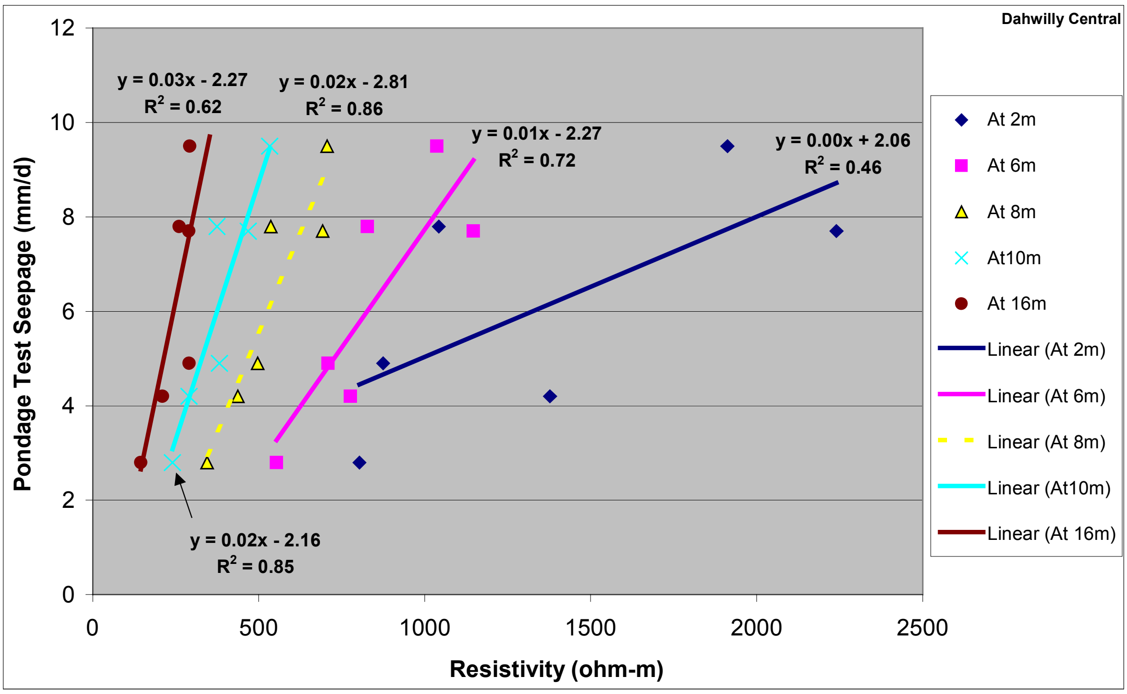


Figure 5.95 shows a relatively uniform resistivity section stretching from pond 2.1 to the eastern part of pond 2.3. Ponds 2.1 and 2.2 have very similar seepage rates (4-5 mm/d), whereas pond 2.3, with the high resistivity zone suggests significantly higher seepage, as confirmed by the pondage test result of 9.5 mm/d.

Plots of pondage test seepage rate against resistivity at various depths within the profile are shown in Figure 5.96. The increasingly improved correlation with depth, peaking immediately below the watertable can be seen at the 8m and 10m depth slices where the seeped water has diluted the saltier background water. At greater depth within the profile (16m), conditions trend towards background groundwater conditions due to dilution and mixing. Therefore there is less distinction between different seepage rate ponds at these depths.

■ **Figure 5.96 Correlations of average resistivity values of sections under ponds for Dahwilly Central**



5.4.4.5 Dahwilly East (Pretty Pine)

Resistivity surveys were conducted along 1.2 km of the Dahwilly Channel at Pretty Pine, about 5km to the east of the Dahwilly central site. Pondage tests were conducted on the western half of the surveyed channel.

Figure 5-97 presents the change in resistivity with depth at the site, over the pondage test areas. This figure shows an increasingly resistive unsaturated zone beneath the channel, with a sharp drop in resistivity at the watertable, which is located around 6m. As at other sites, with increasing depth below the watertable the resistivity continues to decline as the fresher channel water is increasingly diluted. Natural background resistivity conditions may not have been reached at 14m as indicated by the still increasing gradient of the curves between 12m to 14m.

Note that the resistivities are significantly lower than at the Dahwilly central site. This is attributable to the finer grain size and more clayey sands at this site compared to the coarser and 'clean' (ie relatively clay free) sands at the Dahwilly central site. At depth below the watertable however, resistivity values between the two sites are comparable.

■ **Figure 5-97 Resistivity Versus Depth at Dahwilly East**

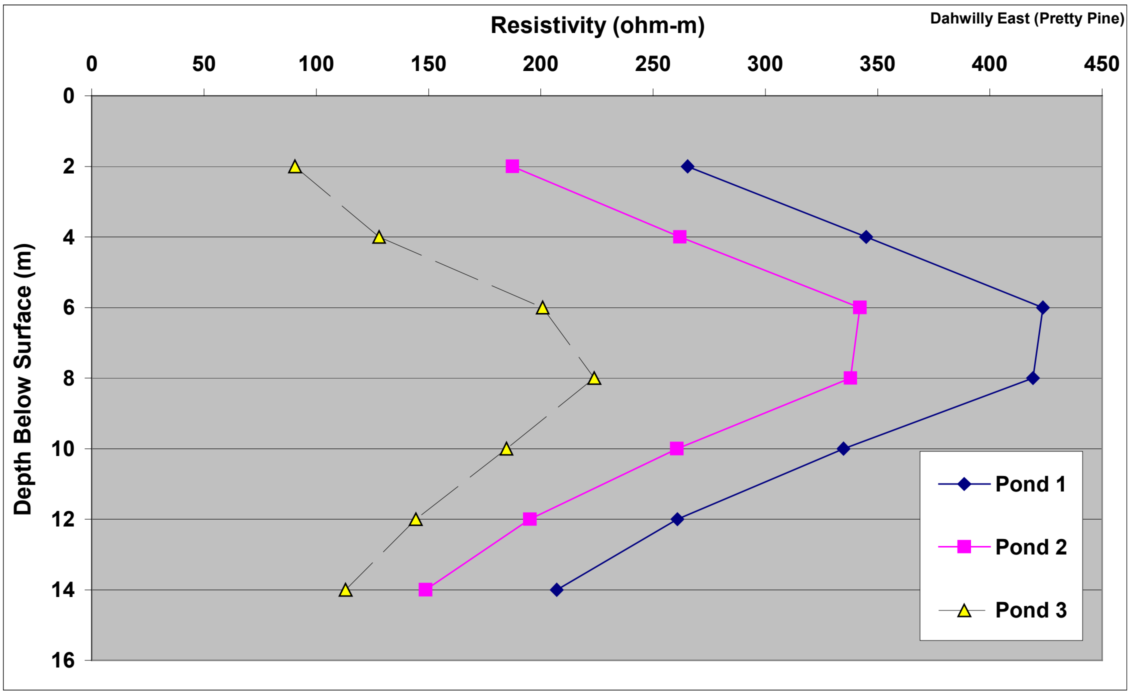
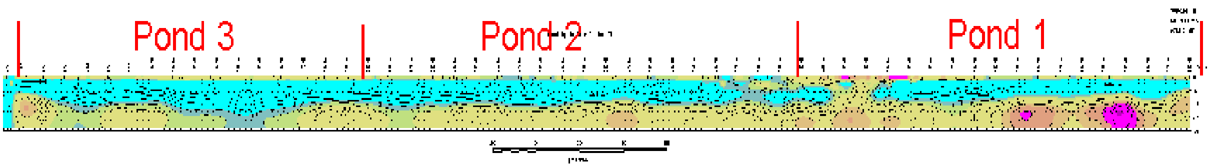
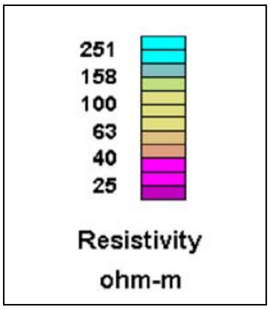


Figure 5.98 shows the resistivity section across the surveyed section is relatively uniform. The section shows a thin conductive surface layer overlying a thick (8-10m) unsaturated zone of higher resistivity above a more conductive layer at depth (due to more saline groundwater). This interpretation is confirmed by the geological long section of the site (refer *Appendix* A) which shows approximately 1.5m of clay to sand clay, overlying sand to clayey sand, to at least 10m. The resistivity section also appears to detect the presence of the clayey sand profile (compared to clean sand) in the western end of pond 1, as indicated by the absence of the high resistance upper layer at this location in Figure 5.98. The section shows a zone of probable higher

seepage on pond 3 and areas of probable lower seepage showing as low resistivity on pond 1.

■ **Figure 5.98 resistivity section from Pretty Pine section of Dahwilly Channel**





■ **Figure 5.99 Correlation of seepage and resistivity from ponds at Pretty Pine**

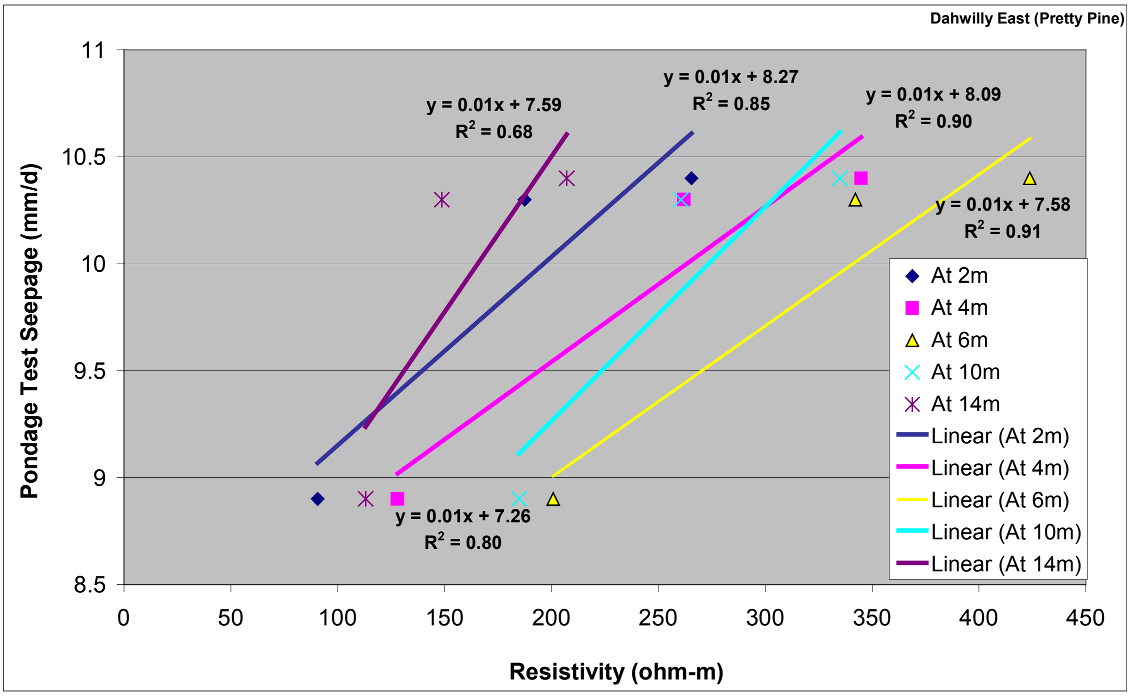


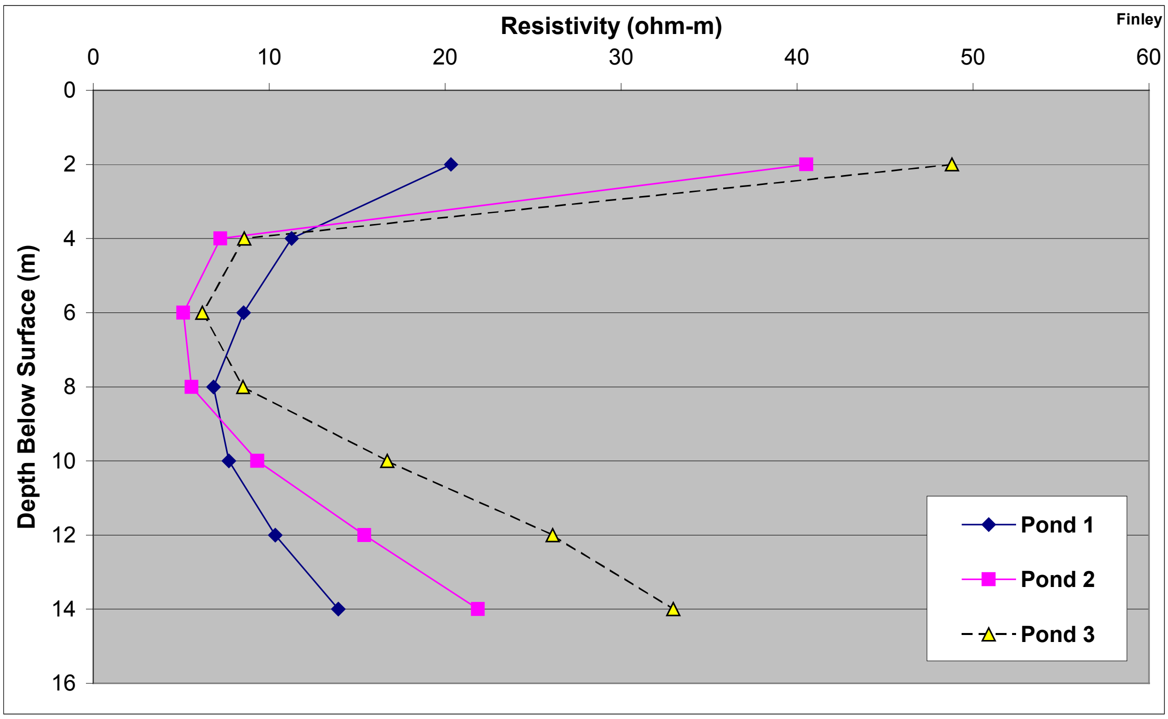
Figure 5.99 shows a good correlation of seepage versus average resistivity for the three ponds at Pretty Pine. However, there is only a narrow range of values for seepage. The best correlation is obtained using only resistivity values from the 6m depth slice. The correlation is less favourable using data from deeper than 10m.

At Pretty Pine the influence of seepage is best seen in the resistivity data at the watertable or within the top few metres of the watertable. Resistivity data from deeper in the section appears to be less affected by seepage. This may be due to the fact that at around 8m, the profile becomes slightly clayey (clayey sand) which may limit vertical migration of seepage into the aquifer. Limited emphasis should be placed on these correlations due to the small number of ponds at the site.

5.4.4.6 Finley

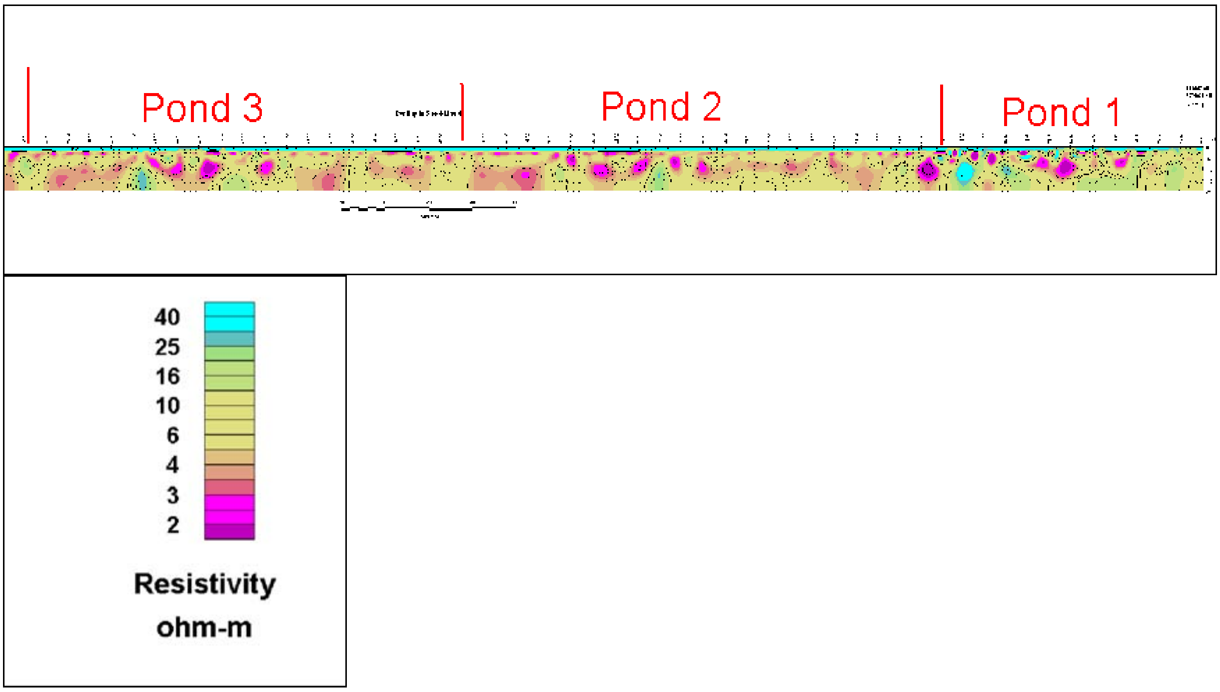
A short section of channel at Finley was surveyed using resistivity profiling covering the pondage test lengths. A plot of resistivity versus depth for the site is presented in Figure 5.101. The upper two metres contains a layer of higher resistivity, most likely caused by shallow seepage into the shallow watertable. There appears to be relatively little seepage impact below 2m with resistivity rapidly dropping at 4m. The resistivity values of between 5-10 ohm-m within the 4 – 10m depth range are among the lowest readings recorded across all of the sites and are due to the very heavy clays and highly saline groundwater at the site (comparable values also observed at Lake View). Between 8 and 10m the resistivity begins to increase again which reflects a change in lithology at this depth from a heavy clay to a sandy clay (refer to Finley Long Section in *Appendix* A).

- **Figure 5-100 Resistivity Versus Depth at Finley**



The resistivity section in Figure 5.101 also shows that the resistivity at the Finley site is much lower than all other sites surveyed. Possible impact on the groundwater is only evident along the surface and at depth on the west end of pond 1. There is also a narrow range of seepage values recorded across the three ponds. The results suggest that the high clay levels at the site are preventing seepage from diffusing into the groundwater except in more permeable narrow zones such as the west end of Pond 1. Most of the seepage is in lateral surface flow.

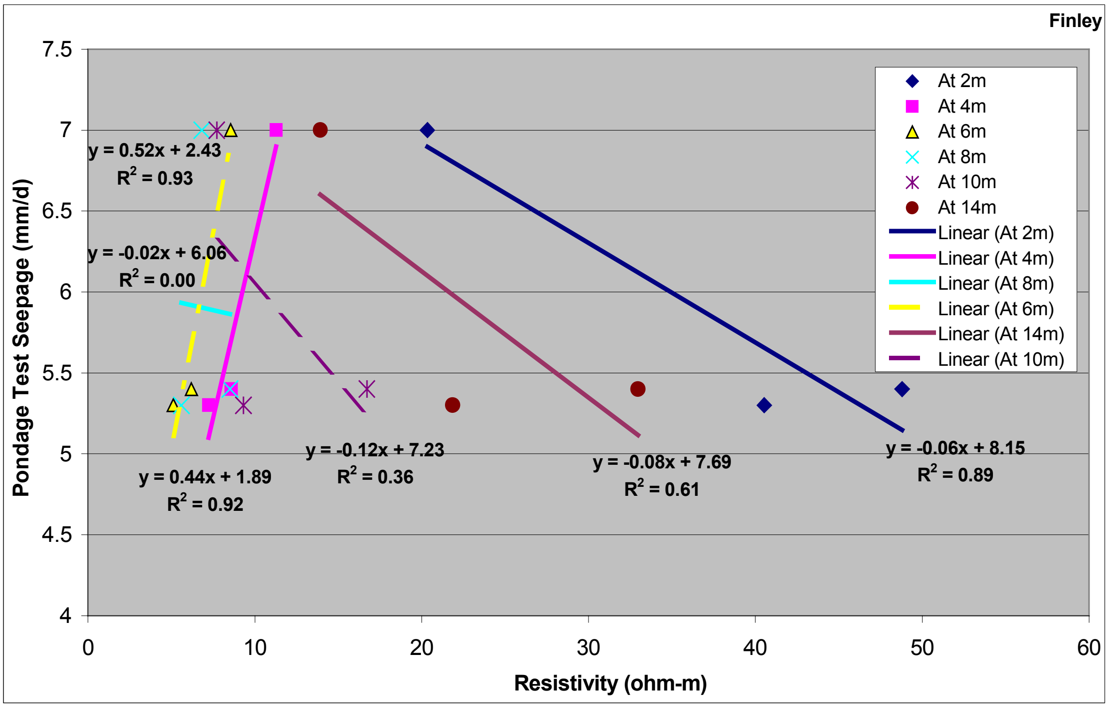
■ **Figure 5.101 Resistivity section at Finley**



The average of the inverted resistivity sections is plotted against pondage seepage tests and presented in Figure 5.102. This figure shows that the best correlations were obtained in the 4m to 6m range. The shallowest resistivity values at 2m have a reverse correlation. It might have been expected that the better correlations would have been obtained at 2m, given that seepage at this site is predominantly shallow and migrates laterally. However this result may be a reflection of the data processing and the fact that the 5m array did not resolve the surface resistivity very well. The fact that a reasonable correlation was obtained at 4m suggests some seepage impact into the watertable.

However, the very narrow spread of seepage values (5.5 – 7 mm/d) at this site limits the conclusions that can be drawn from this analysis. Note that only resistivity values for the western 140m of pond 1 were collected (35m of data was missed on the eastern end of the pond). It was assumed that this did not affect the analysis.

■ **Figure 5.102 Pondage Test Seepage Versus Resistivity at Finley**



5.4.4.7 Lake View Central

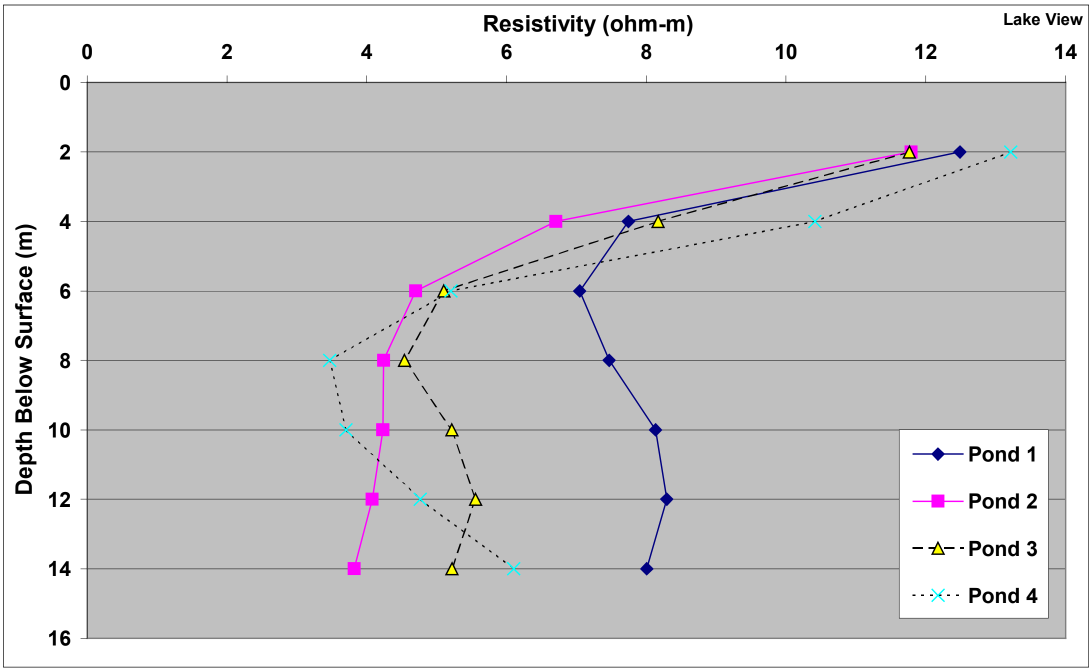
A resistivity survey was conducted along a 2 km section of the Lake View (Central) channel site.
Figure 5.105 presents the change in resistivity with depth at the site, over the pondage test areas. As per the Finley site, the upper two metres contains a layer of higher resistivity, due to seepage into the shallow watertable (approximately 1.5m). The curves suggest that seepage has impacted up to 6m within the profile. Below 6m the resistivity remains reasonably constant, suggesting little seepage impact below this depth and values probably reflect saturated background resistivity conditions.

Figure 5.104 shows the resistivity results plotted against pondage seepage at the Lake View (Central) channel site. The best relationships between resistivity and seepage are achieved using resistivity data from 6m to 8m depth. There is essentially no relationship observed for the 2m and 4m data which might be expected given the shallow watertable at this site. As stated in the Finley section this may well be a reflection of the data processing and subsequent poor resolution of near surface resistivities.

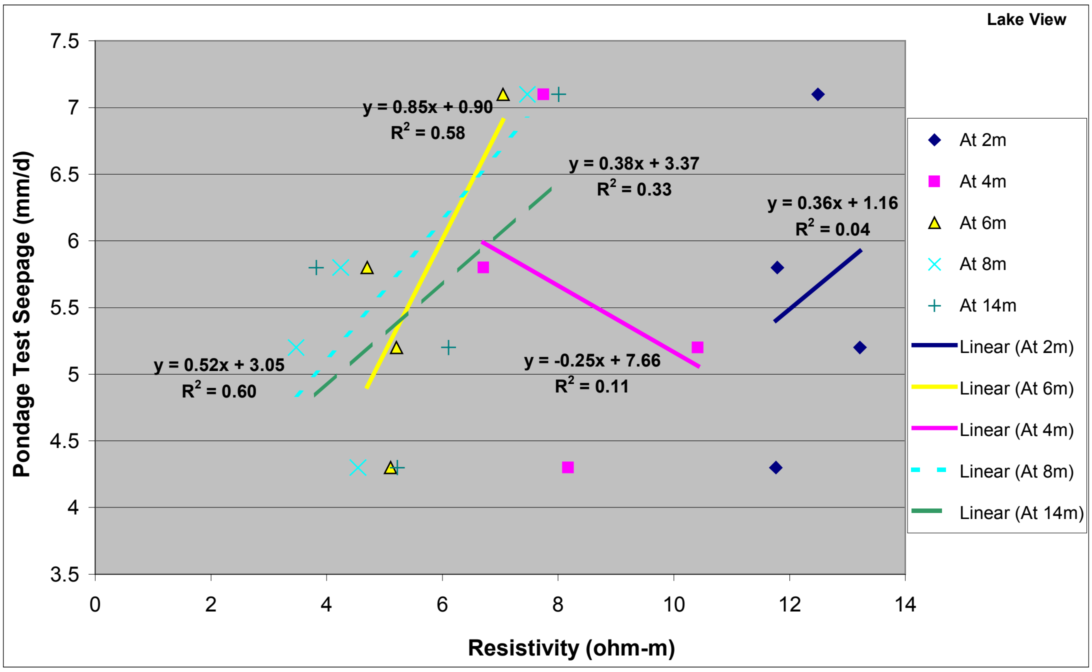
The fact that reasonable correlations were observed for 6 – 8m may also be explained by the site lithology, as much as seepage impacts on the groundwater. This site has a heavy clay starting between 3-8m below surface. Beneath Pond 1 (which contains the highest seepage) the medium to heavy clay starts at 8m depth, compared to Ponds 2-4, where the heavy clay occurs between 2m and 3m from the surface (refer Lake View geological long section, *Appendix* A). Therefore seepage appears to be greatest in

ponds with higher resistivity within clayey sediments, possibly corresponding to sandier sections. The resistivity sections for the site (
Figure 5.105, Figure 5.106 and Figure 5.107) show that there are probable localised seepage paths under pond 1 and to a lesser extent under pond 4, extending to depth. A less well defined potential path under pond 2 is also indicated. For localised seepage paths within large ponds the results are less likely to correlate well, due to the bulk averaging of the resistivity across the entire pond.

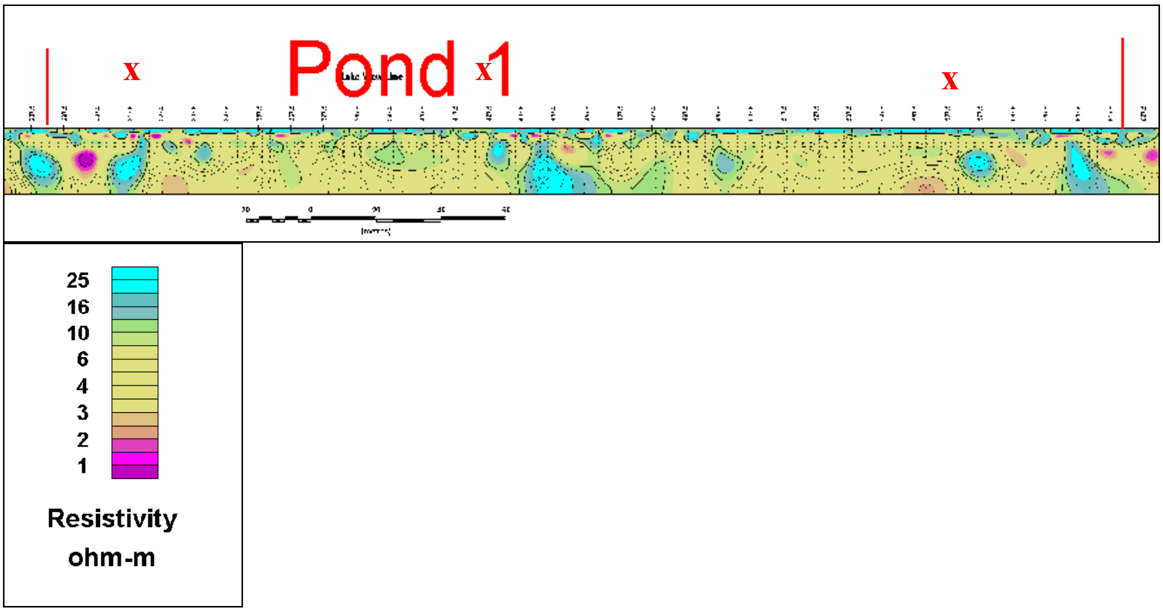
■ **Figure 5-103 Resistivity Versus Depth At Lake View (central) Channel**



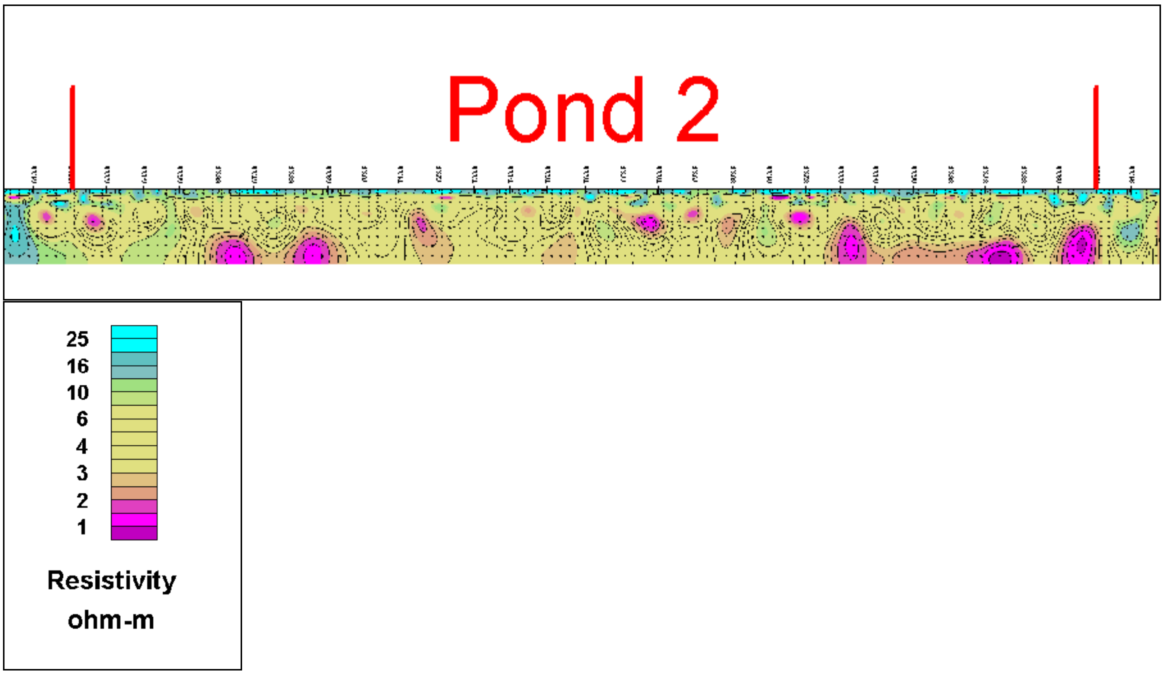
■ **Figure 5.104 Correlation of resistivity with pondage leakage tests for the Lake View (original) test site.**



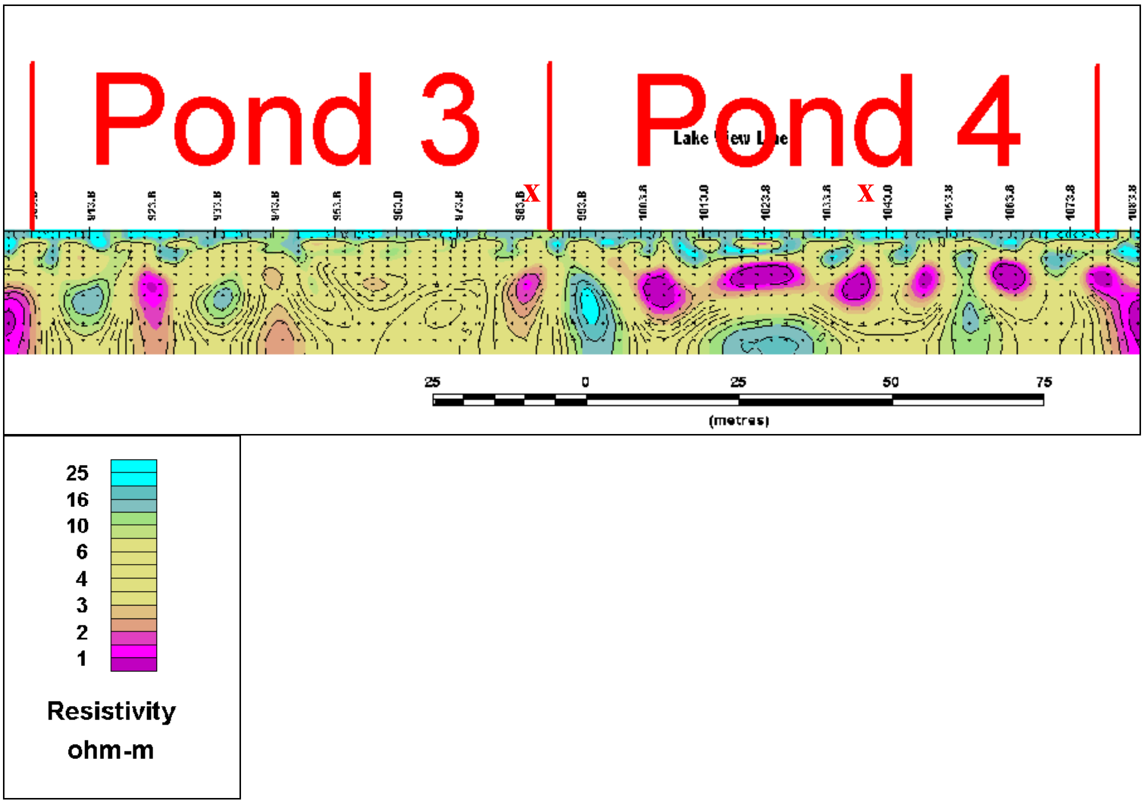
■ **Figure 5.105 Resistivity section under Pond 1 (Possible seepage paths at points marked X; Pond is 270m long)**



■ **Figure 5.106 Resistivity section for Pond 2 at Lake View (original). (Possible seepage paths at points marked X; pond is 280m long)**



■ **Figure 5.107 Resistivity section for ponds 3 and 4 at Lake View (Original) (Possible seepage paths at points marked X; ponds are 80m long)**

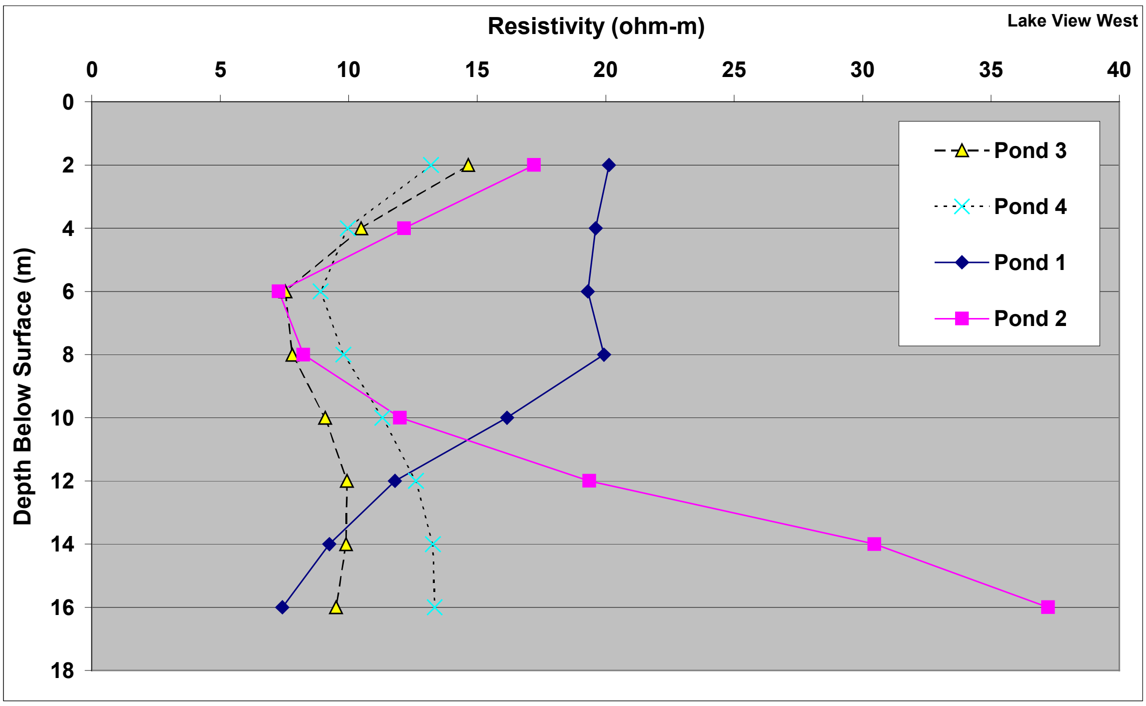


5.4.4.8 Lake View West

A resistivity survey was conducted along a 2km section of the Lake View West channel. Figure 5-108 presents the change in resistivity with depth at the site, over the pondage test areas. The response is reasonably similar to the Lake View (central) site. Depth to watertable at the site is shallow at around 0.5 - 1.5m. As at Lake View (central), the upper part of the profile contains a layer of higher resistivity, due to seepage into the shallow watertable. The resistivities are higher in this upper zone compared to Lake View (central) probably due to the higher seepage rates at Lake View west and greater dilution of the salty groundwater. The curves suggest that seepage has impacted up to 6m within the profile.

For Ponds 3 and Pond 4 the resistivity remains reasonably constant (below 6-8m), suggesting little seepage impact below this depth and values probably reflecting saturated background resistivity conditions. The resistivity below 8m in Pond 1 declines rapidly, back to background levels similar to those observed in Pond 3 and Pond 4. In pond 2 the resistivity significantly increases below 10m, with a value of 37 ohm-m at 16m, compared to around 10 ohm-m for the remaining three ponds. This response is most likely related to a geological anomaly beneath this pond. Drilling at the site was only conducted to 10m however and this cannot be confirmed. At this site lithology changes at this depth are unlikely to impact on seepage in any case.

■ **Figure 5-108 Resistivity Versus Depth at Lake View West**



■ **Figure 5.109 Correlation of resistivity and seepage rates for Lake View West Site**

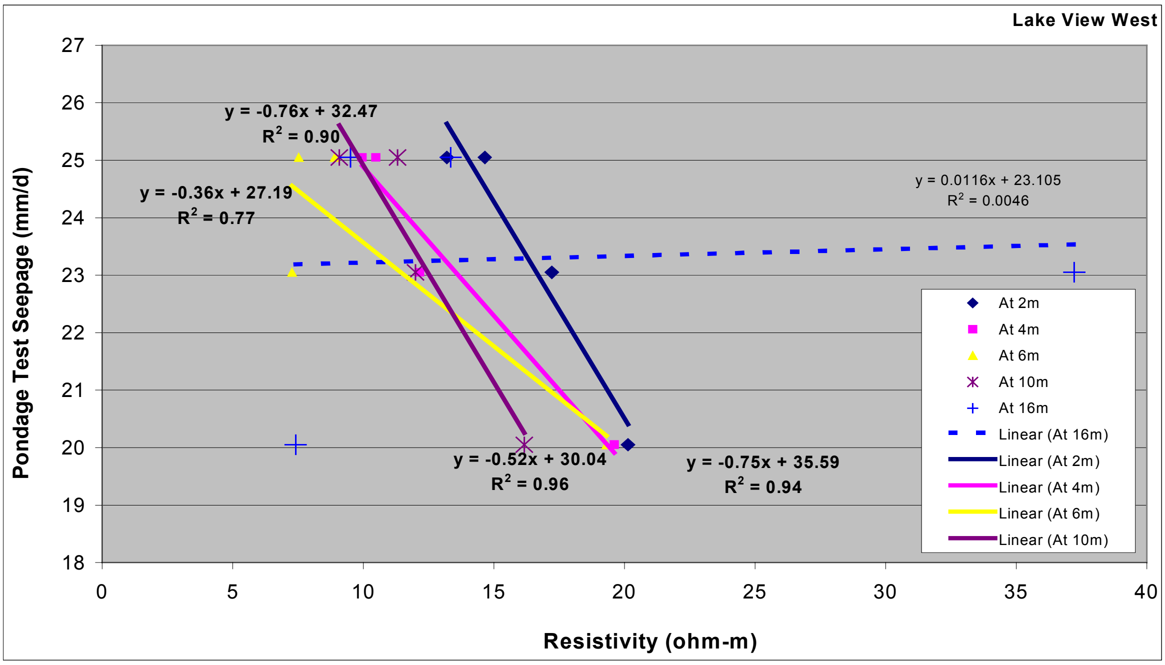


Figure 5.109 shows the resistivity results plotted against pondage seepage at the Lake View West site. All ponds at this site returned high seepage rates. Figure 5.109 shows negative correlations (ie high resistivity equating to low seepage) compared to those detected at other sites. This is largely attributable however to the high resistivity values at Pond 1. The anomalous behaviour of Pond 1 (compared to remaining ponds) is clearly illustrated in Figure 5-108, displaying opposite trends with depth. It would be expected that the best and positive trends would be observed in the 2-4m range, based on the fresh seepage into the shallow watertable aquifer and the fact that it appears that most of the seepage is confined to the upper part of this aquifer. The fact that such a trend was not observed in the resistivity data, but was observed in the EM31 survey conducted at the site (refer Figure 5.64) again suggests that for shallow readings the resistivity resolution may have been unsatisfactory. The wide spread of resistivities at depth is caused by the anomalous readings at depth in Pond 2.

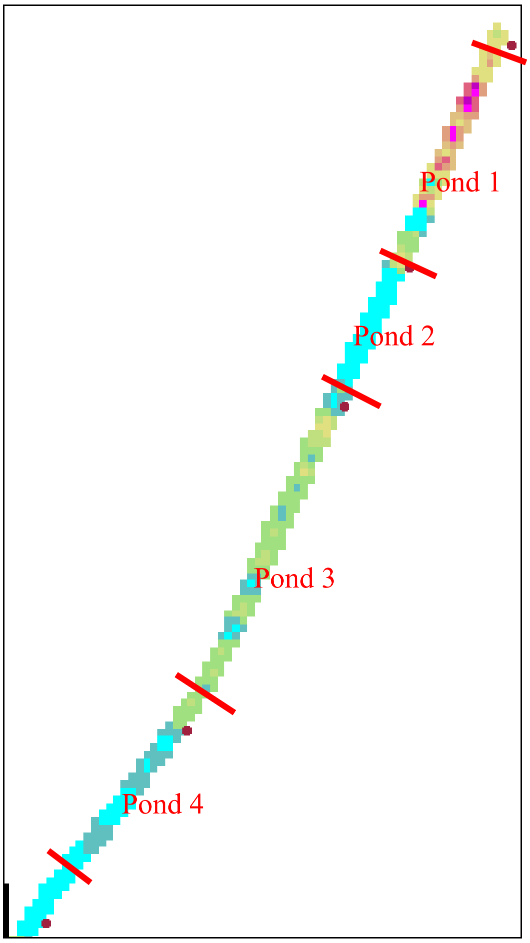
In summary, the lack of a meaningful relationship between resistivity and seepage at this site is attributed to:

- Poor resolution of near surface data by the resistivity array (this is supported by the fact that the EM31 recorded a sensible correlation at this site);
- The ‘anomalous’ result in pond 1. Something at depth (presumably a dramatic change in lithology, although this is not detected in the logs) is causing elevated resistivities relative to other ponds; and,
- The narrow spread of seepage data (20 – 25 mm/d).

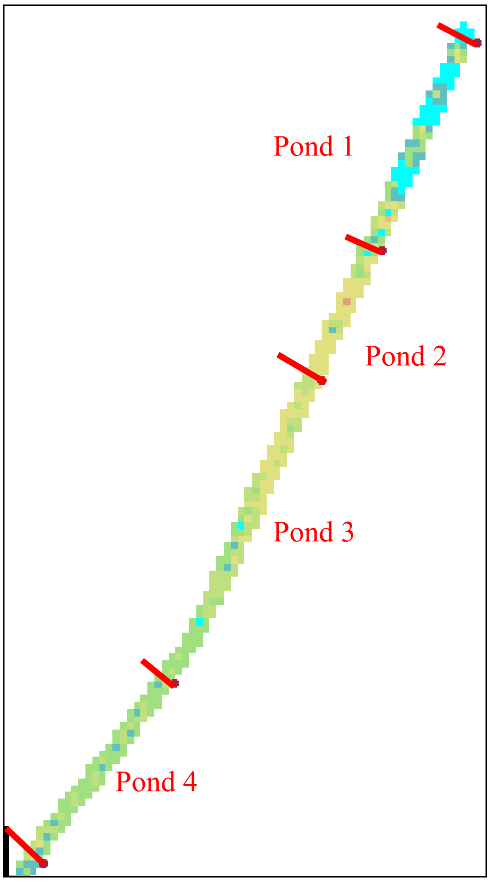
It is not certain the relative contribution each of these factors makes to the overall poor relationship.

Figure 5.110 shows a depth slice of the resistivity at 18m below surface and Figure 5.111 shows the resistivity at 6m below surface. The difference between the two depths is particularly clear for ponds 2 and 4 which both display an increase in resistivity at depth (pond 3 also does but not to the same extent). This suggests a layer of higher permeability may be located at depth. Seepage from the base of the channel appears to be moving laterally in the upper part of the profile but not penetrating to depth. The high resistivity in the near surface and lower seepage rate observed at Pond 1 may be due to a near surface layer of low permeability and porosity, although this is not clearly demonstrated from the logging.

■ **Figure 5.110 Resistivity depth slice at 18m below surface (red is low, yellow moderate and blue high resistivity)**



■ **Figure 5.111 Resistivity at depth of 6m below the channel (red is low, yellow - moderate and blue high resistivity)**



5.4.5 Extrapolation at each Channel

For each of the channels where resistivity surveys were conducted several kilometres apart (Toolondo, Dahwilly and Lake View) this section looks at the accuracy of extrapolation from one site to another, which was one of the key aims of the year three trials.

5.4.5.1 Toolondo

Three sites were trialed at Toolondo channel, all within about 13km of each other:

- Toolondo Central – The original site on which previous years trials had been conducted.
- Toolondo West – Similar to Toolondo Central in terms of geology and hydrogeology.
- Toolondo East – Change in surface soil type compared to Toolondo Central and West: heavy to medium grey cracking clays, compared to weathered sandstone profiles at Toolondo Central and West. Similar geology at depth, however with sandstone at 3-4m.

■ **Figure 5-112 Pondage Test Seepage Versus Resistivity at All Toolondo Sites**

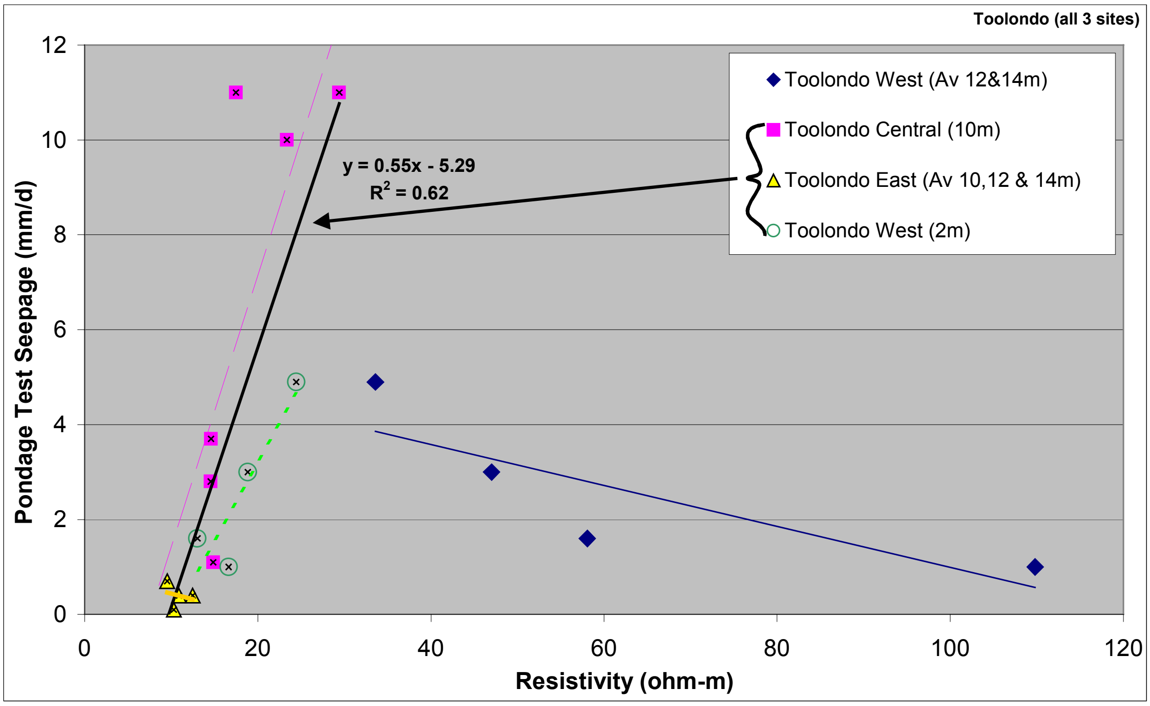


Figure 5-112 plots all of the regression trend lines for the three Toolondo sites. A depth slice or average of depth slices has been selected from just below the watertable, which is between 10-14m across all of the sites. The following observations are made regarding this plot:

- It can immediately be seen that Toolondo East is measured across such a narrow seepage and resistivity range that no meaningful trend can be obtained from it. However, as a collection of points it does lie within the expected range for the Toolondo Central site;
- The Toolondo West trend line does not fit within the Toolondo Central and Toolondo East relationship, and displays an inverse relationship between seepage and resistivity. The possible reasons for this are discussed in Section 5.4.4.1. It is apparent that the effects of seepage on the watertable (which would cause a increase in resistivity) are being masked by the particular lithology of the site. A possible explanation is that the sandstone is much more cemented at this site and this reduced porosity (which will show as an increase in resistivity) may dominate the response. Porosity may be directly related to permeability and thus areas with highest resistivity at depth have lowest seepage.
- A plot of the Toolondo West trend line for the 2m depth slice is shown. This fits reasonably well with the Toolondo Central and East data. In fact the heavy line in this plot is the trend line for the Toolondo Central, East and West (2m depth slice data) sites which results in a reasonable correlation coefficient of 0.62. Section 5.4.4.1 explains that the observed good correlation at 2m is probably due to detection of changes in clay content in the near surface, and does not rely on mapping the seepage plume itself. In practice, without the pondage tests, it could not be known that the upper profile was a better depth to concentrate on than the

section immediately below the watertable, which makes this observation somewhat academic.

The overall conclusion regarding extrapolation from these sites is that if the Toolondo Central data had been used to predict seepage rates at the Toolondo West site, seepage would have been greatly overestimated. This is due to the fact that seepage does not appear to be having an impact on groundwater salinity below the watertable, possibly due to differences in the nature of the sandstone at the Toolondo West site (greater cementing equals reduced porosity which equals higher resistivity but lower seepage), which masks any seepage impacts. This highlights the dangers of extrapolation, even in environments which on the surface and according to available information appeared geologically similar and are quite close to each other (within 5 km). This suggests that interpolation rather than extrapolation is a safer means of using pondage tests in investigations along large reaches of channel.

5.4.5.2 Dahwilly

Two sites were trialed on the Dahwilly channel, approximately 6-7 km apart:

- Dahwilly Central – The original site on which previous years trials had been conducted.
- Dahwilly East – Similar to Dahwilly central in terms of geology and hydrogeology.

■ **Figure 5-113 Pondage Test Seepage Versus Resistivity at Dahwilly Sites**

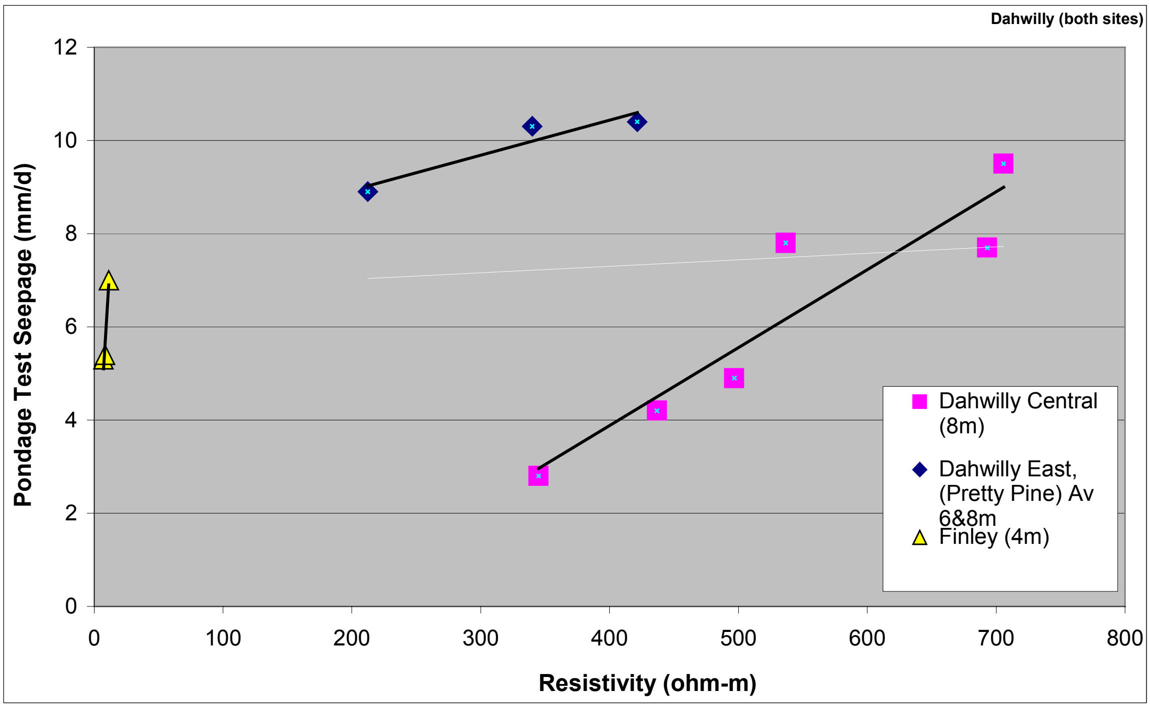


Figure 5-113 plots the regression trend lines for two Dahwilly sites. Finley (the third site tested within Murray Irrigation) is also included for comparison purposes. For the two Dahwilly sites, resistivity depth slices were selected from just below the watertable, which is around 5-6m depth. The following observations are made regarding this plot:

- Two very different trend lines for the two Dahwilly sites are observed. The regression trend line for the combined data set (light line) essentially has a correlation coefficient of zero, indicating no trend between the two sites. Within each site however a reasonable correlation is observed and the trend lines display similar gradients. These results suggest different background conditions at the two sites, despite the apparent similarities of the sub-surface conditions. For the seepage rates observed at Dahwilly East, for the data to fit with the Dahwilly Central site, much higher resistivities would need to be recorded. The lower than 'expected' resistivities at Dahwilly East are most likely explained by the finer sands at this site and the more clayey profile, particularly below the watertable. The sands at the Dahwilly Central Site are very coarse and relatively clay free. The other possible explanation is that the background groundwater at the Dahwilly East site is of higher salinity. The available background information suggests this is not the case (refer Table 5-1), but may not be based on bores close to the site.
- In terms of extrapolating relationships from one site to another, this confirms the outcomes from the Toolondo site – that relationships between resistivity and seepage can change over relatively short distances, even when available information suggests the environments are reasonably similar, and therefore extrapolation without pondage tests is dangerous. The overall conclusion regarding extrapolation from these sites is that if the Toolondo Central resistivity data had been used to predict seepage rates at the Toolondo West site, seepage would have been greatly underestimated at less than 4 mm/d, compared to actual rates of around 10 mm/d. Again, the use of interpolation rather than extrapolation would appear to be the preferred approach. In this case actual on site bore data at Dahwilly East would assist is comparing background groundwater salinities.
- It is apparent that Finley is located in quite a different environment, as suggested by the very low resistivities. The trend line between the data points is almost vertical in comparison to the two trend lines of the two Dahwilly sites. It is therefore not appropriate to include this data set in the Dahwilly analysis.

5.4.5.3 Lake View

Two sites were trialed on the Lake View Channel, approximately 8 km apart:

- Lake View Central – The original site on which previous years trials had been conducted.
- Lake View West – Similar to Lake View Central in terms of geology and hydrogeology.

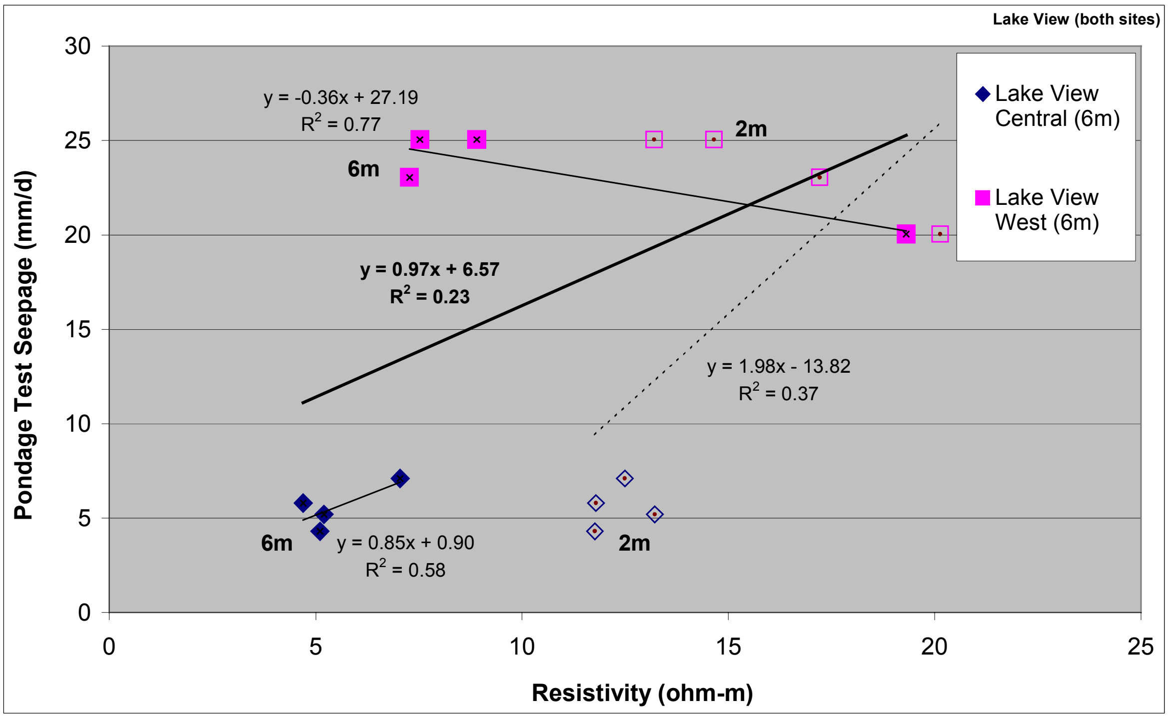
Figure 5-114 plots the regression trend lines for the two Lake View sites. Depth slices from 6m (solid symbols) and from 2m (hollow symbols) are presented. The watertable at both sites is shallow, at between 0.5 - 1.5 m below surface. The following observations are made regarding this plot:

- Two very different trend lines for the individual (6m depth slice) Lake View sites are observed. The regression trend line for the combined 6m depth slice data set (dark line) has a poor coefficient of 0.23, indicating little trend between the two sites. A slightly improved relationship is obtained for the 2m slice (dashed line) although the trend is still only moderate at best. As discussed in Section 5.4.4.8

the inverse correlation at the Lake View West site is largely caused by a possibly anomalous result in pond 1. This same 'outlier' appears to be contributing to the poor overall trend. Further testing would be required for definitive conclusions to be drawn regarding the validity of a relationship between the two sites. In particular the collecting of additional data at seepage rates between the two sites is necessary, as both are clustered about a narrow seepage range.

- As per the previous two sites (Toolondo and Dahwilly) these results suggest different background conditions exist at the two sites. For the seepage rates observed at Lake View West to fit with the Lake View Central site data, much higher resistivities would need to be recorded. The lower than 'expected' resistivities at Lake View West are most likely explained by the gravelly clay which extends to 5m, and probably acts as a better conductor than the sandy clay loams and sandy clays at the Lake View Central Site. If the Lake View Central data had been used to predict seepage rates at the Lake View West site, seepage would have been greatly underestimated (5-10 mm/d instead of 20-25 mm/d).
- Also as per the two previous sites, in terms of extrapolating relationships from one site to another, this confirms that relationships between resistivity and seepage can change over relatively short distances, and therefore extrapolation without pondage tests is dangerous.

Figure 5-114 Pondage Test Seepage Versus Resistivity at Lake View Sites



5.5 Conclusions

The geophysics conclusions are set out in the following manner:

- Discussion and Conclusions
- Summary of EM31 Results
- Summary of EM34 Results
- Summary of Resistivity Results

The general conclusions draw together all of the results and include a comparison of the three techniques and a discussion of: seepage detection mechanisms, confidence in derived relationships, extrapolation of results and comparison of this investigation to recent international studies using geophysics for seepage measurement and detection.

The three sections summarising each of the techniques are based around a summary table for each technique which condenses the key outcomes from each trial into one table, with an emphasis on comparing the results of each trial with the corresponding pondage tests in that section.

5.5.1 Discussion and Conclusions

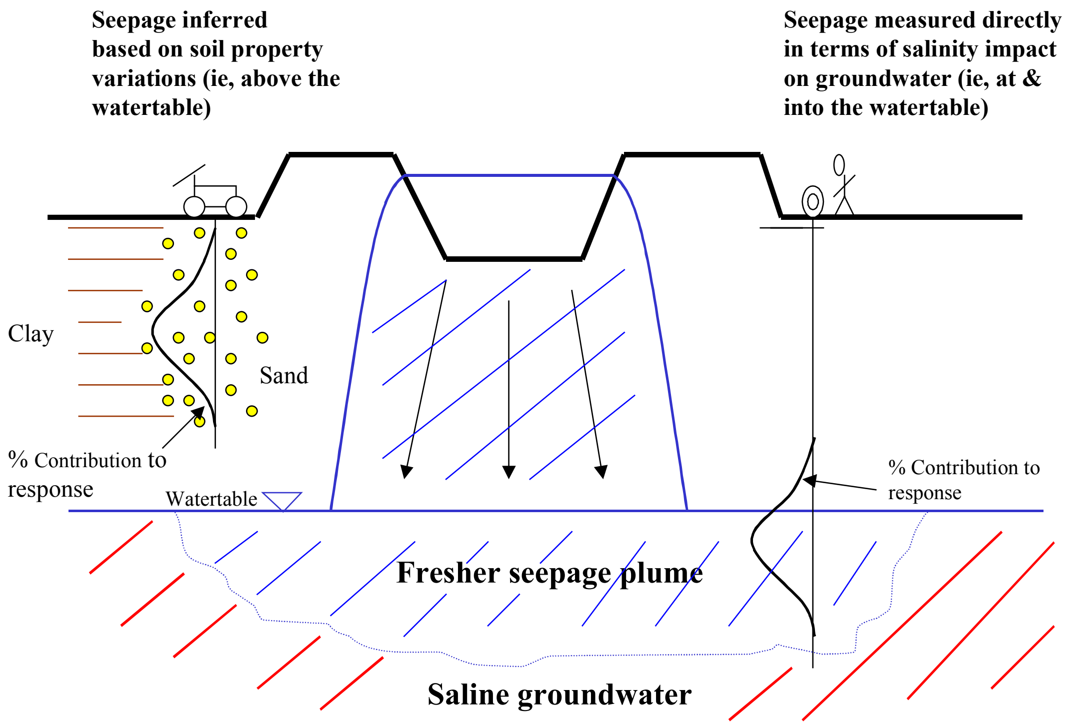
5.5.1.1 Seepage Detection Mechanisms

Geophysical techniques applied to seepage measurement primarily depend upon measuring a contrast in terrain conductivity (or resistivity) in the sub surface profile around the channel. They can be used in one of two ways:

1) Directly measuring the conductivity of the groundwater, and identifying the conductivity contrast of fresher channel water as it seeps into and dilutes saltier native groundwater. Decreasing the salinity of the groundwater will cause a decrease in electrical conductivity (or an increase in its inverse, resistivity).
2) Identifying contrasts in soil properties and inferring the likelihood of seepage through more permeable materials in the zone above the watertable. Formations more likely to allow seepage, such as sands, are naturally lower in conductivity (higher in resistivity) due to lower porosity and lower cation exchange capacity than tighter clay dominated formations. In addition the higher permeability of such formations leads to better drainage and lower salt content, further reducing conductivity. The magnitude of seepage is assumed to be related to unsaturated zone soil properties beneath or adjacent to the channel.

Figure 5-115 visually depicts how these two different approaches can be used to identify or infer seepage.

■ **Figure 5-115 Comparison of how geophysical techniques can be used to identify channel seepage (LHS – inferred from soil property variations, RHS – direct measurement of salinity impact on watertable)**



Technically the second method of 'detection' is not really detection, but the magnitude of seepage is assumed to be related to unsaturated zone soil properties beneath or adjacent to the channel. In many cases this is a reasonable assumption, however the unsaturated zone is not necessarily the controlling influence on seepage. For example, over time most Australian channels tend to silt up and the resulting surface clogging layer is often more restrictive than the unsaturated zone. Therefore unsaturated zone lithology may not be related to seepage rates, as seepage is controlled by the thickness and conductance of the clogging layer.

Nevertheless, it was found that the inferred method of identifying contrasts in soil properties (ie, where the watertable was deeper than the penetration depth of the geophysical equipment) was successful at most sites conducted during the trials (ANCID, 2003). There is less risk however in using the direct method of seepage detection, because as the name implies it is not inferred, but direct. An example of where the 'inferred' method of detection did not work was at Dahwilly Central where an EM31 survey was conducted while the channel was not running. The survey was therefore measuring changes in the unsaturated zone and not in the groundwater. At this site the silt layer in the channel, not the unsaturated zone is the restrictive layer and therefore no correlation was observed. When the survey was repeated with the channel running, a good correlation was obtained.

Some possible limitation of the direct method of seepage detection are listed below: (However, it is still considered the preferred technique over inferring seepage based on soil property variations).

- In relatively non-saline groundwater environments, the fresh seepage water will not contrast with the native groundwater. This is not expected to be a problem in most Australian conditions;
- In environments where the channel seepage water might be rapidly mixed with native groundwater, such as sites with high groundwater gradients or highly transmissive environments, the salinity impact on the groundwater may not be as significant. This can largely be overcome by using survey traverses close to (or on) the channel; and,
- Groundwater salinity variations along the channel will affect the results and this needs to be allowed for in the interpretation.

In summary, it is very important that the depth to watertable is known at the site before selecting a technique. Based on this information a decision can be made as to whether direct or inferred measurement will be undertaken and hence the technique that will be adopted.

5.5.1.2 Comparison of Trialed Geophysical Techniques

The following have been identified as key criteria against which geophysical techniques should be compared:

- Accuracy
- Cost and Speed
- Availability of Operators
- Data Processing

The three techniques trialed in this investigation (EM31, EM34 and resistivity) are discussed in terms of each of these criteria.

Accuracy

In theory on-channel resistivity surveying should be the most accurate of the geophysical techniques trialed, as it is based on a direct method of seepage detection (refer section 5.5.1.1). As the technique allows definition of changes in resistivity / conductivity through the profile, the depth where seepage impacts will be most evident (at and below the watertable) can be targeted. At most sites resistivity surveying results were comparable to EM31 and EM34, and at three sites (Dahwilly Central, Dahwilly East and Finley) the resistivity correlations with pondage tests were better than the EM31 and EM34 correlations. The Dahwilly site demonstrates the benefits of targeting the watertable for seepage detection in an environment where seepage is not controlled by the unsaturated zone, but by a surface clogging layer in the channel.

Resistivity did not prove to be quite as ‘accurate’ as EM31 in environments with a shallow depth to watertable. This was largely attributed to poor near surface resolution of the particular resistivity equipment used in the survey, and not inherent in the resistivity method itself. The resistivity surveying was conducted using equipment that was used for the first time in these trials and as such was largely experimental. The designers of the equipment indicate that improved resolution at shallow depth could relatively easily be achieved in future surveys by slight design modifications (Allen, pers. comm. 1/11/02).

EM34 at 10m coil separation in the horizontal mode provides a similar depth penetration to EM31 (vertical mode) and therefore is similarly accurate (but slower to use). EM34 at a 20m coil separation provides a deeper penetration and focus. At one trial site, the depth focus was apparently too far below the watertable and the critical zone was missed. This is a fundamental limitation with all Geonics EM surveys and other such fixed array type geophysical surveys – the result is averaged over a specific depth interval, which may not be the critical interval of interest.

However, the robustness of the EM31, as demonstrated by the consistent results in the trials is due to its relatively shallow depth focus (1-4m). For channels where there is a shallow watertable (eg, surface to 3-4m), EM31 can be used for direct measurement of seepage, which as discussed above is likely to be more reliable. When the watertable is deep, EM31 infers seepage from near surface soil properties. This works in most instances but may break down where clogging processes rather than unsaturated zone lithology control seepage.

The significant advantage of resistivity surveying is that the final output is a two dimensional profile of resistivity beneath the channel. Not only does this allow easier interpretation of the results but it can also provide an indication of seepage mechanisms. For example, at the Toolondo central site the resistivity profile shows isolated sections of high resistivity (low seepage) emanating from the channel. This is in contrast to the Dahwilly channel where the profile suggested seepage by relatively continuous diffusion along the channel. This seepage mechanism is supported by the lithology at the Dahwilly site, which indicates the entire length of channel is underlain by approximately 10m of medium to coarse grained sand, and hence is more likely to result in uniform seepage rather than seepage 'hotspots'.

Cost and Speed

Approximate costs for the three techniques trialed are given below, based on geophysical surveys undertaken in these trials. However, it is important to note that for geophysical surveys often a significant proportion of the costs are overhead costs (mobilisation, equipment set up etc) and therefore the unit cost per kilometre will usually be substantially less for long sections of channel. Costs will obviously vary depending on site specific condition (eg, on land – fences, other obstacles, on channel – bridges, checks, fences etc).

- EM31 Surveys:
    - Wimmera Mallee Water: For 6 kms, on-land including 4 traverses on each side of channel (over 3 sites): $400/km (includes mobilisation, data processing and mapping).
    - Murray Irrigation: For 8 kms, on-land including 4 traverses on each side of channel (over 4 sites): $340/km (includes mobilisation, data processing and mapping).
    - Murrumbidgee Irrigation: On-land including 4 traverses on each side of channel, on each side of channel, the unit cost ranged from $650/km (3km section) to $800/km (1 km section). (includes mobilisation, data processing and mapping). On-channel survey cost was $330/km for a 3 km section.

EM31 is currently the cheapest of the geophysical methods due to the speed of data acquisition.

- EM34 Surveys:
    - Wimmera Mallee Water: For 4 kms over 2 sites: $250/km (1 traverse only on one side of the channel) ie, $500/km for both sides of channel (excludes mobilisation).
    - Murray Irrigation: For 6 kms (on each side of channel) over 3 sites: $435/km (includes mobilisation).

  EM34 is more expensive than EM31 as two people (on foot) are required to operate the equipment.

- Multi-electrode Resistivity Surveying – The follow costs were for resistivity surveying across 11 sites (approximately 2km each in length) in the Wimmera, Murray and Murrumbidgee Irrigation areas:
    - Resistivity towed array surveys: $900/km [Includes mobilisation (from Adelaide), travel between sites, production and all equipment costs]
    - Data processing costs: $220/km.

  Note that resistivity surveying costs are difficult to quantify given that the technique is relatively new. Costs are likely to come down as the technique is refined, the equipment becomes commercially available and subsequently competition is introduced.

Availability of Operators

A number of commercially operating EM34 and EM31 contractors are in operation in south east Australia, sufficient to ensure reasonable competition and prices. At present on-channel resistivity surveying is still in a development phase and as such there are no commercially operating contractors who specialise in this type of survey. However, a number of geophysical exploration / surveying companies have the capability to develop this type of equipment (such as the company who conducted these trials) and should the demand for such surveying increase, it is expected other companies could also develop this capability. At present however this may be a constraint on resistivity surveying.

Data Processing

Data processing requirements for EM31 and EM34 surveying are minimal. In comparison data processing requirements for resistivity surveying are considerable, due to the cost of inverting the data to produce a resistivity cross section. This is not really a constraint of the technique, but adds to the overall cost of resistivity surveying. It should be ensured that the contractor undertaking the resistivity surveying also has the capability to undertake the data processing. Approximate costs for data processing are provided above.

5.5.1.3 Critical Geophysical Survey Variables

- *Survey timing* – The timing of the geophysical survey will depend on the method of seepage detection being used. If seepage is being inferred from soil properties then the timing of the survey is not critical and can be conducted whether the channel is running or empty. However if direct measurement of seepage is used, the survey must be conducted while the channel is running, and preferably after it has been running for a least one month (depending on depth to watertable and vertical hydraulic conductivity), to ensure seepage has impacted the groundwater.

- *On-channel versus on-land* – During the trials, on-channel (ie, in a boat) EM31 surveys:

- Did not work at one site where the watertable was beyond the range of the EM31 and returned similar (reasonable) results to the on-land survey at another site (Waranga).
- Did work at sites with a shallow watertable; and,
- Were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31.

Further work is required in this area, but the evidence collected in this investigation suggests on-channel EM31 surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. In other words, the method of inferred seepage based on unsaturated zone soil properties does not appear to work on-channel. It is apparent that the flushing effect immediately beneath the channel is dominating changes in lithology. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 3-4m.

However, there is some conflicting evidence, as demonstrated by the trial results summarised above. Overall however, the most consistent results were returned on-land and this is considered the safest option. A possible limitation of on-land surveying, may be at sites which contain significant land salinisation immediately adjacent to the channel. Therefore, if the budget allows, it is recommended that both on-land and on-channel surveys be conducted. Resistivity surveys can be conducted on-channel because of their greater depth penetration capacity.

- *Off-set distance and location for on-land surveys* – The evidence collected in these surveys indicates the best off-set distance for on-land surveys is immediately adjacent the outside toe of the down slope side of the channel. For either method of seepage detection this is recommended. For inferred seepage 'detection' the soil type next to the channel is most likely to be representative of the soil type beneath the channel. For direct measurement, immediately adjacent the channel will be the zone of greatest seepage impact on the watertable. Away from the channel this impact will be diluted. However at sites without a steep gradient or high transmissivity, an average of survey traverses up to 50m on each side of the channel was found to improve the correlation between seepage and the geophysical survey at most sites.

Traverses on either side of the channel are recommended, however if budget is a significant constraint, a traverse on the down-slope side of the channel should be preferred.

- *Other variables:*
  - Trees – In two surveys (Rocklands and Donald), tree plantations adjacent the channel appeared to interfere with the survey results. The postulated mechanism is that the trees are consuming the seeped water and therefore the observed impact (in the geophysical survey) on the native groundwater is lessened.
  - Rain – Rainfall did not interfere with the surveys conducted in these trials. However it is possible that surveys conducted after heavy rainfall on light to moderate soil types (ie which allowed significant infiltration) could interfere with the conductivity / geophysical response and therefore should be avoided. Surveys inferring seepage based on shallow soil properties or direct measurement in shallow watertable environments would be most effected.

5.5.1.4 Repeatability

Generally a high degree of repeatability was observed between duplicate surveys. At two sites where there was a significant different in the results, changes in groundwater conditions due to channel operation accounted for the difference. These sites are described below:

- Donald - A generally consistent increase (approximately 15 mS/m) was observed across the surveyed area between the October 1999 survey and the September 2001 survey. This increase was caused by the more saline conditions at the time of the 2001 survey. The channel had been running for six months prior to the 1999 survey, creating a sub-surface environment dominated by fresh water and a flushed profile. The reduced channel running time prior to the 2001 survey meant a relatively more saline profile and hence higher conductivity.
- Dahwilly - The average EM31 conductivity for a survey conducted when the channel was not running was less than half the conductivity recorded while the channel was running. This is different to what was observed at Donald, due to the different depth of groundwater at the two sites. When the channel is not running at Dahwilly, the watertable is largely out of reach of EM31 detection and the response is a reflection of the coarse and low conductivity sands in the unsaturated zone. When the channel is running, the watertable is elevated into the range of the EM31 detection and hence conductivities increase significantly.

5.5.1.5 Regional Assessment of Key Relationships

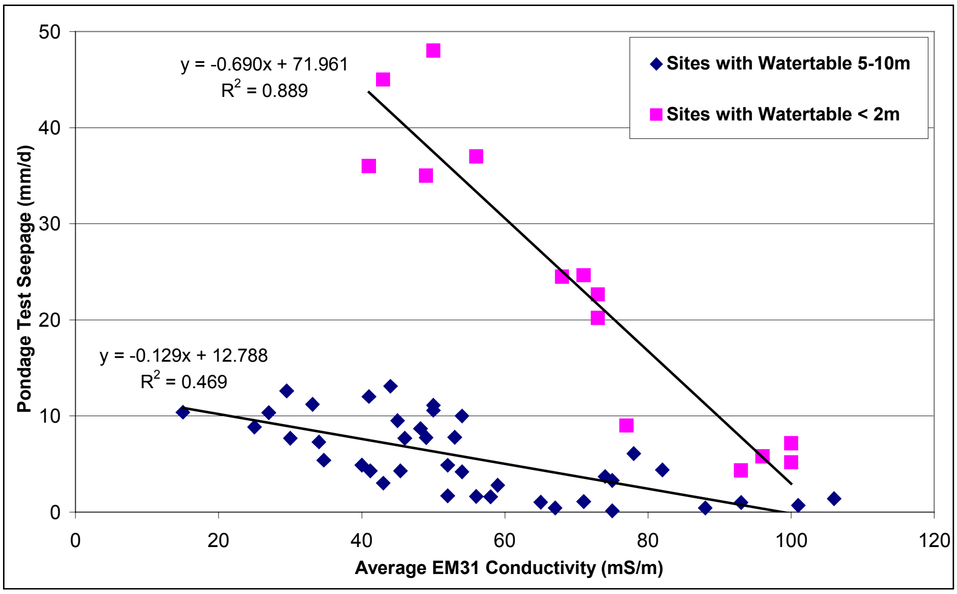
For all of the sites used in the final year of analysis an attempt was made to look for potential correlations between seepage rates across all sites and geophysical response (EM31 and resistivity). This was conducted using multiple linear regression and simple linear regression. The additional explanatory variables included in the multiple linear regression analysis included:

- Soil permeability (vertical hydraulic conductivity): Averages across 4 different depths were used;
- Depth to watertable; and,
- Groundwater salinity.

EM31 Multiple Linear Regression
Multi-variate regression analysis was initially conducted on the entire data set (excluding Finley which was removed as an outlier). This indicated that the following were significant explanatory variables:
- Average EM31 conductivity;
- Depth to watertable; and
- Upper K_v (vertical permeability of the top 2m of the profile).

However, the standard error of estimate (expressed as a percentage of the mean pondage test seepage) for the regression was high (82%). A plot of conductivity versus seepage dividing the data into two categories based on depth to watertable is shown in Figure 5-116.

■ **Figure 5-116 Regional EM31 Assessment: Pondage Test Seepage Versus EM31 Conductivity with Site Divided Based on Depth to Watertable**



Based on this clear division between sites with a shallow and deeper watertable (in an attempt to improve the accuracy of the fitted regression model) the sites were split into two data sets based on these two categories of depth to watertable. The difference in EM31 response between a deep and shallow watertable site is explained by the effect of the shallow and saline groundwater which for a given seepage rate causes a much high conductivity response.

Once the data was split into these two categories, depth to watertable was not found to be a significant explanatory variable, as would be expected. The findings for the two categories are summarised below:

- Watertable Depth Five to Ten Metres - For sites where the watertable is 5-10m below surface, the equation found to provide the best prediction of channel seepage was:

  Seepage = 11.6 – 0.12 *EM31* + 4.4 UK_v *(Equation 1)*

  Where, Seepage = Channel seepage (mm/d)
  EM31 = EM31 conductivity adjacent each side of channel (mS/m)
  UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

  The equation:
  - Was established with 40 data points;
  - Has a correlation coefficient of 0.55;
  - Has a standard error of estimate of 48% (of mean observed seepage rate)

  EM31 was found to be the dominant explanatory variable with soil hydraulic conductivity of secondary importance. Groundwater salinity and depth to groundwater were not found to be significant explanatory variables in the analysis.

- Watertable Less Than Two Metres - For sites with a watertable within two metres of the surface multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond EM31. The fact that soil data was not significant is expected as the groundwater near the surface is likely to dominate the response. It was somewhat surprising that groundwater salinity was not found to be a significant variable for this data set, and is probably a reflection of the limited number of sites (three) that make up the data set.

EM31 - Simple Linear Regression
Simple linear regression, using EM31 only as the explanatory variable, was conducted to determine how much of an improvement the multiple linear regression actually represents. The data was again divided based on depth to watertable.

Watertable Depth Five to Ten Metres
For the sites with a watertable 5 – 10m below surface, the best fitting linear regression equation was found to be:

Seepage = 12.8 – 0.13 *EM31* *(Equation 2)*

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

The equation:
- Was established with 40 data points;
- Has a correlation coefficient of 0.47;
- Has a standard error of estimate of 51% (of mean observed seepage rate)

Confidence intervals (for both 80% and 90%) for this relationship were established and showed that the prediction equation is accompanied by quite broad prediction bands. This probably limits the use of this regional equation to broadly classifying seepage rates (eg into low, medium and high categories), which is not a surprising outcome given the wide range of sites represented by the equation.

A plot of actual seepage versus predicted seepage shows that the equation tends to overestimate seepage for low seepage rates (less than 5 mm/d) and underestimate for high seepage rates, implying a non-linear equation may provide a better fit. An exponential regression equation was applied to the data. The fitted exponential curve showed that while there is only a marginal improvement in the correlation coefficient for the exponential fit (from $R^2 = 0.47$ to 0.48), the standard error actual worsens (from 51 % to 62%). Therefore, overall a less accurate fit is obtained using the non-linear equation, even though it may visually appear to fit the data better.

However the advantage of the exponential fit over the linear fit is that there is less of a pattern displayed in the observed versus predicted seepage plots (which suggests that the more realistic model may in fact be the exponential model). Further, the linear model places a maximum limit on the seepage of about 12 mm/d, whereas the exponential model appears to be more realistic, allowing for higher seepage rates in the very low conductivity range (up to around 20-25 mm/d).

Comparing the linear regression to the multiple regression, the statistics indicate that only a marginal improvement is made to the accuracy of the regression fit in the multiple linear regression analysis (*Equation 1*), compared to the simple regression fit (*Equation 2*). The R^2 for *Equation 1* was 0.55 and the standard error of estimate was 48%. Therefore a relatively modest improvement of 0.08 in the correlation coefficient and 3% in the standard error of estimate is the only improvement gained in adding soil permeability to the regression equation.

<u>Watertable Less Than Two Metres</u>

The best fitting linear equation for sites with a watertable less than 2m is:

$$\text{Seepage} = 72 - 0.69\, EM31 \qquad \textit{(Equation 3)}$$

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

The equation:

- Was established with 14 data points;
- Has a correlation coefficient of 0.89;
- Has a standard error of estimate of 23% (of mean observed seepage rate)

The high correlation coefficient value and the relatively low standard estimate of error suggest a good correlation for the variables. However the results should be tempered by the fact that relatively few data points were used to form the relationship. To improve confidence in the regression equation for the watertable less than two metres scenario, additional points are required in the data set.

Prediction bands (80% and 90%) for estimating seepage based on EM31 response when the watertable is less than 2m, indicate that while the prediction intervals are broader in magnitude than for the prediction bands for the deeper watertable scenario, as a percentage of the seepage range covered by each of the equations, they are narrower.

In summary, multi-variate analysis did not significantly improve the regression model. The permeability of the upper part of the soil profile was found to be a significant parameter, but the improvements to the model with this parameter included were marginal. The benefits of conducting field tests to collect this data are therefore probably outweighed by the costs.

The linear regression equation for sites with a watertable five to ten metres below surface is a reasonable fitting equation, given the range of sites on which it is based. However it should not be relied upon to accurately predict seepage, and should be limited to assigning seepage to low, medium and high categories. The same comments are applicable to the regression equation developed for sites with a shallow watertable (less than two metres). The better statistics for these sites is attributable to the fewer data points and smaller range of environments represented.

Resistivity Multiple Linear Regression

As for the EM31 analysis, the same approach of a regional assessment using multiple and linear regression analysis was conducted for the resistivity results. The same additional variables were used. For the resistivity the ten metre depth slice was adopted. While a more accurate analysis would use the depth at and just below the watertable, for the purpose of a consistent approach, this depth slice was selected. The first cut analysis indicated that depth to watertable was an important variable. Therefore the analysis was again based on division of the data into sites of shallow and deep watertable.

Watertable Depth Five to Ten Metres

For sites where the watertable was five to ten metres below surface (Toolondo and Dahwilly) the equation found to provide the best prediction of channel seepage was:

$$\text{Seepage} = 3 + 0.01\ \text{Resistivity}_{10m} + 7.46\ \text{UK}_v \qquad (\textit{Equation 4})$$

Where,
- Seepage = Channel seepage (mm/d)
- Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)
- UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

The equation:

- Was established with 23 data points;
- Has a correlation coefficient of 0.44;
- Has a standard error of estimate of 61% (of mean observed seepage rate)

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 19% of the mean observed seepage rate (to the power of 0.2). A marginal reduction in the correlation coefficient was observed, decreasing to $R^2 = 0.42$.

The non-linear equation, using resistivity only as an explanatory variable, for predicting channel seepage at sites where the watertable is greater than 2m is:

$$\text{Seepage} = [\,1.12 + 0.0008\ \text{Resistivity}_{10m} + 0.47\ \text{UK}_v\,]^{5} \qquad (\textit{Equation 5})$$

Where, Seepage = Channel seepage (mm/d)
$Resistivity_{10m}$ = Resistivity at 10m depth recorded on channel (ohm m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

Watertable Less Than Two Metres
For sites with a watertable within two metres of the surface (Lake View and Lake View West), multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond the resistivity data.

Resistivity Simple Linear Regression

Watertable Five to Ten Metres
For the resistivity analysis the number of channels fitting this category was reduced to two (3 sites at Toolondo and 2 sites on the Dahwilly Channel). Four points within this data set appeared to be outliers. They were the four high seepage ponds at Dahwilly Central. However they were retained in the analysis as there was no obvious grounds for their removal.

Therefore the linear equation (using resistivity only as an explanatory variable) predicting channel seepage at sites where the watertable is greater than 2m was found to be:

$$Seepage = 4.2 + 0.01\ Resistivity_{10m} \qquad (\textit{Equation 6})$$

Where, Seepage = Channel seepage (mm/d)
$Resistivity_{10m}$ = Resistivity at 10m depth recorded on channel (ohm m)

The equation:

- Was established with 23 data points;
- Has a correlation coefficient of 0.16;
- Has a standard error of estimate of 68% (of mean observed seepage rate)

These statistics indicate that the accuracy of the regression is very poor, in large part due to the four high seepage rate 'outliers' at the Toolondo central site. With these outliers excluded the correlation coefficient improves dramatically to $R^2 = 0.63$. However as discussed above there was no obvious basis for their removal.

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 20% of the mean observed seepage rate (to the power of 0.2). A marginal improvement in the correlation coefficient was observed, increasing to $R^2 = 0.21$.

The non-linear equation, using resistivity only as an explanatory variable, for predicting channel seepage at sites where the watertable is greater than 2m is:

$$Seepage = [\ 1.19 + 0.0008\ Resistivity_{10m}]^{5} \qquad (\textit{Equation 7})$$

Where, Seepage = Channel seepage (mm/d)
$Resistivity_{10m}$ = Resistivity at 10m depth recorded on channel (ohm m)

In summary, neither the linear or non-linear simple regression equations were found to be satisfactory predictors of seepage. The very wide prediction bands for the non-linear prediction equation confirm this conclusion.

Watertable Less Than Two Metres

The linear equation predicting channel seepage at sites where the watertable is less than 2m (data set comprised of only the Lake View channel) is:

$$Seepage = 1.7\ Resistivity_{10m} - 0.66 \qquad (\textit{Equation 8})$$

Where, Seepage = Channel seepage (mm/d)
$Resistivity_{10m}$ = Resistivity at 10m depth recorded on channel (ohm m)

The equation:

- Was established with 8 data points;
- Has a correlation coefficient of 0.62;
- Has a standard error of estimate of 27% (of mean observed seepage rate)

These statistics indicate that the accuracy of the regression is reasonable. However, the results must be interpreted in light of the fact that only a few data points have been used to form the relationship, and all data points were collected on the same channel. Further testing to add different environments to this data set is necessary before a reasonable degree of confidence can be placed in this prediction equation.

The following summary comments are made regarding the linear and multiple regression analysis for the resistivity:

- The multiple regression analysis significantly improved the accuracy of the regression equation compared to the simple regression with only one variable, increasing the coefficient of determination from $R^2 = 0.21$ to $R^2 = 0.42$.
- It is likely the analysis could be significantly improved by using resistivity data at and immediately below the watertable for each of the sites.
- As was the case in the EM31 multi-variate analysis, the variable which was found to be most significant in the regression equation was the vertical hydraulic conductivity in the upper two metres (upper K_v). Again this confirms that the upper soil profile is by far the most significant part of the profile controlling seepage.
- While this analysis indicates a moderately fitting regression equation, it could not be used with the same degree of confidence as the EM31 based equation due to:
  - The lower correlation coefficient;
  - The few number of data points and small range of environments represented by the data points;
  - The unexplained outliers in the resistivity analysis that were not present in the EM31 regression equation.

5.5.1.6 Confidence in Derived Relationships and Extrapolation of Results

Two key issues regarding relationships derived between channel seepage and geophysical response are:

1) What confidence is there that the derived relationship accurately describes seepage within the area tested?; and
2) How confidently can the relationship be used outside of the area tested to predict seepage?

Based on the findings of these investigations, these two issues are summarised below.

Confidence in Derived Relationships

Confidence in the derived seepage-geophysical relationship within the area tested can be assessed by a number of factors, including:

- Correlation coefficient (R^2) – This explains the amount of variation explained by the regression equation. Most geophysical – seepage relationships derived in this investigation had correlation coefficients of between 0.5 to 0.9, and typically were around 0.75, meaning that 75% of the seepage variation could be explained by the geophysical response.

- Standard estimate of error – This is a measure of the degree of scatter about the regression line. A data set may have an R^2 of one but a high degree of scatter. For the regional simple linear regression (EM31) the standard error of estimate (of mean seepage rate) was around 50% for sites with watertable 5-10m below surface and was around 25% for sites with watertable less that 2m. For individual channels this was generally lower at about 20%.

- Prediction interval - Prediction bands for most seepage - conductivity / resistivity regression lines were generally quite broad. These bands suggest that often the regression line can only be used to classify areas into high, moderate and low seepage. The uncertainty is partially due to the data handling processes, which are based on averaging pondage test seepage and geophysical response over long sections of channel. There is also error inherent in the method in that given the large number of variables that simultaneous impact on channel seepage, it is not possible to tightly characterise seepage based on geophysical response. The prediction intervals were generally tighter for sites with greater ranges of seepage. Prediction intervals are likely to be improved by greater number of pondage tests across the broadest possible seepage range.

  Knowing that seepage is probably within a certain range (to a given level of certainty), even if the range is fairly broad, is still considered an improvement on the existing seepage knowledge base of many Rural Water Authorities, and can only lead to more informed decision making.

- Number of data points – The number of data points on which the relationship is derived is also a very important consideration. For instance, some sites with relatively few data points returned very good statistics (high R^2, low SEE and relatively tight prediction bands). These results need to be taken with caution because of the few number of points contributing to the relationship (eg, only two data points will have perfect statistics but the results have no meaning). Generally the more data points contributing to the relationship, the greater the confidence in the relationship.

- Seepage range – The seepage range over which relationship is established is important, as it improves confidence in the robustness of the relationship. A limitation at a number of sites in this study was the narrow range of seepage rates. The trends observed across a very tight seepage range can often be meaningless, and at a number of sites where tests were conducted several kilometres away on the same channel, a more realistic relationship for that channel was derived.

Confidence in Extrapolation

The following points need to be considered when extrapolating a geophysical – seepage relationship outside of the area in which it was developed:

- Was the relationship strong in the area tested – This is the first test. If the relationship was not strong in the area in which it was derived (refer to above discussion) then there will be little confidence in extrapolating such a relationship.
- How representative is the area in which to extrapolate of the tested area – The area in which the relationship was developed must encompass the range of conditions over which the extrapolation is to occur. This may be quite difficult to determine. While soil, geological, hydrogeological maps and even test drilling provide an indication of changes along the channel, the results from these trials suggest that these are generally not at a sufficient scale to detect how they will impact on geophysical response. For example, at the Dahwilly sites which showed reasonably similar characteristics (depth to watertable, groundwater salinity and lithology) the EM31 conductivity response was very different and thus extrapolation from the Dahwilly Central site to the Dahwilly East site would have resulted in significant errors in seepage estimate.

  In fact, the evidence coming out of the trials in terms of extrapolation, even to sites that were apparently similar and usually only several kilometres along the same channel, was that the derived relationship was not suitable to predict seepage at the new site. The key outcome of this is that unless intensive data collection is conducted to ensure continuity of site conditions to the area of extrapolation, interpolation rather than extrapolation must be used. This is explained in further detail in the following section, but essentially means that pondage tests should be conducted at regular intervals along the entire section of interest, to ensure that the full range of site conditions is accounted for in the derived regression relationship.

  The more data points collected from different sections along the channel that are added to generate the regression line, may increase scatter about the regression line. This can be seen in the high standard error of estimates for the Rocklands/Toolondo and Waranga regression equations. This is a reflection of the fact that the ponds in these sites covered a wide area and range of sub-surface conditions. However, while there is more scatter about these lines, these is more confidence in using these relationships for seepage prediction as they encompass a wider spatial range and wider range of conditions, and can therefore be used with greater confidence over a broader area, although at the expense of some degree of accuracy.

5.5.1.7 Preferred Methodology

Based on the trials conducted in this investigation, the following methodology for using geophysics to identify and measure seepage is recommended: (Note that this methodology assumes some prior knowledge as to which channels or sections of channel require investigation. This knowledge may have been acquired based on flow records, visual inspection or a regional investigation using a technique like remote sensing).

1. *Define project objective – why is the work being undertaken?* The types of questions to be asked include:

- Is the primary objective to identify relatively high seepage points or to measure the volume of seepage?
- Is it necessary to establish the rate of seepage? – either the actual or relative rate.
- What degree of confidence in the results is required?
- Over what length of channel is the information required?
- What is the available budget?

At the end of this process there will be a clear definition of the reasons for undertaking the seepage investigation (eg asset management), budget considerations, scale of the operation (eg whole channel, specific channel lengths etc), need for accuracy, or relativity. This process will effect all future decision making.

2. *Collate and Evaluate Site Data* - It is important that information on depth to groundwater, background groundwater salinity, soil type and channel hydraulics are known or gathered), both at the site where the testing is conducted, and over the area the results are to be extrapolated. This does not have to be at a detailed level, but should be sufficient to be able to propose a conceptual model of the seepage mechanism, to detect where changes in these parameters may impact on the geophysical response, and to assist in technique selection. Channel hydraulic information is required to help determine potential channel seepage mechanisms.

3. *Select Technique* - The preferred geophysical seepage measurement technique is one that has a depth focus on and immediately below the watertable. Whether this is achieved using EM or resistivity is not highly important. However, generally it is easier to focus on a given depth with resistivity (EM provides an average across a range) and this can be achieved independent of knowledge of groundwater depth. The advantages and disadvantages of each of the techniques (refer above) need to be assessed in light of the specific project objectives. The recommended technique for a given depth to watertable is outlined below:

Preferred Geophysical Techniques

- The preferred technique for geophysical channel seepage assessment is *directly detecting the impact of seepage on the groundwater*. This means that the instrument must focus on the zone immediately above and several metres below the watertable:

    - For a *shallow watertable* (surface to approximately 5m) *EM31* is suitable for direct seepage detection.
    - For *watertables deeper than 5m*, *EM34* (in ***vertical*** dipole mode) or *resistivity* can be used. However, particularly for deeper watertables, it is easier to focus on a given depth with resistivity and this can be achieved independent of knowledge of groundwater depth. The significant advantage

of resistivity is that it provides a profile of the resistivity beneath the channel. The disadvantage is that resistivity technology for channel seepage assessment is relatively new and therefore more expensive.

- EM31 (vertical dipole) adjacent the channel can be used effectively in areas with deeper watertables, although it does not directly measure the seepage impact on the watertable. This is due to fact that the upper soil layers are the most influential on channel seepage and the relatively shallow depth focus of EM31 measures these upper soil layer properties. The method infers zones of likely channel seepage by identifying materials in the unsaturated zone most susceptible to seepage. A decision to use EM31 in deeper watertable area might be based on:

    - Cost and required accuracy – If a potentially slightly lower level of accuracy is considered acceptable then EM31 represents a cheaper alternative than EM34 or resistivity; or,
    - Lack of alternatives – EM34 or resistivity contractors are not readily available.

It this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes. Otherwise errors will potentially be introduced to the assessment process.

The preferred geophysical techniques for seepage detection are summarised in Table 5-7.

■ **Table 5-7 Recommended Geophysical Technique for Seepage Detection and Measurement**

Watertable Depth (m)	Recommended Technique [1]	Detection Method[2]	Approximate Depth of Penetration (m)[3]	Depth Focus (m)[4]
Surface to 1.5	EM31 (horizontal dipole)[5]	Direct watertable impact	3	0 - 1
1.5 – 5	EM31 (vertical dipole)[5]	Direct watertable impact	6	1 – 3.5
5 – 12	EM34 – 10m coil spacing (vertical dipole)[6]	Direct watertable impact	15	3 - 10
	OR			
	Resistivity[7]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5
12 – 25	EM34 – 20m coil spacing (vertical dipole)[6]	Direct watertable impact	30	6 - 20
	OR			
	Resistivity[7]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5
> 25	Resistivity[9]	Direct watertable impact	NA[10]	NA[11]
	OR			
	EM31 (vertical dipole)[8]	Soil property variations	6	1 - 3.5

1. It is recommended EM techniques are conducted adjacent the channel (additional survey runs can be conducted away from the channel). Resistivity surveys should be conducted on -channel.
2. Direct detection of seepage impacts on the watertable is the recommended technique, but inferred 'detection' based on soil property variations will often provide an adequate simulation and may be more convenient for various reasons (refer to body of report for potential errors associated with this method)
3. Approximate detection of penetration is referred to in the Geonics manual (M^{c}Neil, 1980) as the effective depth of exploration. This is the depth to which approximately 75% of the response is attributed.
4. The 'depth focus' is a term used in this report to describe the depth (range) which is most influential in terms of the relative contribution to the overall EM response (M^{c}Neil,1980).
5. These can be conducted immediately adjacent to the channel or on-channel. Both are recommended if budget allows. If on-channel is used for a watertable of 0-1.5m, the survey should preferentially collect data in vertical dipole mode where the effects of channel water will be less influential. For sites with a watertable 0-1.5m, EM31 on channel may be preferred if significant land salinisation exists adjacent the channel.
6. Horizontal and Vertical Dipole: Note that as applied to EM34, vertical dipole does not refer to the coil orientation with respect to the ground, and is in fact opposite to the coil orientation. In vertical dipole mode the coils should be horizontal to the ground, which is a slower method than horizontal mode where they are held perpendicular to the ground.
7. Resistivity is the preferred direct measurement technique for this depth to watertable but EM34 is provided as a potentially more accessible alternative.
8. This should be conducted immediately adjacent to the channel.
9. This should be conducted on-channel.
10. The penetration depth of resistivity depends of the particular system set up (dipole spacing and length).
11. Resistivity surveys measures resistivity at a range of depths intervals within the profile (ie, there is no depth focus).

4. *Conduct geophysical survey* – Undertake the geophysical survey over the section of interest, giving due consideration to factors such as appropriate timing of the survey and other important variables (refer section 5.5.1.3).

5. *Evaluate results* – Plot geophysical survey results along the section and overlay with known site conditions (soils, geology, hydrogeology and channel hydraulic data). Based on these plots identify areas of suspected high, low and moderate seepage, assuming low conductivity / high resistivity equates to higher seepage.

6. *Conduct test drilling* – Soil bores should be drilled at appropriate intervals along the length of the geophysical survey. The primary aim of the drilling is assist with interpretation of the geophysical survey. Some key principles of the drilling program are described below:
   - Based on the geophysical survey results, conduct drilling across a range of low, moderate and high conductivity / resistivity sites;
   - Drill at least some bores into the watertable, and construct some as permanent observation bores;
   - Generally drilling should be conducted on the outside toe of the channel;
   - Logging and sampling of the bores should ideally be undertaken by someone trained in soil / geological classification and a consistent classification system should be followed.
   - Depending on the density of data collected, presenting the results in a geological long section should be considered.

7. *Conduct pondage tests* - At appropriate intervals over the entire test area pondage tests are to be conducted. The number of tests will depend on the length of channel surveyed and the variability of conditions along the channel. The following guidelines are suggested:
   - Pondage tests should be conducted across a range of low, moderate and high conductivity / resistivity sites so as to establish a regression equation which represents the range of geophysical response across the area.
   - Similarly, based on the soil drilling results, the pondage tests should be based on a range of different soil types and / or groundwater conditions.
   - Pondage tests must be conducted over areas of like conductivity / resistivity. That is they should not staddle areas of (significantly) different geophysical response, as this will complicate interpretation of the results and development of the regression equation.
   - Due to the cost of conducting pondage tests, it is recommended that at least two cells back to back should be conducted at each site for efficiency purposes. Using available structures should also be considered to minimise bank construction costs.
   - The pond length can be variable, but as a guide they should generally not be more than 400-500m and not less than 50m.

By conducting pondage tests in this manner across the area of the geophysical survey, prediction of seepage rates outside of pondage test areas will be based on interpolation rather than extrapolation, which improves confidence in the predicted seepage. While pondage tests are expensive, they are a critical part of the interpretation process.

8. *Develop and evaluate relationship between seepage and geophysical response* – The following key steps should be conducted:
   - Plot geophysical response against pondage test seepage.
   - Outliers in particular should be assessed in light of all available information, including the conceptual seepage mechanism, test drilling results, channel hydraulics etc. If there are legitimate grounds for excluding outliers they should be removed.
   - If from this data two or more different trends can be observed due to identifiable differences in sub-surface conditions, then two different regression equations should be generated.
   - Fit a regression line through the data.
   - Statistical analysis should be conducted to determine the degree of confidence that can be placed in the derived relationship
   - Using the derived relationship the channel length should be divided into seepage categories of various seepage rates based on geophysical response, with accompanying error estimates.

9. *Evaluation* - Evaluate whether investigation objectives have been met. One of the key questions to address is whether there is sufficient confidence in the derived relationship. In addition to the particular statistics of the regression line, this will largely depend on the project objectives. Further pondage tests or other testing may be required to further improve confidence in the relationship.

5.5.1.8 International Developments in Geophysics and Channel Seepage Measurement

Since the writing of the Literature Review conducted as part of this project (ANCID, 2000a), several papers have been published relating to international developments in channel seepage measurement using geophysics. Two key papers are briefly summarised below. The important point relating to this work is that it is focussed in the same direction as the geophysical investigations in these trials: developing geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the two and then extrapolation / interpolation to new areas.

Determining Irrigation Canal Seepage with Electrical Resistivity (Hotchkiss et al, 2001)
<u>Summary of Abstract</u>: Procedures were developed and tested for quantifying seepage losses in unlined irrigation channels reaches on the order of 30m, in the Central Nebraska Public Power and Irrigation District canal system. The procedure uses electrical resistivity (ER) measurements while canals are in service to determine the resistivity of the underlying clay layer. ER data were correlated to canal depth and then to seepage rate. Seepage rates were determined using seepage meters. Accuracy is approximately ± 20%, comparable to that achieved using stream gauges methods (± 5% error of total canal discharge). The ER approach, however can easily pinpoint

seepage zones more precisely, allowing a reduction in the length of canal lining projects.

Comparisons to this investigation:

- The method used in the Hotchkiss et al (2001) study relies on measuring unsaturated zone soil properties and not seepage directly, ie it is a method which infers the likelihood of seepage. It is based on the theory that 'as resistivity increases, seepage rates will also increase because more sandy or less clayey materials will have higher resistivities' (Hotchkiss et al, 2001). This was also shown to be successful in the ANCID investigations project (eg EM31 at deep watertable sites). This is a valid method but potentially has limitations at some sites.
- Seepage meters rather than pondage tests were used as the direct seepage measurement technique (possibly limited by operational requirements, ie could not shut channel down). Confirming the general unreliability of seepage meter readings, 50% of sites where readings were conducted were discarded as unreliable. This highlights the advantage of pondage tests over seepage meters. The only advantage of the seepage meter is that smaller length areas can be selected; 30m used in Hotchkiss et al (2001) study. (It is not recommended pondage tests be conducted over less than 50m of channel).
- Best correlations were found at 4m depth – similar to this project. Soil properties from the upper part of the profile were found to be most influential on seepage rates.
- Due to considerable depth and variation in channel water, the data first had to be correlated to canal depth and then to seepage rate, whereas in this ANCID study, the depth of channel water was reasonably consistent and this step was not required.

5.5.2 Summary of EM34 Results

Table 5-8 presents a summary of all EM34 trials conducted in the program compared to pondage test seepage. All trials were conducted in horizontal dipole mode, at a 10m coil spacing and along the outside toe of the down slope side of the channel. The exception was the two Dahwilly sites where both 10m and 20m coil spacings were used, and survey runs along the outside toe of both sides of the channel were conducted.

Good to moderate relationships were obtained between average EM34 conductivity and the corresponding pondage test seepage at most sites. For EM34 at a 10m coil spacing in horizontal mode, the effective depth of penetration is around 6-7m, with a shallow depth focus at around 1-3m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is predominantly via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

- **Rocklands** – A good relationship was recorded in both surveys. A high degree of repeatability was demonstrated between the two EM34 surveys conducted.
- **Donald Main** – A moderate relationship was recorded in both surveys. Further points are required in the mid-seepage range to appropriately test the relationship. The technique distinguished between high and low seepage but not within the high seepage results range. Possible interference by adjacent trees may have effected results in some ponds. A generally consistent increase in conductivity was observed between repeat surveys. The difference was caused by the higher watertable and reduced channel running time prior to the survey.
- **Toolondo Central** – A moderate relationship was observed but largely skewed by the result in one pond. The relationship distinguished between high and low seepage rates.
- **Dahwilly Central** - Moderate relationship for 10m coil separation but a very low range of conductivity response was recorded across the five ponds used in the analysis. This is because the EM34(10m) configuration does not penetrate to sufficient depth to significantly detect changes in the groundwater and was therefore mainly measuring differences in the unsaturated zone, which is largely uniform at the Dahwilly site. The EM34(20m) configuration penetrated too deeply below the watertable and therefore a uniform response was observed reflecting native groundwater conditions.
- **Dahwilly East** – No relationship was observed. The seepage rate range was too narrow for a meaningful relationship to be derived.

In summary, the only site where no relationship was observed was at Dahwilly East, which was largely due to the narrow seepage rate range. At the Toolondo central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence a reasonable trend was observed (a fact reinforced by the success of EM31 at the site). Significantly, the resistivity surveying showed improved correlations compared to the EM34, for the depth slices focussed immediately below the watertable.

The Donald site survey was focussed on the saturated zone, however the EM31 survey at the site demonstrated a slightly better relationship with pondage test seepage compared to the EM34 (R^2=0.73 compared to R^2=0.50), but neither survey differentiated between the higher seeping ponds. The improved correlation is probably attributable to the deeper depth focus of the EM31 compared to the EM34 (10m, vertical dipole configuration).

At the Rocklands and Dahwilly sites, where the penetration depth (EM34 - 10m coil separation, vertical dipole) was just sufficient to reach the watertable (but the focus was above the watertable), the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone worked to provide a reasonable indicator of seepage. However it is significant that at Dahwilly, where resistivity surveying was conducted, an improved relationship was obtained when the depth slice was focussed immediately below the watertable, where seepage impacts are most discernible.

- **Table 5-8 Summary of EM34 Trials Compared to Pondage Test Seepage**

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Correlation Coefficient	Water-table Depth (approx.)	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Repeatability	Comparison with other geophysical techniques	Reported in Section
Rocklands	EM34, 10m coil separation, horizontal dipole	Nov. 1999	Down gradient outside channel toe	Yes	6	4 - 13 mm/d	0.79	5m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Good Relationship: A good spread of seepage results, relatively low scatter about the regression line and a good correlation coefficient.	-	Refer below (Aug. 2001 survey)	Adjacent channel results very similar to EM31 correlations	5.2.2.1
Rocklands	EM34, 10m coil separation, horizontal dipole	Aug. 2001	Down gradient outside channel toe	Yes	6	4 - 13 mm/d	0.75	5m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Good Relationship: A good spread of seepage results, relatively low scatter about the regression line and a good correlation coefficient.	-	High degree of repeatability demonstrated	-	5.2.2.1
Donald Main	EM34, 10m coil separation, horizontal dipole	Oct. 1999	Down gradient outside channel toe	Yes (commenced operation 4 weeks prior to survey)	6	9 - 45 mm/d	0.43	2m	Primarily dilution of groundwater from fresher seepage water	Moderate Relationship: Good range of seepage results but moderate to poor correlation coefficient. Further points required in mid seepage range. Distinguished between high and low seepage but not within the high seepage results. Possible interference by trees	-	Refer below (Sept. 2001 survey)	A slightly better relationship was established with EM31(v) adjacent the channel (R2=0.73), but still no differentiation between the higher seeping ponds	5.2.2.2
Donald Main	EM34, 10m coil separation, horizontal dipole	Sept. 2001	Down gradient outside channel toe	Yes (commenced operation 4 weeks prior to survey)	6	9 - 45 mm/d	0.50	3m	Primarily dilution of groundwater from fresher seepage water	As above for Oct. 1999 survey	-	A generally consistent increase (15-20 mS/m) observed compared to Oct. 1999 survey. Regression line shifted vertically (but gradient similar). Diff. attributed to higher WT & reduced channel running time	-	5.2.2.2
Toolondo Central	EM34, 10m coil separation, horizontal dipole	Aug. 2001	Down gradient outside channel toe	Yes	6	1 - 11 mm/d	0.50	10m	Primarily inferred from differences in unsat. zone soil properties	Moderate Relationship: Good range of seepage results but moderate correlation coefficient - largely skewed by the result in one pond. Distinguished between high and low seepage rates.	-	-	An improved relationship obtained with EM31, indicating method of detecting lithology changes in the unsaturated zone has worked at this site. For resistivity improved co-efficients were obtained for 10m & 12m slices, due to better penetration into top of saturated zone	5.2.2.3
Dahwilly Central	EM34, 10m coil separation, horizontal dipole	Feb. 2002	Adjacent both outside channel toes	Yes	7 (only 5 used in analysis)	1.1 - 9.5 mm/d (4.2 - 9.5 mm/d: used in analysis)	0.79	5m	Primarily inferred from unsat. zone soil properties & secondarily dilution of g'water	Moderate Relationship: Good correlation coefficient - but very low range of conductivity response across five ponds used in the analysis. The EM34(10m) configuration does not appear to have penetrated to sufficient depth to significantly detect changes in the saturated zone and was therefore mainly measuring differences in the unsaturated zone, which is largely uniform at the Dahwilly site.	This relationship would not have successfully quantified rates at Dahwilly East - would have resulted in significant underestimation	-	Similar strength relationship observed for EM31, with better spread of conductivity results. Stronger resistivity results obtained at 8m & 10m depth slices due to targeting of most effected area of WT.	5.2.2.4
Dahwilly Central	EM34, 20m coil separation, horizontal dipole	Feb. 2002	Adjacent both outside channel toes	Yes	7 (only 5 used in analysis)	1.1 - 9.5 mm/d (4.2 - 9.5 mm/d: used in analysis)	0.04	5m	Primarily dilution of groundwater from fresher seepage water	No relationship: The EM34(20m) configuration appears to have penetrated too deeply into the profile, below the upper zone in the watertable aquifer where seepage effects are most prominent. The uniform response observed is therefore essentially a reflection of the salty native groundwater	NA - No relationship observed	-	-	5.2.2.4

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Correlation Coefficient	Water-table Depth (approx.)	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Repeatability	Comparison with other geophysical techniques	Reported in Section
Dahwilly East (Pretty Pine)	EM34, 10m coil separation, horizontal dipole	Feb. 2002	Adjacent both outside channel toes	Yes	3	8.9 - 10.4 mm/d	0.26	5-6m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Poor relationship: Seepage rate range is too narrow to draw meaningful conclusions	-	-	No relationship observed for EM31. A sensible relationship was observed for the resistivity 6m depth slice.	5.2.2.4
Dahwilly East (Pretty Pine)	EM34, 20m coil separation, horizontal dipole	Feb. 2002	Adjacent both outside channel toes	Yes	3	8.9 - 10.4 mm/d	0.24	5-6m	Primarily dilution of groundwater from seepage	Poor relationship: Seepage rate range is too narrow to draw meaningful conclusions	-	-	-	5.2.2.4

5.5.3 Summary of EM31 Results

Table 5-9 presents a summary of all EM31 trials undertaken in the program compared to pondage test seepage. Trials on land were conducted in vertical dipole mode and generally included 3-4 runs along the outside of the channel, with the outer runs approximately 50m from the channel. The exception was the Waranga Western Channel where due to the length of the survey only one line on the outside toe of each bank was conducted. Trials conducted on-channel were undertaken in both vertical and horizontal dipole.

Good relationships were obtained between average EM31 conductivity and the corresponding pondage test seepage at most sites. At only one site (Tabbita) was there no significant relationship identified. For EM31 in vertical dipole mode, the effective depth of penetration is around 6-7m, with a mid-range depth focus of about 2 – 4.5m (refer 5.3.2.1). This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is largely via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

Toolondo

- Good relationships between EM31 conductivity and pondage tests seepage were recorded in all three surveys at Toolondo Central. This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties.
- A high degree of repeatability between the surveys was observed.
- In-channel (shortly after channel shut down) and on-channel EM31 surveys returned poor results. This is attributed to the fact that an EM31 survey above the watertable ‘works’ by inferring seepage based on soil properties. However immediately beneath the channel, even for low seepage rate ponds the profile beneath the channel is saturated (or near saturated) with seeped water. This uniform saturation produces a uniform conductivity response, and tends to mask changes in lithology resulting in little differentiation between low and high seepage sites. Significantly however the on-channel resistivity survey recorded good correlations between seepage and resistivity (10m and 12m depth slices). The EM31 on-channel however could not 'see' into the watertable.
- Better results were obtained with the EM31 compared to the EM34(10m) at this site, possibly due to the greater number of EM31 traverses conducted (ie away from the channel).
- Three Toolondo Sites (Central, East and West) - The relationship established for all sites was moderately strong. Local correlations at Toolondo Central and Toolondo West were stronger than the combination of sites. The Toolondo East site displayed an opposite correlation, but the very narrow range of seepage rates & the flat regression line indicates this is not a meaningful trend. Confidence bands for the overall regression relationship are wide but indicate that the relationship can be used to differentiate between high and low seepage sites. The data most contributing to the low R^2 and wide confidence bands is the four ponds with sandy banks at Toolondo Central. It is apparent the shallow depth of the sand causing the seepage (largely through channel banks) is largely missed by the EM31(vertical) with a depth focus of around 2 - 4.5m.

- If the Toolondo Central site had been used to predict seepage at Toolondo West, predicted seepage would have been 2-3 times too high. At Toolondo East it would have been essentially accurate (0 mm/d), except in one pond seepage would have been predicted at 4 mm/d when actual seepage is practically zero.

Rocklands

- A good relationship was observed between EM31 response and pondage test seepage at the Rocklands channel trial site (for the adjacent channel EM31 data). This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties. However, with a depth to watertable of around five metres, the EM31 survey may also have been detecting some seepage induced salinity changes in the watertable.
- A poor response was observed when all survey runs were used, largely due to the effect of trees adjacent one pond. The adjacent channel run was less affected and accordingly better results were returned.
- The on-channel results recorded mixed results. In vertical dipole mode no trend was observed. The configuration is focussed on the flushed zone beneath the channel where uniform saturation from seepage appears to be masking lithology response. In horizontal dipole a reasonable correlation was observed, apparently through identification of lithology changes (clay content) immediately beneath the channel. This was the only case observed where on-channel measurement above the watertable successfully correlated with seepage. At other sites the uniform saturation appeared to dominate the response over changes in lithology, however at this site it is apparent that the changes in lithology close to the channel surface are sufficiently contrasting to distinguish between high and low seepage areas.

Donald Main

- A good relationship was observed between EM31 conductivity and pondage test seepage but there is a poor spread of seepage data at the site (1 point of low and 5 of high seepage). With a relatively shallow watertable (2m), the EM31 detects seepage at this site in terms of its impacts on the watertable. The EM31 survey did not distinguish between higher seepage ponds (35 - 48mm/d). Confidence bands are fairly wide for the regression line, particularly at the high conductivity range, but indicate that the relationship can differentiate between high and low seepage sites. Additional data points are required to tighten confidence bands.
- A better relationship was established with EM31 (R^2=0.71) adjacent the channel compared to EM34 (R^2=0.50) but there was still no differentiation observed between the higher seeping ponds. The improved relationship is probably due to the greater depth focus of EM31, particularly on the up-slope side of the channel, allowing deeper penetration into the watertable
- Moderate to good relationships were also observed for the on-channel surveys in both horizontal and vertical dipole. With a shallow depth to watertable the EM31 on-channel survey detects seepage as it impacts the watertable.

Dahwilly

- For a survey conducted when the channel was not running, no relationship was observed between EM31 conductivity and pondage test seepage. The technique failed because the channel was not running and previously seeped water was therefore likely to have thoroughly mixed with native groundwater. Unsaturated zone lithology is a good indicator of seepage at some sites. However at Dahwilly it is not the unsaturated zone controlling seepage rates, but the clogging layer at the channel surface and therefore seepage must be detected directly (ie in terms of impact on watertable) which means the channel must be in operation.
- In a repeat survey conducted when the channel was operating, a good relationship was observed (at Dahwilly Central), confirming the importance of identifying the seepage plume as the primary seepage detection mechanism at this site.
- Two Dahwilly Sites (Central and East) - The relationship established for both sites is moderately strong. Local correlation at the Central site is slightly stronger than the two sites combined. The East site displays a very weak correlation, but this is due to the very narrow seepage range and few data points at this site. Confidence bands are relatively wide, suggesting the regression relationship for both sites can only be used to broadly indicate the likelihood of low or moderate seepage. The slightly deeper depth to watertable at the East site appears to have put the watertable largely beyond the range of EM31 and hence very different results are obtained at the East site. Using the Central site regression relationship to predict seepage at the East site would have resulted in over prediction of 1.5 - 2 times actual seepage.
- Better correlations at both sites were obtained using the resistivity compared to EM31 due to better targeting of the top of the watertable.

Lake View

- A poor relationship between pondage test seepage (July 2001) and EM31 conductivity (June 2000) was obtained at Lake View Central for all data due to rapid mixing of the seepage plume away from the channel. However for adjacent channel data a significantly improved relationship (to moderate) was observed as seepage impacts are less diluted. Interpretation is limited at this site due to the very narrow seepage rate range. Seepage is detected at this site in terms of its impact on watertable salinity.
- No sensible trend was observed at the Lake View Central site using the same EM31 survey data (all lines) and the June 2002 pondage tests. It is anticipated however that a better response could be obtained using the adjacent channel data, as was the case for the July 2001 pondage tests. In addition, the 2002 pondage tests may not have been properly placed over sections of like conductivity.
- Both Sites (Central and West) - The relationship established for both sites is moderately strong with a high correlation coefficient but the two data sets creating the regression line have small conductivity and seepage rate ranges. It is desirable to obtain data in the mid range to improve confidence in the relationship. The Central site could not have been used to predict seepage at the West site. However using Central data from adjacent the channel is likely to improve this correlation.

Tabbita

- No relationship was observed between EM31 conductivity and pondage test seepage. Possible reasons for the failure of the technique at this site include:

  v) Narrow range of seepage rates (little differentiation in rates along section of interest);

  vi) Seepage mechanism may be such that majority of seeped water does not reach watertable but move laterally (evaporating and causing salinisation as evidence adjacent the channel);

  vii) EM31 vertical dipole orientation may penetrate too deeply into the native groundwater, below the zone most effected by seepage; and,

  viii) The method of averaging conductivity may not be appropriate at this site (or the ponds may need to be placed more carefully, ie over shorter sections of high/low conductivity)

Finley

- While a moderate correlation coefficient was obtained for the pondage test – EM31 conductivity relationship at this site (and the highest seeping pond did record the lowest conductivity), the statistics are not meaningful due to the fact that only three data points make up the relationship. The width of the prediction intervals indicate that the regression relationship cannot be used to predict seepage at this site. Additional data points across a wider seepage range are required to improve the relationship.

Waranga Western Channel

- A moderate to poor relationship was recorded between EM31 conductivity and pondage test seepage. However the results should be considered in light of the fact that they represent seepage sites more than 20 km apart (significantly further than other sites). The watertable is generally beyond the penetration depth of the EM31 along the survey reach and therefore the likelihood of seepage is inferred based on soil properties beneath the channel.
- Some of the scatter in the results can be explained by incorrect pond placement (ie not straddling areas of like conductivity) as well as some geological anomalies. When points of high variance and leverage are removed, the correlation coefficient improves to 0.62 (from 0.40). The prediction interval bands suggest the relationship can be used to distinguish between sites of low and high seepage, but is limited in interpreting mid-range seepage.
- An improvement would be expected if the top of the watertable was targeted, rather than inferring seepage from unsaturated zone soil properties. Given that the ponds are significantly spaced apart, this relationship can be used for interpolation, bearing in mind the associated broad prediction intervals associated with the regression line.

In summary, the only site where no relationship was observed was at Tabbita. A number of possible causes for this were identified, but the predominant contributing factor is not known. At two sites (Rocklands and Lake View Central), the adjacent channel data was used instead of all survey run data. This was required to obtain the best relationship, due to the interference effects of trees and rapid mixing of seepage water away from the channel.

At the Toolondo central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence good trends were observed.

The Donald and Lake View site surveys were focussed on the saturated zone, and seepage was detected as it created a conductivity low against higher background conductivity groundwater.

At the Rocklands and Dahwilly sites, where the penetration depth of the EM31 (in vertical dipole) was just sufficient to reach the watertable, the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone combined to provide a reasonable indicator of seepage. However it is significant to note that at Dahwilly, when the channel was not running, no relationship was observed. This suggests seepage impacts in the watertable are the primary detection mechanism at this site, a fact reinforced by the uniform nature of the unsaturated zone lithology at the site. Seepage at Dahwilly is not controlled by the unsaturated zone but by a clogging layer at the base of the channel. Techniques which purely infer seepage from unsaturated zone soil properties will not work at such sites (including remediated or lined channels).

At Waranga a reasonable relationship was observed, considering the distance over which the data forming the relationship was spread. Improvements might be expected using a technique targeting the top of the watertable at this site.

On-channel surveys did not work at sites where the watertable was beyond the range of the EM31 (Toolondo), did work at sites with a shallow watertable (Donald) and were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31 (Rocklands). Further work is required in this area, but the evidence collected in this investigation suggests on-channel surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

■ **Table 5-9 Summary of EM31 Trials Compared to Pondage Test Seepage**

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Correlation Coefficient	Standard Error of Estimate	Water-table Depth (approx.)	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Repeatability	Comparison with other geophysical techniques	Reported in Section
Toolondo (Central)	EM31, vertical dipole	Dec. 2000	4 traverses each side of channel (up to 50m) & One in channel	No (1-2 weeks after channel stopped flowing)	6	1 - 11 mm/d	All data: 0.72; In-channel data: 0.04; Channel sides: 0.73	-	10m	Inferred from unsat. zone soil properties	All Data / Channel sides: Good Relationship – good spread of seepage results, moderate scatter about regression line and a good correlation coefficient. In-channel data: No relationship. Immediately beneath channel soils are uniformly saturated (even for low seepage ponds) which in turn produces a uniform conductivity response. (Outside channel results predominantly measure unsat. zone soil properties)	-	Refer below (Aug. 2001 survey)	Better results obtained than the EM34(10m), possibly due to the greater number of traverses conducted (ie away from the channel). Similar results achieved using resistivity (10m/12m depth slices) but this detects actual seepage impacts in the watertable	5.3.3.1
Toolondo (Central)	EM31, vertical dipole	Aug. 2001	4 traverses each side of channel (up to 50m)	Yes	6	1 - 11 mm/d	All data: 0.81 Adj. channel only: 0.80	-	10m	Inferred from unsat. zone soil properties	All Data: Good Relationship - good spread of seepage results, moderate scatter about regression line and a good correlation coefficient.	-	High degree of repeatability of results compared to Dec. 2000. Correlation coefficient between surveys of 0.96 for average pondage cell response	Refer above	5.3.3.1
Toolondo (Central)	EM31, vertical dipole & horizontal dipole	Aug. 2001	On-channel	Yes	6	1 - 11 mm/d	Horizontal dipole: 0.21 Vertical Dipole: 0.05	-	10m	Inferred from unsat. zone soil and water content properties	No relationship / Very poor relationship: Even for low seepage rate ponds the profile beneath the channel is saturated with seeped water. This uniform saturation produces a uniform conductivity response. Lithology effects appear to be largely masked by seepage saturation at this site	-	-	Significantly, the on-channel resistivity recorded much better correlations (below the watertable) than the on-channel EM31. The EM31 could not 'see' below the watertable whereas the resistivity could target this zone	5.3.3.1
Rocklands	EM31, vertical dipole	Aug. 2001	4 traverses each side of channel (up to 50m)	Yes	6	4 - 13 mm/d	All data: 0.33 Adj. channel only: 0.82	-	5m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Poor relationship for 'All Data' largely due to effect of trees adjacent one pond. Therefore, best relationship observed for 'Adjacent Channel' data (most distant from trees): Good spread of seepage values, moderate scatter about regression line and good correlation coefficient	-	-	Adjacent channel results very similar to EM34 correlations	5.3.3.2
Rocklands	EM31, vertical dipole & horizontal dipole	Aug. 2001	On-channel	Yes	6	4 - 13 mm/d	Horizontal dipole: 0.78 Vertical Dipole: 0.15	-	5m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Horizontal dipole: Reasonable correlation observed through identification of lithology changes (clay content) immediately beneath channel. Did not distinguish between high rates however. Vertical Dipole: No trend observed. Configuration is focussed on flushed zone beneath the channel (immediately above watertable) where uniform saturation from seepage (in clays and sands) appears to be masking lithology response. (Also poor resolution of meter at low conductivities)	-	-	-	5.3.3.2
Donald Main	EM31, vertical dipole	Sept. 2001	4 traverses each side of channel (up to 50m)	Yes (commenced operation 3 weeks prior to survey)	6	9 - 48 mm/d	All data: 0.73 Adj. channel only: 0.69	23%	1.5m (downslope); 3m (upslope)	Primarily dilution of groundwater from fresher seepage water	Moderate to good relationship: Good correlation coefficient, acceptable scatter about regression line (SEE = 23%) but poor spread of seepage data (1 point of low & 5 of high seepage). Did not distinguish between higher seepage ponds (35 - 48mm/d). Confidence bands wide, particularly at high conductivity range, but can differentiate between high & low seepage sites. Additional data points required to tighten confidence bands.	-	-	A slightly better relationship established with EM31adj. the channel compared to EM34 (R2=0.50) but still no differentiation between the higher seeping ponds. Slightly improved relationship probably due to greater depth focus of EM31 (particularly on	5.3.3.3 and 5.3.5.3

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Correlation Coefficient	Standard Error of Estimate	Water-table Depth (approx.)	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Repeatability	Comparison with other geophysical techniques	Reported in Section
														upslope side)	
Donald Main	EM31, vertical dipole & horizontal dipole	Sept. 2001	On-channel	Yes (commenced operation 3 weeks prior to survey)	6	9 - 48 mm/d	Horizontal dipole: 0.83 Vertical Dipole: 0.77	-	1.5m (downslope); 3m (upslope)	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	Moderate to good relationship for both horizontal & vertical dipole: Good correlation coefficient but some scatter about regression line & poor spread of seepage data (1 point of low seepage and 5 of high seepage). Did not distinguish between higher seepage ponds (35 - 48mm/d). Data suggests exponential or other non-linear trend line may provide better fit		-	-	5.3.3.3
Dahwilly Central	EM31, vertical dipole	June. 2000	4 traverses each side of channel (up to 50m)	No (Ceased to operate several weeks prior to survey)	6	4 - 16 mm/d	0.49 (opposite correlation)	-	5-6m	Inferred from unsat. zone soil properties	No relationship observed. Technique failed at this site because the channel was not running at the time (previously seeped water therefore likely to have mixed in with native groundwater) and it primarily targeted the unsaturated zone in any case. While unsaturated zone lithology is a good indicator of seepage at some sites, at Dahwilly it is not the unsaturated zone controlling seepage rates, but the clogging layer at the channel surface.	-	-	EM34 'worked' because the channel was running	5.3.3.4
Lake View Central	EM31, vertical dipole	June. 2000	4 traverses each side of channel (up to 50m)	Yes	5	7 - 9 mm/d	All data: 0.34 Adj. channel only: 0.58	-	1.5m	Primarily dilution of groundwater from fresher seepage water	Poor relationship for All Data due to rapid mixing of seepage plume away from channel, however for Adjacent Channel data this improves to moderate as seepage impacts are more discernible. Interpretation limited at this site due to the very narrow seepage rate range (7-9 mm/d).	-	-	Similar R2 to Lake View Resistivity, March 2002(Res) v July 2001(PT): 0.58 & 0.60.	5.3.3.5
Tabbita	EM31, vertical dipole	June. 2000	4 traverses each side of channel (up to 50m)	Yes	6	6 - 10 mm/d	All data: 0.01	-	1m	Primarily dilution of groundwater from fresher seepage water	No relationship observed. Possible reasons for technique failure at this site: i) Narrow range of seepage rates (little differentiation in rates along section of interest), ii) Seepage mechanism may be such that majority of seeped water does not reach watertable but move laterally (evaporating and causing salinisation), iii) EM31 vertical dipole may penetrate too deeply into native gw, below diluted zone, iv) method of average conductivity ,may not be appropriate at this site (or ponds need to be placed more carefully - over shorter sections of high/low conductivity)	-	-	-	5.3.3.6
Toolondo (Central, East & West) and Rocklands	EM31, vertical dipole	Rockl'ds: Aug. 01 Toolondo (Central, East & West): March 2002	4 traverses each side of channel (up to 50m)	Yes	Rockl'ds: 6 Toolondo: Central - 7, East - 4 and West - 4 Total - 21	0 - 12 mm/d	Rockl'ds: 0.33 (0.84 adj.) Toolondo: Central - 0.78, East - 0.49 (opposite) and West - 0.86 All Sites - 0.47	All Sites: 61%	Rockl'ds: 5m Toolondo (Central, East & West): 10-12m	Inferred from unsat. zone soil properties (& at Rocklands some dilution of g'water with seeped water)	The relationship established for all sites is moderately strong. Local correlations at Rocklands (adj.), Tool. Central, & West are all stronger than the combination of sites. The Tool. East site displays an opposite correlation, but the very narrow range of seepage rates & the flat regression line indicates this is not a meaningful trend. Confidence bands are wide but indicate that the regression relationship can be used to differentiate between high & low seepage sites. The data most influential on the low R2 and wide confidence bands is the 4 sandy ponds at Toolondo Central - it is apparent the shallow depth of the sand causing the seepage is largely missed by EM31(vertical)	If the Toolondo Central site had been used to predict seepage at: Tool. West - predicted seepage would have been 2-3 times too high, Tool. East - essentially accurate (0 mm/d) except one pond would have predicted 4mm/d when actual is 0 mm/d	-	West: Correlations of the 2m & 4m resistivity depth slices with PT seepage match with EM31 correlations, which are focussed in the 1-4m depth range East: no meaningful correlations obtained with resistivity (too narrow seepage range) Central: See above	5.3.5.2
Dahwilly (Central & East)	EM31, vertical dipole	Feb. 2002	4 traverses each side of channel (up to 50m)	Yes	Central - 5 and East - 3; Total - 8	4 - 10 mm/d	Central: 0.64 & East: 0.15; All Sites: 0.58	All Sites: 21%	Central: 5m & East: 6m	Inferred from unsat. zone soil properties & dilution of g'water with seeped water	The relationship established for combined sites is moderately strong. Local correlation at Central site is slightly stronger than the 2 sites combined. The East site displays a very weak correlation, but this is due to the very narrow seepage range and few data points at this site. Confidence bands are relatively wide, suggesting regression	Using Central site to predict seepage at East site: over pred'n of 1.5 -2 times actual seepage, due to slight diff. in	EM31 was conducted in 2000 adjacent to the Central site. No trends were observed as the channel was not	Better correlations at both sites obtained using the resistivity compared to EM31(vert) due to better targeting of the top of the watertable. Similar results obtained for EM34, but	5.3.5.4

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Correlation Coefficient	Standard Error of Estimate	Water-table Depth (approx.)	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Repeatability	Comparison with other geophysical techniques	Reported in Section
											relationship for both sites can only be used to broadly indicate the likelihood of low or moderate seepage. Slightly deeper depth to watertable at East site appears to have put watertable largely beyond EM31(vertical) range and hence very diff. results obtained at East site.	depth to WT (caused EM31 to largely miss seepage impact on gw at East site) and gw salinities between the two sites.	running. In this survey (2002) with the channel running, the EM31 (vertical) detected seepage impacts on the watertable and hence trends and correlations were observed.	EM34 displays wider conductivity range (due to deeper focus)	
Finley	EM31, vertical dipole	Feb. 2002	4 traverses each side of channel (up to 50m)	Yes	3	5 - 7 mm/d	0.47	18%	1.5m	Primarily dilution of groundwater from fresher seepage water	Statistics not meaningful due to low no. data points, (did detect area of higher seepage however as conductivity low) Confidence intervals indicate regression relationship cannot be used to predict seepage at this site Extremely high conductivity site – very clayey profile suggests bank leakage rather than soil seepage is the dominant seepage mechanism Additional data points and wider seepage range required to improve relationship	-	-	Better correlations obtained at 4m using resistivity than the EM31(vert) due to better targeting of the top of the watertable	5.3.5.5
Lake View (Central & West)	EM31, vertical dipole	Central: June 2000 West: May 2002	4 traverses each side of channel (up to 50m)	Yes	Central - 4 & West - 4; Total - 8	4 - 25 mm/d	Central: 0.46 (opposite) & West: 0.54; All Sites: 0.94	17%	Central: 1.5m & West: 0.5m	Primarily dilution of groundwater from fresher seepage water	Good R^2, SEE & prediction interval but 2 data sets creating the regression line have small conductivity and seepage rate ranges – Desirable to obtain some data in mid range to improve confidence No sensible trend at LV Central site – however important to note that the same EM31 data at LV Central when applied to 2001 PTs returned a sensible inverse correlation - this correlation was further improved when the 2 survey lines adj. channel were used (refer above). It is anticipated a better response could be obtained with the current PTs using the adj. channel data (this has not be done however for consistency)	LV Central site could not have been used to predict LV West seepage. However LV Central adjacent data likely to improve correlation (refer 'Summary on Seepage…..' column). LV West data reasonably predicts Central seepage	-	West: The fact that a sensible correlation was not observed for shallow resistivity data but was for EM31 suggests poor resolution of surface data by the resistivity array at this site. Central: Refer above	5.3.5.6
Waranga	EM31, vertical dipole	Nov. 2001	Traverse on each side of channel (outer toe) & on the channel	Yes	11	1 - 13 mm/d	0.40	63%	Variable (approx. 8m)	Primarily inferred from unsat. zone soil properties	Moderate to poor R^2, SEE & prediction interval - however these results should be considered in the light of the fact that they represent seepage sites more than 20 km apart. Some of the scatter in the results can be explained by incorrect pond placement (ie not straddling areas of like conductivity) as well as some geological anomalies. When points of high variance & leverage removed, R2 improves to 0.62. Prediction interval bands suggest relationship can be used to distinguish b'tw.n sites of low & high seepage, but is limited in interpreting mid-range seepage sites Improvement expected if top of WT targeted	Given that the ponds are significantly spaced from each other, this relationship can be used for interpolation, bearing in mind the associated broad prediction intervals associated with the regression line.	-	-	6

5.5.4 Summary of Resistivity Results

Table 5-10 presents a summary of all resistivity data collected in the program compared to pondage test seepage. The depth at which the best correlation was recorded is presented. Good relationships were obtained between average resistivity (from depth slices immediately below the watertable) and the corresponding pondage test seepage at most sites. Key summary comments for each of the sites are listed below:

Toolondo

- Central – At around 10-12m the best correlation was obtained (R^2=0.6), which is the zone immediately below the watertable and fits with the expected mechanism of seepage detection (ie, in the depth interval of groundwater most effected by seepage). Within individual ponds, the resistivity cross sections show sub-sections of localised higher seepage. There is very little correlation in the unsaturated zone.
- East - The very narrow range of seepage rates and resistivity values meant that no meaningful correlations were observed at the Toolondo East site.
- West - At and below the watertable the expected inverse trend between high resistivity - low seepage and low resistivity - high seepage was not observed. It is apparent that the sandstone at this site may be dominating the response. Low permeability sandstone may be causing a high resistivity response (normally associated with high seepage), and masking the effect of seepage on the saline groundwater. Deeper drilling would be required to confirm this interpretation. The reasonable correlations obtained at shallow depth (2m and 4m depth slices) are most likely due to changes in clay content beneath the channel, and corresponds with observed EM31 relationships.
- All Sites – The Toolondo East data (av. 10/12/14m depth slices) lies within the expected extrapolated range for the Central (10m) site. The West (av 10/12m depth slices) data does not fit within the Central and East relationship (possibly due to changes in lithology masking seepage impacts). The West 2m depth slice does fit within the relationship, however without pondage tests it would not have been known that this was the better depth on which to focus.

Dahwilly

- Central - Good correlations were observed at the 6m, 8m and 10m depth slices, which fits with the expected mode of seepage detection below the watertable. Correlation coefficients worsen in the unsaturated zone. Resistivity long sections indicate that seepage is generally diffuse across the surveyed area, in contrast to Toolondo where localised seepage is evident from the resistivity data.
- East – A strong correlation was observed at 6m which corresponds with the top of the watertable. However, the very narrow range of seepage rates and small number of data points limits the significance of these correlations.
- Both Sites - Two vertically offset regression lines for the Dahwilly sites are recorded and there is no observed trend for the combined regression line. This suggests different background conditions (despite apparent similarities between sites), including finer and more clayey sands at Dahwilly East and possibly higher background salinity groundwater.

Finley

- The best correlation was observed at 4m and 6m which corresponds with the zone below the top of the watertable (1.5m). A misleading opposite (inverse) correlation was observed at 2m depth, when a stronger, direct correlation was expected based on depth to watertable. This may be a reflection of the poor surface resolution of the resistivity equipment. The narrow seepage range and small number of data points also limits the significance of the correlations.

Lake View

- Central - The best correlation was observed at 6m and 8m which corresponds with the zone several metres below the top of the watertable (1.5m). A very weak trend was observed at 2m and an (inverse) correlation at 4m depth. It was expected based on the depth to watertable that the best correlations would be observed at around 2-4m depth. This may be a reflection of the poor surface resolution of the resistivity equipment. Site lithology below the watertable may also be significantly contributing to the response. The narrow seepage range also limits the significance of the correlations.
- West – There was no meaningful relationship observed between resistivity and seepage immediately below the watertable. This is attributed to: i) Poor resolution of near surface data (this theory is supported by the reasonable correlation observed between EM31 and seepage at this site) and/or, ii) The 'anomalous' result in pond 1. Something is causing elevated resistivities relative to other ponds at the site (possibly lithology, faulty data collection etc), although nothing obvious was detected in the drilling.
- Both Sites - Neither the 2m or 6m depth slice from Lake View Central could have been used to accurately predict seepage at Lake View West. However a slightly better fitting trend line is obtained for the 2m depth slice. The apparently anomalous result at Pond 1 (Lake View West) is largely skewing these relationships. Using the Lake View Central site to predict seepage at the Lake View West site would have caused significant under estimation of actual seepage.

In summary, most sites displayed a good correlation between seepage and the resistivity at and immediately below the watertable. The two sites that did not were Toolondo West and Lake View West. At Toolondo West it appears that the type of sandstone at this site may be dominating the response, however deeper drilling would be required to confirm this interpretation. A reasonable trend was obtained at shallow depth, but without the information supplied by the pondage tests this could not have been known. The lack of trend at the Lake View West site is probably due to the poor resolution of the resistivity equipment at very shallow depth. This site contains the shallowest watertable across all sites (0.5 – 1m). Improved resolution at shallow depth could relatively easily be improved in future surveys (Allen, pers. comm. 1/11/02). At Toolondo East also no trend was observed but this is solely attributed to the very narrow range of seepage rates at this site.

■ **Table 5-10 Summary of Resistivity Trials Compared to Pondage Test Seepage**

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Watertable Depth (approx.)	Depth of Best Correlation	Correlation Coefficient	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Comparison with other geophysical techniques	Reported in Section
Toolondo West	Resistivity	March. 2002	On-channel	Yes	4	1 - 5 mm/d	12m	2m	0.80	Inferred from unsat. zone soil properties	At & below the WT the expected inverse trend betw'n high resis./low seepage & low resis./high seep was not observed. It is apparent that the s'stone at this site may be dominating the response. Low permeability s'stone may be causing a high resistivity response (normally associated with high seepage), and masking the effect of seepage on the saline groundwater. The reasonable correlations obtained at shallow depth (2&4m) are most likely due to changes in clay content beneath the channel. Deeper drilling would be required to confirm this interpretation	Toolondo East data (Av. 10/12/14m) lies within expected extrapolated range for Central (10m) site. The West (Av 10/12m) data does not fit within Central & East relationship (possibly due to changes in lithology masking seepage impacts). The West 2m depth slice does fit within relationship, however without PTs it would not have been known that this was a better depth to focus on.	The inverse relationship between EM31 conductivity and seepage at this site concurs with the direct relationship between shallow resistivity (2 & 4m) and seepage at this site.	5.4.4.1
Toolondo Central	Resistivity	March. 2002	On-channel	Yes	6	1 - 11 mm/d	10-11m	10m / 12m	0.59 / 0.56	Dilution of groundwater from fresher seepage water	Around 10-12m the best correlation is obtained (R2=0.6), which fits with the expected mechanism of seepage detection (ie in the depth interval of g'water most effected by seepage). Within ponds cross sections show sub-sections of higher seepage. Very little correlation in the unsaturated zone.		Better result obtained than the EM34(10m) due to better targeting of the top of the watertable. Slightly better EM31 surveys results (outside channel) were obtained (R2: 0.7-0.8) but this relies on a different mechanism	5.4.4.2
Toolondo East	Resistivity	March. 2002	On-channel	Yes	4	0 - 1 mm/d	10m	No correlation	No correlation	Dilution of groundwater from fresher seepage water	The very narrow range of seepage rates and resistivity values meant that no meaningful correlations were observed at the Toolondo East site.		No correlations found with other techniques either due to narrow range of variables.	5.4.4.3
Dahwilly Central	Resistivity	March. 2002	On-channel	Yes	6	1 - 10 mm/d	5m	8m / 10m	0.86 / 0.85	Dilution of groundwater from fresher seepage water	Good correlations were observed at 8m & 10m, which fits with the expected mode of seepage detection (ie targeting of the depth interval where g'water is most effected by seepage). The fit at 6m is also good (R2=0.72), but correlation coefficients worsen in the unsaturated zone. Cross sections indicate that seepage is generally diffuse (ie uniform) across the surveyed area.	Two (vertically) offset regression lines for the two Dahwilly sites are recorded. There is no observed trend between the sites. This suggests different background conditions (despite apparent similarities betw'n sites), including finer & more clayey sands at Dahwilly East (& possibly higher background salinity gw).	Better correlations obtained at 8m and 10m than the EM34(10m & 20m) and EM31(vert) due to better targeting of the top of the watertable.	5.4.4.4
Dahwilly East	Resistivity	March. 2002	On-channel	Yes	3	9 - 10 mm/d	5-6m	6m	0.91	Dilution of groundwater from fresher seepage water	The best (and strong) correlation was observed at 6m which corresponds with the top of the watertable. However, the very narrow range of seepage rates and small no. of data points (only 3) limits the significance of these correlations.		Better correlations obtained at 6m than the EM34(10m & 20m) and EM31(vert) due to better targeting of the top of the watertable.	5.4.4.5
Finley	Resistivity	March. 2002	On-channel	Yes	3	5 - 7 mm/d	1.5m	4m / 6m	0.92 / 0.93	Dilution of groundwater from fresher seepage water	The best correlation was observed at 4m & 6m which corresponds with the zone below the top of the watertable (1.5m). A misleading opposite (inverse) correlation was observed at 2m depth, when a stronger, meaningful correlation was expected based on the depth to WT. This may be a reflection of the poor surface resolution by the resistivity equipment. The narrow seepage range & small no. of data points (3) also limits the significance of the correlations.	-	Better correlations obtained at 4m than the EM31(vert) due to better targeting of the top of the watertable	5.4.4.6

Channel	Survey Type	Survey Date	Survey Location	Channel Operating	No. of Pondage Cells	Range of seepage results	Watertable Depth (approx.)	Depth of Best Correlation	Correlation Coefficient	Seepage Measurement Mechanism	Summary on Seepage - Geophysical Relationship	Use of relationship for extrapolation	Comparison with other geophysical techniques	Reported in Section
Lake View Central	Resistivity	March. 2002	On-channel	Yes	4	4 - 7 mm/d	1.5m	6m / 8m	0.58 / 0.60	Dilution of groundwater from fresher seepage water (& possibly lithology below WT)	The best correlation was observed at 6m & 8m which corresponds with the zone several metres below the top of the watertable (1.5m). A very weak trend was observed at 2m and an (inverse) correlation at 4m depth. It was expected based on the depth to WT that the best correlations would be observed at 2-4m depth. This may be a reflection of the poor surface resolution by the resistivity equipment. Site lithology below the watertable may also be significantly contributing to the response. The narrow seepage range also limits the significance of the correlations.	Neither the 2m or 6m depth slice from Lake View Central could have been used to accurately predict seepage at Lake View West. However a slightly better fitting trend line is obtained for the 2m depth slice. The apparently anomalous result at Pond 1 (LV West) is largely skewing these relationships. Using the LV Central site to predict seepage at the West site would have caused sig. under estimation of actual seepage.	Similar R2 to Lake View EM31, June 2000(EM31) v July 2001(PT): 0.58.	5.4.4.7
Lake View West	Resistivity	March. 2002	On-channel	Yes	4	20 - 25 mm/d	0.5 - 1m	No correlation	No correlation	Dilution of groundwater from fresher seepage water	Lack of meaningful relationship between resistivity - seepage immediately below the watertable attributed to: i) Poor resolution of near surface data (supported by reasonable correlation between EM31 & PT at this site) and/or, ii) 'Anomalous' result in pond 1. Something (lithology?) causing elevated resistivities relative to other ponds, although nothing obvious detected in drilling.		A sensible (inverse) correlation was obtained at this site between EM31 and PT (R2=0.54). The fact that such a correlation was not observed for shallow resistivity data suggests poor resolution of surface data by the resistivity array.	5.4.4.8

6. Waranga Western Channel: Case Study

This section presents a case study of channel seepage aspects of a channel capacity upgrade of the Waranga Western Channel (WWC). The WWC is an open irrigation channel maintained by Goulburn-Murray Water (G-MW), in north-west Victoria. The location of the channel is shown in section 5, Figure 5-1.

6.1 Study Objectives

It was proposed that the Waranga Western Channel (WWC), an open irrigation channel maintained by Goulburn-Murray Water (G-MW), be upgraded in capacity. The area proposed for upgrade was from the Loddon Weir to west of Boort (north-west Victoria), approximately 50km in total length. The increase in capacity is required primarily to supply additional irrigation water to a new horticultural development near the Boort area, as well as to meet the needs of existing customers in the region.

The channel has a well-documented record of existing seepage problems. The extent of channel seepage in the Boort West of Loddon Salinity Management Plan area has been a concern to local landholders for a number of years. The Channel Seepage subcommittee of the Boort West of Loddon Community Working Group initiated a Channel Seepage Program in 1993 (McConachy, 1993). However previous investigations were unable to satisfactorily identify priority sites for remedial works (G-MW, 2000). In addition, there was concern that new seepage paths may be opened up during the upgrading works program.

Therefore G-MW required quantification of sections in the WWC channel with existing seepage problems and identification and quantification of sections where new seepage paths might be opened up. To this end, geotechnical and geophysical investigations were carried out along the channel.

6.2 Outline of Work Undertaken

The following investigative works were undertaken on the WWC:

- EM31 survey – November 2001: A 46km EM31 survey was conducted on-channel and on-land on each side of the channel. This was coupled with drilling of 128 bores adjacent the channel (to 4m depth) to ground truth the survey;
- Additional geotechnical drilling – March 2002: An additional 107 bores were drilled and 34 piezometers installed. Bores were generally drilled to a depth of at least 6m, and some up to 10m. Work was conducted in accordance with AS1726-1993 Geotechnical Site Investigations;
- Pondage tests – May/June 2002: 12 pondage tests were conducted at various locations along the length of channel under investigation.

The chapter is based on the chronological reporting of the above three stages of investigation, with an initial section describing site conditions.

6.3 Site Conditions

6.3.1 Geology and Hydrogeology

The WWC traverses through Shepparton Formation surface sediments that are widespread throughout the southern Murray Basin. These consist predominantly of clays to sandy clays, with shoe string sand deposits (fine to medium grained) which intersect the channel at various locations along the study length. Underlying the Shepparton Formation along most of the channel length is extremely weathered to moderately weathered sandstone. The sandstone represents the indurated zone of the top of the Parilla Sands aquifer. In sections along the channel this indurated zone rises very close to the surface and in part intersects the channel.

Depth to groundwater also varies along the channel however typically the depth of the watertable is between 6 – 10 metres, but has been recorded within several metres of the surface in some locations immediately adjacent the channel. According to the 1: 250,000 scale St Arnaud Hydrogeological mapsheet, the regional groundwater is typically highly saline, between 3,000 and 35,000 mg/L TDS. The salinity generally increases in the direction of groundwater flow, towards the north-west. However, in the proximity of the Loddon River, the groundwater freshens significantly to between 1,000 and 3,000 mg/L TDS.

6.3.2 Channel Conditions

- Channel capacity: from 270 Ml/d to 1200 Ml/d
- Regular operation procedures - None
- The channel has been in operation for more than 70 years.
- Channel maintenance - Weed spraying once a year. No de-silting has been conducted in the last 25 years. Over this time, the channel has deposited a significant silt deposit on the bed of the channel. Longitudinal surveys conducted as part of the investigation indicate that in some sections of channel the silt layer is up to 0.4m thick, but generally it is between 0.05 - 0.15m in thickness. This layer will have a very significant impact on seepage rates, and it is likely that in most sections of the channel this clogging layer will be the controlling influence on seepage rates, rather than underlying soil types and geology.

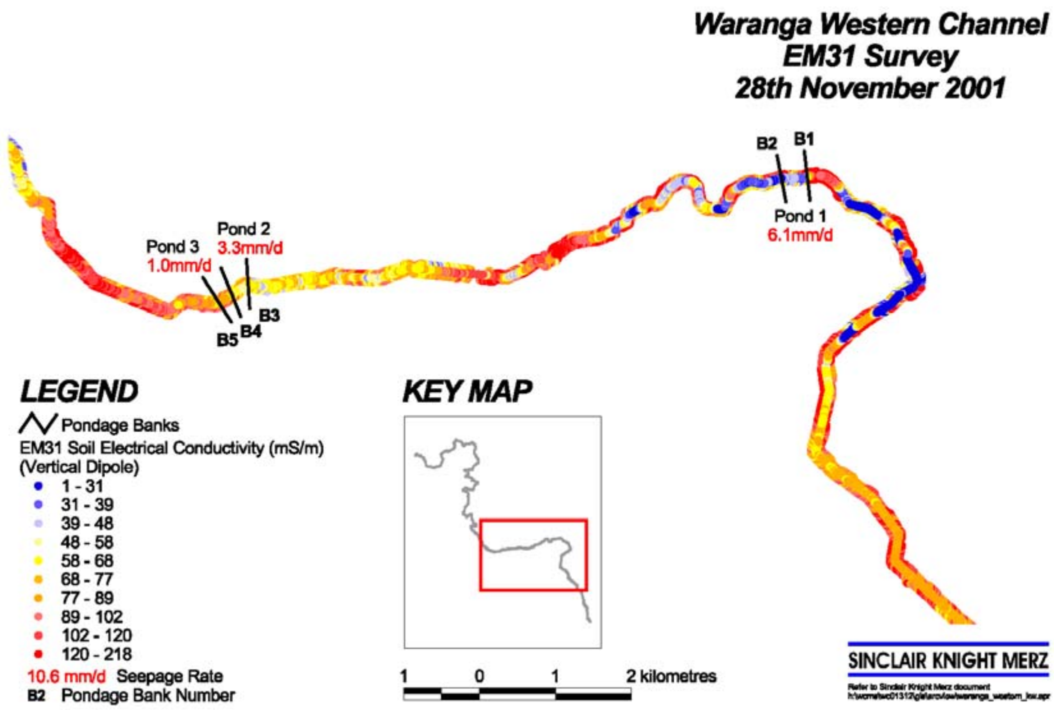
6.4 EM31 Survey and Initial Drilling

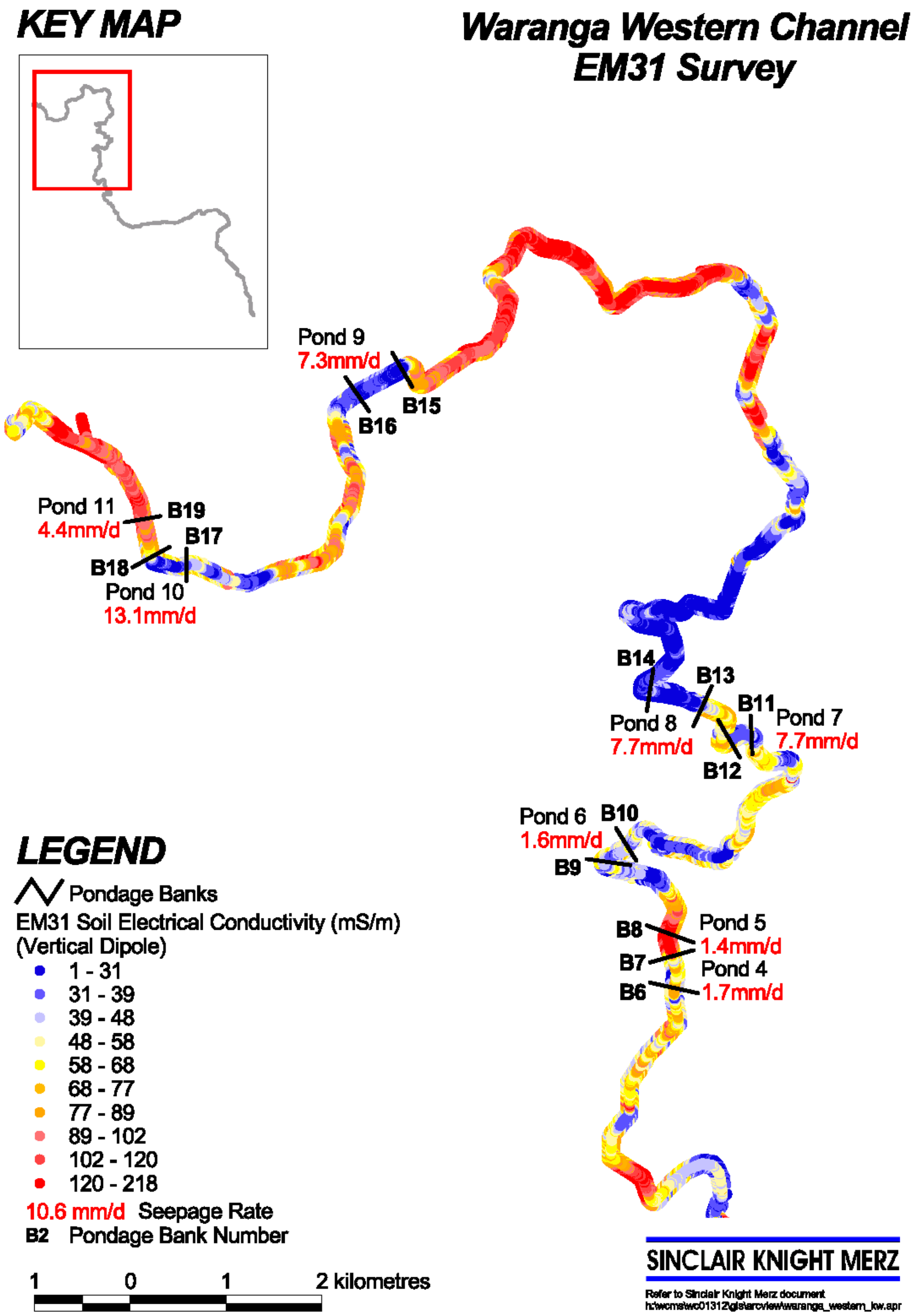
6.4.1 Description of EM31 and Drilling Program

An EM31 survey (vertical dipole) was conducted by Ken Bates Soil Surveying in November 2001. The survey included a traverse on each side of the channel, immediately adjacent the channel toe, as well as a survey on the channel. The on-channel survey (and the pondage test results) is depicted in Figure 6-1. With a depth to watertable of approximately 6-10m the EM31 is largely measuring unsaturated zone soil / lithology properties. (Note that due to high density of data collection, and small figure size, this plot overlaps many data points and may give a slightly misleading representation of conductivities, depending on which layer was plotted last).

To assist with interpretation of the EM31 survey, a drilling program of 128 boreholes (to 4m depth) was conducted. Bores were drilled adjacent to the channel, over the length of the proposed upgrade. This was later supplemented by a total of 12 test-pits, excavated by backhoe, at selected locations adjacent to the channel. The EM31 contractor developed a seepage risk map, dividing the channel into low, medium and high seepage risk categories based on EM value (check). The high risk section of the channel totalled approximately one-third (15km) of the length of the channel.

- **Figure 6-1 EM31 Survey on the Waranga Western Channel**




KEY MAP
Waranga Western Channel
EM31 Survey
Pond 9
7.3mm/d
B15
B16
Pond 11
4.4mm/d
B19
B17
B18
Pond 10
13.1mm/d
B14
B13
B11
Pond 7
7.7mm/d
Pond 8
7.7mm/d
B12
Pond 6
B10
1.6mm/d
B9
B8
Pond 5
1.4mm/d
B7
Pond 4
B6
1.7mm/d
LEGEND
Pondage Banks
EM31 Soil Electrical Conductivity (mS/m)
(Vertical Dipole)
1 - 31
31 - 39
39 - 48
48 - 58
58 - 68
68 - 77
77 - 89
89 - 102
102 - 120
120 - 218
10.6 mm/d Seepage Rate
B2 Pondage Bank Number
1 0 1 2 kilometres
SINCLAIR KNIGHT MERZ
Refer to Sinclair Knight Merz document
h:\wcms\wc01312\gis\arcview\waranga_western_kw.apr

6.4.2 Analysis

A correlation was sought between the results of the EM31 survey and the ground conditions encountered during the drilling. The soil logs and the EM31 survey data were examined in order to review the interpretations of the risk of channel seepage as shown on the 'risk' maps produced by the EM31 contractor. The EM31 survey results, together with the textural soil descriptions of the bore logs determine whether the survey results are reasonable with respect to the nominated seepage risk.

The textural descriptions of the soils (130 soil bores in total) comply with Northcote (1979) classification system and for each texture a permeability description was provided (Table 6-1). Sandstone, interpreted as being representative of the upper Parilla Sands formation, was regularly encountered in the soil bores, and textures were assigned to this unit according to the degree of weathering.

- **Table 6-1 Distribution of Impermeability Grades**

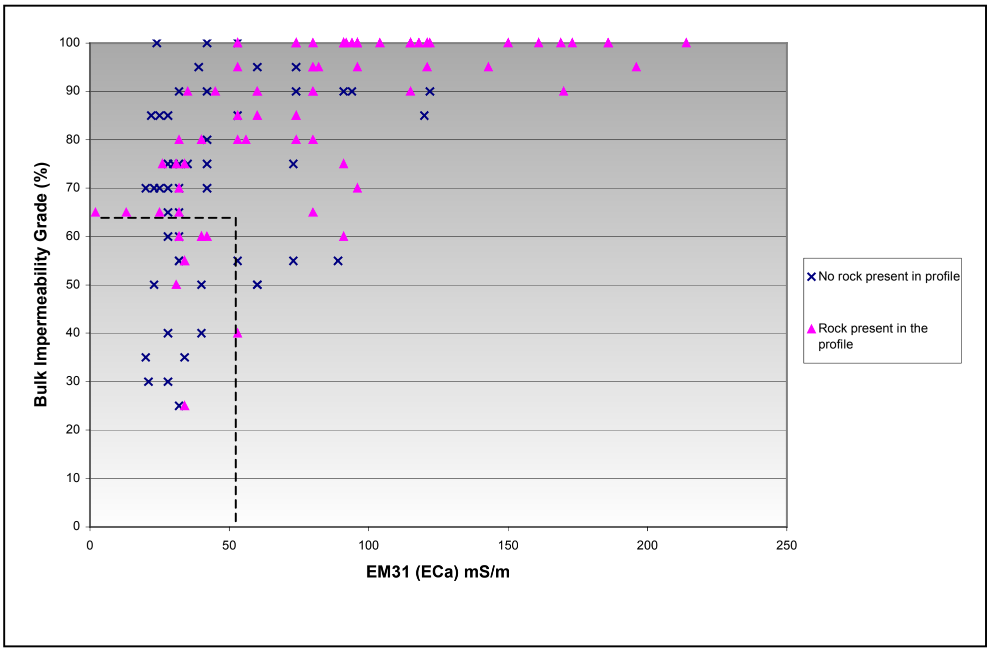
Textural Description	Permeability Description	Impermeability Classification
Medium to heavy clay	Very low	1.00
Light clay	Low	0.85
Silty clay, sandy clay, fine sandy clay, fine sandy clay loam, silty clay loam, clay loam, sandy clay loam	Medium	0.70
Silty loam	Medium to High	0.55
Loam, light sandy clay loam, sandy loam, clayey sand, loamy sand	High	0.40
Fine sand	High to Very High	0.25
Sand, coarse sand, fine gravel, gravel	Very High	0.10

An 'impermeability classification' was assigned to each texture; 0.10 being representative of the most permeable and 1.0 representative of the least permeable soils (Table 1). Subsequently, for each bore, an impermeability grade was assigned to the individual textural intervals. A bulk impermeability grade (%) was derived for each bore according to the thickness and impermeability classification of each textural interval in the soil profile.

The distribution of the EM31 survey results with respect to the bulk impermeability grade is presented in Figure 6-2. The results are separated into two classifications, no rock present in the profile and rock present in the profile. Variation permeabilities were assigned to the rock intervals, and therefore the rock in the profile does not appear to affect the relationship between the EM31 survey results and permeability.
The data suggests there is a coarse relationship between the EM31 survey results and the permeability of the soils, with lower EM31 readings (lower conductivity), in some instances, associated with soils of higher permeability. Accordingly, it was considered reasonable that the EM31 survey results be used to *broadly* assess the potential degree of seepage risk.

The data suggests there is a coarse relationship between EM31 conductivity and the permeability of the soils, with low EM31 conductivity, in some instances, associated with soils of higher permeability. Accordingly, it was considered reasonable that the EM31 survey results be used to *broadly* assess the potential degree of seepage risk.

■ **Figure 6-2 Bulk Impermeability Grade vs EM31 Conductivity (Initial Drilling Program**



Importantly, the EM31 data are highly scattered (with respect to the bulk impermeability grade), and therefore, the potential for seepage cannot be definitively inferred from the EM results. For example, according to the data analysis, a low EM31 reading does not necessarily imply a high soil permeability. On the basis of the highly dispersive relationship, the highest seepage rates may not necessarily be associated with the lowest EM 31 results. Further, it was noted that caution should be exercised, in using the data *solely* to identify seepage risk on the basis that a range of factors may affect the EM31 survey results. The results could not be used to quantify seepage rates. The absence of pondage tests was seen as a deficiency in the program methodology.

6.4.3 Initial Identification of High Priority Areas

The high risk section of the channel as categorised on the EM31 contractor supplied map totalled approximately one-third (15km) of the length of the channel.

A combination of the EM31 results and the impermeability grade was used to identify sections of channel which were considered to represent 'very high' risk areas (as opposed to the 'high' risk categorisation based solely on the EM31 survey). These were defined as zones where the EM31 was less than or equal to 50 mS/m and the bulk impermeability was less than or equal to 65%. This category is marked on Figure 6-2 by the dashed lines. Four significant lengths of channel were identified as fitting these criteria (ignoring short lengths of channel, ie less than 200m). The details of these reaches are presented in Table 6-2. This table also presents the overlap with known (ie visible) seepage sites.

■ **Table 6-2 Very High Risk Sections [EM31 (mS/m) < 50 and Impermeability Grade < 65%] as identified from EM31 survey and original drilling program**

Site	Chainage (m)	Length (m)	Overlap With Known Seepage Sites
1	196,340 – 198,500	2,160	No
2	201,250 – 205,000	3,750	202,090 – 202,590 (500m)
3	213,930 – 214,710	780	214,010-214,620 (610m)
4	217,060 – 217,660	600	No
Total		7,290m	1,110m

6.5 Additional Drilling Program

The total area identified for seepage control works (very high risk areas as defined above) and rock excavation (also required as part of the upgrade) exceeded initial cost estimates for the upgrading project and were greater than the available funding. These initial estimates were based on preliminary costings prepared before geotechnical investigations were carried out. It was apparent to G-MW that further investigation was required to further refine the 'very high risk' areas, and potentially reduce the 7.2 km recommended for lining.

6.5.1 Description

The additional phase of the geotechnical investigation involved the drilling and logging of an additional 107 boreholes, and was carried out in March 2002. A total of 34 piezometers were also installed in selected boreholes. The initial geotechnical investigation carried out in association with the EM31 survey was done relatively quickly and cheaply. The drill-rig used was a trailer mounted custom made rig that could not penetrate the rock or cemented sandstone layers. Relatively simple borelogs were prepared. The subsequent geotechnical investigation was completed in accordance with AS1726-1993, Geotechnical Site Investigations. The rig used had the ability to penetrate quite hard rock layers. The bores were generally drilled to 6 metres depth. The locations of boreholes for the second geotechnical investigation were selected in order to further refine the extent of:

- 'Very high risk' seepage zones; and
- Zones where rock material intersects the channel profile.

6.5.2 Refinement of High Priority Areas

Methodology

The status of the classification of the original 'very high' risk sections in light of the additional bore information was assessed, in addition to potential new areas of very high risk outside the originally defined areas. Using the new bore information, the following tasks were conducted:

- Calculation of impermeability grade of new bores (as conducted previously - refer previous section for methodology);
- Plot of impermeability grade verses EM31 value;
- Construction of geological cross sections, using divisions of high, moderate and low permeability; and,
- Identification of bores / sections logged with high moisture content / saturation.

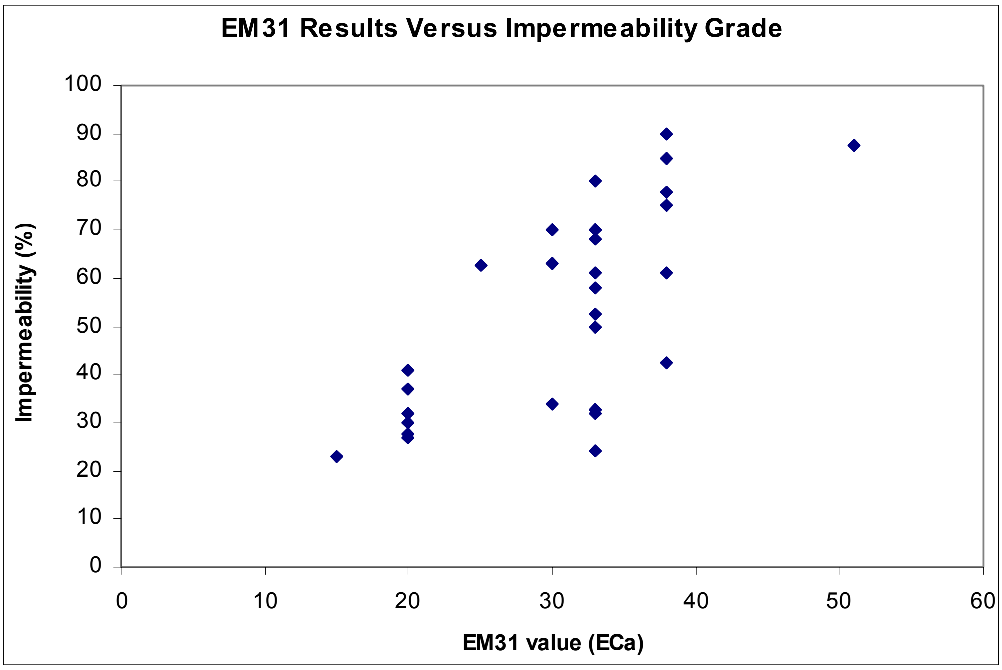
For sections outside of the very high risk zones the review involved:

- Identification of bores with greater than 50% content of gravel, sand, clayey sand etc (ie potentially high permeability).

Results

Figure 6-3 plots the results of the impermeability rating for each of the new bores drilled within the very high risk zones against the corresponding EM31 value. This figure shows that, in general, lower EM31 readings (lower conductivity), are generally associated with soils of higher permeability (lower impermeability), as suggested by the bore data (as was previously observed). It was therefore considered reasonable that the EM31 survey results (extrapolated from bores) be used to *broadly* assess the potential degree of seepage risk.

■ Figure 6-3 - EM31 Versus Impermeability Grade: Additional Bores Within Very High Risk Areas



However this plot does display some scatter, particularly around the middle part of the graph, which indicates that caution needs to be applied in using the EM31 versus soil permeability relationship as the definitive tool for identifying potential seepage areas. The uncertainty in the results highlighted the need for pondage tests to be undertaken. The advantage of obtaining a relationship between EM response and pondage tests is that it represents a direct relationship between seepage and the EM data. EM versus soil permeability is one step removed and requires additional interpretation to account for the fact that soil permeability is not a direct measure of seepage.

Based on the cross sections constructed for the four areas of 'very high risk', together with the EM31 results recommendations were made as to whether the 'very high' risk rating should be maintained in the light of the new data. An example of the process that was used to assess each section is presented in Table 6-3.

■ Table 6-3 Review of Very High Risk Rating: Section 1

Chainage (m) (Site Ref. Name)	Reccom-endation	Length Very High Risk Sites (m)		Discussion / Justification	Moisture Content
		Original	Revised		
196,340 – 196,900 1A	Leave as very high risk	560	560	BH168 – BH170 identified significant sand layers at depth and coinciding with new design bed in BH168. While BH169 – 170 only have permeable layers below the design bed, the gravel in BH170 is very close to the design bed surface and the GrSC in BH169 could provide a seepage path. BH53 indicates sand intersecting the channel, however it is on the upgradient side, and the EM31 conductivity does not indicate the same very low response recorded around BH168. Therefore whether the very high risk classification should extend to, say CH197,150, should be determined by drilling on the down gradient side of the channel in this location	The moisture content in all these bores was low, indicating that current seepage rates may not be as high as suggested by the EM31 and bulk impermeability analysis. However, the channel remodelling works, including de-silting, will re-establish connection between the channel and the higher permeability layers. This may create seepage pathways suggested by the geological cross sections, but currently blocked by the silt bed.
196,900 – 197,600 1B	Down-grade to high risk	700	0	This section has been down-graded to high risk, primarily based on the information from BH171, which indicated Sandy Clays for most of the profile. The decrease in EM31around Ch197,600 indicates the potential for seepage is increasing at this location	
197,600 – 198,000 1C	Leave as very high risk	400	400	This section should maintain its very high risk classification due to the extremely sandy profile intersecting the channel (BH50). While this bore is on the upslope side (LHS), the extent of the sand profile and the very low EM31 response (RHS) in this section indicates potential high seepage	
198,000 – 198,250 1D	Down-grade to high risk	250	0	The predominantly clayey profile of BH60 warrants down-grading this section to high risk	
198,250 – 198,700 1E	Leave as very high risk + Upgrade 200m to very high risk	250	450	High sand content in BH173 & BH51 indicates this section should stay in the very high risk section. Although the sand in BH173 is at depth, sand on the LHS (BH51) intersects the channel indicating the presence of a significant seepage pathway.	
Total		**2,160**	**1,410**		

Bores Outside of Very High Risk Sections

Areas outside of the original very high risk regions (as identified in the previous review) were assessed. This was undertaken by identifying bores which contained a greater than 50% content of high permeability material. Two potentially significant sections of channel susceptible to seepage were identified. Other shorter sections with seepage potential were identified, but available evidence suggests these are quite isolated occurrences, ie less than 100m.

Summary

Following the review of the additional drilling the areas classified as very high seepage risk actually increased by 990m (from 7290m to 8280m). This included some areas being removed and some added to the very high risk category. To assist with prioritisation of these sites it was recommended that the profiles with significant sand layers intersecting the channel be considered the highest priority (as de-silting of the channel will expose these layers and allow potentially very high seepage). Table 6-4 lists these priority sites.

Table 6-4 Prioritisation of Very High Risk Sites

Priority	Section	Chainage	Length (m)
1	1A	196,340 – 196,900	560
2	2A	199,900 – 201,000	1,100
3	2C	201,600 – 203,300	1,700
4	3A	213,840 – 214,760	920
5	4A	216,850 – 217,800	950
Total			5230

G-MW recognised that in addition to the drilling program, pondage tests were required to:

- Quantify seepage rates (and potentially identify a relationship between EM31 and pondage test seepage rates);
- Confirm interpretation of seepage rates based on geology and EM31 data.

6.6 Pondage Tests

6.6.1 Description

Pondage tests on their own will provide additional point data on certain reaches of the channel. This data will be useful for identifying likely seepage rates for the type of sub-surface conditions encountered at that site, and other similar sites based on soil bore information.

However, while a large number of bores have been drilled along the channel, the EM31 remains the only continuous data available. The assessment methodology described in Section 6.4 and 6.5 rely significantly on the EM31 results and an attempt was required to confirm the appropriateness of this reliance. It is therefore important to attempt to identify the relationship between EM31 response and pondage test seepage, particularly given the spread of results identified in the EM31 versus impermeability relationship. If a reasonable relationship can be identified, greater confidence can be placed in using the EM31 data for determining seepage control locations.

Some concern was expressed by G-MW on the necessity of conducting pondage tests when the degree of siltation in the channel means that pondage tests conducted now are unlikely to be unrepresentative of seepage rates post de-silting and construction. While post-silting rates are likely to be much higher than existing rates, it is reasonable to assume that the areas of highest seepage now, will be the areas of highest seepage post-construction and the low areas now will still relatively be the low seepage areas post de-silting, or at worst this will be the case after several years of channel operation.

Therefore the primary reason for conducting pondage tests was to confirm the interpretation of the EM31 (ie that the lowest conductivity does in fact equal the highest seepage), upon which the entire selection process of the sections to be clay lined was based. The secondary reason for conducting the pondage tests was to identify existing seepage rates along the channel. These figures will allow a reasonable estimate of the water savings resulting from channel lining.

These figures will also assist in improving the decision making process as to the cut-off criteria to be applied in determining which areas of channel should be remediated. The current approach (which identified 8.3km of very high priority channel sections) has a some what arbitrary cut-off. Being able to assign approximate seepage rates to conductivity response will assist in refining this process.

G-MW proposed pondage tests locations and produced justification of these sites. The basis of the site selection was on selection of different types of (potentially) high seepage sites (eg rock sites, high risk EM31, 'wet' sites, previous core trenching, historically known seepage etc). These are reasonable criteria on which to select sites, as seepage across a range of these different types of environments needs to be known. However it should not be the only selection criteria, and the important task of attempting to link the EM31 to the pondage tests also needs to be considered. It was recommended that pondage tests be conducted in the following manner:

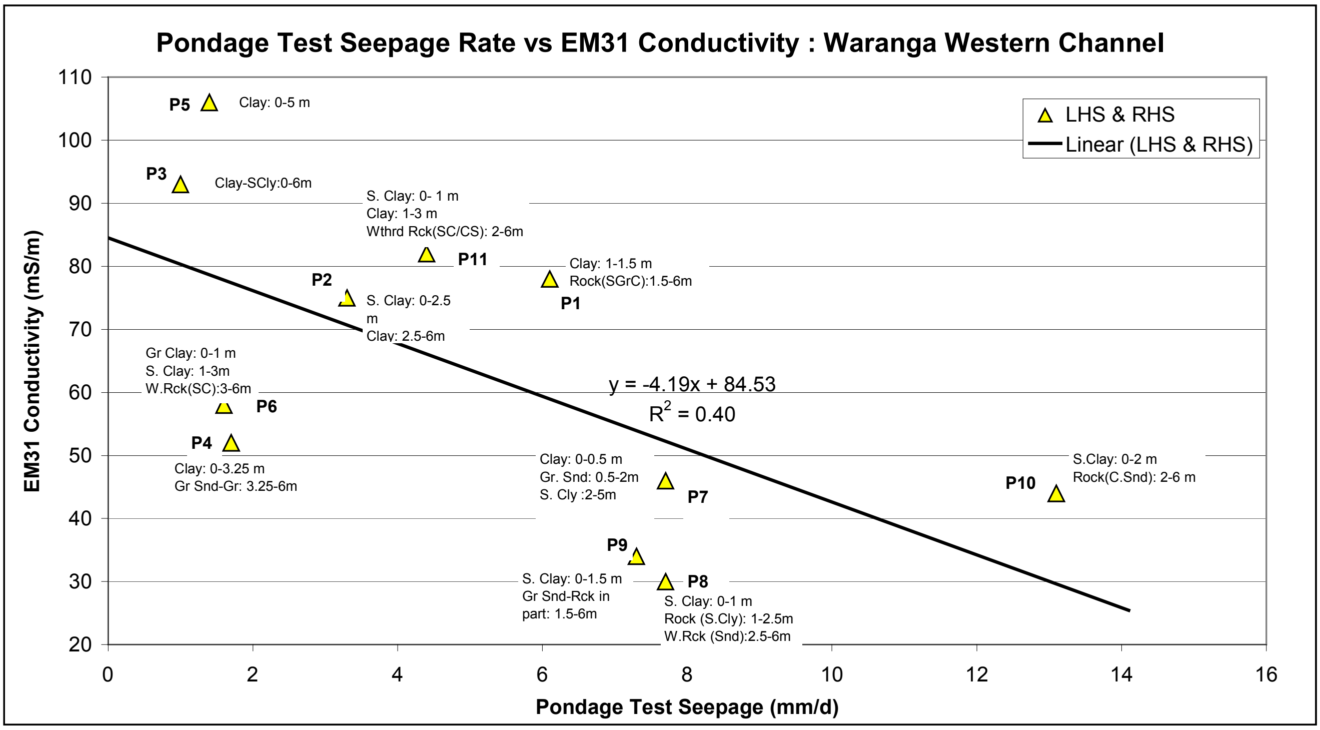
- Cover a range of EM31 response, not just high risk but also low risk areas. This means conducting tests where seepage rates are low. (Sites initially selected by G-MW sites sufficiently covered the low conductivity range, however further tests were recommended in the higher EM31 conductivity response area);
- 2-3 cells in 3-4 different areas along the channel (ie 6-12 cells total);
- Relatively short length cells (150-300m);
- Each individual cell should target a section of like EM31 response - If the area of the pondage banks crosses over significantly different EM31 conductivities, meaningful interpretation of the EM31 results in relation to the seepage rates is difficult, as the pondage test provides no indication as to where the seepage is occurring. If each cell covers an area of similar EM31 response, meaningful assessment can be made of the seepage versus EM31 relationship; and,
- Tests should be a minimum duration of one week.

6.6.2 Analysis

Figure 6.6 summarises the relationship between the pondage tests and EM31 results (land based EM31 data). The pondage test seepage (mm/d) is plotted against the average EM31 conductivity (mS/m) over the corresponding pond length. The pondage test seepage rate used in this analysis excludes the results of the first day of the tests, as they were not representative of the longer term seepage rate. The EM31 data is the average of the land based EM31 results on each side of the channel (ie excludes the on-channel results taken from the boat). Each point in the figure is also labelled with the pond number and a very brief summary of the dominant geology for the section, based on the nearest bore information.

This figure shows that a moderate to poor linear relationship exists between the two variables, with a correlation coefficient of 0.40. (A similar correlation coefficient was obtained for the boat EM31 data versus the pondage tests). The standard estimate of error was 63% of the mean, which is indicative of the fairly high degree of scatter about the fitted line. Given that these results represent ponds up to 20 km apart this relationship was considered reasonable. The likely cause of some of the scatter in the results is discussed below.

■ **Figure 6-4 Pondage Test Seepage Versus EM31 Conductivity**



Seepage Inferred from Unsaturated Zone Properties: The depth to watertable along the WWC channel is generally 8-10m below surface and therefore usually out of the range of the EM31 equipment. Therefore seepage is not directly measured, but inferred from the lithology under / beneath the channel. An example of the problems this may cause is highlighted in pond 4, where EM31 response belies the real seepage rate.

Pond 4 contains a clay layer to about 3m which is underlain by gravel and gravelly sand. The EM31 (in vertical dipole) is still strongly influenced by material at depth and therefore this very permeable material below 3m is significantly contributing to the relatively low conductivity (52 mS/m). However, the upper 3m of clay is providing a more than adequate buffer to seepage and thus pondage seepage rates are low (approx 2 mm/d). This highlights the limitations of using geophysical techniques to 'detect' seepage based on unsaturated zone soil properties.

Further, the WWC is a channel with a significant silt bed. Generally the silt layer rather than soil properties beneath the channel limit the seepage rate. This will contribute to misleading results when comparing unsaturated zone lithology to seepage rates, and is certainly the cause of some of the scatter in the WWC regression relationship (pond 6 appears to be a good example of this). Direct measurement of seepage impacts in the watertable are likely to improve this relationship and the statistics of the regression equation. This improvement was observed in a similar channel in this ANCID study where the silt layer was controlling seepage rate where the unsaturated zone was of high permeability (in the Dahwilly channel - refer section 5).

Pond Placement: The placement of the ponds may also explain some the deviations of the data points from the trend line. The ponds were designed to be located over sections of like EM31 conductivity. However due to field restraints imposed on the locations of some of the ponds and also potentially due to error in locating the pond banks in the field, the pondage tests did not always cover areas of like conductivity. As noted previously, it is important that this is the case, because this method assumes that a particular conductivity will correlate to a particular seepage rate. Therefore if a ponded area contains a wide range of conductivities the assumptions behind the analysis are compromised.

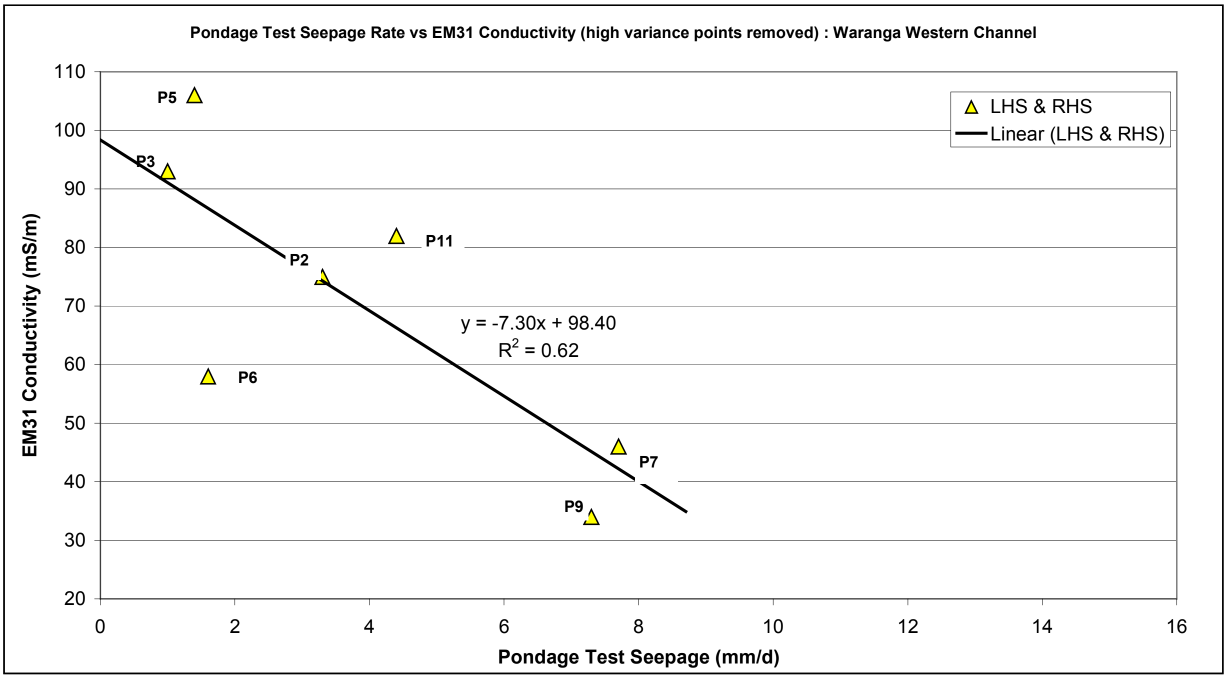
A good measure of the variability of the data is the standard deviation. Table 6-5 displays the results of the pondage tests, the average EM31 conductivity for the pond, the standard deviation of the EM31 conductivity for each pond and the standard deviation as a percentage of the average EM31 conductivity for the section. Results for both the land based and boat based results are presented. For the land based data, Pond 1 (49%), Pond 8 (33%) and Pond 10 (32%) have the highest standard deviations as a percentage of the average result and therefore display the greatest variance about the mean. This indicates that these ponds are not well located over sections of like conductivity, and are therefore less likely to plot well on the regression line in Figure6-4.

- **Table 6-5 Standard Deviation of EM31 Conductivity Data**

Pond No.	PT Seepage	Av EM 31 Cond. (mS/m)		Stand. Dev. of Cond.		Stand. Dev. / Av EM31 Cond.	
	mm/d	Land	Boat	Land	Boat	Land	Boat
1	6.1	78	37	38	13	49%	35%
2	3.3	75	57	13	6	17%	11%
3	1	93	72	13	9	14%	13%
4	1.7	52	64	10	13	19%	20%
5	1.4	106	132	21	18	20%	14%
6	1.6	58	42	14	7	24%	17%
7	7.7	46	35	13	2	28%	6%
8	7.7	30	28	10	7	33%	25%
9	7.3	34	32	5	3	15%	9%
10	13.1	44	33	14	5	32%	15%
11	4.4	82	79	17	17	21%	22%

Figure 6-5 plots EM31 conductivity versus pondage test seepage with the 3 points of high variance and pond 4 removed. This improves the fit considerably, with an R^2 of 0.62, however most of this improvement is due to the removal of the pond 4 data point (refer above discussion) which is perhaps not justifiable. Therefore Figure 6-4 is used in the analysis.

■ **Figure 6-5 Pondage Test Seepage Vs EM31 Conductivity, With Removal of High Variance Points & P4**



Implications of Correlation for Use of EM31 Data

The most important aspect of the pondage test data assessment was to consider the implications of the observed correlation (between pondage test and EM31), in light of how the EM31 data have been used to date in the investigation. This is important given that the priority areas for lining have relied significantly on the EM31 results. In other words, was the right thing done in relying on the EM31 results as an accurate predictor of seepage locations?

The variability of the data in Figure 6-4 indicates that a high degree of confidence cannot be placed in the EM31 data for determining exact seepage rates. However in broad terms, EM31 appears to have been accurate in predicting between high and low seepage rates. This 'broad brush' use of the regression equation is confirmed by the wide prediction interval bands which have been plotted in Figure 6.6. 80% and 90% prediction interval bands have been plotted and indicate that:

1) There can be 80% confident that when EM31 conductivity is greater than 70 mS/m, seepage rates are less than 8 mm/d; and,

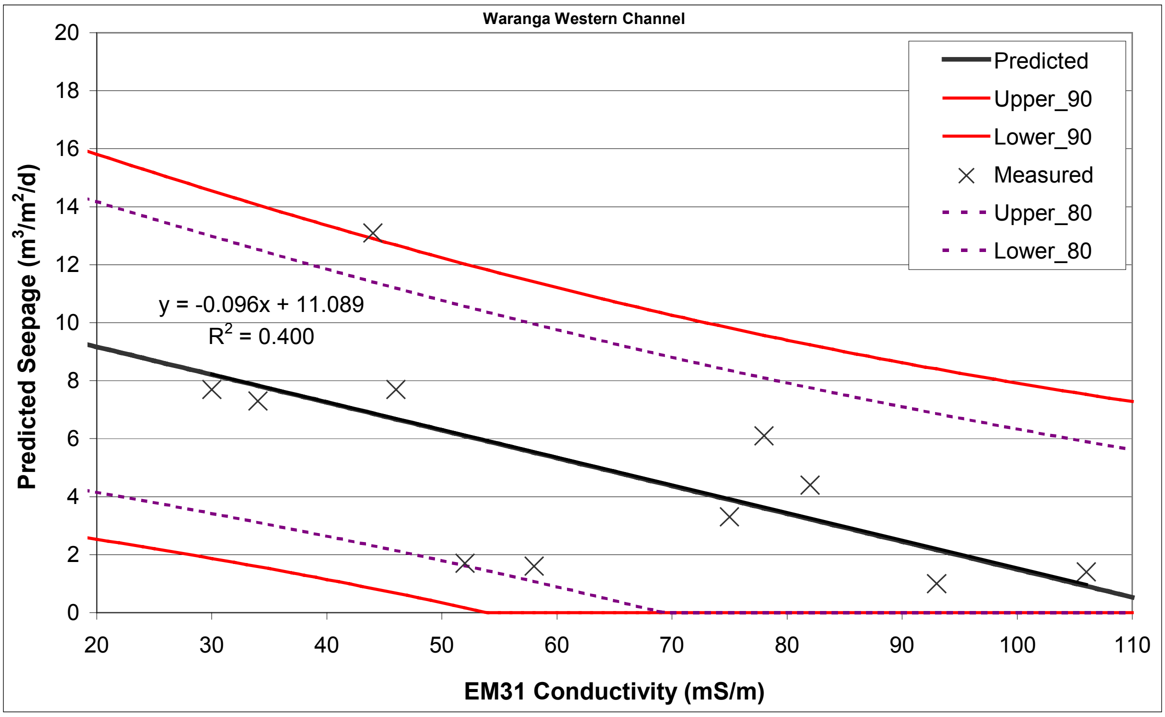
2) When EM31 conductivity is 30 mS/m or less, we can be 80% confident that seepage rates are greater than 4 mm/d.

With the pondage tests locations containing high EM31 variability removed, the confidence intervals contract significantly. This statistical analysis indicates that the interpretation of areas of high EM31 conductivity as low seepage risk and areas of low EM31 as areas of higher seepage risk is reasonable but limited to broad classification.

The confidence bands indicate that there is little confidence in EM31 to distinguish between areas of ‘moderate’ seepage (P7, 8 & 9: 7-8 mm/d) and ‘high’ seepage (P10: 13 mm/d).

However given that the only data point in the ‘high’ range (Pond 10) displayed high variance, a more accurate conclusion would be that there is no reliable data in the ‘high’ seepage rate range in order to conclude one way or another whether EM31 can distinguish between the high and moderate seepage rate areas. Therefore areas of low EM conductivity need to be assessed in conjunction with drilling data. This approach was followed as much as possible in the lining selection review.

- **Figure 6.6 Waranga Western Channel Pondage Test Seepage Versus EM31 Conductivity – Prediction Interval Bands**



6.6.3 Final Refinement of High Priority Areas

Based on the results of the pondage test areas and relationship with EM31 and the drilling program, the areas recommended for remediation were finalised. Sites were defined as either priority one or priority two seepage risk sites, depending on the degree of perceived seepage risk. Priority one sites were considered to require remediating as part of the upgrade, while priority two sites were to be monitored closely for seepage following the upgrade. EM31 predicted seepage was not used as the sole means of assigning seepage risk, given the uncertainty in the EM31 – seepage relationship. Geological data and visual observations were also integrated into the decision making.

6.7 Conclusions

It was proposed that the Waranga Western Channel (WWC), an open irrigation channel maintained by Goulburn-Murray Water (G-MW), be upgraded in capacity along approximately 50 km of the channel length. The channel has a well-documented record of existing seepage problems. The extent of seepage in this section of the channel had been a concern to local land holders for a number of years. In addition, there was concern that new seepage paths may be opened up during the upgrading works program. Therefore G-MW required quantification of sections of existing seepage problems in the WWC channel and identification and quantification of sections where new seepage paths might be opened up. To this end, geotechnical and geophysical investigations were carried out along the channel, including the following investigative works (in chronological order):

- EM31 survey – November 2001: A 46 km EM31 survey was conducted on-channel and on-land on each side of the channel. This was coupled with drilling of 128 bores adjacent the channel (to 4m depth) to ground truth the survey;
- Additional geotechnical drilling – March 2002: An additional 107 bores were drilled and 34 piezometers installed. Bores were generally drilled to a minimum depth of 6m, and some up to 10m;
- Pondage tests – May/June 2002: 12 pondage tests were conducted at various locations along the length of channel under investigation.

The high risk section of the channel, as categorised by the EM31 contractor based on EM31 magnitude, totalled approximately one-third (15km) of the length of the investigated section of the channel. To further refine this area, a combination of the EM31 results and impermeability grade (a lithological classification devised for the investigation based on the amount of clay in the profile) was used to identify sections of channel which were considered to represent 'very high' risk areas. Using this system, four significant lengths of channel were identified as very high risk. The total length of 'very high risk' area was 7.2 km. It was apparent to G-MW that further investigation was required before committing to the significant expense of lining such a length of channel.

A further 107 bores were drilled (to greater depth than the original drilling program). The above process using impermeability grade (incorporating results from the new bores) and EM31 response was again conducted. Following the review of the additional drilling, the areas classified as very high seepage risk actually increased by about 1 km (from 7.3 km to 8.3 km). This included some areas being removed and some added to the very high risk category.

It was recognised that in addition to the drilling program, pondage tests were required to quantify seepage rates (and potentially identify a relationship between EM31 and pondage test seepage rates) and confirm interpretation of seepage rates based on geology and EM31 data. Therefore 12 pondage tests were conducted at various intervals along the channel, covering a range of environments and areas of different geophysical response.

A moderate to poor relationship was recorded between EM31 conductivity and pondage test seepage. However given that these represent seepage sites more than 20 km apart (significantly further than other sites tested in the trials), this was not unexpected. The watertable along the WWC is generally beyond the penetration depth of the EM31 and therefore the likelihood of seepage is inferred based on soil properties beneath the channel. This will contribute to misleading results when comparing unsaturated zone lithology to seepage rates, and is the cause of some of the scatter in the WWC regression relationship. For example, the WWC contains a significant silt bed which generally controls the seepage rate rather than soil properties beneath the channel. Some of the scatter in the results could also be explained by incorrect pond placement (ie not straddling areas of like conductivity). When points of high variance and leverage were removed, the correlation coefficient improved to 0.62 (from 0.40).

The prediction interval bands suggested the relationship could be used to distinguish between sites of low and high seepage, but is limited in interpreting mid-range seepage. An improvement would be expected if the top of the watertable was targeted, rather than inferring seepage from unsaturated zone soil properties, as much of the seepage in the WWC is controlled by the silt layer in the channel and not the unsaturated zone permeability. Given that the ponds were significantly spaced apart, it was concluded that this relationship can be used for interpolation, bearing in mind the associated broad prediction intervals associated with the regression line.

Based on the results of the pondage tests and relationship with EM31 and the drilling program, areas recommended for remediation were finalised. Sites were defined as either priority one or priority two seepage risk sites, depending on the degree of perceived seepage risk. Priority one sites were considered to require remediating as part of the upgrade, while priority two sites were to be monitored closely for seepage following the upgrade. Given the uncertainty in the EM31 – seepage relationship, the EM31 predicted seepage was not used as the sole means of assigning seepage risk but geological data and visual observations were also integrated into the decision making.

The Waranga Western Channel seepage investigation is a good example of the integration of geophysical, geological and pondage test data to determine areas of highest seepage risk. In the end the required objectives were achieved, however the investigation could have been improved by following the process outlined in this report (refer to conclusions - geophysics). That is, a geophysical survey targeting the top of the watertable, followed by test drilling to a suitable depth (based on the geophysical survey results) and then followed up by pondage tests, also based on the results of the geophysical survey and the test drilling. By clearly establishing this process from the outset, this would have avoided the need for two rounds of drilling, and probably could have provided GM-W with a more rapid answer.

7. Discussion of Results

7.1 Overview

In response to increasing concern regarding channel seepage issues, the Australian Committee of Irrigation and Drainage (ANCID) representing Australian rural water authorities (RWAs), in conjunction with the Murray Darling Basin Commission (MDBC) initiated a project to investigate channel seepage measurement. One of the main objectives of the study was to trial and document a range of seepage identification, measurement and quantification techniques.

- *Project initiated by ANCID and MDBC*

Channel seepage measurement trials were conducted from early 2000 to mid 2002, by Wimmera Mallee Water (WMW), Murray Irrigation Limited (MIL) and Murrumbidgee Irrigation (MI). In addition, results from channel seepage measurement investigations conducted on the Waranga Western Channel (by Goulburn-Murray Water) were incorporated into the final year of the trials.

- *Trials were conducted between 2000-2002 in four RWAs*

Based on the outcomes of other components of the project [the Literature Review (ANCID, 2000a), the RWA survey (ANCID, 2000b)], and consideration of the primary objectives of the study, the trials focussed on the following techniques:

- Pondage tests
- Point measurement (channel full and empty),
- Geophysical techniques,
- Groundwater techniques,
- Soil classification; and,
- Remote sensing.

- *The trial program developed was based on early components of the project*

Pondage tests were conducted at all sites, as they were the basis on which other techniques were assessed. Drilling was also conducted at all sites in order to identify sub-surface conditions. The final year of trials focussed on geophysics, which in the first two years of the trial program had demonstrated the greatest potential for meeting RWA requirements for rapid and low cost channel seepage assessment.

- *Pondage tests and drilling were conducted at all sites. The final year of trials focussed on geophysics*

The following techniques were not included in the trials:

- Inflow-Outflow Tests: Not sufficiently accurate for measuring losses over relatively short sections of channel (ie 1-2km). Over relatively long lengths of channel this is an appropriate technique, and therefore the technique is suitable for identifying and prioritising, at an RWA wide level, channels which have higher losses compared to others in the system.
- Mathematical Modelling - The intensity of data collection and level of specialist input required does not make this method practical for use by RWAs for most channel seepage investigations.
- Hydrochemical Techniques and Tracing of Leakage Plume - The high cost and expertise required of such trials means they are generally not practical solutions for RWAs.

7.1.1 Assessment Methodology

In undertaking these channel seepage investigations, the basic approach adopted was:

- Identification of test site locations;
- Gathering available information on test sites;
- Measuring rates of seepage at test sites using direct measurement techniques – pondage tests were used for this purpose (refer to section 7.2);
- Comparison of the direct measurement technique with indirect techniques; and,
- Extrapolation of results beyond the test zone to interpret seepage distribution – this was applied for techniques which compared favourably with the direct technique.

- *A common methodology was adopted at each site, including assessment of seepage with direct techniques and comparison with indirect techniques*

7.1.2 Description of Trial Sites

The seepage investigation sites all lie within the Murray Darling Basin. The channels investigated were main delivery channels, ranging in capacity from 80 ML/d (Tabbita) to 600 ML/d (Rocklands). With respect to lithology, sites ranged from a clay profile, to a sand profile, as well as sites with rock at or near the surface. Groundwater salinity ranged from moderately fresh to highly saline. Groundwater depths ranged from very shallow (0.5 – 1.5m) to moderately deep (9-10m). Channel dimensions were reasonably similar, with the depth of water at full supply level (FSL) typically 1.5m and wetted perimeters of between 9-16m.

- *All trial sites were within the Murray Darling Basin. Sites varied in terms of channel capacity, lithology and groundwater salinity and depth*

7.2 Pondage Tests

Pondage tests involve blocking a section of channel for a period and applying a water balance to determine the seepage losses. They are widely considered the most accurate means of channel seepage measurement and were adopted as the baseline technique against which other techniques were assessed. Pondage tests were therefore conducted across all sites, totalling 81 ponds.

- *Pondage tests are considered the most accurate means of measurement. They were adopted as the baseline technique in the trials*

Seepage rates ranged in magnitude across the sites from 0.1 mm/d (Toolondo East) to 48 mm/d (Donald). The average and median seepage rate across all sites was 9.7 mm/d and 7.0 mm/d respectively. Some sites anticipated to have high seepage rates actually contained low rates (due to surface clogging layer), while others expected to have low rates were found to have a high rate of seepage. Visible evidence of seepage was found to not necessarily imply high seepage rates.

- *Seepage rates across all sites ranged from 0.1-48 mm/d, with a median rate of 7.0 mm/d*

At three sites where pondage tests were repeated, a good degree of repeatability was observed. The maximum difference between seepage rates was 25%. Differences in pondage test rates from one season to another are probably attributable to changes in depth to watertable and channel bed properties. The differences are considered acceptable for the purposes of this investigation, and not considered to be significantly due to errors in the pondage test method.

- *Where pondage tests were duplicated, a good degree of repeatabiility was observed*

7.3 Sub-surface Characterisation

Sub-surface characterisation by soil and geological profiling was conducted to assist in general site characterisation (provided information on soils, depth to groundwater and groundwater salinity) as well as to assist in geophysical interpretation. Bores were generally drilled adjacent to the channel, up to 10 m in depth.

- *Sub-surface characterisation was undertaken to assist in site characterisation and to assist in geophysical interpretation*

An attempt was made to estimate seepage based on average soil permeabilities, using different weightings to test the influence of the soil across a range of depths. The upper 2m of the soil profile gave the best indication of some relationship between permeability and seepage rate, however no clear relationship between soil permeability and seepage rate was obtained. A combination of factors is likely to contribute to the absence of a relationship. Two types of factor contribute to the absence of a clearly defined relationship between seepage and soil permeability (Kv):

- *No clear relationship between average soil permeability and seepage rate was obtained*

- *Limitations inherent in method* – There was insufficient definition of changes in soil type along channel (ie low sampling density). Further, the process of assigning Kv to soil type is inaccurate. The hydraulic conductivity for the particular soil type should be field tested rather than assigned from literature.
- *Factors apart from soil type are the primary control on seepage rate*: The two most common factor are:
  - Bank dominated seepage (ie due to poor bank construction etc) and,
  - Surface clogging layer.

  These factors explain why sites like Finley and Dahwilly can have such similar seepage rates, even though the underlying soil at Dahwilly has permeability many orders of magnitude higher than the clay at Finley. Seepage rates at Dahwilly are controlled by the clogging layer on the base of the channel while seepage rates at Finley are controlled by lateral bank seepage.

The density of sampling required and the cost of seepage rate tests in specific soil types, and in addition to the fact that soil type is not always the factor controlling seepage, means that it is not likely to be an accurate or cost effective means of seepage quantification. However it remains a critical part of the data gathering and site characterisation phase of a channel seepage investigation.

- *Sub-surface characterisation for quantifying channel seepage is unlikely to be accurate or cost-effective*

7.4 Point Tests

Five point test trials were conducted during the investigation, using ring infiltrometers, disc permeameters and Idaho seepage meters. The trials were conducted at Toolondo (Central), Dahwilly (Central), Tabbita, and the Donald Main Channel.

- *Five point test trials were conducted during the investigation using ring infiltrometers, disc permeameters and Idaho seepage meters*

i) *Dahwilly (Central): Ring Infiltrometer and Disc Permeameter* – Both the ring infiltrometer and the disc permeameter failed to characterise the true seepage rates of the ponds. This is most likely due to the inadequate sampling density of the testing program. However, results were of the same order of magnitude as the pondage tests. The results of the two techniques were very poorly correlated against each other. This is probably due to error in the infiltration rings.

ii) *Toolondo (Central): Ring Infiltrometer and Disc Permeameter* - Seepage rates obtained from the disc permeameter and ring infiltrometer tests on the Toolondo channel were several orders of magnitude higher than actual seepage rates (from the pondage tests). Tests measured the hydraulic conductivity of a sand layer in the channel, rather than the underlying more restricting clay and silt layer. In a relative sense the tests distinguished between the higher seeping pond and the lower seeping pond. Best results were obtained for the lower quartile data indicating that the higher results were unreasonably biasing the true seepage rates.

iii) *Dahwilly (Central): Idaho Seepage Meter* – For three of the ponds there was a distinct linear trend between the Idaho seepage meter results and the pondage test results. However the lowest seepage pond (8 mm/d) returned the highest weighted Idaho meter reading of 59 mm/d. This eliminated any overall correlation in the results. It is concluded that too few Idaho tests were conducted to adequately characterise the channel. Idaho seepage meter rates were generally two to three times higher than the pondage test rate, but in the 'outlying' pond was eight times higher. It is surmised that the base of the channel is seeping at a higher rate than the walls, a theory supported by site geology.

An attempt was made to correlate the Idaho seepage meter results with the EM31 survey data. The resulting correlation was inverse, as expected, but the fit was quite poor. The EM31 conductivity did not distinguish between Idaho seepage meter rates in the 5 – 40 mm/d range, but did differentiate the two highest seepage sites (80 mm/d). Definitive conclusions could not be drawn from these results as the conductivity range is very narrow (39 –45 mS/m) and the data set small.

iv) *Tabbita: Ring Infiltrometer* – Ring infiltrometer tests were conducted in three ponds on the Tabbita Channel. The ring infiltrometer results did not distinguish between the pondage test seepage rates of the ponds. Median seepage rates for the three ponds were all between 4-5 mm/d, compared to pondage tests rates of 6-8.5 mm/d. The very narrow spread of the pondage tests range at the site limits the statistical significance of these results. The lower ring infiltrometer seepage compared to the pondage test seepage is either due to the low sampling density of the testing program (therefore missing 'hotpots') or to the fact that walls of the channel are seeping more than the channel bed.

v) *Donald Main Channel: Idaho Seepage Meter* – Idaho seepage meter tests were conducted in four ponds on the Donald Main Channel. The seepage meter results were comparable in magnitude to the pondage test results. The correlation between the pondage test results and the Idaho results was moderate to poor. The limited number of pondage sections on which the trend is based (4) and the limited number of Idaho tests within each pond (5-6) are contribute to the poor correlation.

An attempt was made to correlate the Idaho seepage meter results with the EM31 survey data. No correlation was observed. The EM31 conductivity clearly distinguished between seepage rates in two of the ponds, but no distinction was made in the remaining ponds. The reason for this is unclear.

- *These trials confirmed that point tests are generally not reliable for directly quantifying seepage, due to the impractically large number of tests required*

These trials have confirmed that point tests are generally not reliable for directly quantifying seepage. Due to variable and sometimes erratic values obtained in measurements, the trials have illustrated that a large number of tests is required to sufficiently determine the true seepage rate of a section of channel. Therefore they are generally not considered reliable for absolute quantitative purposes and should generally be limited to determining the distribution of seepage losses (i.e., relative seepage). Even for this use a large number of tests are recommended to minimise the effects of local variability. These conclusions equate to the findings of the literature review (ANCID, 2000a).

In addition, it was apparent in a number of channels that the bed of the channel was seeping at a different rate to the walls of the channel. This appeared to be occurring at a number of the point test sites, as evidenced by higher seepage rates in the base of the channel than the pondage test rates. This is in contrast to the normal phenomenon with point tests where lower seepage rates than actual are often obtained (due to the non-detection of seepage 'hot spots'). In these cases, even very high density point test sampling in the bed of the channel cannot determine the actual seepage rate.

- *Beds of the channels appeared to be seeping at a different rate to the walls*

In terms of choice of equipment for point testing:

- The Idaho seepage meter appeared to provide the most reliable results of the three instruments. This concurs with the fact that the channel is full during the test and that truly saturated flow is being measured. However there are very few operators skilled in the use of the equipment and therefore testing is limited by their availability. The tests are also very expensive, due to the fact two operators are required, including one skilled in the use of the meter.
- Definitive comments cannot be made regarding the accuracy of the disc permeameter compared to the ring infiltrometer. Some trouble was encountered however with the ring infiltrometer in terms of seepage outside of the ring. The disc permeameter is simpler to use than the ring infiltrometer, both in terms of operation and manual handling.

- *The Idaho Seepage meter appeared to provide the most reliable results of the three instruments*

7.5 Groundwater Techniques

Groundwater observation bores are often required as part of the site characterisation phase of a channel seepage investigation. Quantitative analysis of seepage rates was conducted on the Donald Main Channel based on changes in groundwater level before and after channel filling. Groundwater response to the operation of the channel is was observed in adjacent channel bores, with rises of more than two metres within weeks of channel commencement. Bores at 50m distance from the channel displayed rises between 0.5 m and 1 m.

- *Relatively rapid responses in ground-water levels were observed adjacent to Donald Main Channel in response to channel filling/emptying*

Groundwater levels at the Donald Main Channel were used to estimate seepage adjacent two bore lines using the Dupuit Forcheimer equation for flow in an unconfined aquifer. Assuming an aquifer thickness of 10m, seepage estimates approximately equal to pondage test seepage were obtained for an assumed hydraulic conductivity of 0.2 m/d. Qualitative assessment only was conducted on the Tabbita site. Very clear response to channel shutdown was observed in groundwater hydrographs at this site.

- *Groundwater levels were used to estimate seepage rates*

Use of groundwater bores for quantitative analysis of seepage rates is not considered an accurate or cost effective means for typical Rural Water Authority channel seepage investigations. In order of increasing importance the method is not considered accurate due to:

- *Use of groundwater bores for quantitative analysis is not considered accurate or cost effective for most RWA purposes*

- Sensitivity to hydraulic conductivity inputs (eg Tabbita – depending on input hydraulic conductivity, seepage rates of varying orders of magnitude can be obtained) and the cost of obtaining sufficiently reliable estimates.
- Relies on assumptions regarding pre-channel groundwater levels. These can be estimated from conditions before and after channel filling, but depending on site hydrogeology this assumption may or may not be accurate.
- It is essentially a type of point test and does not answer the question of what area of the channel is seeping. A high density of bore transects would be required for meaningful identification of local areas of channel seepage.
- Relies on an assumption of aquifer thickness (this may be able to be calculated but in a deep aquifer this may be very expensive).

However, groundwater observation bores are a very valuable part of the site characterisation phase of a channel seepage investigation. Further, groundwater bores are a very useful post-remediation assessment tool, particularly for assessing the effectiveness of remediation on reducing near channel land degradation. Where land degradation issues are a significant driver in a channel seepage investigation, groundwater bores are likely to form a key investigative tool, although as discussed above should not be relied upon to provide an accurate quantitative analysis.

- *Groundwater bores are a very useful post-remediation tool*

7.6 Remote Sensing

A remote sensing trial was planned in the Wimmera. However the trial was not undertaken due to RWA budget constraints. Previously collected data (ie. prior to ANCID trials) was evaluated with a view to incorporating the results into the project but unfortunately the data was not in a form suitable for inclusion in the project. While remote sensing trials were not conducted, based on the literature review and preparation of the brief for the proposed trials, it is concluded that remote sensing techniques:

- *A remote sensing trial was planned but eventually not under-taken due to budget constraints*

- Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage. It should not be used if it is known that the seepage mechanism is predominantly vertical, such as likely to occur at sites with a deep watertable;
- Will be most useful in environments where lateral seepage is predominant. For example, sites with a high watertable, shallow impermeable layer or bank seepage - these environments represent conditions most likely to facilitate lateral seepage and cause the seepage to have a surface expression; and,
- Remote sensing should primarily be regarded as a seepage identification tool and not for seepage quantification purposes.

- *Remote sensing techniques are best suited to investigations concerned with land degradation associated with channel seepage and/or where lateral seepage is predominant*

7.7 Geophysics

The geophysics conclusions are set out in the following manner:

- General Conclusions
- Summary of EM31 Results
- Summary of EM34 Results
- Summary of Resistivity Results

7.7.1 General Conclusions

7.7.1.1 Seepage Detection Mechanisms

Geophysical techniques applied to seepage measurement primarily depend upon measuring a contrast in terrain conductivity (or resistivity) in the sub surface profile around the channel. They can be used in one of two ways:

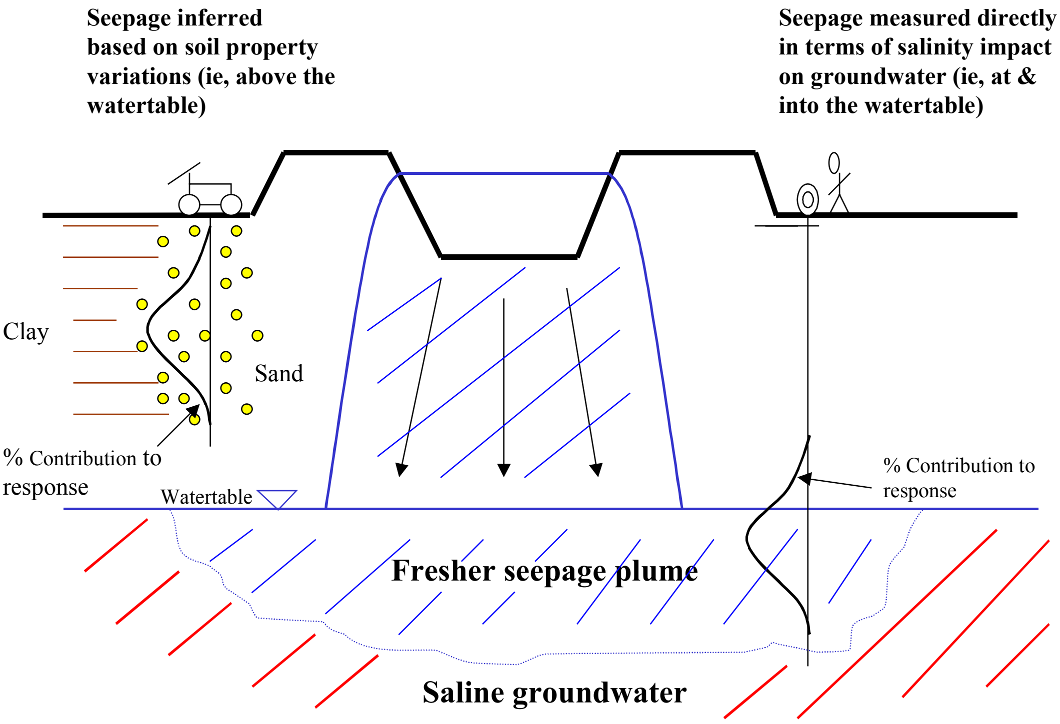
1) Directly measuring the conductivity of the groundwater, and identifying the conductivity contrast of fresher channel water as it seeps into and dilutes more saline native groundwater. Decreasing the salinity of the groundwater will cause a decrease in electrical conductivity (or an increase in its inverse, resistivity).

2) Identifying contrasts in soil properties and inferring the likelihood of seepage through more permeable materials in the zone above the watertable. Formations more likely to allow seepage, such as sands, are naturally lower in conductivity (higher in resistivity) due to lower porosity and lower cation exchange capacity than tighter clay dominated formations. In addition the higher permeability of such formations leads to better drainage and lower salt content, further reducing conductivity. The magnitude of seepage is assumed to be related to unsaturated zone soil properties beneath or adjacent to the channel.

- *Geophysical techniques identify or measure seepage by detecting contrasts in terrain conductivity by either:*
- *Directly measuring seepage induced changes in ground-water conductivity, or*
- *Identifying contrasts in soil properties above the watertable*

Figure 7-1 visually depicts how these two different approaches can be used to identify or infer seepage.

■ Figure 7-1 Comparison of how geophysical techniques can be used to identify channel seepage (LHS – inferred from soil property variations, RHS – direct measurement of salinity impact on watertable)



Technically the second method of 'detection' is not really detection, but the magnitude of seepage is assumed to be related to unsaturated zone soil properties beneath or adjacent to the channel. In many cases this is a reasonable assumption. However the unsaturated zone is not necessarily the controlling influence on seepage. For example, over time most Australian channels tend to silt up and the resulting surface clogging layer is often more restrictive than the unsaturated zone. Therefore unsaturated zone lithology may not be related to seepage rates, as seepage is controlled by the thickness and conductance of the clogging layer.

- *The inferred method of 'detection' assumes the magnitude of seepage is related to unsaturated zone soil properties*

Nevertheless, it was found that the inferred method of identifying contrasts in soil properties (ie, where the watertable was deeper than the penetration depth of the geophysical equipment) was successful at most sites conducted during the trials (ANCID, 2003). There is less risk however in using the direct method of seepage detection, because as the name implies it is not inferred, but direct. An example of where the 'inferred' method of detection did not work was at Dahwilly Central where an EM31 survey was conducted while the channel was not running. The survey was therefore measuring changes in the unsaturated zone and not in the groundwater. At this site the silt layer in the channel, not the unsaturated zone is the restrictive layer and therefore no correlation was observed. When the survey was repeated with the channel running, a good correlation was obtained.

- *The inferred method 'detection' was successful at most sites but not all. There is less risk in the direct method of detection.*

Some possible limitations of the direct method of seepage detection are listed below: (However, it is still considered the preferred technique over inferring seepage based on soil property variations).

- In relatively non-saline groundwater environments, the fresh seepage water will not contrast with the native groundwater. As a guide it is recommended that the groundwater salinity is at least 3 to 4 times higher than the channel water salinity. This is not expected to be a problem in most Australian conditions;
- In environments where the channel seepage water might be rapidly mixed with native groundwater, such as sites with high groundwater gradients or highly transmissive environments, the salinity impact on the groundwater may not be as significant. This can largely be overcome by using survey traverses close to (or on) the channel; and,
- Groundwater salinity variations along the channel will affect the results and this needs to be allowed for in the interpretation.

- *Possible limitations of the direct method of detection are in non-saline groundwater environments, sites with steep ground-water gradients or high transmissivities and sites with highly variable groundwater salinity*

In summary, it is very important that the depth to watertable is known at the site before selecting a technique. Based on this information a decision can be made as to whether direct or inferred measurement will be undertaken and hence the technique that will be adopted.

- *Knowledge of depth to watertable is important before technique selection*

7.7.1.2 Comparison of Trialed Geophysical Techniques

The following have been identified as key criteria against which geophysical techniques should be compared:

- Accuracy
- Cost and Speed
- Availability of Operators
- Data Processing

The three techniques trialed in this investigation (EM31, EM34 and resistivity) are discussed in terms of each of these criteria.

Accuracy

In theory on-channel resistivity surveying should be the most accurate of the geophysical techniques trialed, as it is based on a direct method of seepage detection (refer Section 7.7.1.1). As the technique allows definition of changes in resistivity / conductivity through the profile, the depth where seepage impacts will be most evident (at and below the watertable) can be targeted. At most sites resistivity surveying results were comparable to EM31 and EM34, and at three sites (Dahwilly Central, Dahwilly East and Finley) the resistivity correlations with pondage tests were better than the EM31 and EM34 correlations. The Dahwilly site demonstrates the benefits of targeting the watertable for seepage detection in an environment where seepage is not controlled by the unsaturated zone, but by a surface clogging layer in the channel.

- *Theoretically resistivity surveying should be the most accurate technique. At most sites resistivity was comparable to EM and at three sites the results were more accurate*

Resistivity did not prove to be quite as 'accurate' as EM31 in environments with a shallow depth to watertable. This was largely attributed to poor near surface resolution of the particular resistivity equipment used in the survey, and not inherent in the resistivity method itself. The resistivity surveying was conducted using equipment that was used for the first time in these trials and as such was largely experimental. The designers of the equipment indicate that improved resolution at shallow depth could relatively easily be achieved in future surveys, by using exponentially rather than linearly spaced arrays (Allen, pers. comm. 31/10/02).

EM34 at 10m coil separation in the horizontal mode provides a similar depth penetration to EM31 (vertical mode) and therefore is similarly accurate (but slower to use). EM34 at a 20m coil separation provides a deeper penetration and focus. At one trial site, the depth focus was apparently too far below the watertable and the critical zone was missed. This is a fundamental limitation with all Geonics EM surveys and other such fixed array type geophysical surveys – the result is averaged over a specific depth interval, which may not be the critical interval of interest.

- *Fixed array geophysical surveys are limited in that the result is averaged over a specific depth interval*

However, the robustness of the EM31, as demonstrated by the consistent results in the trials is due to its relatively shallow depth focus (1-4m). For channels where there is a shallow watertable (eg, surface to 3-4m), EM31 can be used for direct measurement of seepage, which as discussed above is likely to be more reliable. When the watertable is deep, EM31 infers seepage from near surface soil properties. This works in most instances but may break down where clogging processes rather than unsaturated zone lithology control seepage.

- *EM31 was generally demonstrated to be a robust technique at both deep and shallow watertable sites*

The significant advantage of resistivity surveying is that the final output is a two dimensional profile of resistivity beneath the channel. Not only does this allow easier interpretation of the results but it can also provide an indication of seepage mechanisms. For example, at the Toolondo Central site the resistivity profile shows isolated sections of high resistivity (low seepage) emanating from the channel. This is in contrast to the Dahwilly channel where the profile suggested seepage by relatively continuous diffusion along the channel. This seepage mechanism is supported by the lithology at the Dahwilly site, which indicates the entire length of channel is underlain by approximately 10m of medium to coarse grained sand, and hence is more likely to result in uniform seepage rather than seepage 'hotspots'.

- *Resistivity surveying has advantage of providing a profile of resistivity beneath the channel*

Cost and Speed

Approximate costs for the three techniques trialed are given below, based on geophysical surveys undertaken in these trials. However, it is important to note that for geophysical surveys often a significant proportion of the costs are overhead costs (mobilisation, equipment set up etc) and therefore the unit cost per kilometre will usually be substantially less for long sections of channel. Costs will obviously vary depending on site specific conditions (eg, on land – fences, other obstacles, on channel – bridges, checks, fences etc).

- *The unit cost per kilometre will reduce as the survey length increases*

- EM31 Surveys:
  - Wimmera Mallee Water: For 6 kms, on-land including 4 traverses on each side of channel (over 3 sites): $400/km (includes mobilisation, data processing and mapping).
  - Murray Irrigation: For 8 kms, on-land including 4 traverses on each side of channel (over 4 sites): $340/km (includes mobilisation, data processing and mapping).
  - Murrumbidgee Irrigation: On-land including 4 traverses on each side of channel, on each side of channel, the unit cost ranged from $650/km (3km section) to $800/km (1 km section). (includes mobilisation, data processing and mapping). On-channel survey cost was $330/km for a 3 km section.

  EM31 is currently the cheapest of the geophysical methods due to the speed of data acquisition.

- *EM31 is currently the cheapest geophysical method due to the speed of data acquisition*

- EM34 Surveys:
  - Wimmera Mallee Water: For 4 kms over 2 sites: $250/km (1 traverse only on one side of the channel) ie, $500/km for both sides of channel (excludes mobilisation).
  - Murray Irrigation: For 6 kms (on each side of channel) over 3 sites: $435/km (includes mobilisation).

  EM34 is more expensive than EM31 as two people (on foot) are required to operate the equipment.

- *EM34 is more expensive than EM31 as two people are required for operation*

- Multi-electrode Resistivity Surveying – The follow costs were for resistivity surveying across 11 sites (approximately 2km each in length) in the Wimmera, Murray and Murrumbidgee Irrigation areas:
  - Resistivity towed array surveys: $900/km [Includes mobilisation (from Adelaide), travel between sites, production and all equipment costs]
  - Data processing costs: $220/km.

  Note that resistivity surveying costs are difficult to quantify given that the on-channel application of the technique is relatively new. Costs are likely to come down as the technique is refined, the equipment becomes commercially available and subsequently competition is introduced.

- *Resistivity surveying costs for seepage assessment are difficult to quantify as the technique is new – costs are likely to come down over time*

Availability of Operators

A number of commercial EM34 and EM31 contractors are in operation in South East Australia, sufficient to ensure reasonable competition and prices. At present on-channel resistivity surveying is still in a development phase and as such there are no commercially operating contractors who specialise in this type of survey. However, a number of geophysical exploration / surveying companies have the capability to develop this type of equipment (such as the company who conducted these trials) and should the demand for such surveying increase, it is expected other companies could also develop this capability. However at present this may be a constraint on resistivity surveying.

Data Processing

Data processing requirements for EM31 and EM34 surveying are minimal. By comparison, data processing requirements for resistivity surveying are considerable, due to the cost of inverting the data to produce a resistivity cross section. This is not really a constraint of the technique, but adds to the overall cost of resistivity surveying. Care needs to be taken to ensure that the contractor undertaking the resistivity surveying also has the capability to undertake the data processing. Approximate costs for data processing are provided above.

7.7.1.3 Critical Geophysical Survey Variables

- *Survey timing* – The timing of the geophysical survey will depend on the method of seepage detection being used. If seepage is being inferred from soil properties then the timing of the survey is not critical and can be conducted whether the channel is running or empty. However if direct measurement of seepage is used, the survey must be conducted while the channel is running, and preferably after it has been running for a least one month (depending on depth to watertable and vertical hydraulic conductivity), to ensure seepage has impacted the groundwater.
- *On-channel versus on-land* – During the trials, on-channel (ie, in a boat) EM31 surveys:
  - Did not work at one site where the watertable was beyond the range of the EM31 and returned similar (reasonable) results to the on-land survey at another site (Waranga);
  - Did work at sites with a shallow watertable; and,
  - Were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31.

  Further work is required in this area, but the evidence collected in this investigation suggests on-channel EM31 surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. In other words, the method of inferred seepage based on unsaturated zone soil properties does not appear to work on-channel. It is apparent that the flushing effect immediately beneath the channel is dominating changes in lithology. For EM31 systems this would preclude their on-channel use when the watertable is deeper than approximately 3-4m.

  However, there is some conflicting evidence, as demonstrated by the trial results summarised above. Overall however, the most consistent (EM) results were returned on-land and this is considered the safest option. A possible limitation of on-land surveying, may be at sites which contain significant land salinisation

- *On-channel EM31 surveys should generally only be conducted when depth to watertable is 3-4m or less*
- *More consistent EM results were returned on-land than on-channel.*

immediately adjacent to the channel. Therefore, if the budget allows, it is recommended that both on-land and on-channel surveys be conducted. Resistivity surveys can be conducted on-channel because of their variable and greater depth penetration capacity.

- *Off-set distance and location for on-land surveys* – The evidence collected in these surveys indicates the best off-set distance for on-land surveys is immediately adjacent the outside toe of the down slope side of the channel. For either method of seepage detection this is recommended. For inferred seepage 'detection' the soil type next to the channel is most likely to be representative of the soil type beneath the channel. For direct measurement, immediately adjacent tothe channel will be the zone of greatest seepage impact on the watertable. Away from the channel this impact will be diluted. However at sites without a steep gradient or high transmissivity, an average of survey traverses up to 50m on each side of the channel was found to improve the correlation between seepage and the geophysical survey at most sites.

  Traverses on either side of the channel are recommended. However if the budget is a significant constraint, a traverse on the down-slope side of the channel should be the priority.

- *On-land surveys should be conducted adjacent to the outside toe of the channel*

- *Other variables:*
  - Trees – In two surveys (Rocklands and Donald), tree plantations adjacent to the channel appeared to interfere with the survey results. The postulated mechanism is that the trees are consuming the seeped water and therefore the observed impact (in the geophysical survey) on the native groundwater is lessened.
  - Rain – Rainfall did not interfere with the surveys conducted in these trials. However it is possible that surveys conducted after heavy rainfall on light to moderate soil types (ie which allowed significant infiltration) could interfere with the conductivity / geophysical response and therefore should be avoided. Surveys inferring seepage based on shallow soil properties or direct measurement in shallow watertable environments would be most affected.

- *Other variables such as trees and rain may interfere with survey results*

7.7.1.4 Repeatability

Generally a high degree of repeatability was observed between duplicate surveys. At two sites where there was a significant difference in the results, changes in groundwater conditions due to channel operation accounted for the difference. These sites are described below:

- *Change in ground-water elevation accounted for any differences in duplicate surveys*

- Donald - A generally consistent increase (approximately 15 mS/m) was observed across the surveyed area between the October 1999 survey and the September 2001 survey. This increase was caused by the more saline conditions at the time of the 2001 survey. The channel had been running for six months prior to the 1999 survey, creating a sub-surface environment dominated by fresh water and a flushed profile. The reduced channel running time prior to the 2001 survey meant a relatively more saline profile and hence higher conductivity.
- Dahwilly - The average EM31 conductivity for a survey conducted when the channel was not running was less than half the conductivity recorded while the channel was running. This is different to what was observed at Donald, due to

the different depth of groundwater at the two sites. When the channel is not running at Dahwilly, the watertable is largely out of reach of EM31 detection and the response is a reflection of the coarse and low conductivity sands in the unsaturated zone. When the channel is running, the watertable is elevated into the range of the EM31 detection and hence conductivities increase significantly.

7.7.1.5 Regional Assessment of Key Relationships

For all of the sites used in the final year of analysis an attempt was made to look for potential correlations between seepage rates across all sites and geophysical response (EM31 and resistivity). This was conducted using multiple linear regression and simple linear regression. The additional explanatory variables included in the multiple linear regression analysis included:

- Soil permeability (vertical hydraulic conductivity): Averages across 4 different depths were used;
- Depth to watertable; and,
- Groundwater salinity.

An attempt was made to look for potential correlations between seepage rates, geophysical response and other key variables

EM31 Multiple Linear Regression

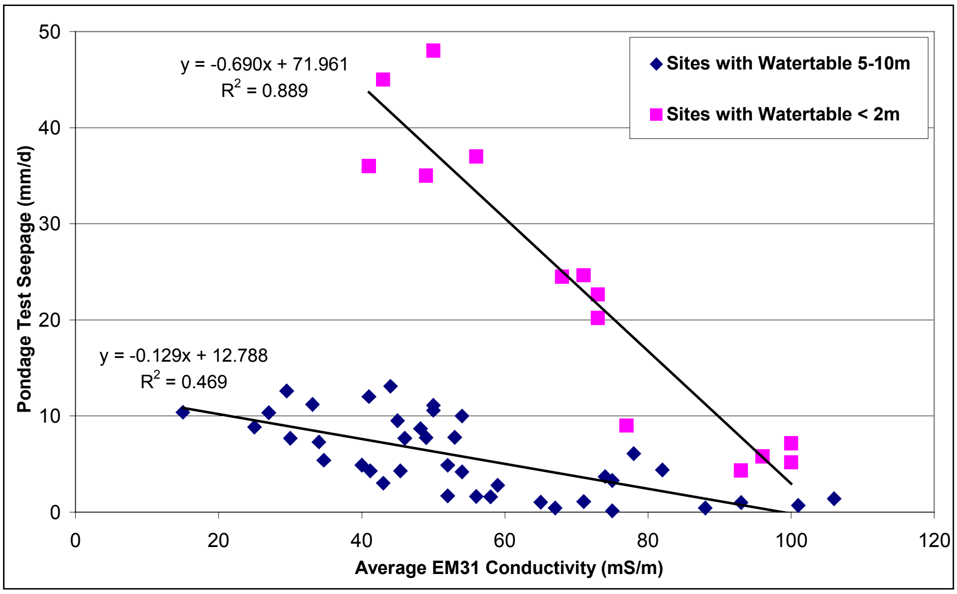
Multi-variate regression analysis was initially conducted on the entire data set (excluding Finley which was removed as an outlier). This indicated that the following were significant explanatory variables:

- Average EM31 conductivity;
- Depth to watertable; and
- Upper K_v (vertical permeability of the top 2m of the profile).

For the EM31 multi-variate regression analysis, average EM31 conductivity, depth to watertable and the permeability of the upper 2m were significant explanatory variables

However, the standard error of estimate (expressed as a percentage of the mean pondage test seepage) for the regression was high (82%). A plot of conductivity versus seepage dividing the data into two categories based on depth to watertable is shown in Figure 7-2.

Figure 7-2 Regional EM31 Assessment: Pondage Test Seepage Versus EM31 Conductivity with Sites Divided Based on Depth to Watertable



Based on this clear division between sites with shallow and deeper watertables (in an attempt to improve the accuracy of the fitted regression model) the sites were split into two data sets based on these two categories of depth to watertable. The difference in EM31 response between a deep and shallow watertable site is explained by the effect of the shallow and saline groundwater which for a given seepage rate causes a much higher conductivity response.

- *A clear division between sites with a shallow and deep watertable was observed. The data sets were split along these lines*

Once the data was split into these two categories, depth to watertable was not found to be a significant explanatory variable, as would be expected. The findings for the two categories are summarised below:

- Watertable Depth Five to Ten Metres - For sites where the watertable is 5-10m below surface, the equation found to provide the best prediction of channel seepage was:

  Seepage = 11.6 – 0.12 *EM31* + 4.4 UK_v *(Equation 1)*

  Where, Seepage = Channel seepage (mm/d)
  EM31 = EM31 conductivity adjacent each side of channel (mS/m)
  UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

  The equation:
  - Was established with 40 data points;
  - Has a correlation coefficient of 0.55;
  - Has a standard error of estimate of 48% (of mean observed seepage rate)

  EM31 was found to be the dominant explanatory variable with soil hydraulic conductivity of secondary importance. Groundwater salinity and depth to groundwater were not found to be significant explanatory variables in the analysis.

- *For sites with a water-table 5-10m below surface, EM31 was the dominant explanatory variable. Soil permeability was of secondary importance*

- Watertable Less Than Two Metres - For sites with a watertable within two metres of the surface multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond EM31. The fact that soil data was not significant is expected as the groundwater near the surface is likely to dominate the response. It was somewhat surprising that groundwater salinity was not found to be a significant variable for this data set, and is probably a reflection of the limited number of sites (three) that make up the data set.

- *For sites with a water-table within 2m of the surface EM31 was the only significant explanatory variable*

EM31 - Simple Linear Regression
Simple linear regression, using EM31 only as the explanatory variable, was conducted to determine how much of an improvement the multiple linear regression actually represents. The data was again divided based on depth to watertable.

Watertable Depth Five to Ten Metres
For the sites with a watertable 5 – 10m below surface, the best fitting linear regression equation was found to be:

Seepage = 12.8 – 0.13 *EM31* *(Equation 2)*

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

The equation:

- Was established with 40 data points;
- Has a correlation coefficient of 0.47;
- Has a standard error of estimate of 51% (of mean observed seepage rate)

- *Confidence intervals for the regional simple linear regression equation indicates the equation is useful for broadly classifying seepage rates*

Confidence intervals (for both 80% and 90%) for this relationship were established and showed that the prediction equation is accompanied by quite broad prediction bands. This probably limits the use of this regional equation to broadly classifying seepage rates (eg into low, medium and high categories), which is not a surprising outcome given the wide range of sites represented by the equation.

- *An exponential regression equation displayed a slightly less accurate statistical fit but visually appears more appropriate*

A plot of actual seepage versus predicted seepage shows that the equation tends to over-estimate seepage for low seepage rates (less than 5 mm/d) and under-estimate for high seepage rates, implying a non-linear equation may provide a better fit. An exponential regression equation was applied to the data. The fitted exponential curve showed that while there is only a marginal improvement in the correlation coefficient for the exponential fit (from R^2 = 0.47 to 0.48), the standard error actual worsens (from 51 % to 62%). Therefore, overall a less accurate fit is obtained using the non-linear equation, even though it may visually appear to fit the data better.

However the advantage of the exponential fit over the linear fit is that there is less of a pattern displayed in the observed versus predicted seepage plots (which suggests that the more realistic model may in fact be the exponential model). Further, the linear model places a maximum limit on the seepage of about 12 mm/d, whereas the exponential model appears to be more realistic, allowing for higher seepage rates in the very low conductivity range (up to around 20-25 mm/d).

- *Only a marginal improvement is observed in the multiple regression compared to the liner regression*

Comparing the linear regression to the multiple regression, the statistics indicate that only a marginal improvement is made to the accuracy of the regression fit in the multiple linear regression analysis (*Equation 1*), compared to the simple regression fit (*Equation 2*). The R^2 for *Equation 1* was 0.55 and the standard error of estimate was 48%. Therefore a relatively modest improvement of 0.08 in the correlation coefficient and 3% in the standard error of estimate is the only improvement gained in adding soil permeability to the regression equation.

<u>Watertable Less Than Two Metres</u>

The best fitting linear equation for sites with a watertable less than 2m is:

$$\text{Seepage} = 72 - 0.69\, EM31 \qquad \textit{(Equation 3)}$$

Where, Seepage = Channel seepage (mm/d)
EM31 = EM31 conductivity adjacent each side of channel (mS/m)

The equation:

- Was established with 14 data points;
- Has a correlation coefficient of 0.89;
- Has a standard error of estimate of 23% (of mean observed seepage rate)

The high correlation coefficient value and the relatively low standard estimate of error suggest a good correlation for the variables. However the results should be tempered by the fact that relatively few data points were used to form the relationship. To improve confidence in the regression equation for the watertable less than two metres scenario, additional points are required in the data set.

- *For linear regression at sites with a shallow watertable a good statistical fit was obtained, but relatively few data points were used to form the relationship*

Prediction bands (80% and 90%) for estimating seepage based on EM31 response when the watertable is less than 2m, indicate that while the prediction intervals are broader in magnitude than for the prediction bands for the deeper watertable scenario, as a percentage of the seepage range covered by each of the equations, they are narrower.

In summary, multi-variate analysis did not significantly improve the regression model. The permeability of the upper part of the soil profile was found to be a significant parameter, but the improvements to the model with this parameter included were marginal. The cost of conducting field tests to collect this data therefore probably outweighs the benefits.

- *Multi-variable analysis did not significantly improve the regression model*

The linear regression equation for sites with a watertable five to ten metres below surface is a reasonable fitting equation, given the range of sites on which it is based. However it should not be relied upon to accurately predict seepage, and should be limited to assigning seepage to low, medium and high categories. The same comments are applicable to the regression equation developed for sites with a shallow watertable (less than two metres). The better statistics for these sites are attributed to the fewer data points and smaller range of environments represented.

Resistivity Multiple Linear Regression

As for the EM31 analysis, the same approach of a regional assessment using multiple and linear regression analysis was conducted for the resistivity results. The same additional variables were used. For the resistivity the ten metre depth slice was adopted. While a more accurate analysis would use the depth at and just below the watertable, for the purpose of a consistent approach, this depth slice was selected. The first cut analysis indicated that depth to watertable was an important variable. Therefore the analysis was again based on division of the data into sites of shallow and deep watertable.

Watertable Depth Five to Ten Metres

For sites where the watertable was five to ten metres below surface (Toolondo and Dahwilly) the equation found to provide the best prediction of channel seepage was:

$$\text{Seepage} = 3 + 0.01\ \text{Resistivity}_{10m} + 7.46\ \text{UK}_v \qquad (\textit{Equation 4})$$

Where,
Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

The equation:

- Was established with 23 data points;
- Has a correlation coefficient of 0.44;
- Has a standard error of estimate of 61% (of mean observed seepage rate)

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 19% of the mean observed seepage rate (to the power of 0.2). A marginal reduction in the correlation coefficient was observed, decreasing to $R^2 = 0.42$.

- *For sites with a water-table 5-10m below surface, resistivity and the permeability of the upper 2m were significant explanatory variables. A power transform slightly improved the regression statistics*

The non-linear equation, using resistivity only as an explanatory variable, for predicting channel seepage at sites where the watertable is greater than 2m is:

$$\text{Seepage} = [\,1.12 + 0.0008\ \text{Resistivity}_{10m} + 0.47\ UK_v\,]^5 \qquad (\textit{Equation 5})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)
UK_v = Vertical hydraulic conductivity of top 2m of profile (m/day)

<u>Watertable Less Than Two Metres</u>
For sites with a watertable within two metres of the surface (Lake View and Lake View West), multiple linear regression analysis did not find any other variables that were significant explanatory variables beyond the resistivity data.

- *For sites with a water table within 2m of the surface, resistivity was the only significant explanatory variable*

Resistivity Simple Linear Regression

<u>Watertable Five to Ten Metres</u>
For the resistivity analysis the number of channels fitting this category was reduced to two (3 sites at Toolondo and 2 sites on the Dahwilly channel). Four points within this data set appeared to be outliers. They were the four high seepage ponds at Dahwilly Central. However they were retained in the analysis as there was no obvious grounds for their removal.

Therefore the linear equation (using resistivity only as an explanatory variable) predicting channel seepage at sites where the watertable is greater than 2m was found to be:

$$\text{Seepage} = 4.2 + 0.01\ \text{Resistivity}_{10m} \qquad (\textit{Equation 6})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

The equation:

- Was established with 23 data points;
- Has a correlation coefficient of 0.16;
- Has a standard error of estimate of 68% (of mean observed seepage rate)

- *For simple linear regression at sites with a watertable 5-10m below surface, a very poor statistical fit was observed between resistivity and seepage rate, largely due to several outliers*

These statistics indicate that the accuracy of the regression is very poor, in large part due to the four high seepage rate 'outliers' at the Toolondo Central site. With these outliers excluded the correlation coefficient improves dramatically to $R^2 = 0.63$. However as discussed above there was no obvious basis for their removal.

- *A power transform did not significantly improve the regression statistics*

Various transforms were examined to improve the accuracy of the regression. It was found that raising the seepage to the power of 0.2 improved the model with respect to the standard error of estimate, which was reduced to 20% of the mean observed seepage rate (to the power of 0.2). A marginal improvement in the correlation coefficient was observed, increasing to $R^2 = 0.21$.

The non-linear equation, using resistivity only as an explanatory variable, for predicting channel seepage at sites where the watertable is greater than 2m is:

$$\text{Seepage} = [\,1.19 + 0.0008\ \text{Resistivity}_{10m}]^{5} \qquad (\textit{Equation 7})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

In summary, neither the linear nor the non-linear simple regression equations were found to be satisfactory predictors of seepage. The very wide prediction bands for the non-linear prediction equation confirm this conclusion.

Watertable Less Than Two Metres

The linear equation predicting channel seepage at sites where the watertable is less than 2m (data set comprised of only the Lake View channel) is:

■ *For linear regression at sites with a shallow watertable, a good statistical fit was obtained but the relationship is based on relatively few data pointsl*

$$\text{Seepage} = 1.7\ \text{Resistivity}_{10m} - 0.66 \qquad (\textit{Equation 8})$$

Where, Seepage = Channel seepage (mm/d)
Resistivity_{10m} = Resistivity at 10m depth recorded on channel (ohm m)

The equation:

- Was established with 8 data points;
- Has a correlation coefficient of 0.62;
- Has a standard error of estimate of 27% (of mean observed seepage rate)

These statistics indicate that the accuracy of the regression is reasonable. However, the results must be interpreted in light of the fact that only a few data points have been used to form the relationship, and all data points were collected on the same channel. Further testing to add different environments to this data set is necessary before a reasonable degree of confidence can be placed in this prediction equation.

The following summary comments are made regarding the linear and multiple regression analysis for the resistivity:

❑ The multiple regression analysis significantly improved the accuracy of the regression equation compared to the simple regression with only one variable, increasing the coefficient of determination from $R^2 = 0.21$ to $R^2 = 0.42$.

■ *It is likely the resistivity regression analysis could be significantly improved by using resistivity data at and immediately below the watertable*

❑ It is likely the analysis could be significantly improved by using resistivity data at and immediately below the watertable for each of the sites.

❑ As was the case in the EM31 multi-variate analysis, the variable which was found to be most significant in the regression equation was the vertical hydraulic conductivity in the upper two metres (upper K_v). Again this confirms that the upper soil profile is by far the most significant part of the profile controlling seepage.

❑ While this analysis indicates a moderately fitting regression equation, it could not be used with the same degree of confidence as the EM31 based equation due to:

- The lower correlation coefficient;
- The few number of data points and small range of environments represented by the data points;
- The unexplained outliers in the resistivity analysis that were not present in the EM31 regression equation.

7.7.1.6 Confidence in Derived Relationships and Extrapolation of Results

Two key issues regarding relationships derived between channel seepage and geophysical response are:

1. What confidence is there that the derived relationship accurately describes seepage within the area tested?; and,
2. How confidently can the relationship be used outside of the area tested to predict seepage?

Based on the findings of these investigations, these two issues are summarised below.

Confidence in Derived Relationships

Confidence in the derived seepage-geophysical relationship within the area tested can be assessed by a number of factors, including:

- *Confidence in the derived seepage geophysical relationship within an area can be assessed by the correlation coefficient, standard estimate of error, prediction interval, number of data points and seepage rate range*

- Correlation coefficient (R^2) – This explains the amount of variation explained by the regression equation. Most geophysical – seepage relationships derived in this investigation had correlation coefficients of between 0.5 to 0.9, and typically were around 0.75, meaning that 75% of the seepage variation could be explained by the geophysical response.
- Standard estimate of error – This is a measure of the degree of scatter about the regression line. A data set may have an R^2 of one but a high degree of scatter. For the regional simple linear regression (EM31) the standard error of estimate (of mean seepage rate) was around 50% for sites with the watertable 5-10m below surface and was around 25% for sites with the watertable less that 2m. For individual channels this was generally lower at about 20%.
- Prediction interval - Prediction bands for most seepage - conductivity / resistivity regression lines were generally quite broad. These bands suggest that often the regression relationship can only be used to classify areas into high, moderate and low seepage. The uncertainty is partially due to the data handling processes, which are based on averaging pondage test seepage and geophysical response over long sections of channel. There is also error inherent in the method in that given the large number of variables that simultaneous impact on channel seepage, it is not possible to tightly characterise seepage based on geophysical response. The prediction intervals were generally tighter for sites with greater ranges of seepage. Prediction intervals are likely to be improved by a greater number of pondage tests across the broadest possible seepage range.

  Knowing that seepage is probably within a certain range (to a given level of certainty), even if the range is fairly broad, is still considered an improvement on the existing seepage knowledge base of many Rural Water Authorities, and can only lead to more informed decision making.

- Number of data points – The number of data points on which the relationship is derived is also very important. For instance, some sites with relatively few data points returned very good statistics (high R^2, low SEE and relatively tight prediction bands). These results need to be viewed with caution because of the low number of points contributing to the relationship (eg, only two data points will have perfect statistics but the results have no meaning). Generally the more data points contributing to the relationship, the greater the confidence in the relationship.
- Seepage range – The seepage range over which relationship is established is important, as it improves confidence in the robustness of the relationship. A limitation at a number of sites in this study was the narrow range of seepage rates. The trends observed across a very tight seepage range can often be meaningless, and at a number of sites where tests were conducted several kilometres away on the same channel, a more realistic relationship for that channel was derived.

Confidence in Extrapolation

The following points need to be considered when extrapolating a geophysical – seepage relationship outside of the area in which it was developed:

- Was the relationship strong in the area tested – This is the first test. If the relationship was not strong in the area in which it was derived (refer to above discussion) then there will be little confidence in extrapolating such a relationship.
- How representative is the area in which the extrapolation is to occur, of the area in which the relationship was developed. The area in which the relationship was developed must encompass the range of conditions over which the extrapolation is to occur. This may be quite difficult to determine. While soil, geological, hydrogeological maps and even test drilling provide an indication of changes along the channel, the results from these trials suggest that these are generally not at a sufficient scale to detect how they will impact on geophysical response. For example, at the Dahwilly sites which showed reasonably similar characteristics (depth to watertable, groundwater salinity and lithology), the EM31 conductivity response was very different and thus extrapolation from the Dahwilly Central site to the Dahwilly East site would have resulted in significant errors in seepage estimate.

  In fact, the evidence coming out of the trials in terms of extrapolation, even to sites that were apparently similar and usually only several kilometres along the same channel, was that the derived relationship was not suitable to predict seepage at the new site. The key outcome of this is that unless intensive data collection is conducted to ensure continuity of site conditions to the area of extrapolation, interpolation rather than extrapolation must be used. This is explained in further detail in the following section, but essentially means that pondage tests should be conducted at regular intervals along the entire section of interest, to ensure that the full range of site conditions is accounted for in the derived regression relationship.

  The more data points collected from different sections along the channel that are added to generate the regression line, may increase scatter about the regression line. This can be seen in the high standard error of estimates for the Rocklands/Toolondo and Waranga regression equations. This is a reflection of

- *When considering the validity of extrapolating a geophysical-seepage relationship to a new area, the strength of the original relationship needs to be assessed, and the representativeness of the new area to conditions where the relationship was derived* the fact that the ponds in these sites covered a wide area and range of sub-surface conditions. However, while there is more scatter about these lines, there is more confidence in using these relationships for seepage prediction as they encompass a wider spatial range and wider range of conditions, and can therefore be used with greater confidence over a broader area, although at the expense of some degree of accuracy.

7.7.1.7 Preferred Methodology

Based on the trials conducted in this investigation, and the methodology outlined in the guidelines (ANCID, 2003) the following methodology for using geophysics to identify and measure seepage is recommended: (Note that this methodology assumes some prior knowledge as to which channels or sections of channel require investigation. This knowledge may have been acquired based on flow records, visual inspection or a regional investigation using a technique like remote sensing).

1. *Define project objective – why is the work being undertaken?* The types of questions to be asked include:
   - Is the primary objective to identify relatively high seepage points or to measure the volume of seepage?
   - Is it necessary to establish the rate of seepage? – either the actual or relative rate.
   - What degree of confidence in the results is required?
   - Over what length of channel is the information required?
   - What is the available budget?

■ *The first step in an investigation is to define the project objective*

At the end of this process there will be a clear definition of the reasons for undertaking the seepage investigation (eg asset management), budget considerations, scale of the operation (eg whole channel, specific channel lengths etc), need for accuracy, or relativity. This process will effect all future decision making.

2. *Collate Site Data* It is assumed that if decisions for action have been made, there is already some knowledge of site conditions. In the event that there are no details key data should be collected. It is important that information on depth to groundwater, background groundwater salinity, soil type and channel hydraulics are known or gathered, both at the site where the testing is conducted, and over the area the results are to be extrapolated.

■ *Collation and evaluation of site data will assist in development of a seepage mechanism conceptual model and in technique selection*

3. *Evaluate Site Data* - It is possible that the process of evaluating the data will have already been performed, formally or intuitively, to identify the need for action at the site. Evaluation does not have to be at a detailed level, but should be sufficient to be able to propose a conceptual model of the seepage mechanism, to detect where changes in these parameters may impact on the geophysical response, and to assist in technique selection. Channel hydraulic information is required to help determine potential channel seepage mechanisms.

4. *Select Technique* - The preferred geophysical seepage measurement technique is one that has a depth focus on and immediately below the watertable. Whether this is achieved using EM or resistivity is not highly important. However, generally it

is easier to focus on a given depth with resistivity (EM provides an average across a range) and this can be achieved independent of knowledge of groundwater depth. The advantages and disadvantages of each of the techniques (refer above) need to be assessed in light of the specific project objectives. The recommended technique for a given depth to watertable is outlined below:

Preferred Geophysical Techniques

- The preferred technique for geophysical channel seepage assessment is *directly detecting the impact of seepage on the groundwater*. This means that the instrument must focus on the zone immediately above and several metres below the watertable:
  - For a *shallow watertable* (surface to approximately 5m) *EM31* is suitable for direct seepage detection.
  - For *watertables deeper than 5m*, *EM34* (in ***vertical*** dipole mode, with the coil spacing dependent on the watertable depth) or *resistivity* can be used. However, particularly for deeper watertables, it is easier to focus on a given depth with resistivity and this can be achieved independent of knowledge of groundwater depth. The significant advantage of resistivity is that it provides a profile of the resistivity beneath the channel. The disadvantage is that resistivity technology for channel seepage assessment is relatively new and therefore more expensive.
- EM31 (vertical dipole) adjacent the channel can be used effectively in areas with deeper watertables, although it does not directly measure the seepage impact on the watertable. This is due to fact that the upper soil layers are the most influential on channel seepage and the relatively shallow depth focus of EM31 measures these upper soil layer properties. The method infers zones of likely channel seepage by identifying materials in the unsaturated zone most susceptible to seepage. A decision to use EM31 in an area with a deep watertable might be based on:
  - Cost and required accuracy – If a potentially slightly lower level of accuracy is considered acceptable then EM31 represents a cheaper alternative than EM34 or resistivity; or,
  - Lack of alternatives – EM34 or resistivity contractors are not readily available.

It this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes. Otherwise errors will potentially be introduced to the assessment process.

The preferred geophysical techniques for seepage detection are summarised in Table 7-1.

- *The preferred geophysical technique is one that is focussed on and immediately below the watertable*
- *The recommended technique for sites with a shallow watertable is EM31*
- *For sites with a water table deeper than 5m, EM34 or resistivity are recommended*
- *EM31 can be used for sites with deeper watertables but relies on inferring rather than directly measuring seepage*

■ Table 7-1 Recommended Geophysical Technique for Seepage Detection and Measurement

Watertable Depth (m)	Recommended Technique [1]	Detection Method[2]	Approximate Depth of Penetration (m)[3]	Depth Focus (m)[4]
Surface to 1.5	EM31 (horizontal dipole)[5]	Direct watertable impact	3	0 - 1
1.5 – 5	EM31 (vertical dipole)[5]	Direct watertable impact	6	1 – 3.5
5 – 12	EM34 – 10m coil spacing (vertical dipole)[6] OR Resistivity[7, 9] OR EM31 (vertical dipole)[8]	Direct watertable impact Direct watertable impact Soil property variations	15 NA[10] 6	3 - 10 NA[11] 1 - 3.5
12 – 25	EM34 – 20m coil spacing (vertical dipole)[6] OR Resistivity[7, 9] OR EM31 (vertical dipole)[8]	Direct watertable impact Direct watertable impact Soil property variations	30 NA[10] 6	6 - 20 NA[11] 1 - 3.5
> 25	Resistivity[9] OR EM31 (vertical dipole)[8]	Direct watertable impact Soil property variations	NA[10] 6	NA[11] 1 - 3.5

1. It is recommended EM techniques are conducted adjacent the channel (additional survey runs can be conducted away from the channel). Resistivity surveys should be conducted on-channel.
2. Direct detection of seepage impacts on the watertable is the recommended technique, but inferred 'detection' based on soil property variations will often provide an adequate simulation and may be more convenient for various reasons (refer to body of report for potential errors associated with this method). Note that direct detection relies on a salinity contrast between the channel water and the groundwater. It is recommended the groundwater should be at least 3 to 4 times more saline than the channel water, a condition that will be met in the vast majority of Australian conditions.
3. Approximate detection of penetration is referred to in the Geonics manual (McNeil, 1980) as the effective depth of exploration. This is the depth to which approximately 75% of the response is attributed.
4. The 'depth focus' is a term used in this report to describe the depth (range) which is most influential in terms of the relative contribution to the overall EM response (McNeil,1980).
5. These can be conducted immediately adjacent to the channel or on-channel. Both are recommended if budget allows. If on-channel is used for a watertable of 0-1.5m, the survey should preferentially collect data in vertical dipole mode where the effects of channel water will be less influential. For sites with a watertable 0-1.5m, EM31 on channel may be preferred if significant land salinisation exists adjacent the channel.
6. Horizontal and Vertical Dipole: Note that as applied to EM34, vertical dipole does not refer to the coil orientation with respect to the ground, and is in fact opposite to the coil orientation. In vertical dipole mode the coils should be horizontal to the ground, which is a slower method than horizontal mode where they are held perpendicular to the ground.
7. Resistivity is the preferred direct measurement technique for this depth to watertable but EM34 is provided as a potentially more accessible alternative.
8. This should be conducted immediately adjacent to the channel.
9. This should be conducted on-channel.
10. The penetration depth of resistivity depends of the particular system set up (dipole spacing and length).
11. Resistivity surveys measures resistivity at a range of depths intervals within the profile (ie, there is no fixed depth focus).

5. Conduct Field Trials

5a. Conduct geophysical survey – Undertake the geophysical survey over the section of interest, giving due consideration to factors such as appropriate timing of the survey and other important variables (refer Section 7.7.1.3).

▪ *Conduct geophysical survey*

5b. Evaluate results – Plot geophysical survey results along the section and overlay with known site conditions (soils, geology, hydrogeology and channel hydraulic data). Based on these plots identify areas of suspected high, low and moderate seepage, assuming low conductivity / high resistivity equates to higher seepage.

▪ *Evaluate results and identify areas of suspected high, low and moderate seepage*

5c. Conduct test drilling – Soil bores should be drilled at appropriate intervals along the length of the geophysical survey. The primary aim of the drilling is assist with interpretation of the geophysical survey. Some key principles of the drilling program are described below:

▪ *Conduct test drilling to assist with geo-physical interpretation*

- Based on the geophysical survey results, conduct drilling across a range of low, moderate and high conductivity / resistivity sites;
- Drill at least some bores into the watertable, and construct some as permanent observation bores;
- Generally drilling should be conducted on the outside toe of the channel;
- Logging and sampling of the bores should ideally be undertaken by someone trained in soil / geological classification and a consistent classification system should be followed.
- Depending on the density of data collected, presenting the results in a geological long section should be considered.

5d. Conduct pondage tests - At appropriate intervals over the entire test area pondage tests are to be conducted. The number of tests will depend on the length of channel surveyed and the variability of conditions along the channel. The following guidelines are suggested:

▪ *Conduct pondage tests across a range of geophysical survey response*

- Pondage tests should be conducted across a range of low, moderate and high conductivity / resistivity sites so as to establish a regression equation which represents the range of geophysical response across the area.
- Similarly, based on the soil drilling results, the pondage tests should be based on a range of different soil types and / or groundwater conditions.
- Pondage tests must be conducted over areas of like conductivity / resistivity. That is they should not staddle areas of (significantly) different geophysical response, as this will complicate interpretation of the results and development of the regression equation.
- Due to the cost of conducting pondage tests, it is recommended that at least two cells back to back should be conducted at each site for efficiency purposes. Using available structures should also be considered to minimise bank construction costs.
- The pond length can be variable, but as a guide they should generally not be more than 400-500m and not less than 50m.

By conducting pondage tests in this manner across the area of the geophysical survey, prediction of seepage rates outside of pondage test areas will be based on interpolation rather than extrapolation, which improves confidence in the predicted seepage. While pondage tests are expensive, they are a critical part of the interpretation process.

5e. Develop and evaluate relationship between seepage and geophysical response – The following key steps should be conducted:

- Plot geophysical response against pondage test seepage.
- Outliers in particular should be assessed in light of all available information, including the conceptual seepage mechanism, test drilling results, channel hydraulics etc. If there are legitimate grounds for excluding outliers they should be removed.
- If from this data two or more different trends can be observed due to identifiable differences in sub-surface conditions, then two different regression equations should be generated.
- Fit a regression line through the data.
- Statistical analysis should be conducted to determine the degree of confidence that can be placed in the derived relationship
- Using the derived relationship the channel length should be divided into seepage categories of various seepage rates based on geophysical response, with accompanying error estimates.

■ Develop and evaluate relationship between seepage and geophysical response, including regression analysis and statistical significance of the relationship

6. *Evaluation* - Evaluate whether investigation objectives have been met. One of the key questions to address is whether there is sufficient confidence in the derived relationship. In addition to the particular statistics of the regression line, this will largely depend on the project objectives. Further pondage tests or other testing may be required to further improve confidence in the relationship.

■ Evaluate whether original investigation objectives have been met

7.7.1.8 International Developments in Geophysics and Channel Seepage Measurement

Since the writing of the Literature Review conducted as part of this project (ANCID, 2000a), a paper was published relating to international developments in channel seepage measurement using geophysics. The paper is briefly summarised below. The important point relating to this work is that it is focussed in the same direction as the geophysical investigations in these trials: developing geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the two and then extrapolation to new areas.

Determining Irrigation Canal Seepage with Electrical Resistivity (Hotchkiss et al, 2001)

Summary of Abstract: Procedures were developed and tested for quantifying seepage losses in unlined irrigation channel reaches in the order of 30m in length, in the Central Nebraska Public Power and Irrigation District canal system. The procedure uses electrical resistivity (ER) measurements while canals are in service to determine the resistivity of the underlying clay layer. ER data were correlated to canal depth and then to seepage rate. Seepage rates were determined using seepage meters. Accuracy is approximately ± 20%, comparable to that achieved using stream gauges methods (± 5% error of total canal discharge). The ER approach, however can easily pinpoint seepage zones more precisely, allowing a reduction in the length of canal lining projects.

Comparisons to this investigation:

- The method used in the Hotchkiss et al (2001) study relies on measuring unsaturated zone soil properties and not seepage directly, ie it is a method which infers the likelihood of seepage. It is based on the theory that 'as resistivity increases, seepage rates will also increase because more sandy or less clayey materials will have higher resistivities' (Hotchkiss et al, 2001). This was also shown to be successful in the ANCID investigations project (eg EM31 at deep watertable sites). This is a valid method but potentially has limitations at some sites (refer section 7.7.1.1).
- Seepage meters rather than pondage tests were used as the direct seepage measurement technique (possibly limited by operational requirements, ie could not shut channel down). Confirming the general unreliability of seepage meter readings, 50% of sites where readings were conducted were discarded as unreliable. This highlights the advantage of pondage tests over seepage meters. The only advantage of the seepage meter is that smaller length areas can be selected; 30m used in Hotchkiss et al (2001) study. (It is not recommended pondage tests be conducted over less than 50m of channel).
- Best correlations were found at 4m depth – similar to this project. Soil properties from the upper part of the profile were found to be most influential on seepage rates.
- Due to considerable depth and variation in channel water, the data first had to be correlated to canal depth and then to seepage rate, whereas in this ANCID study, the depth of channel water was reasonably consistent and this step was not required.

The method used in the US study relied on inferred rather than direct seepage detection

7.7.2 Summary of EM34 Results

Good to moderate relationships were obtained between average EM34 conductivity and the corresponding pondage test seepage at most sites. For EM34 at a 10m coil spacing in horizontal mode, the effective depth of penetration is around 6-7m, with a shallow depth focus at around 1-3m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is predominantly via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

Good to moderate relationships were obtained between EM34 and pondage test seepage at most sites

- **Rocklands** – A good relationship was recorded in both surveys. A high degree of repeatability was demonstrated between the two EM34 surveys conducted.
- **Donald Main** – A moderate relationship was recorded in both surveys. Further points are required in the mid-seepage range to appropriately test the relationship. The technique distinguished between high and low seepage but not within the high seepage results range. Possible interference by adjacent trees may have affected results in some ponds. A generally consistent increase in conductivity was observed between repeat surveys. The difference was caused by the higher watertable and reduced channel running time prior to the survey.
- **Toolondo Central** – A moderate relationship was observed but largely skewed by the result in one pond. The relationship distinguished between high and low seepage rates.

The technique distinguished between high and low seepage but not within the high seepage range

- **Dahwilly Central** - Moderate relationship for 10m coil separation but a very low range of conductivity response was recorded across the five ponds used in the analysis. This is because the EM34(10m) configuration does not penetrate to sufficient depth to significantly detect changes in the groundwater and was therefore mainly measuring differences in the unsaturated zone, which is largely uniform at the Dahwilly site. The EM34(20m) configuration penetrated too deeply below the watertable and therefore a uniform response was observed reflecting native groundwater conditions.
- **Dahwilly East** – No relationship was observed. The seepage rate range was too narrow for a meaningful relationship to be derived.

In summary, the only site where no relationship was observed was at Dahwilly East, which was largely due to the narrow seepage rate range. At the Toolondo Central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence a reasonable trend was observed (a fact reinforced by the success of EM31 at the site). Significantly, the resistivity surveying showed improved correlations compared to the EM34, for the depth slices focussed immediately below the watertable.

- *The only site where no relationship was observed between seepage and EM34 was due to the narrow seepage rate range*

The Donald site survey was focussed on the saturated zone. However the EM31 survey at the site demonstrated a slightly better relationship with pondage test seepage compared to the EM34 (R^2=0.73 compared to R^2=0.50), but neither survey differentiated between the higher seeping ponds. The improved correlation is probably attributable to the deeper depth focus of the EM31 compared to the EM34 (10m, vertical dipole configuration).

At the Rocklands and Dahwilly sites, where the penetration depth (EM34 - 10m coil separation, vertical dipole) was just sufficient to reach the watertable (but the focus was above the watertable), the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone worked to provide a reasonable indicator of seepage. However it is significant that at Dahwilly, where resistivity surveying was conducted, an improved relationship was obtained when the depth slice was focussed immediately below the watertable, where seepage impacts are most discernible.

7.7.3 Summary of EM31 Results

Good relationships were obtained between average EM31 conductivity and the corresponding pondage test seepage at most sites. At only one site (Tabbita) was there no significant relationship identified. For EM31 in vertical dipole mode, the effective depth of penetration is around 6-7m, with a mid-range depth focus of about 2 – 4.5m. This meant that at sites where the watertable was deeper than 5m, only a limited proportion of the response was caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is largely via inference based on soil properties in the unsaturated zone. Key summary comments for each of the sites are listed below:

Toolondo
- Good relationships between EM31 conductivity and pondage tests seepage were recorded in all three surveys at Toolondo Central. This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties.

- A high degree of repeatability between the surveys was observed.
- In-channel (shortly after channel shut down) and on-channel EM31 surveys returned poor results. This is attributed to the fact that an EM31 survey above the watertable 'works' by inferring seepage based on soil properties. However immediately beneath the channel, even for low seepage rate ponds the profile beneath the channel is saturated (or near saturated) with seeped water. This uniform saturation produces a uniform conductivity response, and tends to mask changes in lithology resulting in little differentiation between low and high seepage sites. Significantly however the on-channel resistivity survey recorded good correlations between seepage and resistivity (10m and 12m depth slices). The EM31 on-channel however could not 'see' into the watertable.

■ Good relationships were obtained between EM31 and pondage tests in all three surveys at Toolondo Central and a high degree of repeatability between surveys were observed.

- Better results were obtained with the EM31 compared to the EM34(10m) at this site, possibly due to the greater number of EM31 traverses conducted (ie away from the channel).
- Three Toolondo Sites (Central, East and West) - The relationship established for all sites was moderately strong. Local correlations at Toolondo Central and Toolondo West were stronger than the combination of sites. The Toolondo East site displayed an opposite correlation, but the very narrow range of seepage rates and the flat regression line indicates this is not a meaningful trend. Confidence bands for the overall regression relationship are wide but indicate that the relationship can be used to differentiate between high and low seepage sites. The data most contributing to the low R^2 and wide confidence bands is the four ponds with sandy banks at Toolondo Central. It is apparent the shallow depth of the sand causing the seepage (largely through channel banks) is largely missed by the EM31(vertical) with a depth focus of around 2 - 4.5m.

■ The relationships established across the three Toolondo sites were moderately strong but local correlations at each of the sties were stronger

- If the Toolondo Central site had been used to predict seepage at Toolondo West, predicted seepage would have been 2-3 times too high. At Toolondo East it would have been essentially accurate (0 mm/d), except in one pond where seepage was predicted at 4 mm/d when actual seepage is practically zero.

Rocklands

- A good relationship was observed between EM31 response and pondage test seepage at the Rocklands channel trial site (for the adjacent channel EM31 data). This indicates that seepage was able to be successfully inferred based on unsaturated zone soil properties. However, with a depth to watertable of around five metres, the EM31 survey may also have been detecting some seepage induced salinity changes in the watertable.

■ A good relationship was obtained between EM31 adjacent channel data and pondage test seepage

- A poor response was observed when all survey runs were used, largely due to the effect of trees adjacent one pond. The adjacent channel run was less affected and accordingly better results were returned.
- The on-channel results recorded mixed results. In vertical dipole mode no trend was observed. The configuration is focussed on the flushed zone beneath the channel where uniform saturation from seepage appears to be masking lithology response. In horizontal dipole a reasonable correlation was observed, apparently through identification of lithology changes (clay content) immediately beneath the channel. This was the only case observed where on-channel measurement above the watertable successfully correlated with seepage. At other sites the uniform saturation appeared to dominate the response over changes in lithology, however at this site it is apparent that the changes in lithology close to the

■ The on channel results were mixed: no trend in vertical dipole mode and a reasonable correlation in horizontal dipole mode

channel surface are sufficiently contrasting to distinguish between high and low seepage areas.

Donald Main

- A good relationship was observed between EM31 conductivity and pondage test seepage but there is a poor spread of seepage data at the site (1 point of low and 5 of high seepage). With a relatively shallow watertable (2m), the EM31 detects seepage at this site in terms of its impacts on the watertable. The EM31 survey did not distinguish between higher seepage ponds (35 - 48mm/d). Confidence bands are fairly wide for the regression line, particularly at the high conductivity range, but indicate that the relationship can differentiate between high and low seepage sites. Additional data points are required to tighten confidence bands.

- *The technique distinguished between high and low seepage but not within the high seepage range. There was a poor spread of seepage data at the site*

- A better relationship was established with EM31 (R^2=0.71) adjacent the channel compared to EM34 (R^2=0.50) but there was still no differentiation observed between the higher seeping ponds. The improved relationship is probably due to the greater depth focus of EM31, particularly on the up-slope side of the channel, allowing deeper penetration into the watertable

- Moderate to good relationships were also observed for the on-channel surveys in both horizontal and vertical dipole. With a shallow depth to watertable the EM31 on-channel survey detects seepage as it impacts the watertable.

Dahwilly

- For a survey conducted when the channel was not running, no relationship was observed between EM31 conductivity and pondage test seepage. The technique failed because the channel was not running and previously seeped water was therefore likely to have thoroughly mixed with native groundwater. Unsaturated zone lithology is a good indicator of seepage at some sites. However at Dahwilly it is not the unsaturated zone controlling seepage rates, but the clogging layer at the channel surface and therefore seepage must be detected directly (ie in terms of impact on watertable) which means the channel must be in operation.

- *No relationship was observed for the survey as the channel was not running during the survey. A repeat survey when the channel was operating obtained a good relationship*

- In a repeat survey conducted when the channel was operating, a good relationship was observed (at Dahwilly Central), confirming the importance of identifying the seepage plume as the primary seepage detection mechanism at this site.

- <u>Two Dahwilly Sites (Central and East)</u> - The relationship established for both sites is moderately strong. Local correlation at the Central site is slightly stronger than the two sites combined. The East site displays a very weak correlation, but this is due to the very narrow seepage range and few data points at this site. Confidence bands are relatively wide, suggesting the regression relationship for both sites can only be used to broadly indicate the likelihood of low or moderate seepage. The slightly deeper watertable at the East site appears to have put the watertable largely beyond the range of EM31 and hence very different results are obtained at the East site. Using the Central site regression relationship to predict seepage at the East site would have resulted in over prediction of 1.5 - 2 times actual seepage.

- *The slightly deeper watertable at the East site contributed to the poor results and different response at this site*

- Better correlations at both sites were obtained using the resistivity compared to EM31 due to better targeting of the top of the watertable.

- *Resistivity results were better than EM31 due to better targeting of the water table*

Lake View

- A poor relationship between pondage test seepage (July 2001) and EM31 conductivity (June 2000) was obtained at Lake View Central for all data due to rapid mixing of the seepage plume away from the channel. However for adjacent channel data a significantly improved relationship (to moderate) was observed as seepage impacts are less diluted. Interpretation is limited at this site due to the very narrow seepage rate range. Seepage is detected at this site in terms of its impact on watertable salinity.

- A poor relationship was obtained using all data but a much improved relationship was observed using adjacent channel data

- No sensible trend was observed at the Lake View Central site using the same EM31 survey data (all lines) and the June 2002 pondage tests. It is anticipated however that a better response could be obtained using the adjacent channel data, as was the case for the July 2001 pondage tests. In addition, the 2002 pondage tests may not have been properly placed over sections of like conductivity.

- Both Sites (Central and West) - The relationship established for both sites is moderately strong with a high correlation coefficient but the two data sets creating the regression line have small conductivity and seepage rate ranges. It is desirable to obtain data in the mid range to improve confidence in the relationship. The Central site could not have been used to predict seepage at the West site. However using Central data from adjacent the channel is likely to improve this correlation.

- A moderately strong relationship was obtained for both sites, but the two data sets have narrow conductivity and seepage rate ranges

Tabbita

- No relationship was observed between EM31 conductivity and pondage test seepage. Possible reasons for the failure of the technique at this site include:
  - i) Narrow range of seepage rates (little differentiation in rates along section of interest);
  - ii) Seepage mechanism may be such that majority of seeped water does not reach watertable but move laterally (evaporating and causing salinisation as evidence adjacent the channel);
  - iii) EM31 vertical dipole orientation may penetrate too deeply into the native groundwater, below the zone most effected by seepage; and,
  - iv) The method of averaging conductivity may not be appropriate at this site (or the ponds may need to be placed more carefully, ie over shorter sections of high/low conductivity)

- No relationship between EM31 and pondage test seepage was obtained at Tabbita

Finley

- While a moderate correlation coefficient was obtained for the pondage test – EM31 conductivity relationship at this site (and the highest seeping pond did record the lowest conductivity), the statistics are not meaningful due to the fact that only three data points make up the relationship. The width of the prediction intervals indicate that the regression relationship cannot be used to predict seepage at this site. Additional data points across a wider seepage range are required to improve the relationship.

- Additional data points are required at Finley to enable meaningful interpretation

Waranga Western Channel

- A moderate to poor relationship was recorded between EM31 conductivity and pondage test seepage. However the results should be considered in light of the fact that they represent seepage sites more than 20 km apart (significantly further than other sites). The watertable is generally beyond the penetration depth of the EM31 along the survey reach and therefore the likelihood of seepage is inferred based on soil properties beneath the channel.

- Some of the scatter in the results can be explained by incorrect pond placement (ie not straddling areas of like conductivity) as well as some geological anomalies. When points of high variance and leverage are removed, the correlation coefficient improves to 0.62 (from 0.40). The prediction interval

- A moderate to poor relationship was between EM31 and pondage test seepage was recorded at Waranga. The relationship can be used however to distinguish between low and high seepage bands suggest the relationship can be used to distinguish between sites of low and high seepage, but is limited in interpreting mid-range seepage.

- An improvement would be expected if the top of the watertable was targeted, rather than inferring seepage from unsaturated zone soil properties. Given that the ponds are significantly spaced apart, this relationship can be used for interpolation, bearing in mind the associated broad prediction intervals associated with the regression line.

- *An improvement in the seepage geophysical relationship is likely if the watertable was targeted*

In summary, the only site where no relationship was observed was at Tabbita. A number of possible causes for this were identified, but the predominant contributing factor is not known. At two sites (Rocklands and Lake View Central), the adjacent channel data was used instead of all survey run data. This was required to obtain the best relationship, due to the interference effects of trees and rapid mixing of seepage water away from the channel.

- *At only one site was no relationship observed between seepage and EM31*

At the Toolondo Central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence good trends were observed.

The Donald and Lake View site surveys were focussed on the saturated zone, and seepage was detected as it created a conductivity low against higher background conductivity groundwater.

At the Rocklands and Dahwilly sites, where the penetration depth of the EM31 (in vertical dipole) was just sufficient to reach the watertable, the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone combined to provide a reasonable indicator of seepage. However it is significant to note that at Dahwilly, when the channel was not running, no relationship was observed. This suggests seepage impacts in the watertable are the primary detection mechanism at this site, a fact reinforced by the uniform nature of the unsaturated zone lithology at the site. Seepage at Dahwilly is not controlled by the unsaturated zone but by a clogging layer at the base of the channel. Techniques which purely infer seepage from unsaturated zone soil properties will not work at such sites (including remediated or lined channels).

- *Seepage at the Dahwilly site is controlled by a surface clogging layer – therefore techniques which infer seepage based on unsaturated zone soil properties will not work*

At Waranga a reasonable relationship was observed, considering the distance over which the data forming the relationship was spread. Improvements might be expected using a technique targeting the top of the watertable at this site.

On-channel surveys did not work at sites where the watertable was beyond the range of the EM31 (Toolondo), did work at sites with a shallow watertable (Donald) and were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31 (Rocklands). Further work is required in this area, but the evidence collected in this investigation suggests on-channel surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

- *Evidence suggests on-channel EM31 surveys should only be conducted where the watertable can be penetrated*

7.7.4 Summary of Resistivity Results

Good relationships were obtained between average resistivity (from depth slices immediately below the watertable) and the corresponding pondage test seepage at most sites. Key summary comments for each of the sites are listed below:

Toolondo

- Central – At around 10-12m the best correlation was obtained (R^2=0.6), which is the zone immediately below the watertable and fits with the expected mechanism of seepage detection (ie, in the depth interval of groundwater most effected by seepage). Within individual ponds, the resistivity cross sections show sub-sections of localised higher seepage. There is very little correlation between seepage rates and resistivity in the unsaturated zone.

▪ Best correlations were obtained at 10-12m, the zone immediately below the watertable

- East - The very narrow range of seepage rates and resistivity values meant that no meaningful correlations were observed at the Toolondo East site.
- West - At and below the watertable the expected inverse trend between high resistivity - low seepage and low resistivity - high seepage was not observed. It is apparent that the sandstone at this site may be dominating the response. Low permeability sandstone may be causing a high resistivity response (normally associated with high seepage), and masking the effect of seepage on the saline groundwater. Deeper drilling would be required to confirm this interpretation. The reasonable correlations obtained at shallow depth (2m and 4m depth slices) are most likely due to changes in clay content beneath the channel, and corresponds with observed EM31 relationships.

▪ Expected correlations were not observed at Toolondo West, possibly due to effects of low permeability sandstone

- All Sites – The Toolondo East data (averaging 10/12/14m depth slices) lies within the expected extrapolated range for the Central (10m) site. The West (averaging 10/12m depth slices) data does not fit within the Central and East relationship (possibly due to changes in lithology masking seepage impacts). The West 2m depth slice does fit within the relationship. However without pondage tests it would not have been known that this was the better depth on which to focus.

Dahwilly

- Central - Good correlations were observed at the 6m, 8m and 10m depth slices, which fits with the expected mode of seepage detection below the watertable. Correlation coefficients worsen in the unsaturated zone. Resistivity long sections indicate that seepage is generally diffuse across the surveyed area, in contrast to Toolondo where localised seepage is evident from the resistivity data.

▪ Good correlations observed at and below the watertable. Seepage was generally diffuse.

- East – A strong correlation was observed at 6m which corresponds with the top of the watertable. However, the very narrow range of seepage rates and small number of data points limits the significance of these correlations.
- Both Sites - Two parallel but vertically offset regression lines for the Dahwilly sites are recorded and there is no observed trend for the combined regression line. This suggests different background conditions (despite apparent similarities between sites), including finer and more clayey sands and possibly higher background salinity groundwater at Dahwilly East.

▪ Different background conditions were the probable cause of lack of trend in combined regression equation

Finley

- The best correlation was observed at 4m and 6m which corresponds with the zone below the top of the watertable (1.5m). A misleading opposite (inverse) correlation was observed at 2m depth, when a stronger, direct correlation was expected based on depth to watertable. This may be a reflection of the poor surface resolution of the resistivity equipment. The narrow seepage range and small number of data points also limits the significance of the correlations.

Lake View

- Central - The best correlation was observed at 6m and 8m which corresponds with the zone several metres below the top of the watertable (1.5m). A very weak trend was observed at 2m and an (inverse) correlation at 4m depth. It was expected based on the depth to watertable that the best correlations would be observed at around 2-4m depth. This may be a reflection of the poor surface resolution of the resistivity equipment. Site lithology below the watertable may also be significantly contributing to the response. The narrow seepage range also limits the significance of the correlations.

■ Best correlations were observed at 6-8m. Poor surface resolution of resistivity equipment may have caused the weak trend at 2-4m

- West – There was no meaningful relationship observed between resistivity and seepage immediately below the watertable. This is attributed to:
  i) Poor resolution of near surface data (this theory is supported by the reasonable correlation observed between EM31 and seepage at this site) and/or
  ii) The 'anomalous' result in pond 1.

  Something is causing elevated resistivities relative to other ponds at the site (possibly lithology, faulty data collection etc), although nothing obvious was detected in the drilling.

- Both Sites - Neither the 2m or 6m depth slice from Lake View Central could have been used to accurately predict seepage at Lake View West. However a slightly better fitting trend line is obtained for the 2m depth slice. The apparently anomalous result at Pond 1 (Lake View West) is largely skewing these relationships. Using the Lake View Central site to predict seepage at the Lake View West site would have caused significant under-estimation of actual seepage.

■ Seepage at Lake View West was under-estimated using the Lake View Central regression equation

In summary, most sites displayed a good correlation between seepage and the resistivity at and immediately below the watertable. The two sites that did not were Toolondo West and Lake View West. At Toolondo West it appears that the type of sandstone at this site may be dominating the response. However deeper drilling would be required to confirm this interpretation. Further investigation into the potential variations in resistivity in sandstone is required (eg, potential effects of iron content in rock or amount of clay in the cementing material). A reasonable trend was obtained at shallow depth, but without the information supplied by the pondage tests this could not have been known.

■ Most sites displayed a good correlation between seepage and resistivity at and immediately below the watertable

The lack of trend at the Lake View West site is probably due to the poor resolution of the resistivity equipment at very shallow depth. This site contains the shallowest watertable across all sites (0.5 – 1m). Improved resolution at shallow depth could relatively easily be improved in future surveys by using exponentially rather than linearly spaced arrays (Allen, pers. comm. 31/10/02). At Toolondo East also no trend was observed but this is solely attributed to the very narrow range of seepage rates at this site.

7.8 Waranga Western Channel Case Study

It was proposed that the Waranga Western Channel (WWC), an open irrigation channel maintained by Goulburn-Murray Water (G-MW), be upgraded in capacity along approximately 50 km of the channel length. The channel has a well-documented record of existing seepage problems. The extent of seepage in this section of the channel had been a concern to local landholders for a number of years. In addition, there was concern that new seepage paths may be opened up during an upgrading works program. Therefore G-MW required quantification of sections of existing seepage problems in the WWC with identification and quantification of sections where new seepage paths might be opened up. To this end, geotechnical and geophysical investigations were carried out along the channel, including the following investigative works (in chronological order):

- *The upgrading of the Waranga Western Channel, in addition to existing seepage concerns, initiated an investigation to identify (and quantify) high risk channel sections*

- EM31 survey – November 2001: A 46 km EM31 survey was conducted on-channel and on-land on each side of the channel. This was coupled with drilling of 128 bores adjacent the channel (to 4m depth) to ground truth the survey;
- Additional geotechnical drilling – March 2002: An additional 107 bores were drilled and 34 piezometers installed. Bores were generally drilled to a depth of at least 6m, and some up to 10m;
- Pondage tests – May/June 2002: 12 pondage tests were conducted at various locations along the length of channel under investigation.

The high risk section of the channel, as categorised by the EM31 contractor based on EM magnitude, totalled approximately one-third (15km) of the length of the investigated portion of the channel. To further refine this area, a combination of the EM31 results and impermeability grade (a lithological classification devised for the investigation based on the amount of clay in the profile) was used to identify sections of channel which were considered to represent 'very high' risk areas. Using this system, four significant lengths of channel were identified as very high risk. The total length of the 'very high risk' area was 7.2 km. It was apparent to G-MW that further investigation was required before committing to the significant expense of lining such a length of channel.

- *The initial EM31 survey identified 15km of high seepage risk channel. Combined with lithological data 7.2km of this section was identified as very high risk*

A further 107 bores were drilled (to greater depth than the original drilling program). The above process using impermeability grade (incorporating results from the new bores) and EM31 response was again conducted. Following the review of the additional drilling, the areas classified as very high seepage risk actually increased by about 1 km (from 7.3 km to 8.3 km). This included some areas being removed and some being added to the very high risk category.

It was then recognised that, in addition to the drilling program, pondage tests were required to quantify seepage rates (and potentially identify a relationship between EM31 and pondage test seepage rates) and confirm interpretation of seepage rates based on geology and EM31 data. Therefore 12 pondage tests were conducted at various intervals along the channel, covering a range of environments and areas of different geophysical response.

- *Pondage tests were conducted to quantify seepage rates and confirm geophysical interpretation*

A moderate to poor relationship was recorded between EM31 conductivity and pondage test seepage. However when considered in light of the fact that they represent seepage sites more than 20 km apart (significantly further than other sites tested in the trials), this was not unexpected. The watertable along the Waranga channel is generally beyond the penetration depth of the EM31 and therefore the likelihood of seepage is inferred based on soil properties beneath the channel. Some of the scatter in the results could be explained by incorrect pond placement (ie not straddling areas of like conductivity) as well as some geological anomalies. When points of high variance and leverage were removed, the correlation coefficient improved to 0.62 (from 0.40).

- *A moderate to poor EM31 seepage relationship was observed, but represents sites more than 20km apart*

The prediction interval bands suggested the relationship could be used to distinguish between sites of low and high seepage, but is limited in interpreting mid-range seepage. An improvement would be expected if the top of the watertable was targeted, rather than inferring seepage from unsaturated zone soil properties, as much of the seepage in the Waranga Western Channel is probably controlled by the silt layer in the channel and not the unsaturated zone. Given that the ponds were significantly spaced apart, it was concluded that this relationship can be used for interpolation, bearing in mind the associated broad prediction intervals associated with the regression line.

- *The EM31 seepage relationship could be used to distinguish between sites of high and low seepage.*

Based on the results of the pondage test areas, the relationship with EM31 and the drilling program, the areas recommended for remediation were finalised. Sites were defined as either priority one or priority two seepage risk sites, depending on the degree of perceived seepage risk. Priority one sites were considered to require remediating as part of the upgrade, while priority two sites were to be monitored closely for seepage following the upgrade. Given the uncertainty in the EM31 – seepage relationship, the EM31 predicted seepage was not used as the sole means of assigning seepage risk but geological data and visual observations were also integrated into the decision making.

- *Based on the EM31 - seepage relationship, pondage tests and drilling, sites were defined in terms of seepage priority*

The Waranga Western Channel seepage investigation is a good example of the integration of geophysical, geological and pondage test data to determine areas of highest seepage risk. In the end the required objectives were achieved. However the investigation could have been improved by following the process outlined in the geophysical conclusions section of this report. That is, a geophysical survey, followed by test drilling to a suitable depth (based on the geophysical survey results) and then followed up by pondage tests, also based on the results of the geophysical survey and the test drilling. By clearly establishing this process from the outset, this would have avoided the need for two rounds of drilling, and probably could have provided GM-W with a more rapid answer.

8. Conclusions

8.1 Overview

In response to increasing concern regarding channel seepage issues, ANCID representing Australian RWAs, in conjunction with the MDBC initiated a project to investigate channel seepage measurement. Trials were conducted in four RWAs from 2000 to mid 2002. They were focussed on the following techniques:

- Pondage tests
- Point measurement (channel full and empty),
- Geophysical techniques,
- Groundwater techniques,
- Soil classification; and,
- Remote sensing.

The following techniques were not included in the trials:

- Inflow-Outflow Tests: These were deemed not sufficiently accurate for measuring losses over relatively short sections of channel (ie 1-2km).
- Mathematical Modelling - The intensity of data collection and level of specialist input required means this method is not practical for most RWA investigations.
- Hydrochemical Techniques and Tracing of Leakage Plume - The high cost and expertise required means they are generally not practical solutions for RWAs.

8.2 Pondage Tests

Pondage tests were conducted across all sites (totalling 81 ponds), as they were the basis on which other techniques were assessed. Seepage rates ranged from 0.1 mm/d to 48 mm/d. The average and median seepage rate across all sites was 9.7 mm/d and 7.0 mm/d respectively. Some sites anticipated to have high seepage rates actually contained low rates, while others expected to have low rates were found to have a high rate of seepage. Visible evidence of seepage was found to not necessarily imply high seepage rates. At sites where pondage tests were repeated, a good degree of repeatability was observed; the maximum difference between rates was 25%, with differences attributed to changes in depth to watertable and channel bed properties.

8.3 Sub-surface Characterisation

Sub-surface characterisation was conducted to assist in general site characterisation as well as to assist in geophysical interpretation. An attempt to estimate seepage based on average soil permeability yielded no clear relationship between soil permeability and seepage rate. The absence of a relationship was attributed to limitations inherent in the method adopted (in particular the inadequate sampling density and the process of assigning permeability to soil type), and the fact that in many of the channels studied, factors apart from soil type are the primary control on seepage, including bank dominated seepage and the influence of surface clogging layers. The density of sampling and permeability testing required, in addition to the fact that soil type is not always the factor controlling seepage, means that sub-surface characterisation is not likely to be either an accurate or cost effective means of seepage quantification. However, it remains a critical part of the site characterisation phase of a channel seepage investigation.

8.4 Point Tests

Five point test trials were conducted during the investigation, using ring infiltrometers, disc permeameters and Idaho seepage meters. These trials confirmed that point tests are generally not reliable for directly quantifying seepage. Due to variable and sometimes erratic values obtained in measurements, a large number of tests is required to sufficiently determine the true seepage rate of a section of channel. Therefore point tests are generally not considered reliable for absolute quantitative purposes and should generally be limited to determining the distribution of seepage losses (ie, relative seepage). Even for this purpose a large number of tests are recommended to minimise the effects of local variability. The Idaho seepage meter appeared to provide the most reliable results of the three instruments, probably a reflection of the fact that the channel is full during the test and that truly saturated flow is being measured.

8.5 Groundwater Techniques

Quantitative analysis of seepage rates was conducted on the Donald Main Channel based on changes in groundwater level before and after channel filling. Qualitative assessment only was conducted on the Tabbita site. Groundwater levels at the Donald Main Channel were used to estimate seepage using the Dupuit Forcheimer equation and seepage estimates approximately equal to pondage test seepage were obtained, depending on the input aquifer hydraulic conductivity used. Therefore, use of groundwater bores for quantitative analysis of seepage is not considered accurate or cost effective for typical RWA channel seepage investigations, due to the sensitivity of the solution to hydraulic conductivity inputs and the cost of obtaining sufficiently reliable estimates. In addition, bores are essentially a type of point test and as such do not address the question of where the channel is seeping. A high density of bore transects would be required for meaningful identification of local areas of seepage.

However, groundwater observation bores are a very valuable part of the site characterisation phase of a channel seepage investigation. Further, groundwater bores are a very useful post-remediation assessment tool, particularly for assessing the effectiveness of remediation on reducing near channel land degradation. Where land degradation issues are a significant driver in a channel seepage investigation, groundwater bores are likely to form a key investigative tool, although as discussed above should not be relied upon to provide an accurate quantitative analysis.

8.6 Remote Sensing

A remote sensing investigation was planned as part of the trials but was eventually not undertaken due to budget constraints. Based on the literature review and preparation of the brief for the proposed trials, it is concluded that remote sensing techniques:

- Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage. It should not be used where the seepage mechanism is predominantly vertical;
- Will be most useful where lateral seepage is predominant. For example, sites with a high watertable, shallow impermeable layer or bank seepage are likely to facilitate lateral seepage and cause seepage to have a surface expression; and,
- Should primarily be regarded as a seepage identification tool and not for seepage quantification purposes.

8.7 Geophysics

8.7.1 General Conclusions

8.7.1.1 Seepage Detection Mechanisms

Geophysical techniques identify or measure channel seepage by detecting contrasts in terrain conductivity below the channel in one of two ways:

1) Directly measuring seepage induced changes in groundwater conductivity; or,
2) Identifying contrasts in soil properties above the watertable and inferring the likelihood of seepage.

Technically the second method of 'detection' is not really detection, but the magnitude of seepage is assumed to be related to unsaturated zone soil properties. In many cases this is a reasonable assumption, supported by the fact that the inferred method of detection was successful at most, but not all sites investigated in the trials. The unsaturated zone is not necessarily the controlling influence on seepage, and particularly in Australian conditions seepage is often controlled by a clogging (silt) layer. Therefore, there is less risk in using the direct method of seepage detection. The direct method of detection cannot be used in relatively non-saline groundwater environments, as the fresh seepage water will not contrast with the native groundwater. As a guide it is recommended that groundwater salinity is at least three to four times higher than the channel water salinity.

It is very important that the depth to watertable is known at the site before selecting a geophysical technique. Based on this information a decision can be made as to whether direct or inferred measurement will be undertaken and hence the technique that will be adopted.

8.7.1.2 Comparison of Trialed Geophysical Techniques

The following have been identified as key criteria against which geophysical techniques should be compared:

- Accuracy
- Cost and Speed
- Availability of Operators
- Data Processing

The three techniques trialed in this investigation (EM31, EM34 and resistivity) are discussed in terms of each of these criteria.

Accuracy

The accuracy of a given geophysical technique will depend on whether inferred or direct seepage detection is used. Generally direct measurement should be considered more reliable than inferred measurement. For direct measurement the accuracy will depend on how well the watertable is targeted. Therefore in theory on-channel resistivity surveying should be the most accurate geophysical technique, as it is based on direct seepage detection and can target the watertable independent of depth. At most sites in the trials resistivity surveying results were comparable to EM31 and EM34, and at three sites correlations with pondage tests were better than the EM correlations. The other significant advantage of resistivity surveying is that the final output is a two dimensional profile of resistivity beneath the channel. This allows easier interpretation of the results and provides an indication of seepage mechanisms.

The fundamental limitation with all EM surveys and other such fixed array type geophysical surveys is that the result is averaged over a specific depth interval, which may not be the critical interval of interest. Therefore (for direct detection) the accuracy depends on how well the watertable is targeted by the particular EM equipment, which in turn depends on the watertable depth. If the correct EM equipment is selected to suit the watertable depth, in theory it should be close to the accuracy of resistivity surveying.

The robustness of EM31, as demonstrated by the consistent results in the trials is due to its relatively shallow depth focus (1-4m). For channels where there is a shallow watertable (eg, surface to 3-4m), EM31 can be used for direct measurement of seepage, which as discussed above is likely to be more reliable. When the watertable is deep, EM31 infers seepage from near surface soil properties, which is suitably accurate in most instances.

Cost and Speed
EM31 surveys are the cheapest geophysical method, due to the speed of data acquisition; EM34 is more expensive as two people are required for operation and the equipment must be carried by hand. Resistivity surveying costs are difficult to quantify given that the on-channel application of the technique is relatively new. Costs are likely to come down as the technique is refined, and the equipment becomes commercially available.

Availability of Operators
A number of commercial EM34 and EM31 contractors are in operation in South East Australia. At present on-channel resistivity surveying is still in a development phase and as such there are no commercially operating contractors who specialise in this type of survey, but a number of geophysical exploration / surveying companies have the capability to develop this type of equipment.

Data Processing
Data processing requirements for EM31 and EM34 surveying are minimal. By comparison, data processing requirements for resistivity surveying are much higher, due to the cost of inverting the data to produce a resistivity cross section.

8.7.1.3 Critical Geophysical Survey Variables

- *Survey timing* – If direct measurement of seepage is used, the survey must be conducted while the channel is running (preferably for at least several weeks), however if seepage is being inferred from soil properties then the timing of the survey is not critical and can be conducted whether the channel is running or empty.
- *On-channel versus on-land* – Further work is required in this area, but overall in the trials the most consistent results were returned on-land and this is considered the safest option. Evidence collected in this investigation suggests on-channel EM31 surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. In other words, the method of inferred seepage based on unsaturated zone soil properties

does not appear to work on-channel. For EM31 systems this would preclude their use on-channel when the watertable is deeper than approximately 3-4m.

If budget allows, it is recommended that both on-land and on-channel surveys be conducted. Resistivity surveys can (and should) be conducted on-channel because of their greater depth penetration capacity.

- *Off-set distance and location for on-land surveys* – The evidence collected in these surveys indicates the best off-set distance for on-land surveys is immediately adjacent the outside toe of the channel. At sites without a steep gradient or high transmissivity, an average of survey traverses up to 50m on each side of the channel was found to improve the correlation between seepage and the geophysical survey at most sites. Traverses on either side of the channel are recommended, but if the budget is a significant constraint, a traverse on the down-slope side of the channel should be the priority.

8.7.1.4 Repeatability

Generally a high degree of repeatability was observed between duplicate surveys. At two sites where there was a significant difference in the results, changes in groundwater conditions due to channel operation accounted for the difference.

8.7.1.5 Regional Assessment of Key Relationships

For all of the sites used in the final year of analysis, multiple and simple linear regression was undertaken to look for potential regional correlations between seepage rates and geophysical response (for both EM31 and resistivity). The multi-variate regression analysis indicated that, apart from the geophysical response, depth to watertable was the next most significant explanatory variable.

Based on distinct trends between sites with shallow and deeper watertables, the sites were split into two data sets based on depth to watertable, in order to improve the accuracy of the fitted regression model. For sites with a deep watertable (5-10m below surface) the permeability of the top 2m of the profile was shown to be an explanatory variable of secondary importance.

Statistically the regional fitted regression models were generally moderate to good, with correlation coefficients of around 0.5 – 0.6 and standard error of estimates of around 50%. In some cases a higher correlation coefficient and relatively low standard estimate of error was obtained, however this was for data sets with fewer data points – greater number of points are required to improve confidence in these models. Confidence intervals (80% and 90%) for the regression lines were generally fairly broad, indicating that these regional equations can only be used to broadly classify seepage rates (eg, into low, medium and high categories). Consequently it is recommended that there is currently insufficient confidence in these regression equations for their use to predict seepage at new sites without local calibration against pondage tests.

In most instances the multi-variate analysis did not significantly improve the regression model. The addition of the soil permeability parameter (for sites with a deep watertable), while statistically significant, generally only resulted in marginal improvements to the model. The cost of conducting field tests to collect this data therefore probably outweighs the benefits.

For the resistivity analysis, the ten metre depth slice was adopted as the variable for use in the model. While a more accurate analysis could be conducted using the depth at and just below the watertable, for the purpose of a consistent approach, this depth slice was selected. (There also appeared to be some inaccuracies in the near surface resistivity data). It is likely the analysis could be significantly improved by using resistivity data at and immediately below the watertable for each of the sites. In addition, the fewer data points and smaller range of environments used in the resistivity analysis contributed to the poorer fit of the model. This adds greater uncertainty to use of the model, compared to the EM31 regression equations.

8.7.1.6 Confidence in Derived Relationships and Extrapolation of Results

Two key issues regarding relationships derived between channel seepage and geophysical response need to be assessed:

1. *What confidence is there that the derived relationship accurately describes seepage within the area tested*? - Confidence in the derived seepage-geophysical relationship within the area tested can be assessed by a number of statistical indicators, including: the correlation coefficient, standard error of estimate, and prediction interval. The number of data points and seepage rate range represented should also be considered.
2. *How confidently can the relationship be used outside of the area tested in order to predict seepage*? - When extrapolating a geophysical-seepage relationship outside of an area from which it was developed, firstly the strength of the original relationship needs to be assessed (refer above). Secondly, the representativeness of the new area in comparison to the conditions where the relationship was derived should be evaluated.

8.7.1.7 Preferred Methodology

Based on the trials conducted in this investigation, and the methodology outlined in the guidelines (ANCID, 2003) the following methodology for using geophysics to identify and measure seepage is recommended:

1. *Define project objective* – The key issue that needs to be addressed is identification of the primary reason the work is being undertaken.
2. *Collate Site Data* – Basic site information including depth to groundwater, groundwater salinity, soil type and channel hydraulics should be collated at the testing site and over the area the results are to be extrapolated.
3. *Evaluate Site Data* - This should be at a level to enable development of a first cut conceptual model of the seepage mechanism, to detect where parameter changes may impact on geophysical response, and to assist in technique selection.
4. *Select Technique* - The preferred geophysical seepage measurement technique is one that directly detects the impact of seepage on the groundwater. To do this it must have a depth focus on and immediately below the watertable. The recommended technique for a given depth to watertable is outlined below:

   Direct Detection

   - *Shallow watertable* (surface to approximately 5m): *EM31* is recommended.
   - *Watertable deeper than 5m: EM34* (in vertical dipole mode, with the coil spacing dependent on the depth to watertable) or on-channel *resistivity* can

be used. However, particularly for deeper watertables, it is easier to focus on a given depth using resistivity.

Note that direct detection requires native groundwater salinity to be at least three to four times more saline than channel water salinity.

Inferred 'Detection'

- *EM31* (vertical dipole) adjacent the channel can be used effectively in areas with deeper watertables to infer seepage based on upper soil layer properties.

A decision to use EM31 in an area with a deep watertable might be made due to budget constraints, where a potentially slightly lower level of accuracy is considered acceptable, or due to a lack of alternatives (eg, EM34 or resistivity contractors not readily available). It this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes.

5. *Conduct Field Trials*

5a. Conduct geophysical survey – Undertake geophysical survey in section of interest.

5b. Evaluate results – Plot survey results and overlay with known site conditions (soils, hydrogeology, etc). Identify areas of suspected high, low and moderate seepage.

5c. Conduct test drilling – Soil bores should be drilled at appropriate intervals along the section to assist with interpretation of the geophysical survey. Bore locations should be based on the geophysical survey results, and should cover a range of low, moderate and high conductivity / resistivity;

5d.. Conduct pondage tests – The number of pondage tests will depend on the length of channel surveyed and the variability of conditions along the channel. Pondage tests should be conducted across a range of low, moderate and high conductivity / resistivity sites so as to establish a regression equation which represents the range of geophysical response and should also cover the range of soil types. Individual cells must be conducted over areas of like conductivity / resistivity.

5e. Develop and evaluate the relationship between seepage and geophysical response – This involves plotting average geophysical response against pondage test seepage, removal of outliers as appropriate, fitting of a regression line, statistical analysis to determine the degree of confidence that can be placed in the derived relationship and use of the derived relationship to predict seepage in new areas.

6. *Evaluation* – Evaluate whether investigation objectives have been met.

8.7.1.8 International Developments in Geophysics and Channel Seepage Measurement

Since the writing of the Literature Review conducted as part of this project (ANCID, 2000a), a paper from the US (Hotchkiss et al, 2001) was published describing a similar use of geophysics to measure channel seepage as that adopted in these trials. The method relied on inferred rather than direct measurement of seepage. The important point relating to this work is that it is focussed in the same direction as the geophysical investigations in these trials. That is, developing geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the two and then extrapolation to new areas.

8.7.2 Summary of EM34 Results

Good to moderate relationships were obtained between average EM34 conductivity and the corresponding pondage test seepage at most sites. EM34 with a 10m coil spacing in horizontal mode was the main EM34 set up used. For this particular configuration, the effective depth of penetration is around 6-7m, with a shallow depth focus of around 1-3m. Therefore at sites where the watertable was deeper than 5m, only a limited proportion of the response is caused by seepage impacts in the saturated zone. Therefore at these sites the seepage detection mechanism is predominantly via inference based on unsaturated zone soil properties.

Rocklands – A good relationship was recorded in both surveys. A high degree of repeatability was demonstrated between the two EM34 surveys conducted.

Donald Main – A moderate relationship was recorded in both surveys. The technique distinguished between high and low seepage but not within the high seepage rate range. A consistent increase in conductivity was observed between repeat surveys, caused by a change in watertable elevation.

Toolondo Central – A moderate relationship was observed, largely skewed by one pond. The relationship distinguished between high and low seepage rates.

Dahwilly Central – A moderate relationship was observed but this was over a narrow conductivity range, reflecting the site's relatively uniform unsaturated zone. The EM34(20m) configuration penetrated too deeply below the watertable and the uniform response reflected native groundwater conditions. Significantly, the resistivity surveying improved the relationship, as the zone immediately below the watertable could be targeted, where seepage impacts are most distinct.

Dahwilly East – No relationship was observed. The seepage rate range was too narrow for a meaningful relationship to be derived.

In summary, the only site where no relationship was observed was at Dahwilly East, which was largely due to the narrow seepage rate range. At the Toolondo Central site, where conductivity measurement was entirely above the watertable (ie, inferred), the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence a reasonable trend was observed. At the Rocklands and Dahwilly sites, where the penetration depth was just sufficient to reach the watertable (but the focus was above the watertable), the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone worked to provide a reasonable indicator of seepage.

8.7.3 Summary of EM31 Results

Good relationships were obtained between average EM31 conductivity and the corresponding pondage test seepage at most sites. At only one site (Tabbita) was there no significant relationship identified. For EM31 in vertical dipole mode, the effective depth of penetration is around 6-7m, with a mid-range depth focus of about 2 – 4.5m. Therefore where the watertable is deeper than 5m, only a limited proportion of the response is caused by seepage impacts in the saturated zone. At these sites the seepage detection mechanism is largely via inference based on soil properties in the unsaturated zone. Summary comments for each site are listed below:

Toolondo - Good relationships between EM31 and pondage test seepage were recorded in all three surveys at Toolondo Central and a high degree of repeatability between surveys was observed. Poor results were obtained for on-channel surveys, supporting the theory that on-channel EM31 surveys are not suitable when the watertable is beyond the EM31 range (ie, 6m). The relationship established across the three Toolondo sites was moderately strong but local correlations at each of the sites were stronger. The Toolondo East site displayed an opposite correlation, but the very narrow range of seepage rates indicates this is not a meaningful trend.

Rocklands - A good relationship was observed between EM31 response adjacent the channel and pondage test seepage. A poor response was observed when all survey runs were used, largely due to the effect of trees adjacent one pond. On-channel results were varied. No trend was observed in vertical dipole mode and a reasonable correlation was observed in horizontal dipole mode.

Donald Main - A good relationship was observed between EM31 and pondage test seepage. The technique distinguished between high and low seepage but not within the high seepage range. Moderate to good relationships were also observed for the on-channel surveys in both dipole modes, supporting the theory that EM31 on-channel surveys are suitable if the depth to watertable is within the EM31 range (ie, 6m).

Dahwilly - For a survey conducted when the channel was not running, no relationship was observed between EM31 and seepage. In a repeat survey conducted when the channel was operating, a good relationship was observed. The initial survey failed because water seeped from the previous season had mixed with the native groundwater, and no salinity contrast remained. While unsaturated zone lithology is a good indicator of seepage at some sites, at Dahwilly it is not the unsaturated zone controlling seepage, but the clogging layer at the channel surface. Therefore seepage must be detected in terms of its direct impact on the watertable.

The relationship established for the two Dahwilly sites was moderately strong, despite the fact that the East site on its own displays a very weak correlation, due to a very narrow seepage rate range. The slightly deeper watertable at the East site appears to have put the watertable largely beyond the range of the EM31 and hence very different results are obtained compared to the Central site. Better correlations at both sites were obtained using the resistivity due to better targeting of the watertable.

Lake View – A poor relationship was obtained at Lake View central using all data, but a much improved relationship (to moderate) was observed using adjacent channel data. Interpretation is limited at this site due to the very narrow seepage rate range. The relationship established for both sites was moderately strong with a high correlation coefficient but the two data sets creating the regression line have small conductivity and seepage rate ranges.

Tabbita - No relationship was observed between EM31 and seepage at this site. Possible reasons for the failure of the technique at this site include the narrow range of seepage rates, the seepage mechanism may be such that majority of seeped water does not reach watertable, EM31 vertical dipole orientation may penetrate too deeply into the native groundwater, and the method of averaging conductivity may not be appropriate at this site.

Finley - A moderate correlation coefficient was obtained for the pondage test – EM31 relationship but the statistics are not meaningful as only three data points make up the relationship.

Waranga Western Channel - A moderate to poor relationship was recorded, however the results represent seepage sites more than 20 km apart. The watertable is generally beyond the penetration depth of the EM31 along the survey reach and therefore seepage is inferred based on soil properties. Some of the scatter in the results can be explained by incorrect pond placement as well as some geological anomalies. When points of high variance and leverage are removed, the correlation coefficient improves to 0.62 (from 0.40). The prediction interval bands suggest the relationship can be used to distinguish between sites of low and high seepage.

In summary of the EM31 results, the only site where no relationship was observed was at Tabbita. A number of possible causes for this were identified, but the predominant contributing factor is not known. At two sites the adjacent channel data was used instead of all survey run data. This was required to obtain the best relationship, due to the interference effects of trees and rapid mixing of seepage water away from the channel. At the Toolondo Central site, where conductivity measurement was entirely above the watertable, the unsaturated zone lithology was a sufficiently accurate indicator of seepage and hence good trends were observed. The Donald and Lake View site surveys were focussed on the saturated zone, and seepage was detected as it created a conductivity low against higher background conductivity groundwater. At Waranga, a reasonable (to poor) relationship was observed, however improvements might be expected using a technique targeting the top of the watertable at this site.

At the Rocklands and Dahwilly sites, where the penetration depth of the EM31 (in vertical dipole) was just sufficient to reach the watertable, the combination of measuring lithology changes in the unsaturated zone and seepage impacts in the saturated zone combined to provide a reasonable indicator of seepage. However it is significant to note that when the channel was not running, no relationship was observed. This suggests seepage impacts in the watertable are the primary detection mechanism at this site. Seepage at Dahwilly is not controlled by the unsaturated zone but by a clogging layer at the base of the channel. Techniques which purely infer seepage from unsaturated zone soil properties will not work at such sites.

On-channel surveys did not work at sites where the watertable was beyond the range of the EM31 (Toolondo), did work at sites with a shallow watertable (Donald) and were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31 (Rocklands). Further work is required in this area, but the evidence collected in this investigation suggests on-channel surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. For EM31 systems this would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

8.7.4 Summary of Resistivity Results

Good relationships were obtained between average resistivity (from depth slices immediately below the watertable) and the corresponding pondage test seepage at most sites. Key summary comments for each of the sites are listed below:

Toolondo - At the Toolondo Central site the best correlations between seepage and resistivity were obtained around 10-12m (R^2=0.6), which is the zone immediately below the watertable. There was very little correlation in the unsaturated zone. At Toolondo East the very narrow range of seepage rates and resistivity values meant that no meaningful correlations were observed. At Toolondo West the expected inverse trend between low resistivity and high seepage at and below the watertable was not observed. It was apparent that the low permeability sandstone may have been causing a high resistivity response (normally associated with high seepage), and masking the effect of seepage on the saline groundwater. The reasonable correlations obtained at shallow depth are most likely due to changes in clay content beneath the channel, and correspond with observed EM31 – seepage relationships at the site.

Based on the regression relationship established at the Toolondo Central site, the Toolondo East data lies within the expected extrapolated range for the Central site. The Toolondo West data does not fit within the Central and East relationship however, possibly due to changes in lithology described above.

Dahwilly - Good correlations were observed at Dahwilly Central (for the 6m to 10m depth slices), which fits with the expected mode of seepage detection below the watertable. At Dahwilly East a strong correlation was observed at 6m which corresponds with the top of the watertable. However, this is based on a very narrow range of seepage rates and small number of data points.

The two regression lines for the Dahwilly sites are parallel but vertically offset and there is no observed trend for the combined regression line. This suggests different background conditions, including more clayey sands and possibly higher background salinity groundwater at Dahwilly East.

Finley - The best correlation was observed at 4 - 6m which corresponds with the zone below the top of the watertable (1.5m). An inverse correlation observed at 2m depth is probably a reflection of the poor surface resolution of the resistivity equipment.

Lake View - At Lake View Central the best correlation was observed at 6m and 8m, which corresponds with the zone several metres below the top of the watertable (1.5m). A very weak trend was observed at 2m and an inverse correlation at 4m depth. As previously noted, this may be a reflection of the poor near surface resolution of the resistivity equipment. Site lithology below the watertable may also be significantly contributing to the response. At the Lake View West site there was no meaningful relationship immediately below the watertable. This is attributed to either poor near surface resolution and/or an 'anomalous' resistivity result in one pond.

Neither the relationship derived from the 2m or 6m depth slice from Lake View Central could have been used to accurately predict seepage at Lake View West. Using the Central site to predict seepage at the Lake View West site would have caused significant under-estimation of actual seepage.

In summary, most sites displayed a good correlation between seepage and the resistivity at and immediately below the watertable. The two sites that did not were Toolondo West and Lake View West. At Toolondo West it appears that the type of sandstone at this site may be dominating the response. However deeper drilling would be required to confirm this interpretation.

The lack of a correlation at the Lake View West site is probably due to the poor resolution of the resistivity equipment at very shallow depth. This site contains the shallowest watertable across all sites (0.5 – 1m). Improved resolution at shallow depth could relatively easily be improved in future surveys by using exponentially rather than linearly spaced arrays (Allen, pers. comm. 31/10/02). At Toolondo East also no trend was observed but this is solely attributed to the very narrow range of seepage rates at this site.

8.8 Waranga Western Channel Case Study

It was proposed that the Waranga Western Channel (WWC), an open irrigation channel maintained by Goulburn-Murray Water (G-MW), be upgraded in capacity along approximately 50 km of the channel length. The channel has a well-documented record of existing seepage problems. There was also concern that new seepage paths may be opened up during the upgrading works program. Therefore G-MW required quantification of sections with existing seepage problems and identification and quantification of sections where new seepage paths might be opened up. To this end, geotechnical and geophysical investigations were carried out along the channel, including an EM31 survey (November 2001) coupled with drilling of 128 shallow bores, additional geotechnical drilling (March 2002) including the drilling of an additional 107 bores, and twelve pondage tests (May/June 2002) conducted at various locations along the channel.

Initially a combination of the EM31 results and a lithological classification devised for the investigation based on the amount of clay in the profile was used to identify sections of channel which were considered to represent ‘very high’ risk areas. It was then recognised that, in addition to the drilling program, pondage tests were required to quantify seepage rates and confirm interpretation of seepage rates based on geology and EM31 data. Therefore 12 pondage tests were conducted at various intervals along the channel, covering a range of environments and geophysical response.

A moderate to poor relationship was recorded between EM31 conductivity and pondage test seepage. The prediction interval bands accompanying the relationship suggested it could be used to distinguish between sites of low and high seepage, but is limited in interpreting mid-range seepage. It was concluded that this relationship could be used for prediction, bearing in mind the associated broad prediction intervals associated with the regression equation.

Based on the results of the pondage tests, the regression relationship between EM31 and the pondage tests and the drilling program, the areas recommended for remediation were finalised. Sites were defined as either priority one or priority two seepage risk sites, depending on the degree of perceived seepage risk. Given the broad confidence intervals in the EM31 – seepage relationship, the EM31 predicted seepage was not used as the sole means of assigning seepage risk but geological data and visual observations were also integrated into the decision making process. The WWC seepage investigation is a good example of the integration of geophysical, geological and pondage test data to determine areas of highest seepage risk.

9. Recommendations

This study makes the following recommendations:

- Of the techniques trialed in this investigation, future channel seepage measurement investigations should focus on geophysical techniques, as these have shown the most promise to cost-effectively and relatively accurately quantify channel seepage. Remote sensing trials, however, were not conducted in these investigations. This technique has the potential for rapid assessment of long sections of channel where seepage has a surface expression, and as such deserves carefully planned field trials in Australian conditions. The baseline data collected in this report could be used to assist in calibration of such trials.

- Rural Water Authorities should adopt the preferred technique as outlined in the conclusions of this report (and the Guidelines Manual; ANCID, 2003) for channel seepage measurement investigations. This methodology relies on geophysics (preferably using direct detection of seepage impacts in the groundwater) to identify seepage, and pondage tests and soil bores to calibrate and interpret the geophysical response.

- A considerable amount of geophysical data and interpretation was conducted in this study. However the conclusions drawn were still limited by the size of the data sets, and the limited range of environments over which the data was collected. For example, more surveys are required at channels with a depth to watertable of two to five metres. It is therefore recommended that a national database be established to record all channel seepage measurement geophysical trials. Surveys entered into the database must include a minimum level of site information, including direct measurement of seepage rates, depth to watertable, groundwater salinity, description of soil type and geology and channel hydraulic information.

- Further study into the best method of establishing a relationship between the geophysical response and seepage rates is required. At present the bulking process of averaging the geophysical response over the entire pondage test area necessarily introduces errors into the geophysical – seepage relationship. Further investigation could focus on improved statistical methods for processing the geophysical data (eg Geostatistics). Alternatively it could focus in the direction of improving field techniques to directly measure seepage for comparison with the geophysical response. For example, if a cheap method of bank construction could be devised (eg manually inserted barriers) greater numbers of pondage tests could be conducted which would significantly improve the regression equations resulting from these relationships.

- The resistivity surveys undertaken in the final year of the trials were the culmination of the investigation. These surveys showed significant promise, as they allowed targeting of the seepage impacts on the watertable and visualisation of seepage processes. However problems were encountered with the shallow depth resolution of the equipment, which affected the accuracy of the results at sites with a shallow depth to watertable. Further experimental trials to overcome these teething problems are recommended. Investigation into means of reducing resistivity data processing time (and thus costs) are also recommended.

- Exploration of a method which detects seepage by measuring changes from background conditions is recommended. A significant problem encountered in these trials when attempting to extrapolate a relationship from one section of a channel to another, was caused by the fact that the background conditions change along the channel. This means that the relationship between seepage and geophysical response changes. A possible means around this is to conduct a survey adjacent to the channel but away from channel seepage influence (eg 50-100m away). These results would then be subtracted from the adjacent channel (or on-channel) survey results. In theory the remaining difference should be representative of channel seepage induced changes and not lithological changes. Such a technique may allow improved transferability of correlations on or between channels. This could even be undertaken with existing data sets of EM31 surveys conducted in these trials using the 50m traverse line, provided there are no seepage impacts at this distance. Possible limitations with this method may include the effects of salinisation away from the channel and different land uses adjacent to the channel.

- Further testing of the relative merits of on-channel fixed array surveys compared to adjacent channel fixed array surveys are required. The evidence collected in this investigation suggests on-channel (fixed array) surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. However these conclusions are only based on evidence from three sites and further work is required to confirm this conclusion.

- A means of calibrating geophysical surveys where pondage tests cannot be conducted needs to be explored. On small to medium channels where pondage tests cannot be conducted for operational reasons, points tests using the Idaho meter could be used, although this could be expensive to ensure proper calibration. For very large channels were pondage tests cannot be conducted due to the very high expense of bank construction, alternative means of calibration need to be devised.

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Systat, version 9, Copyright 1998. (Statistical software package used in analysis).

Appendix A Geological Long Sections

A.1 Wimmera Mallee Water Geological Long Sections

Figure A-1 Donald Main Channel Geological Long Section

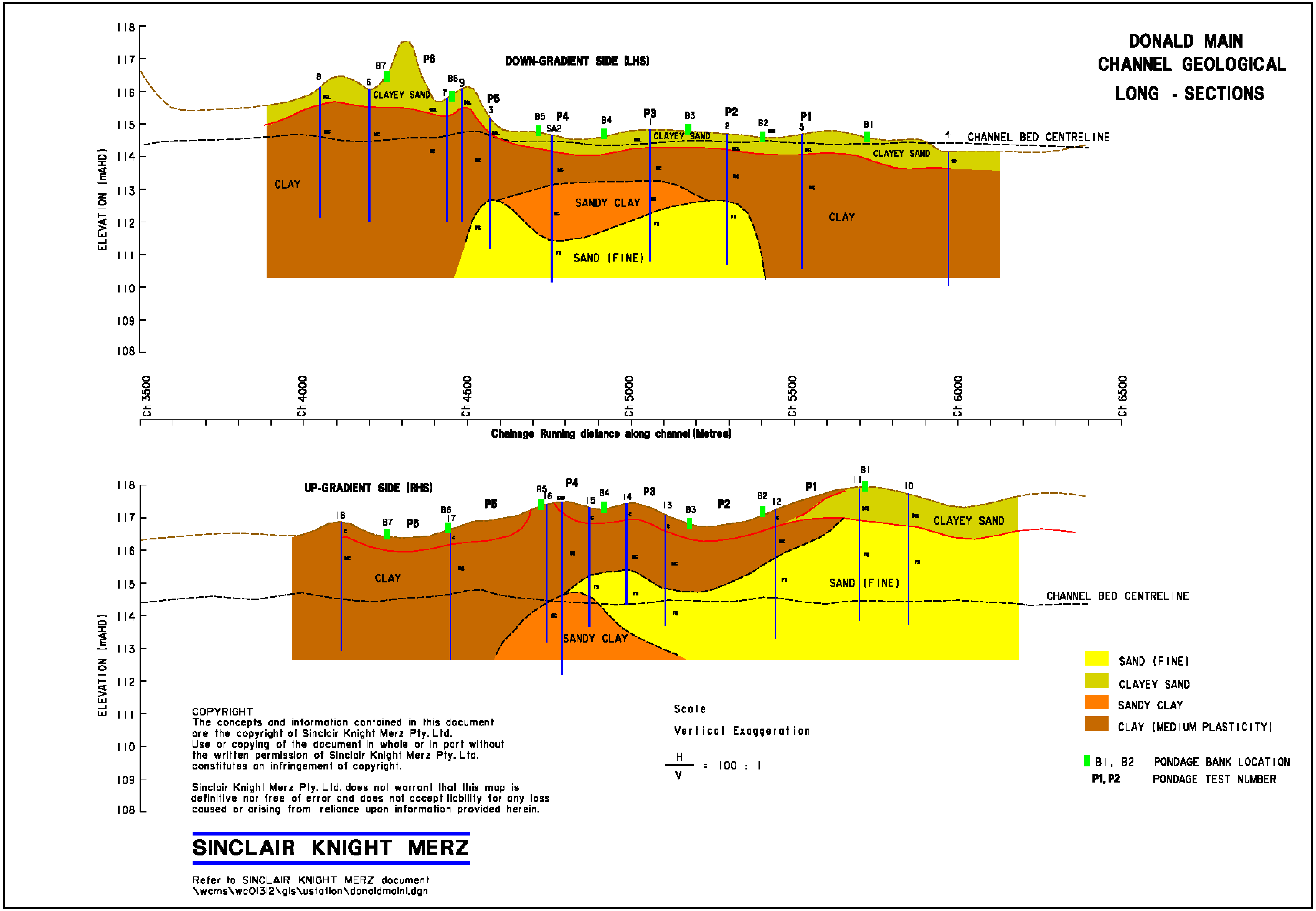

Figure A-2 Rocklands Channel Geological Long Section

ROCKLANDS CHANNEL GEOLOGICAL LONG - SECTION

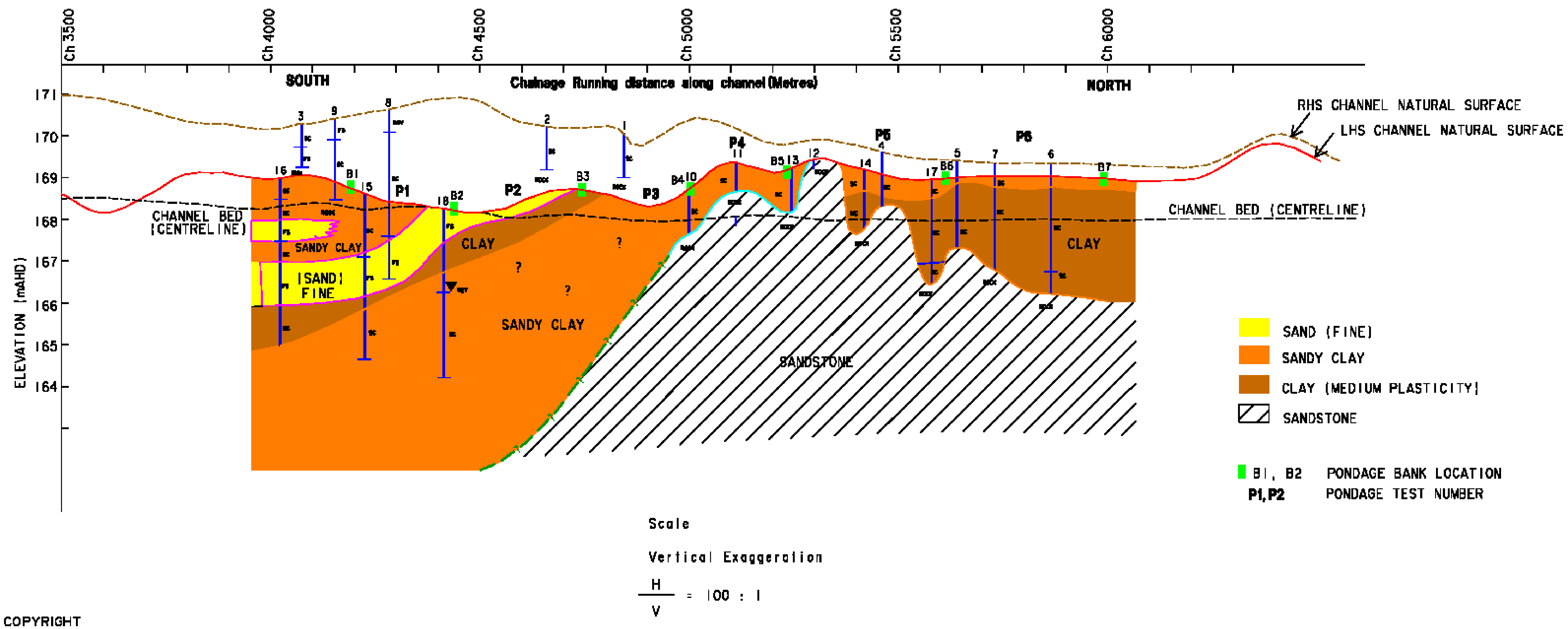

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Figure A-3 Toolondo Central Channel Geological Long Section

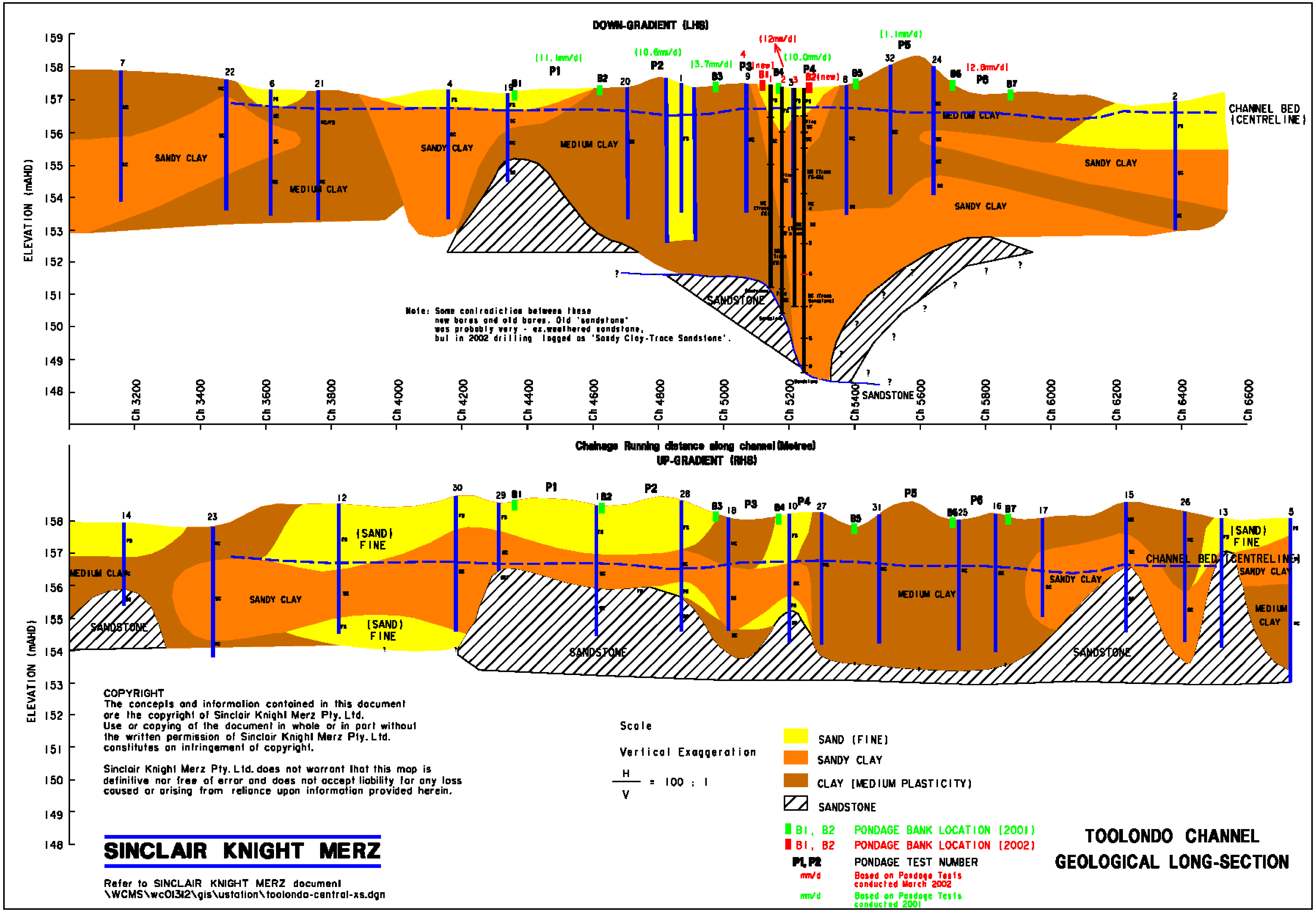

Figure A-4 Toolondo West Geological Long Section

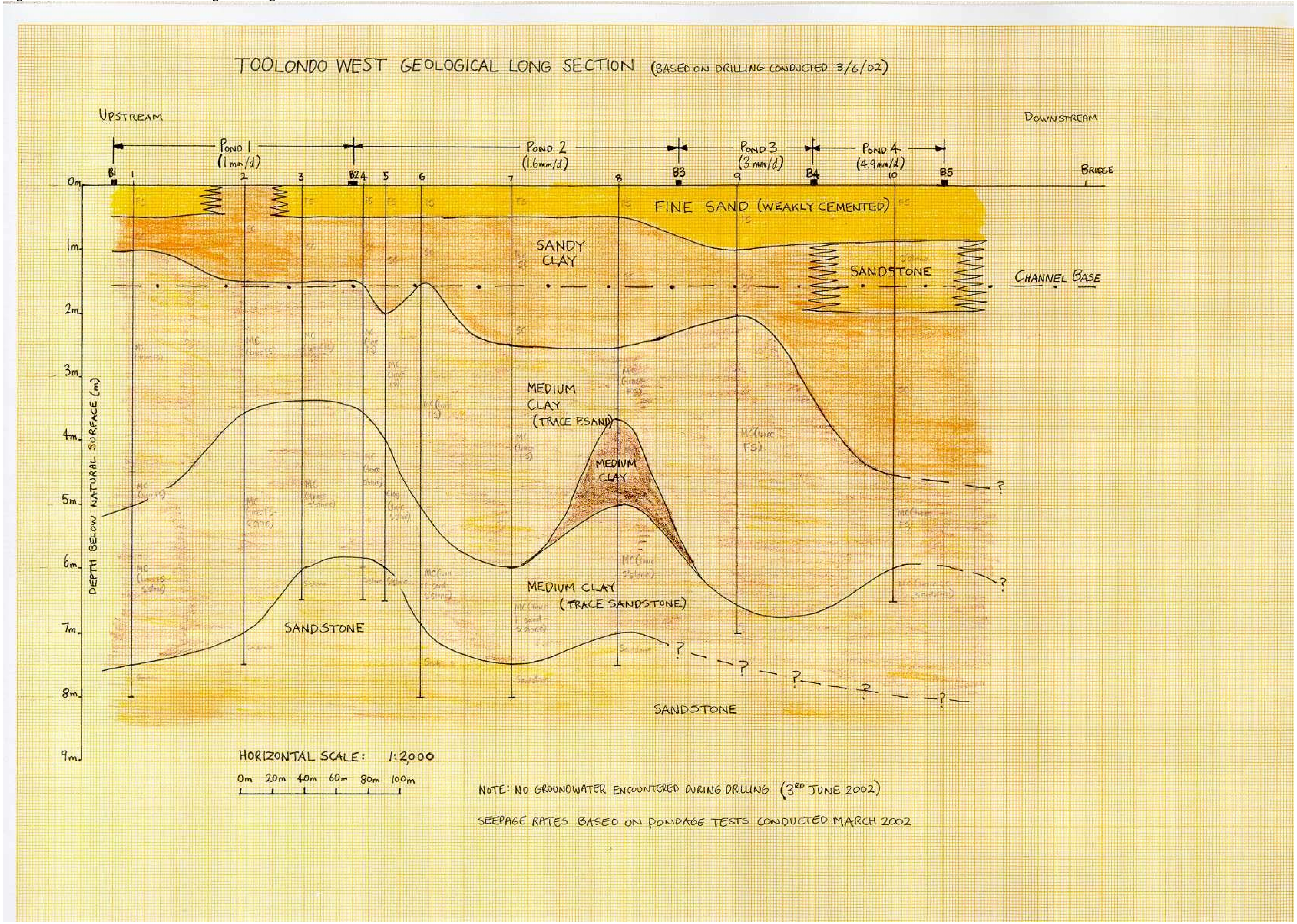

Figure A-5 Toolondo East Geological Long Section

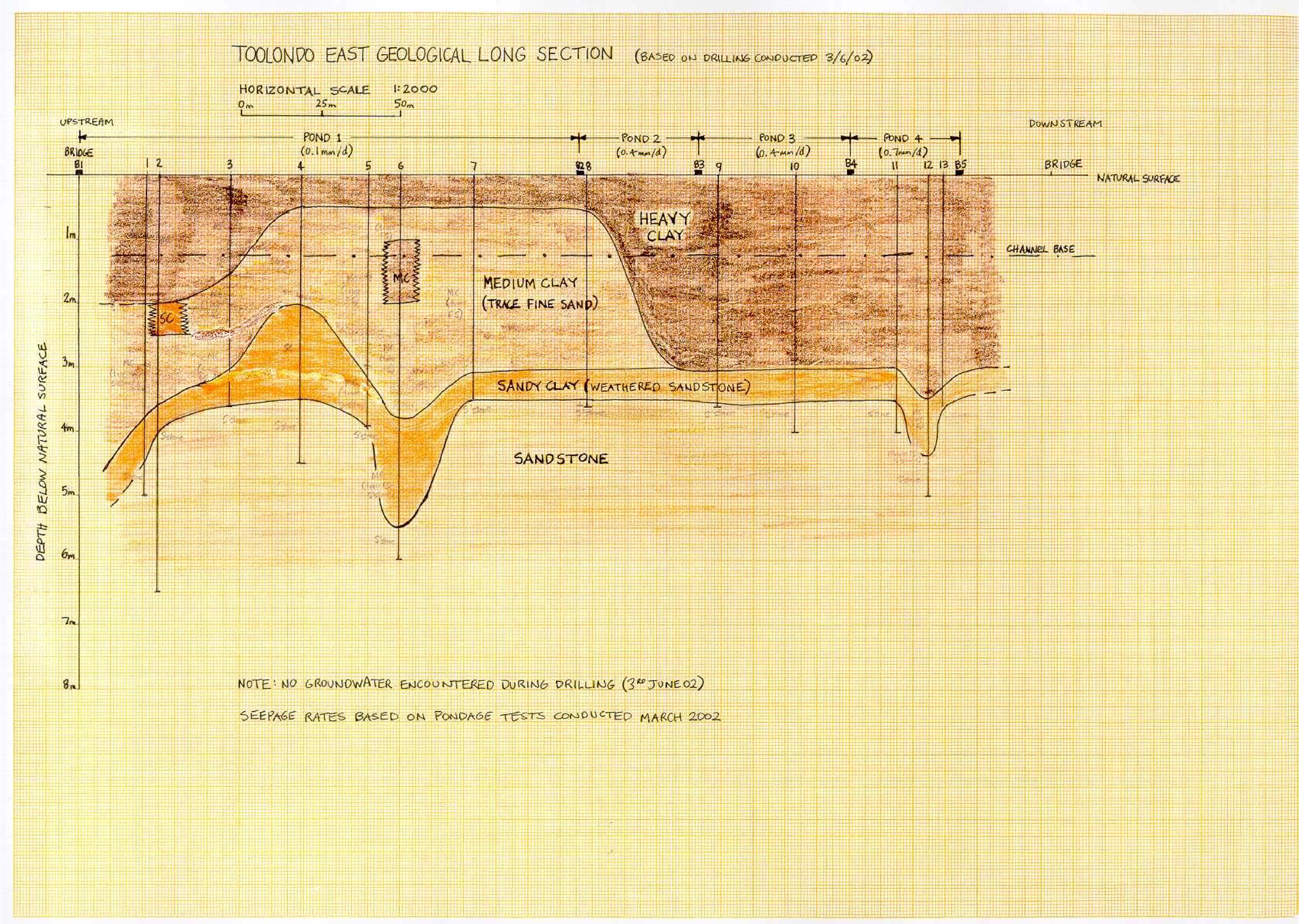

Figure A-6 Tabbita Geological Long Section

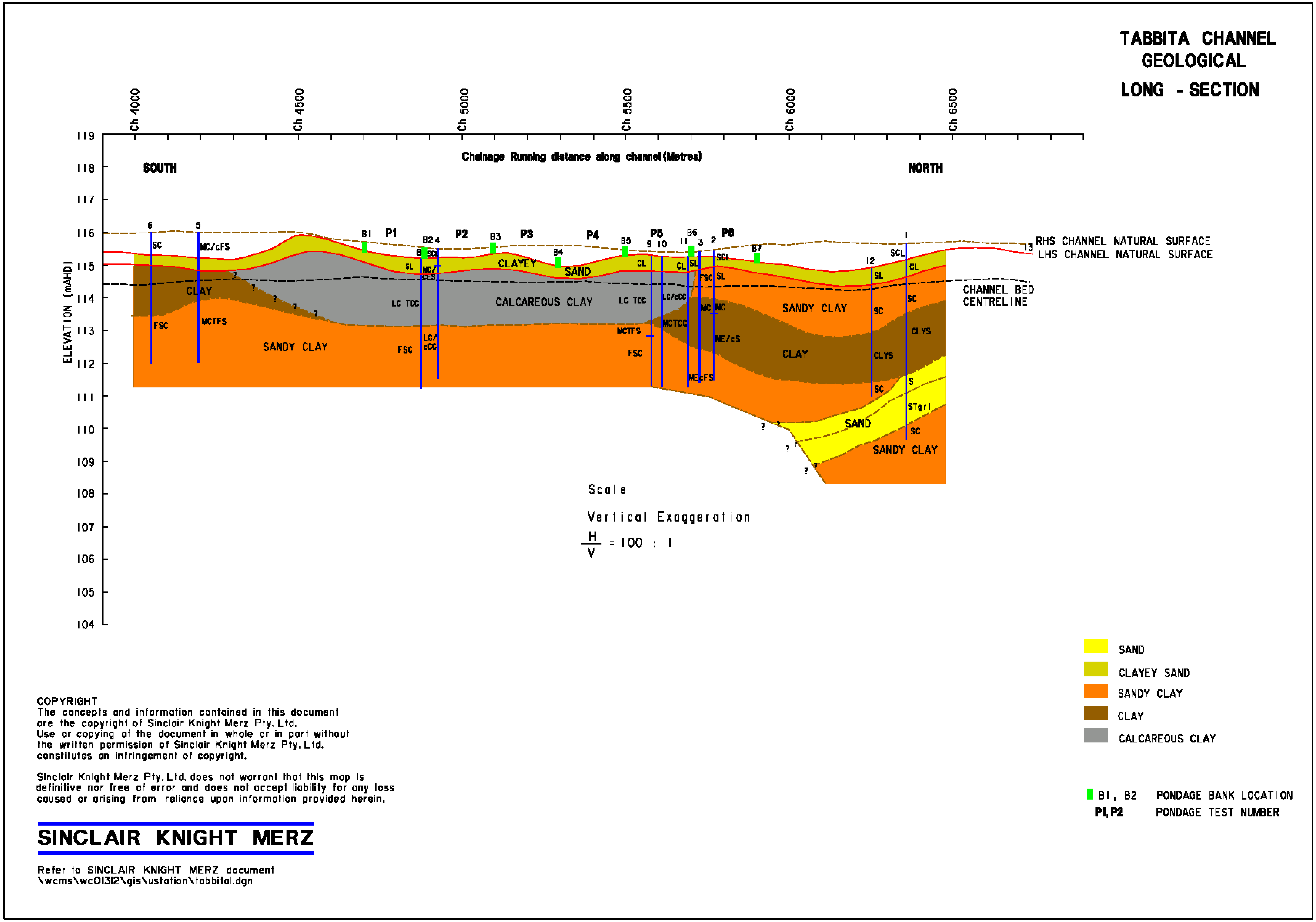

Figure A-7 Lake View Central Geological Long Section (based on 2000 drilling)

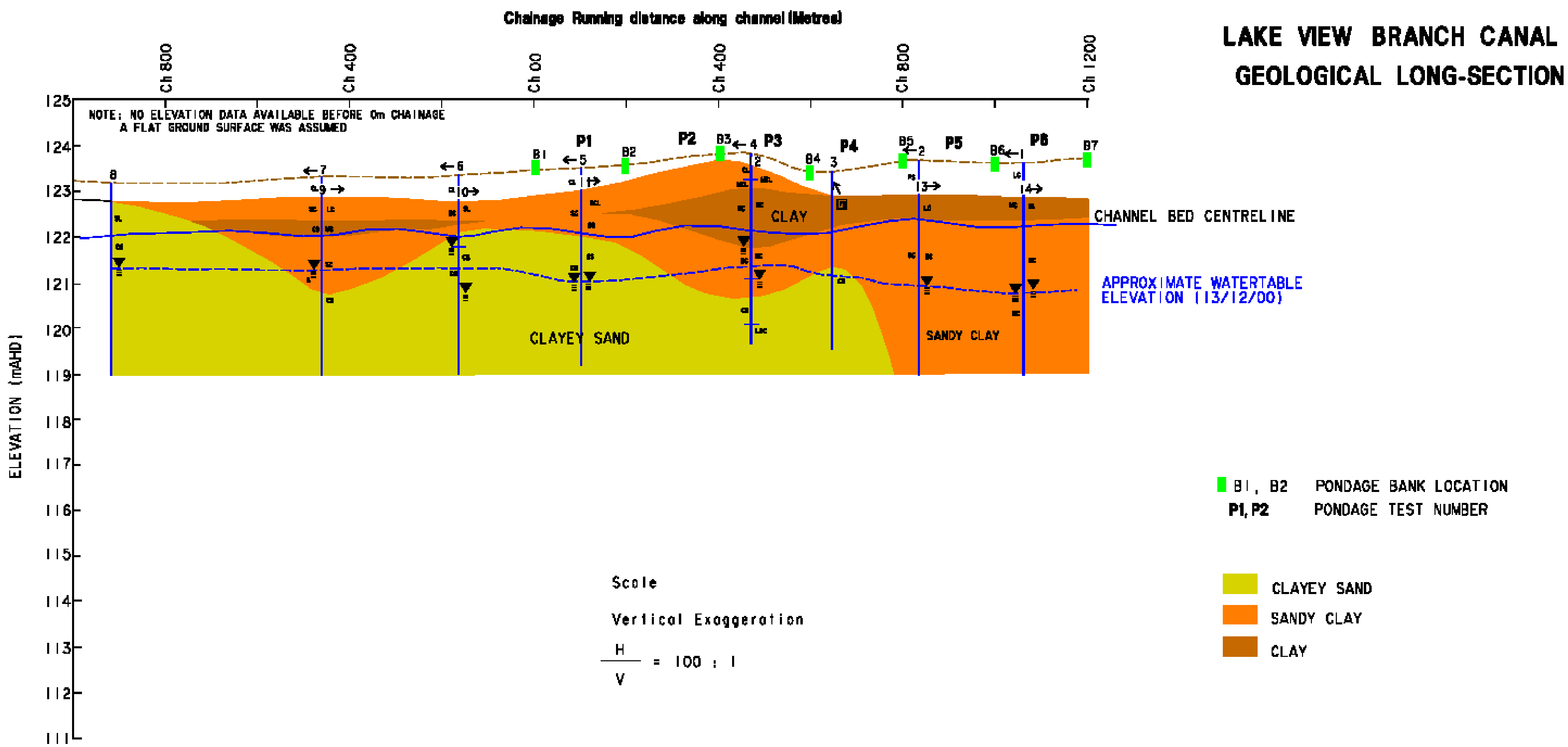

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Figure A-8 Lake View Central Geological Long Section (based on 2000 & 2002 drilling)

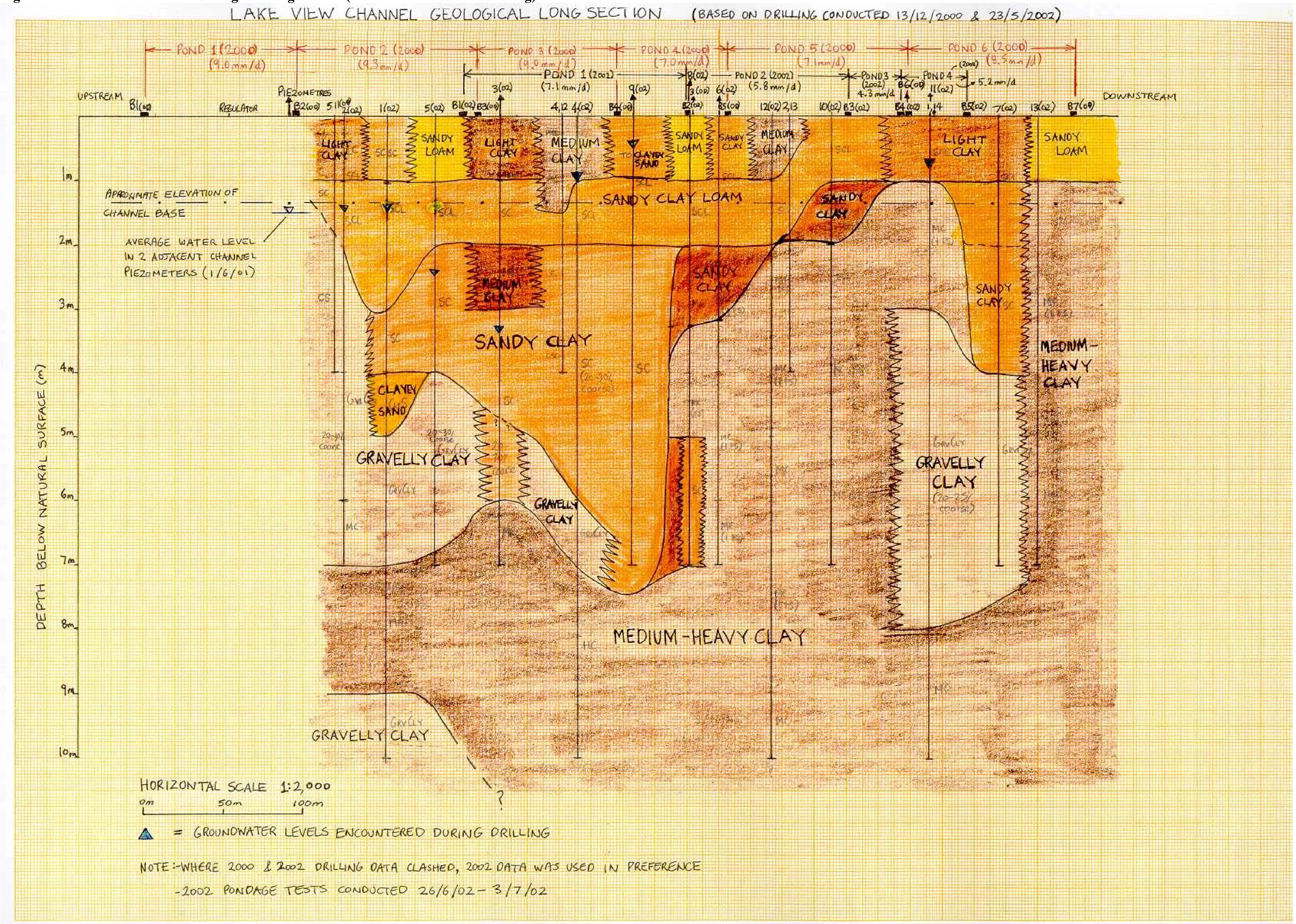
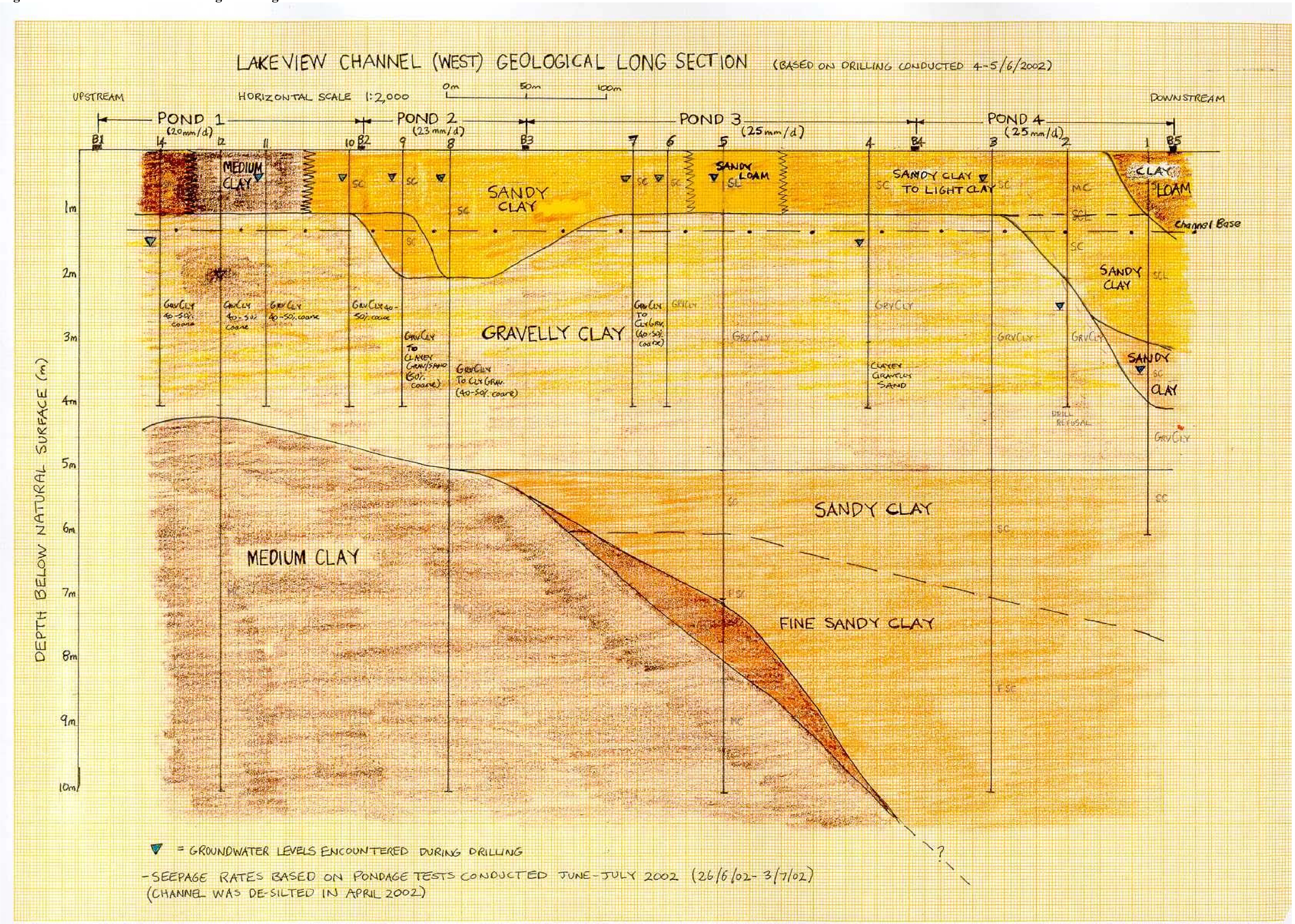


Figure A-9 Lake View West Geological Long Section



A.3 Murray Irrigation Limited Geological Long Sections

Figure A-10 Dahwilly Central Geological Long Section (Based on 2000 drilling)

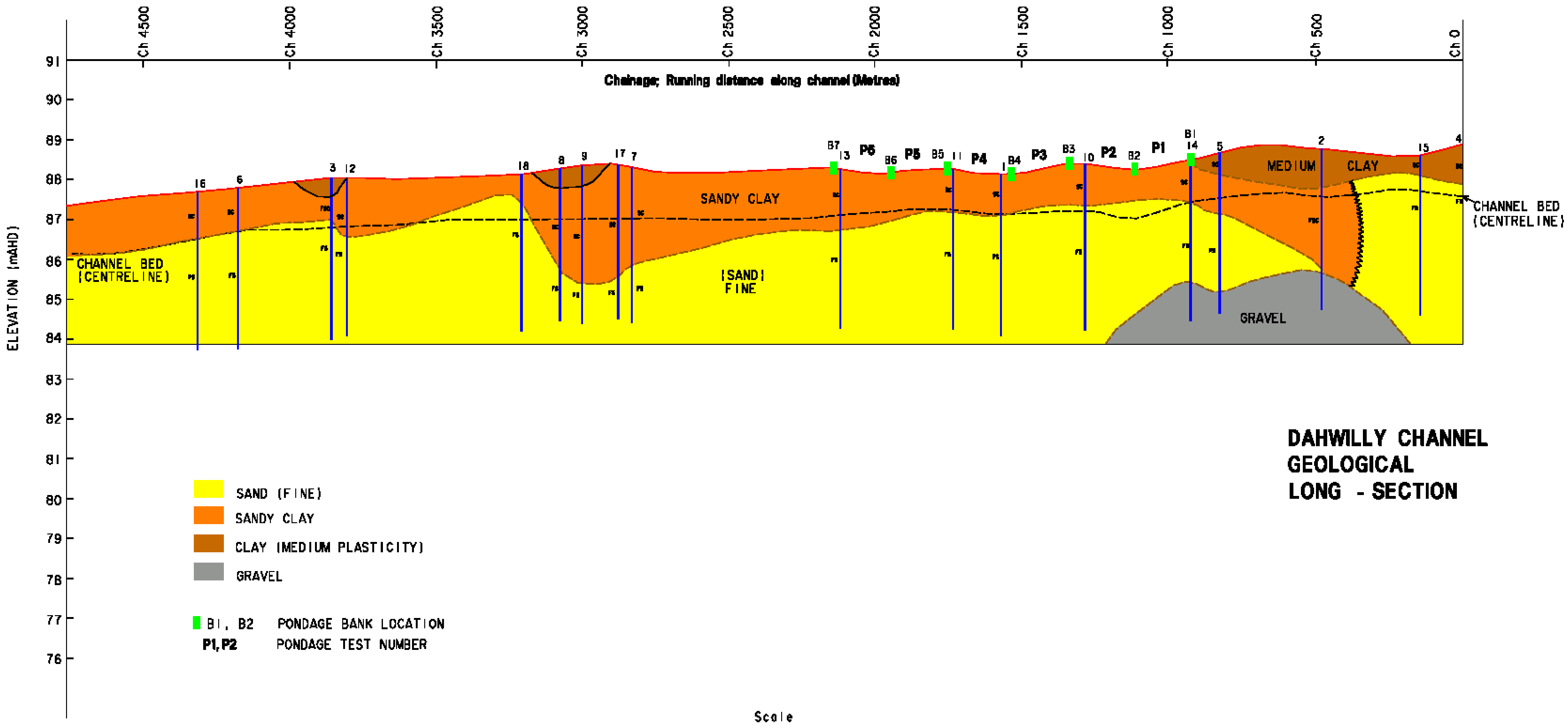


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Figure A-11 Dahwilly Central Geological Long Section (Based on 2002 drilling)
(Note: Pond 6 & 7 in Figure A-11 are the same ponds as Pond 1 & 2 respectively in Figure A-10. Pond 6 & 7 were lined in July 2001.)

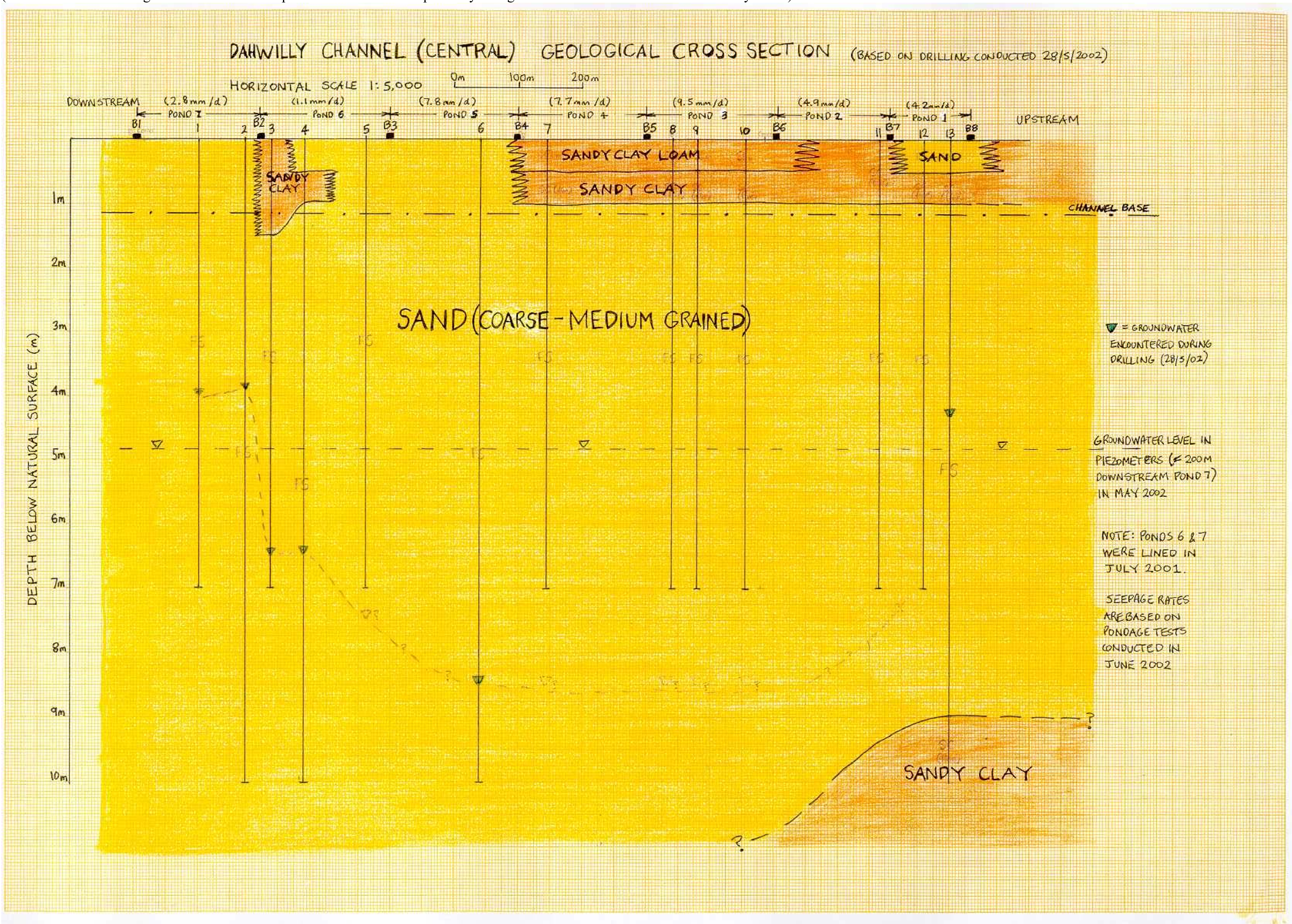


Figure A-12 Dahwilly East (Pretty Pine) Geological Long Section

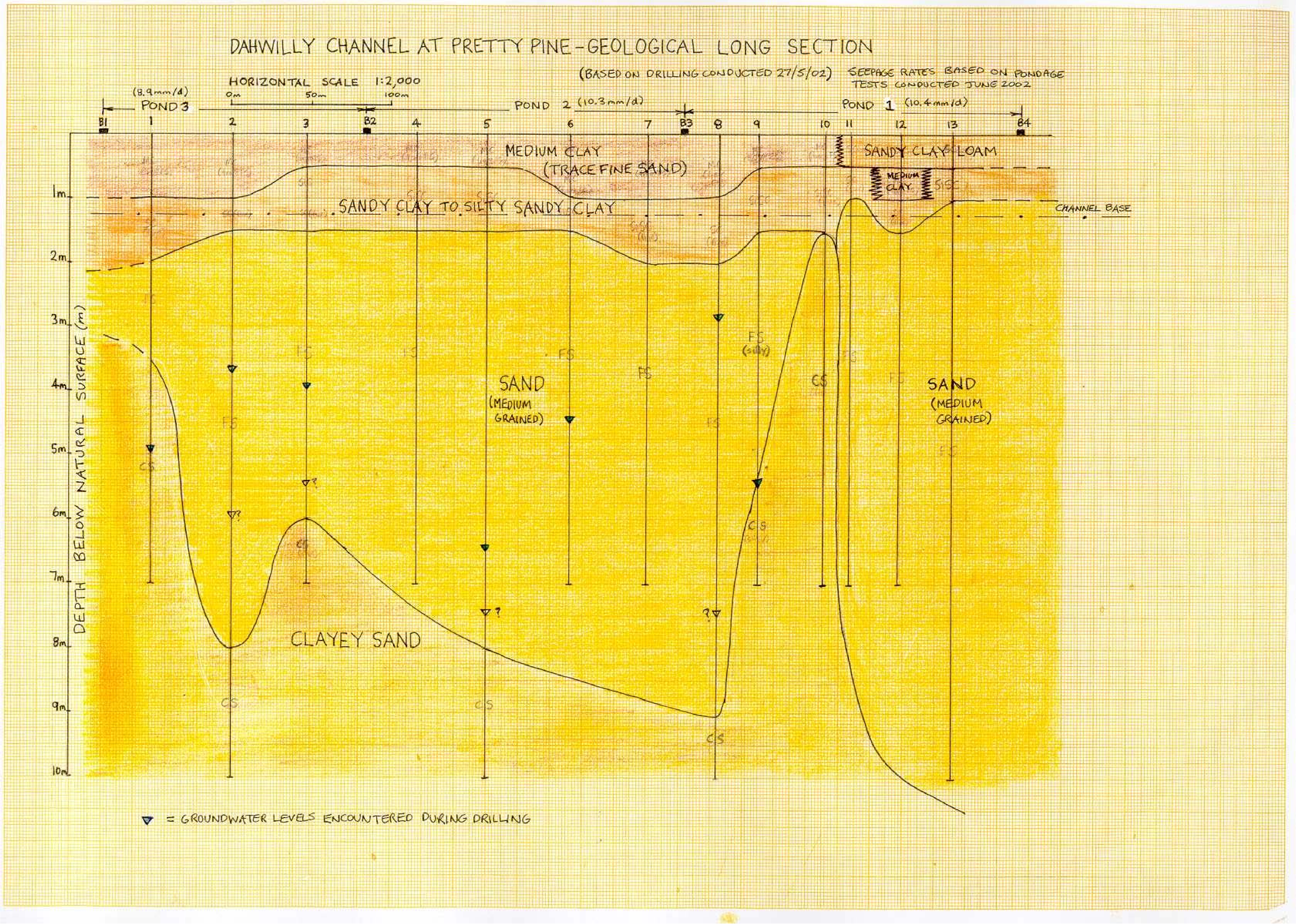
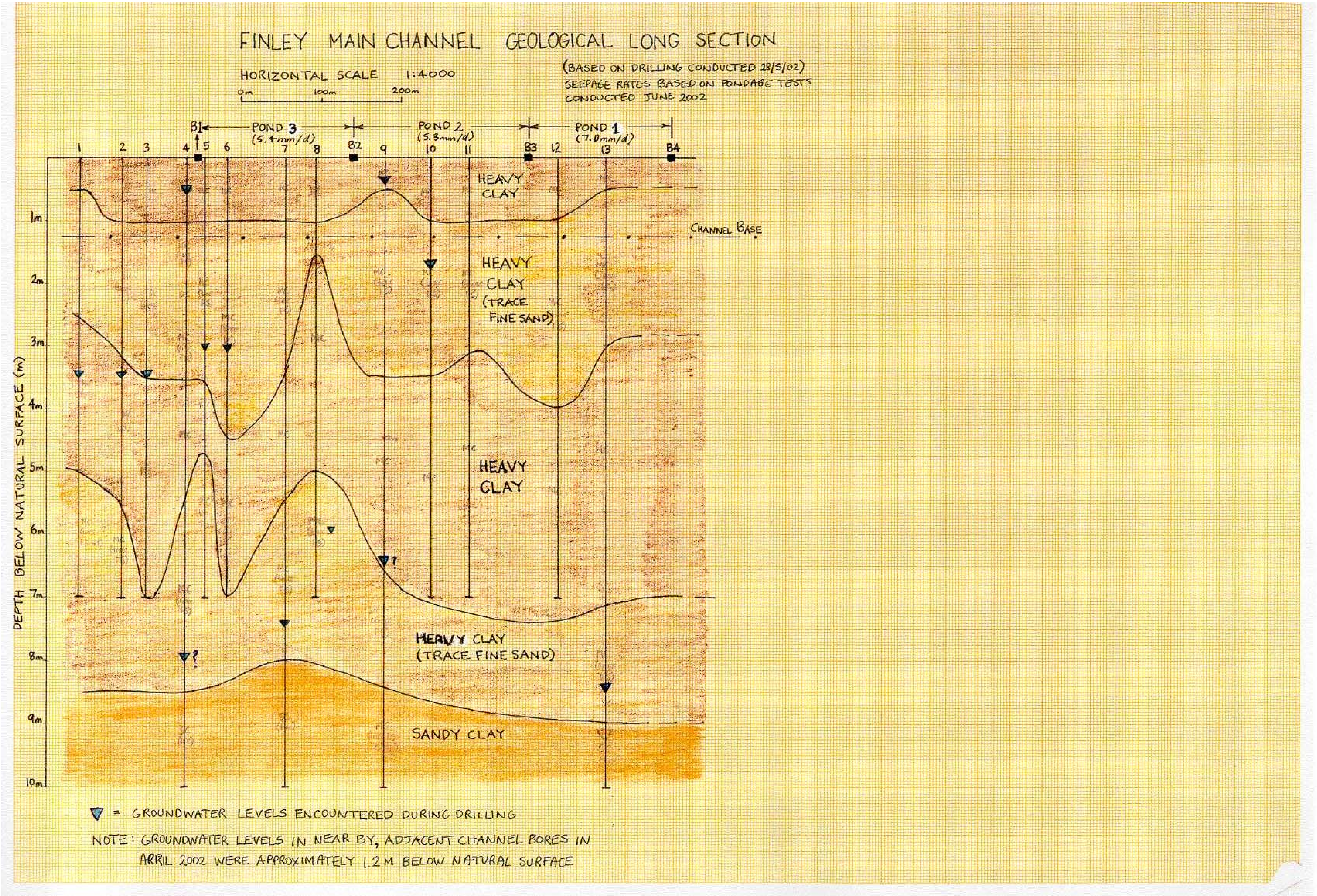


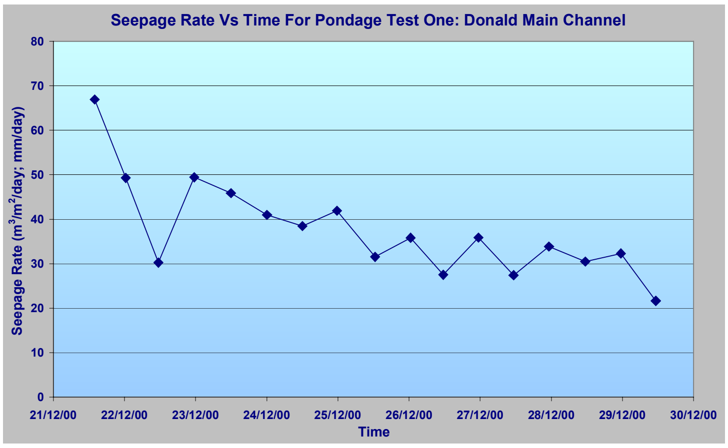
Figure A-13 Finley Geological Long Section

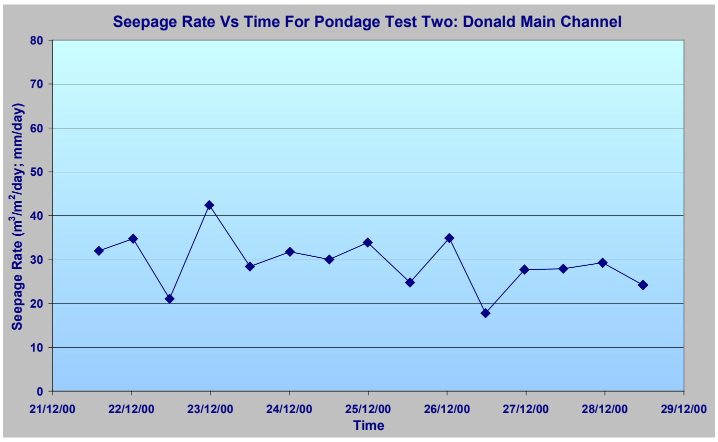


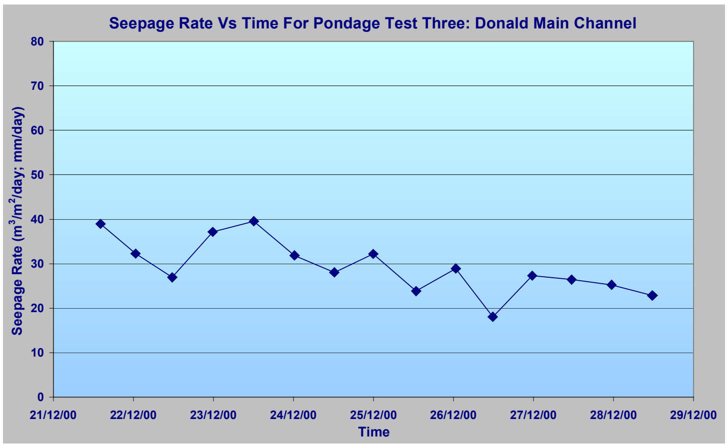
Appendix B Pondage Test Results

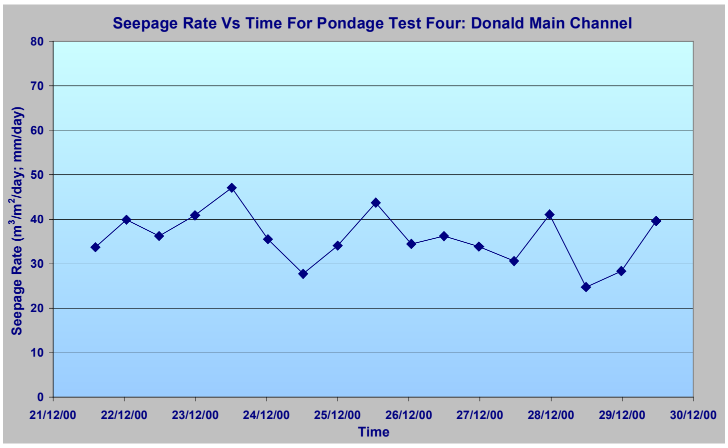
B.1 Wimmera Mallee Water Geological Long Sections

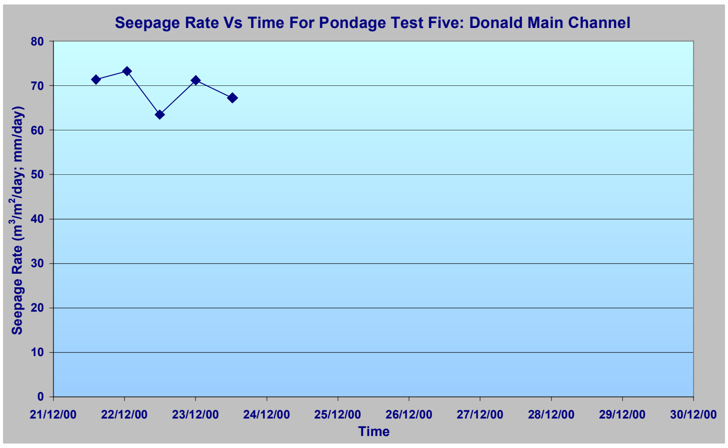
B.1.1 Donald Main Pondage Tests: 21st - 29th December, 2000

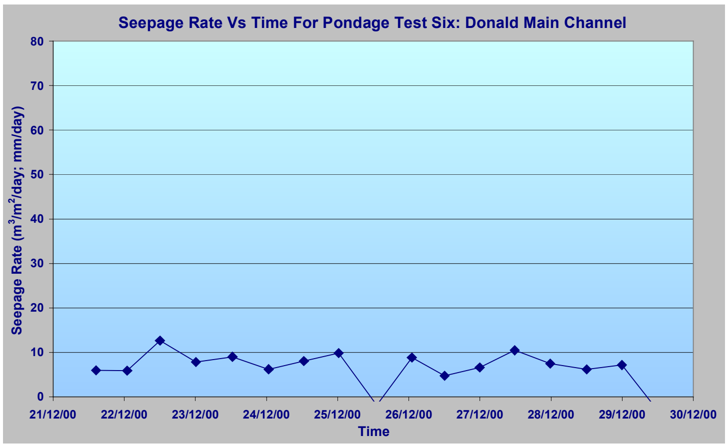




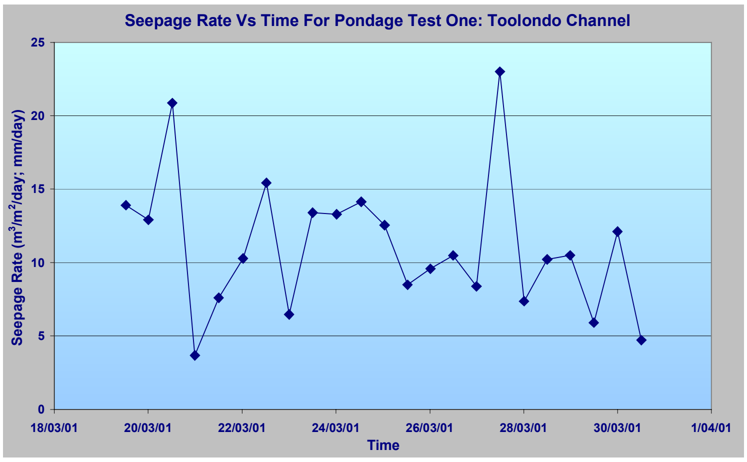


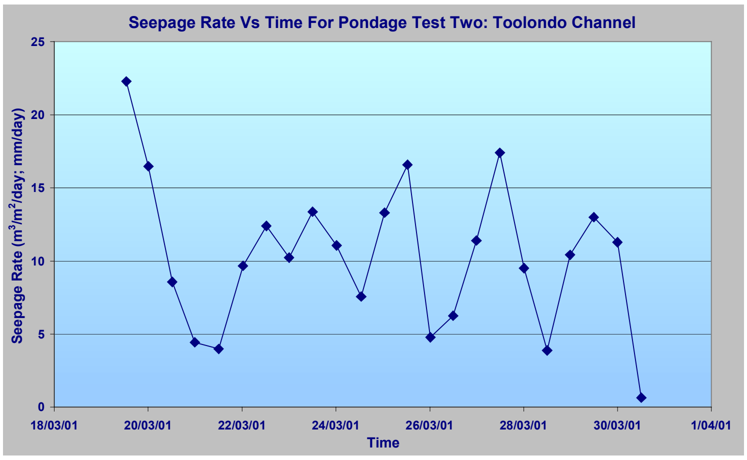


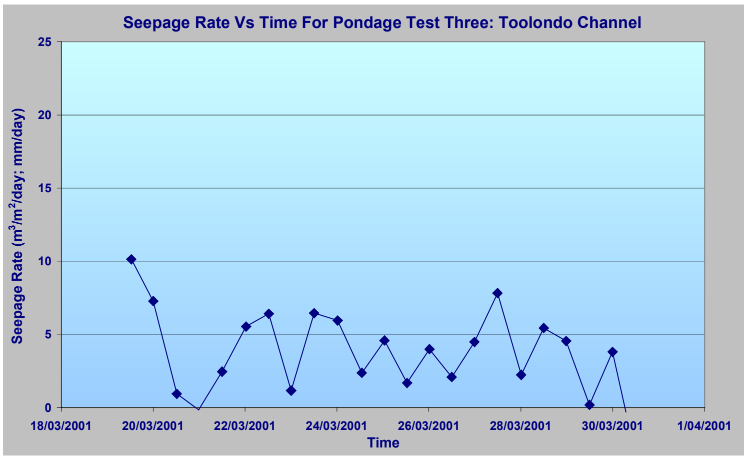


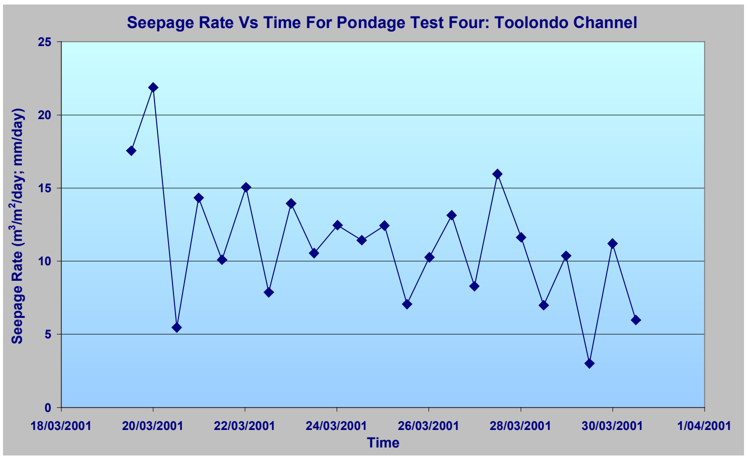


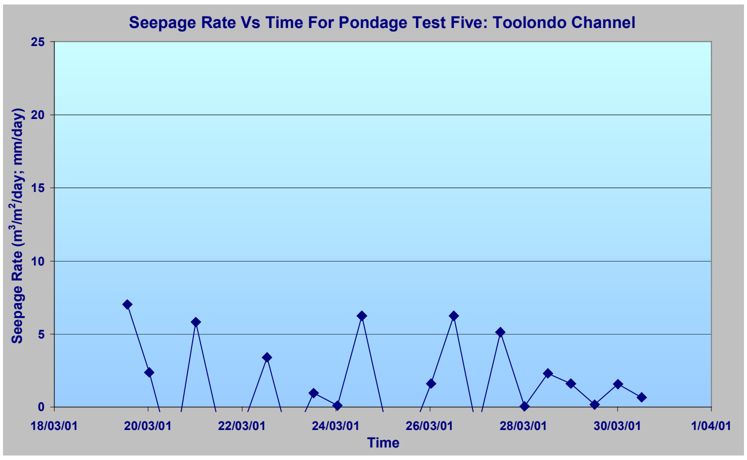
B.1.2 Toolondo Central Pondage Tests: 19th March – 1st April, 2001

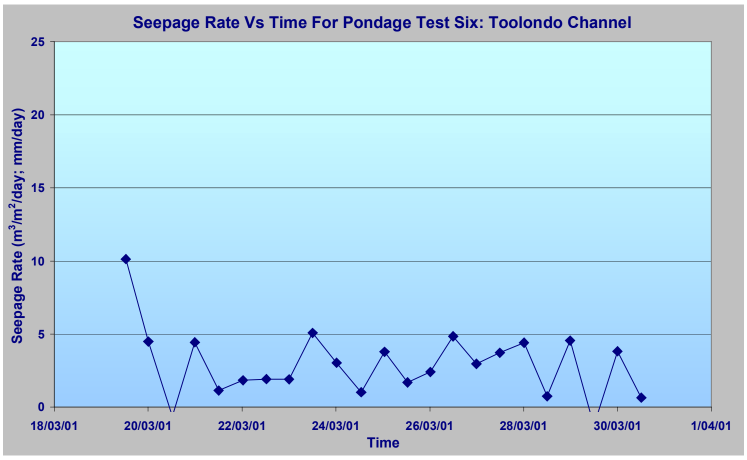




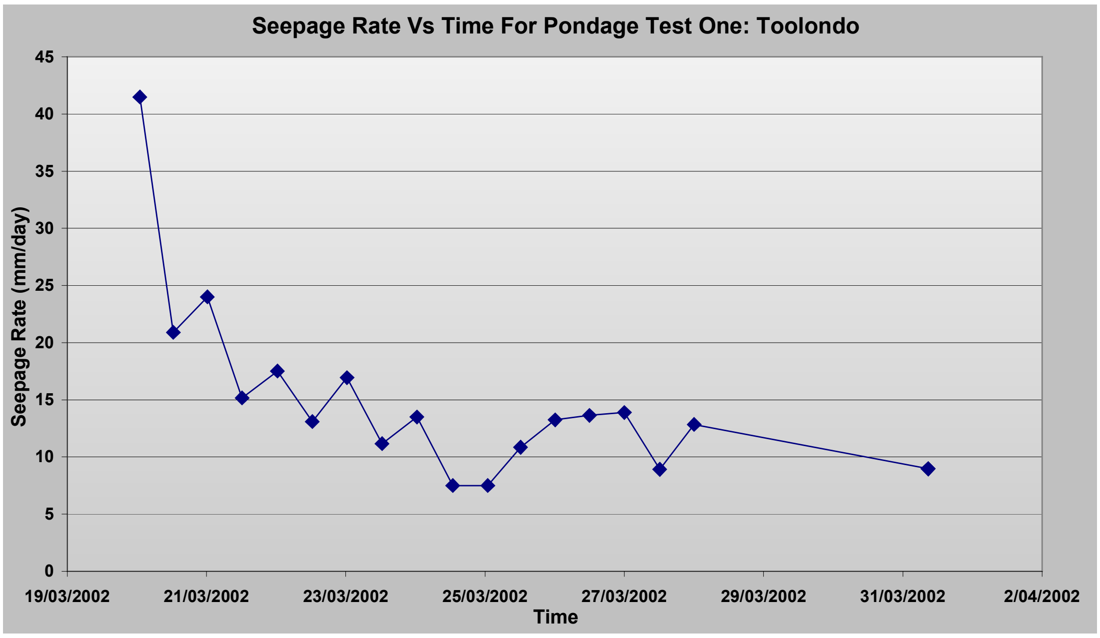




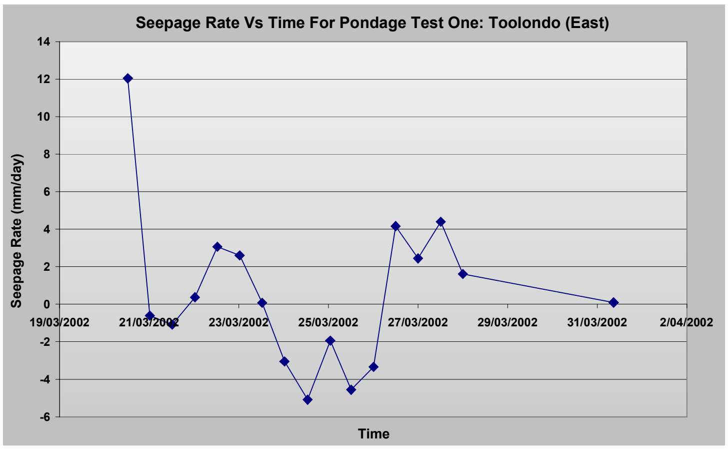


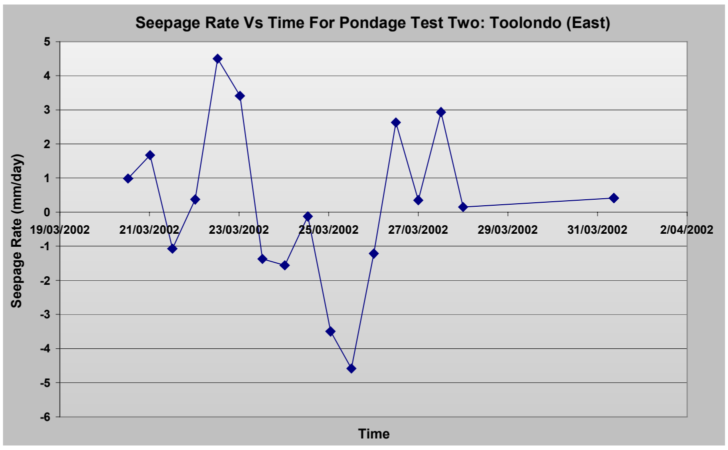


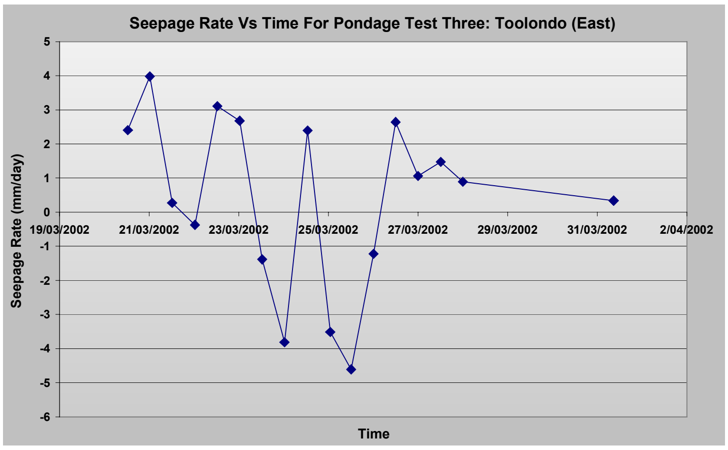
B.1.3 Toolondo Central Pondage Test: 19th March – 3rd April, 2002

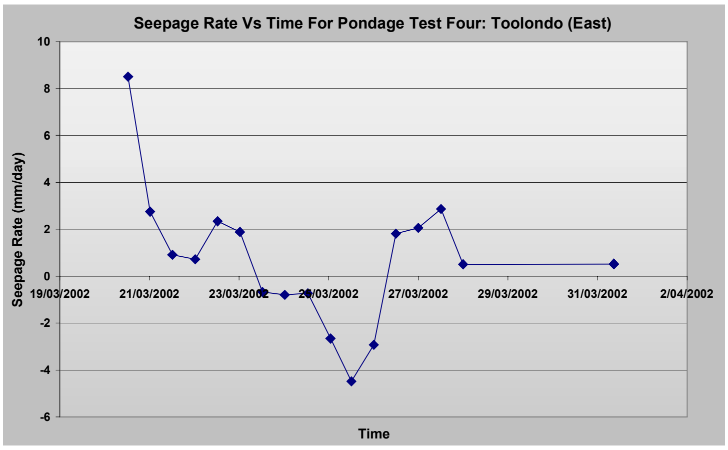


B.1.4 Toolondo East Pondage Tests: 20th March – 3rd April, 2002

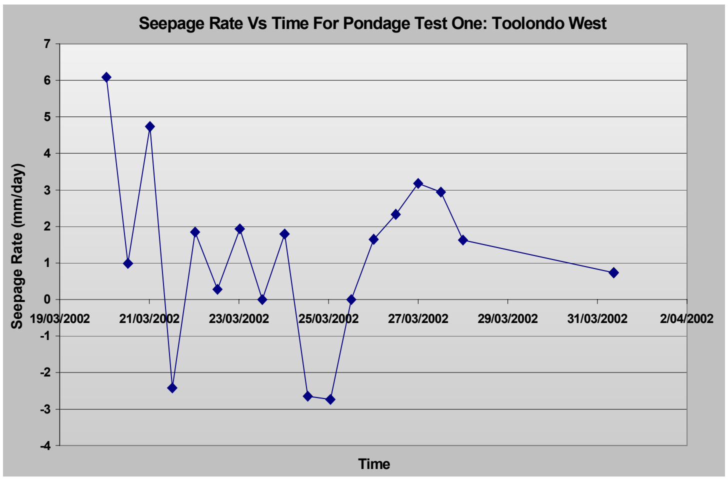


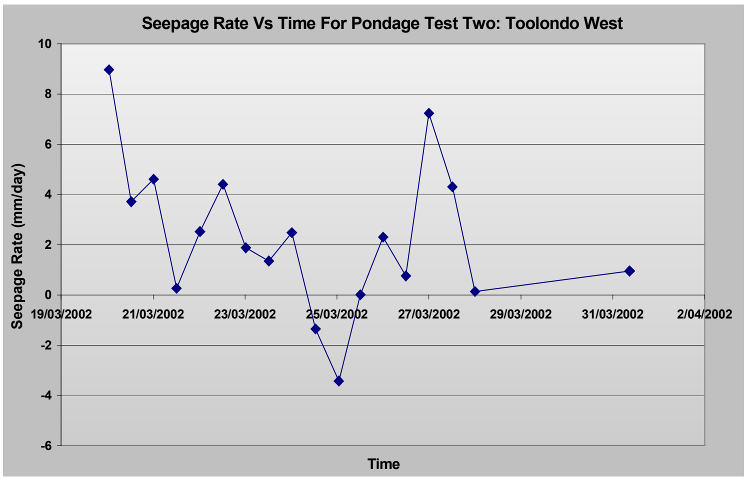


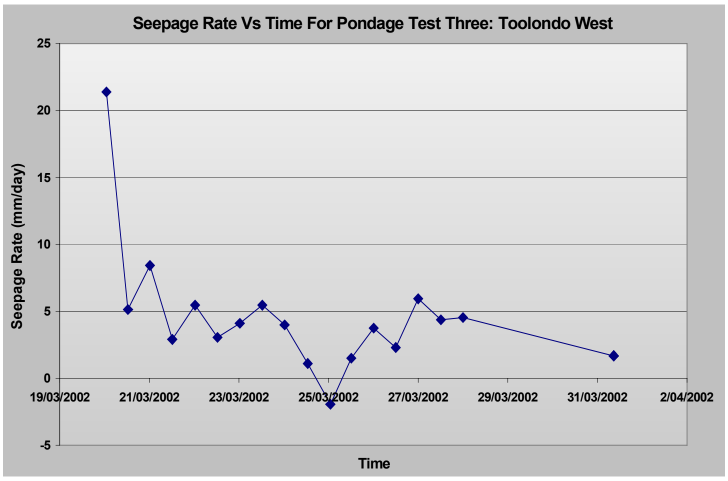


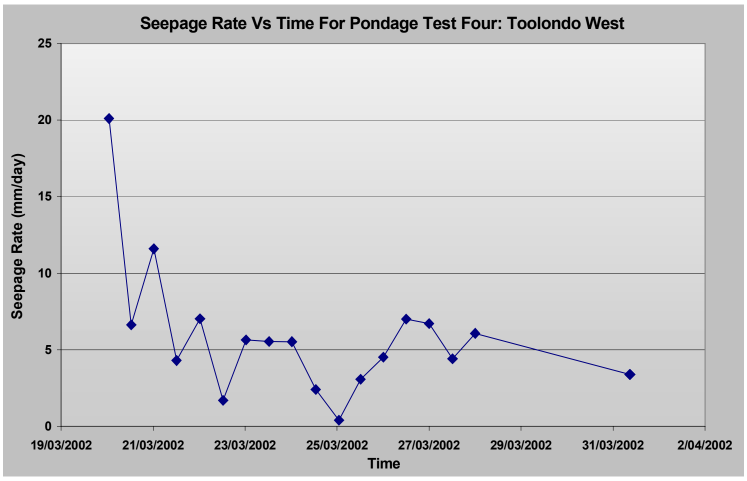


B.1.5 Toolondo West Pondage Tests: 19th March – 3rd April, 2002

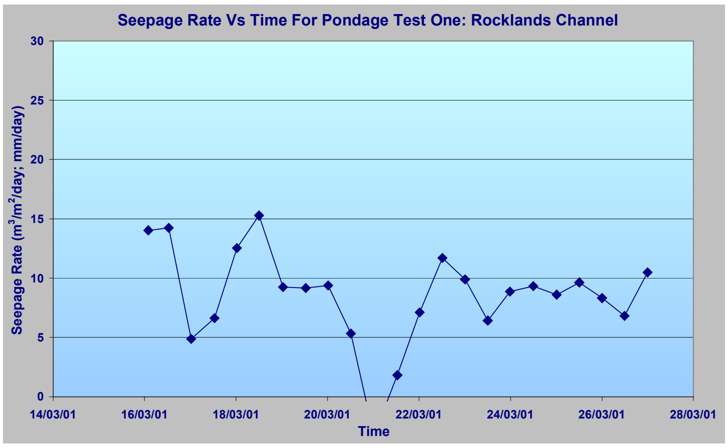


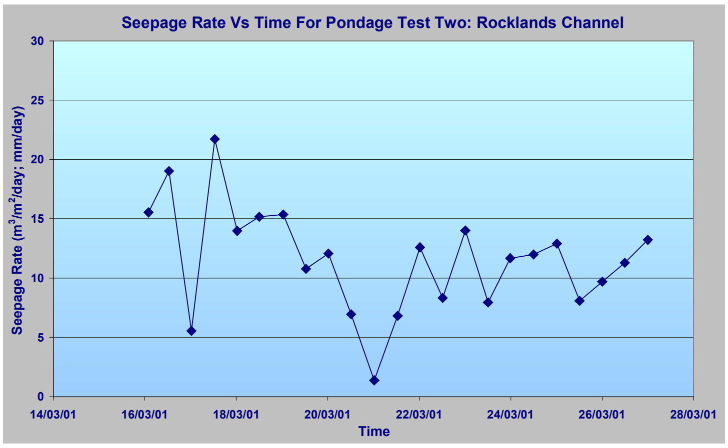


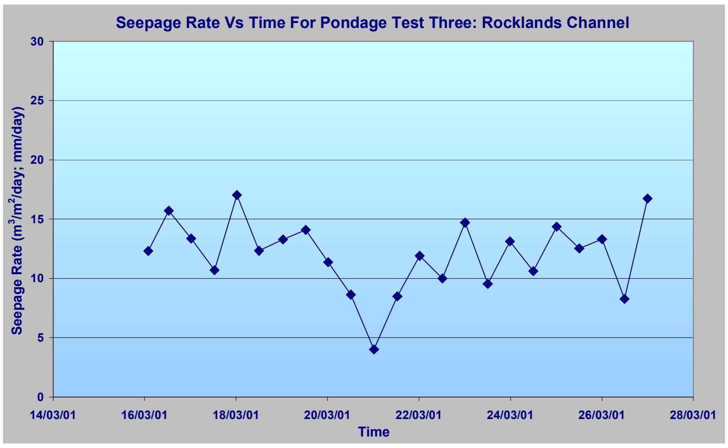


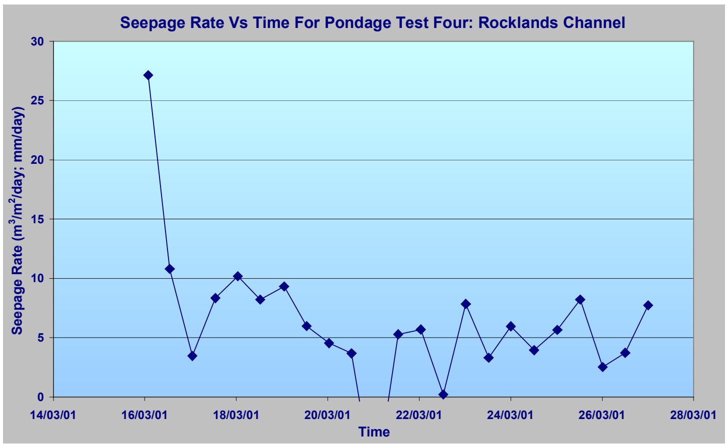


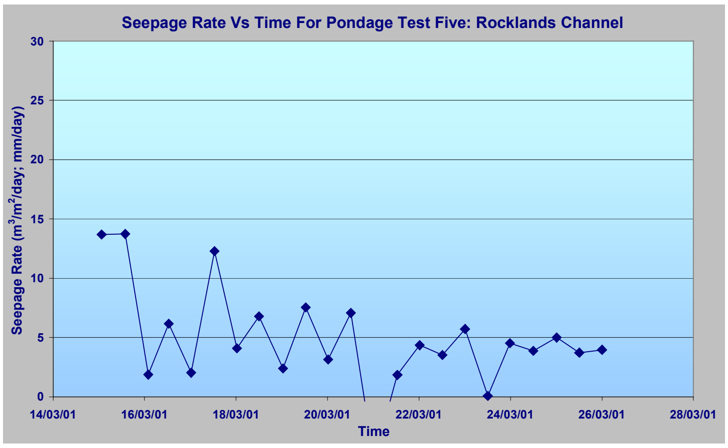
B.1.6 Rocklands Pondage Tests: 15th - 29th March, 2001

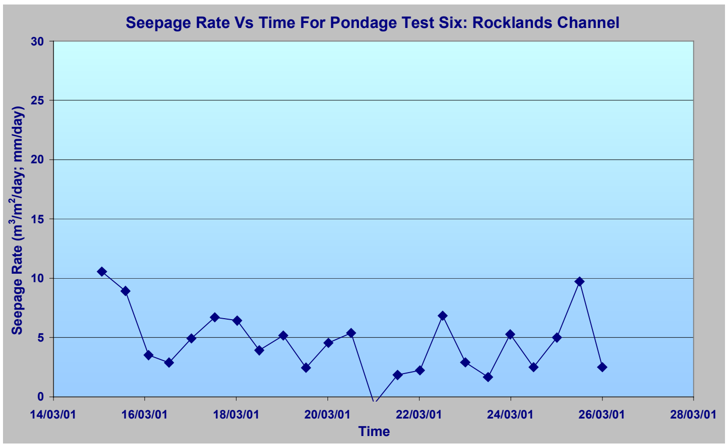






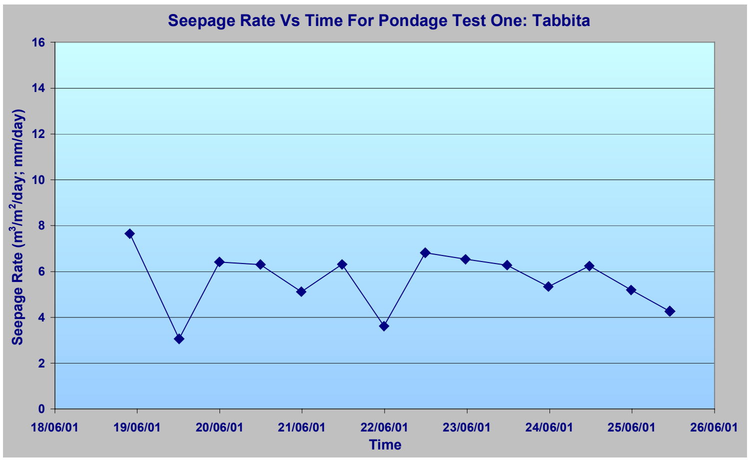


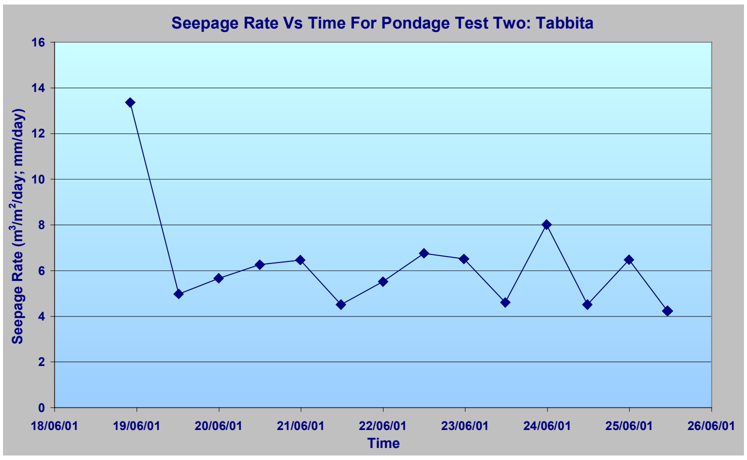


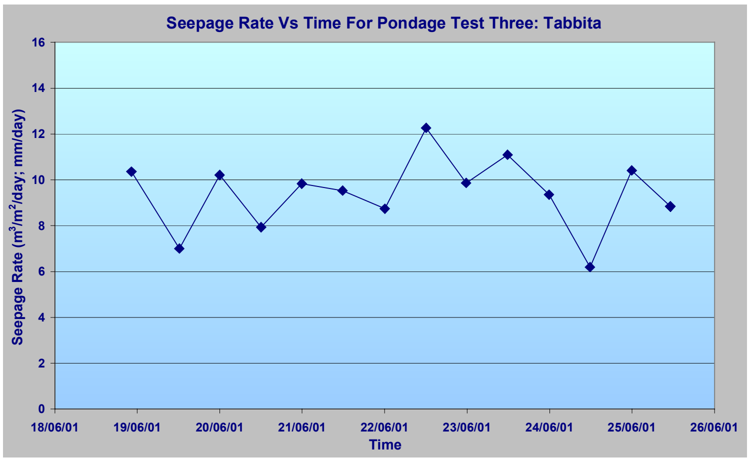


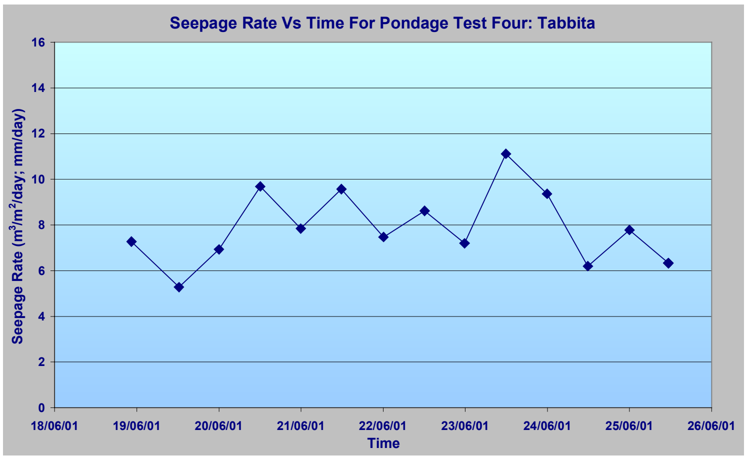
B.2 Murrumbidgee Irrigation Pondage Test Results

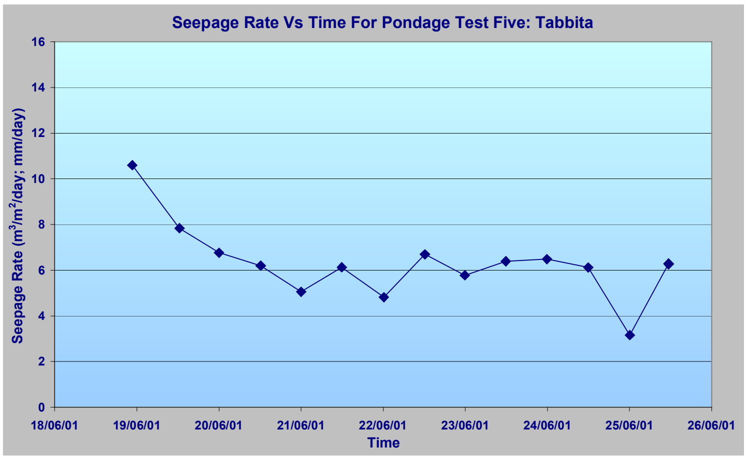
B.2.1 Tabbita Pondage Tests: 18th– 25th June, 2001

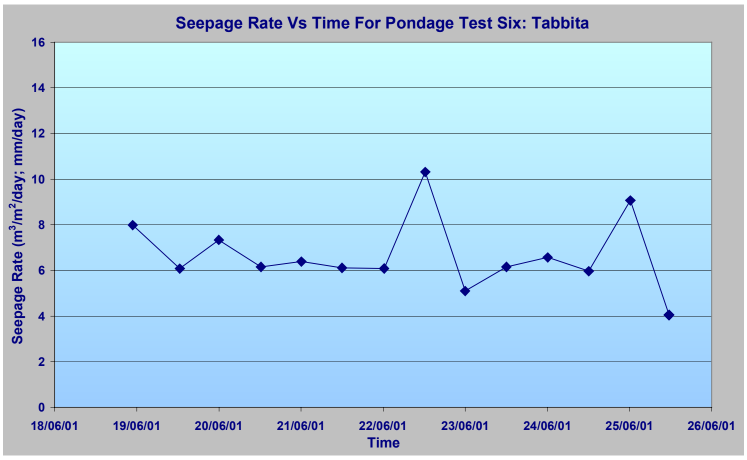




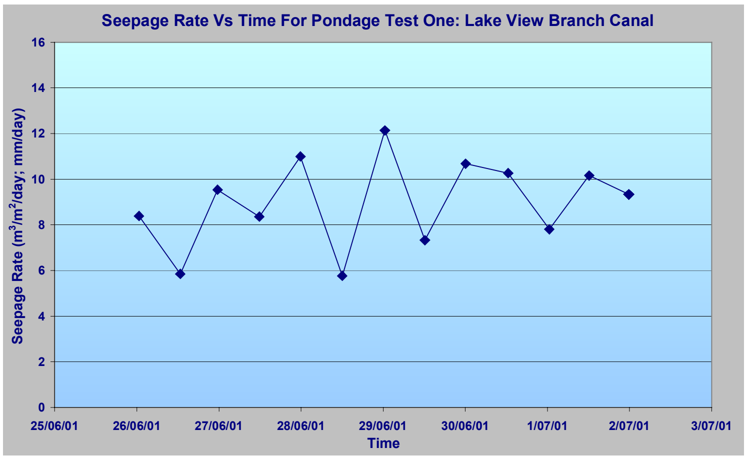


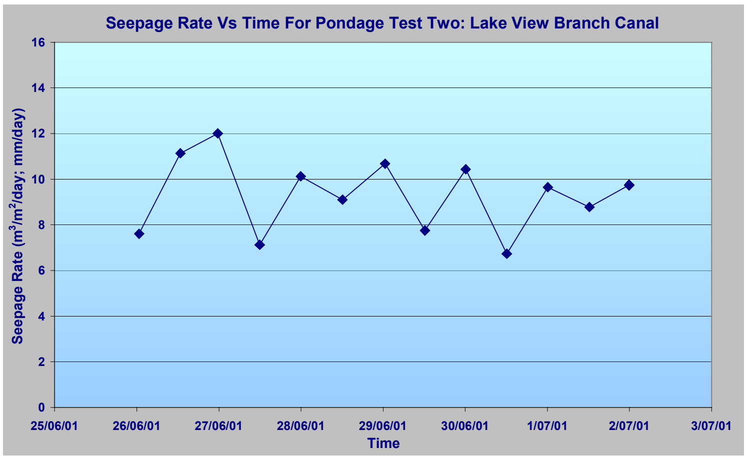


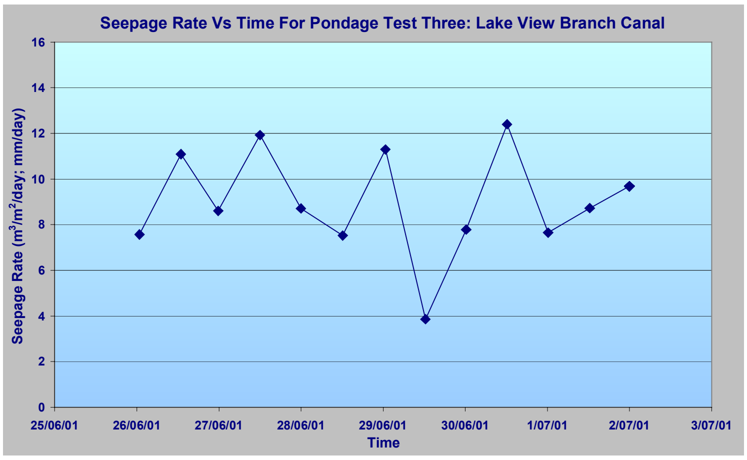


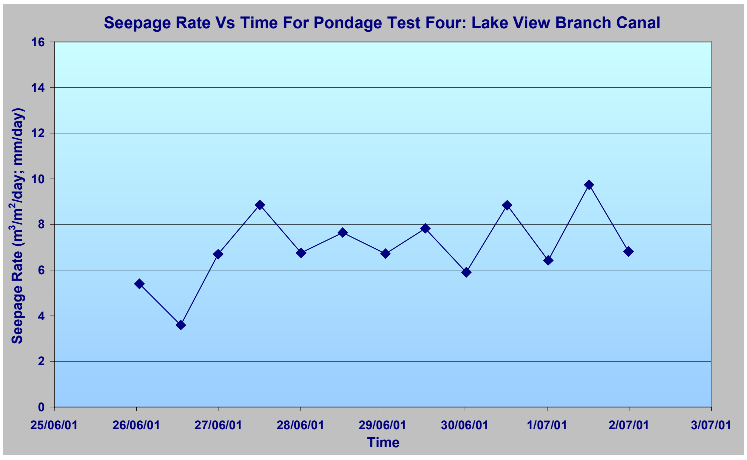


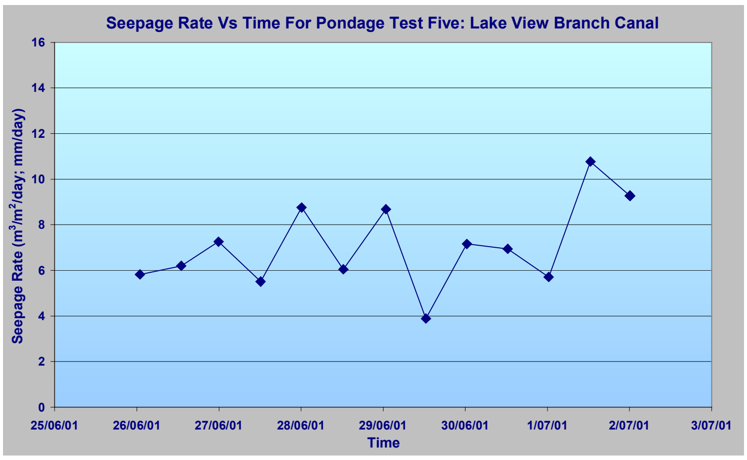
B.2.2 Lake View Central Pondage Tests: 25th June – 2nd July, 2001

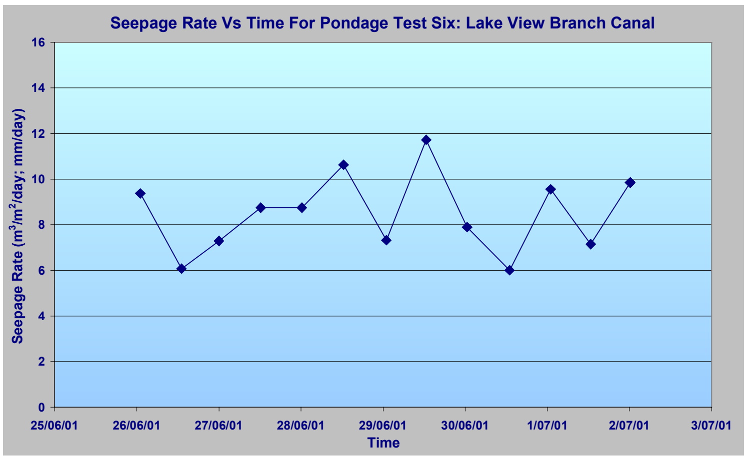




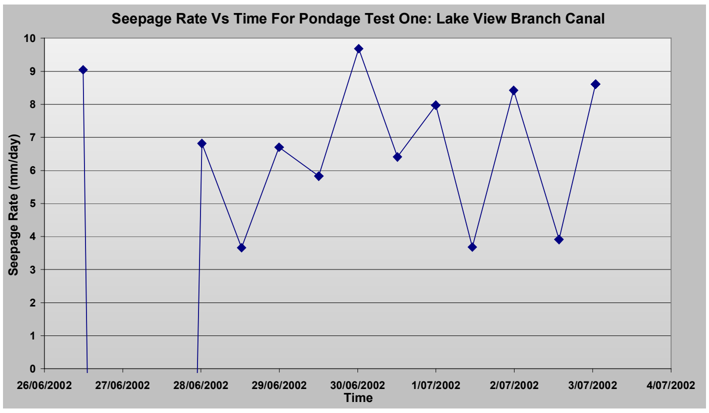


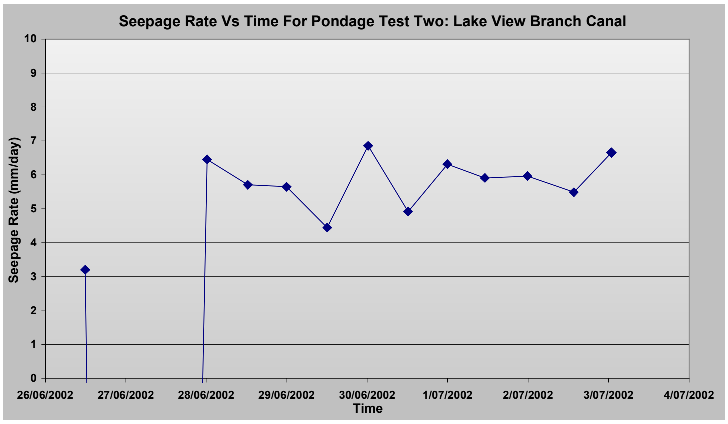


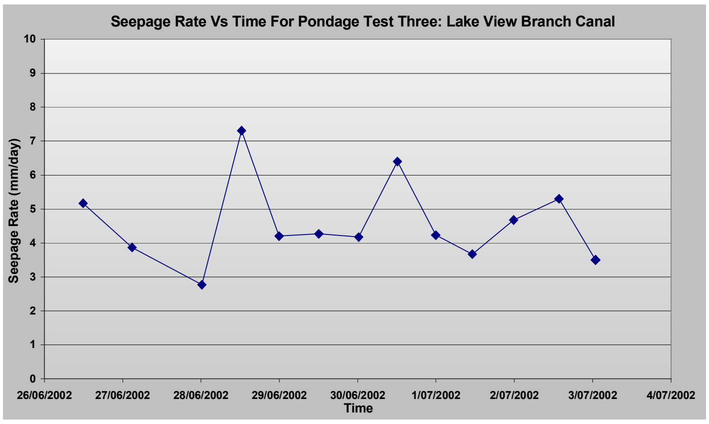


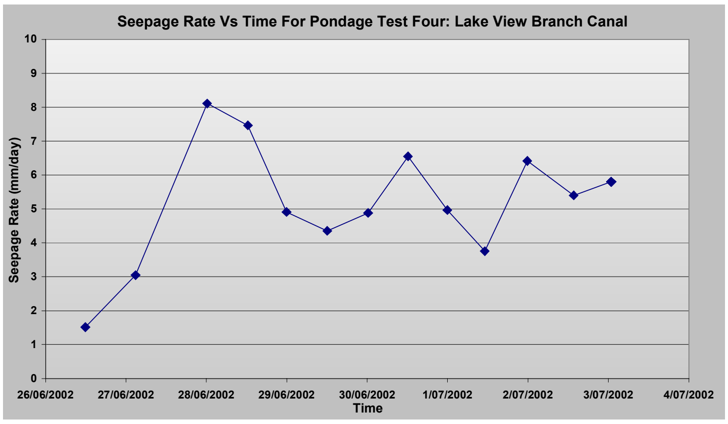


B.2.3 Lake View Central Pondage Tests: 26th June – 7th July, 2002

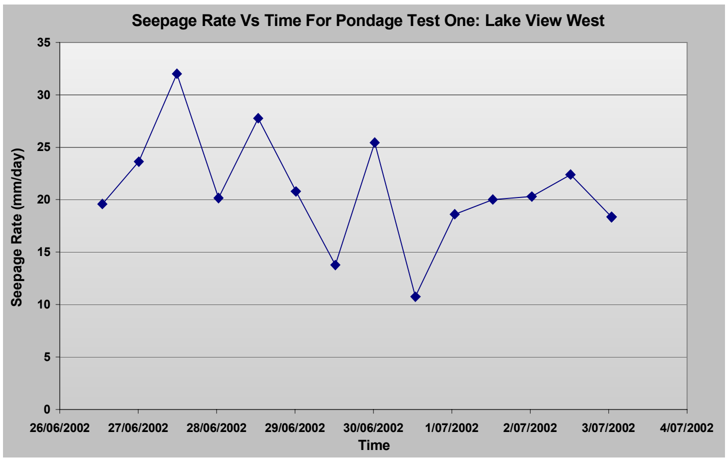


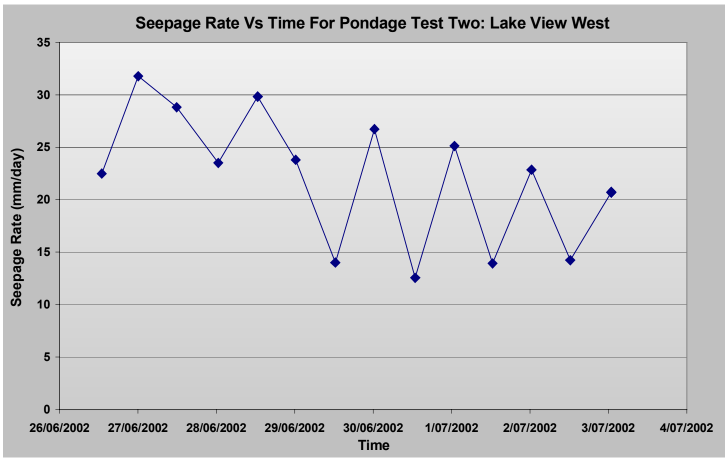


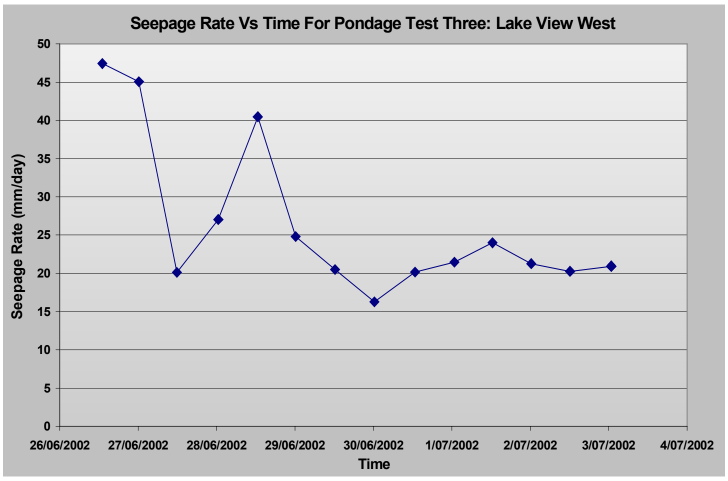


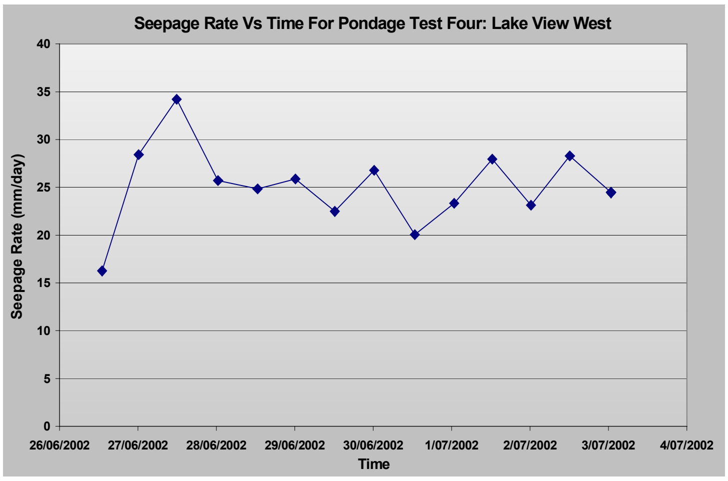


B.2.4 Lake View West Pondage Tests: 26th June – 7th July, 2002



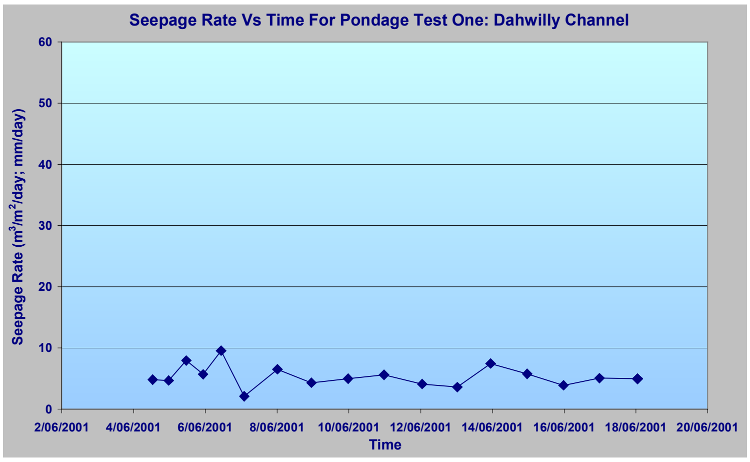


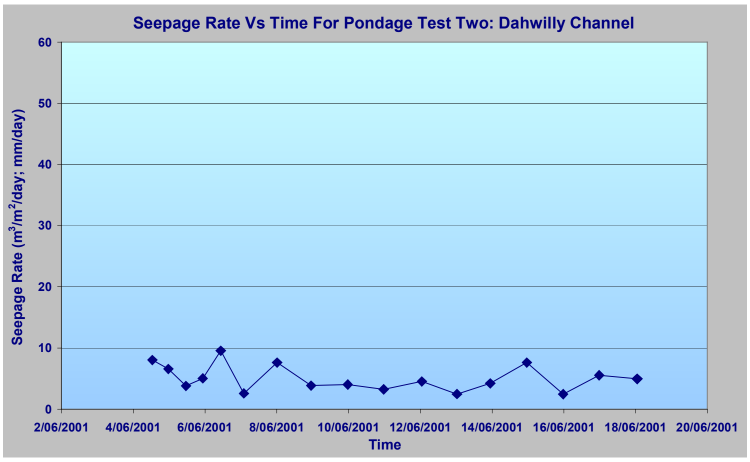


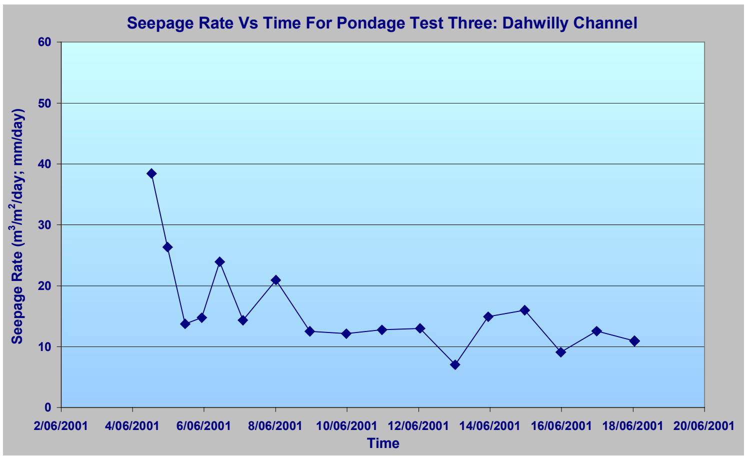


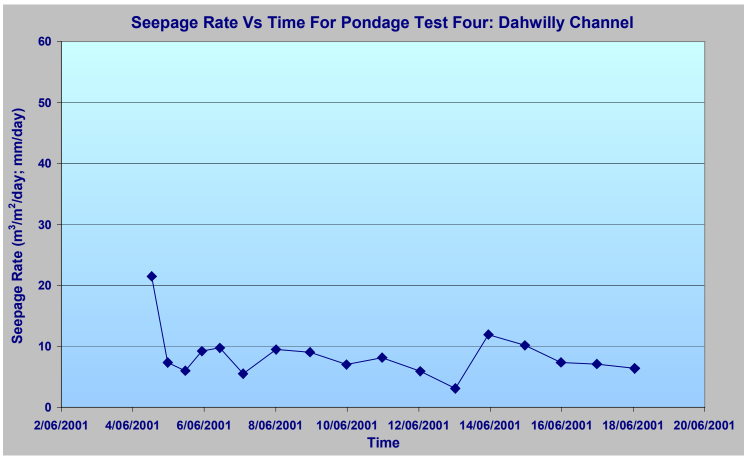
B.3 Murray Irrigation Limited Pondage Test Results

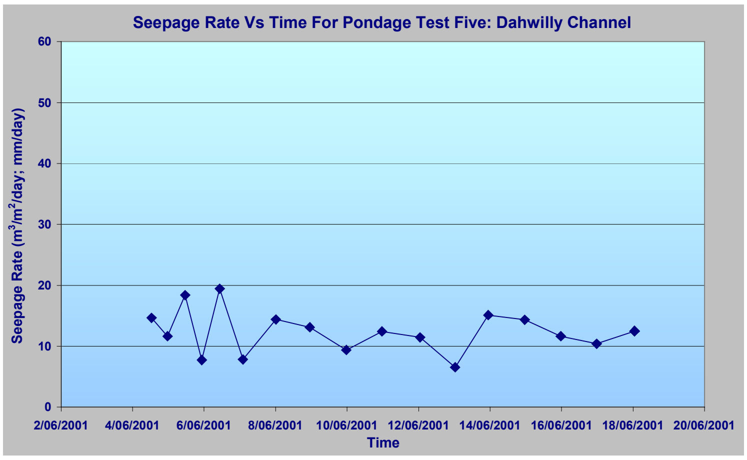
B.3.1 Dahwilly Pondage Tests: 4th– 18th June, 2001

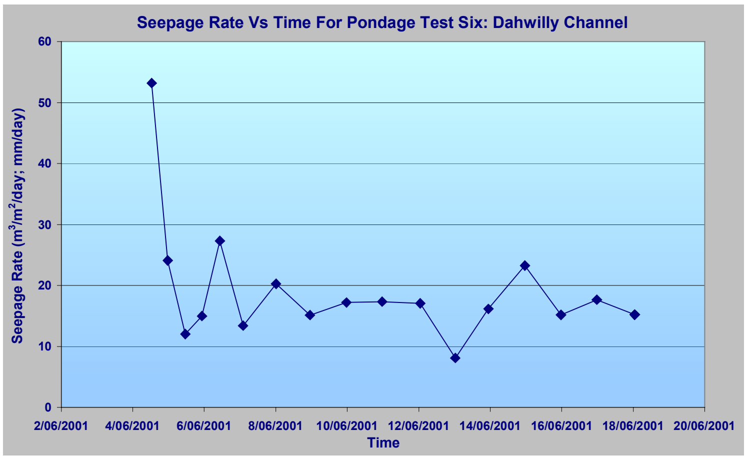




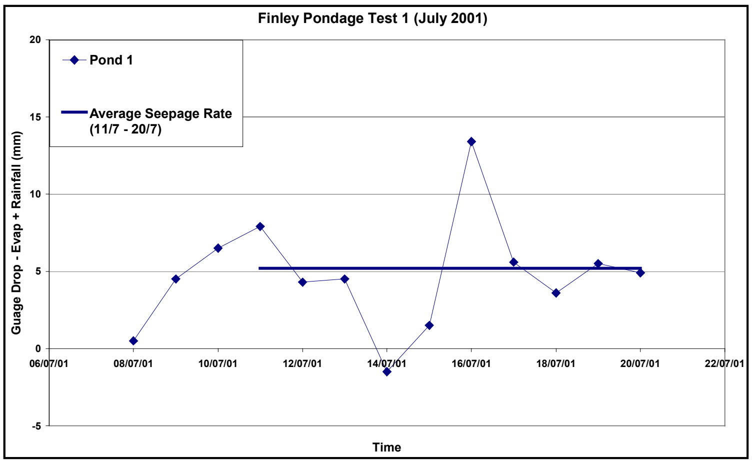


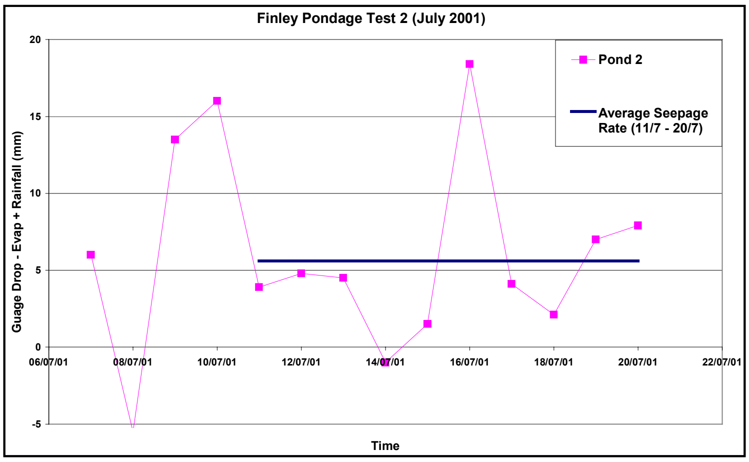


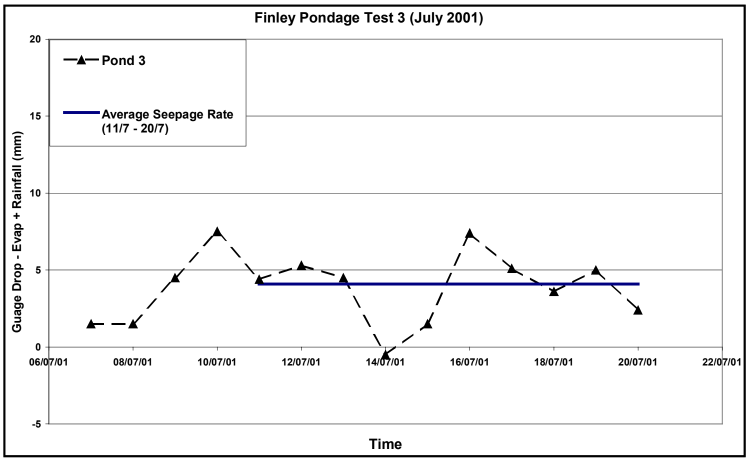


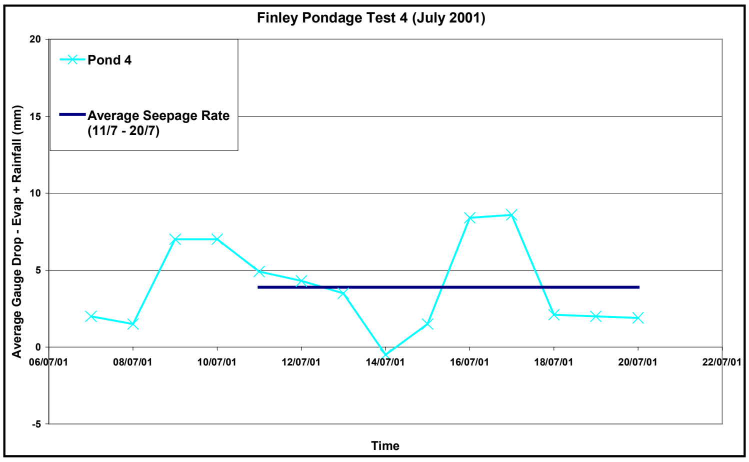


B.3.2 Finley Pondage Tests: 6th– 20th July, 2001

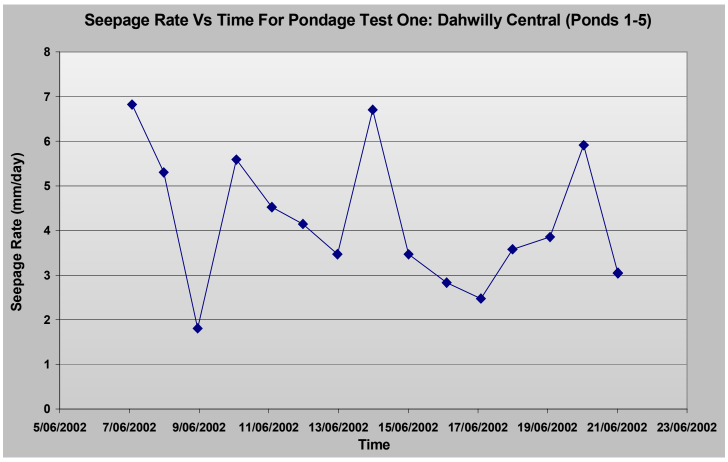




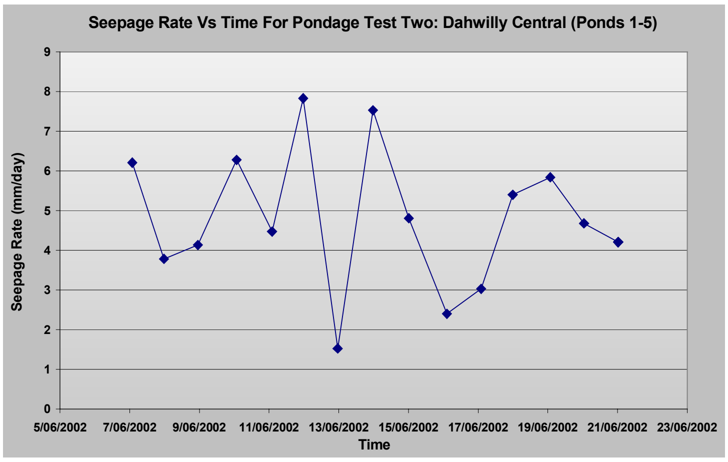




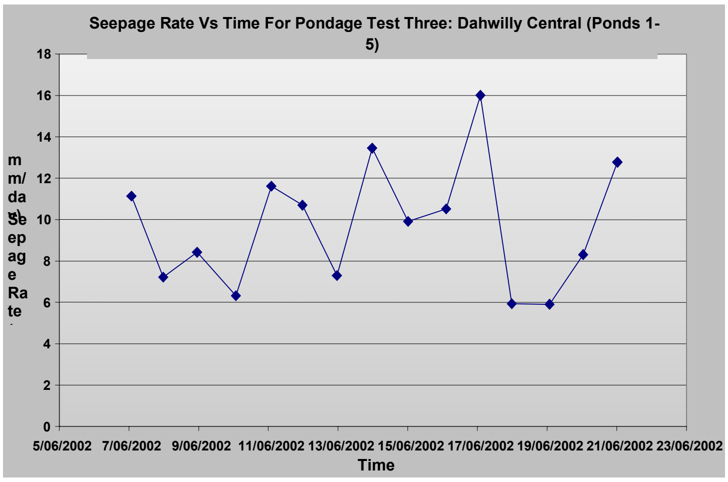
B.3.3 Dahwilly Pondage Tests: 6th– 21st June, 2002



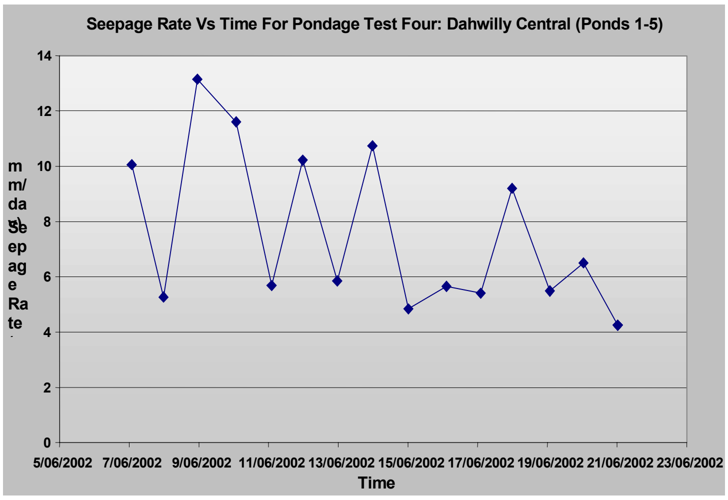
Seepage Rate Vs Time For Pondage Test One: Dahwilly Central (Ponds 1-5)



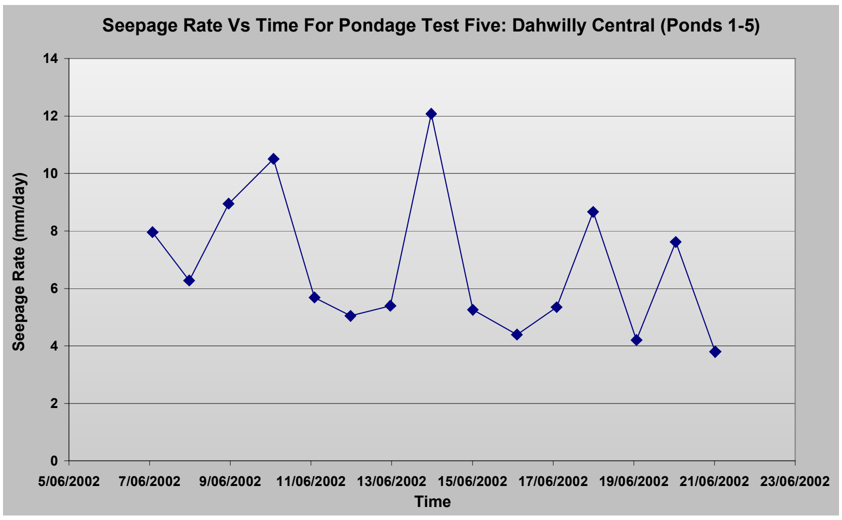
Seepage Rate Vs Time For Pondage Test Two: Dahwilly Central (Ponds 1-5)



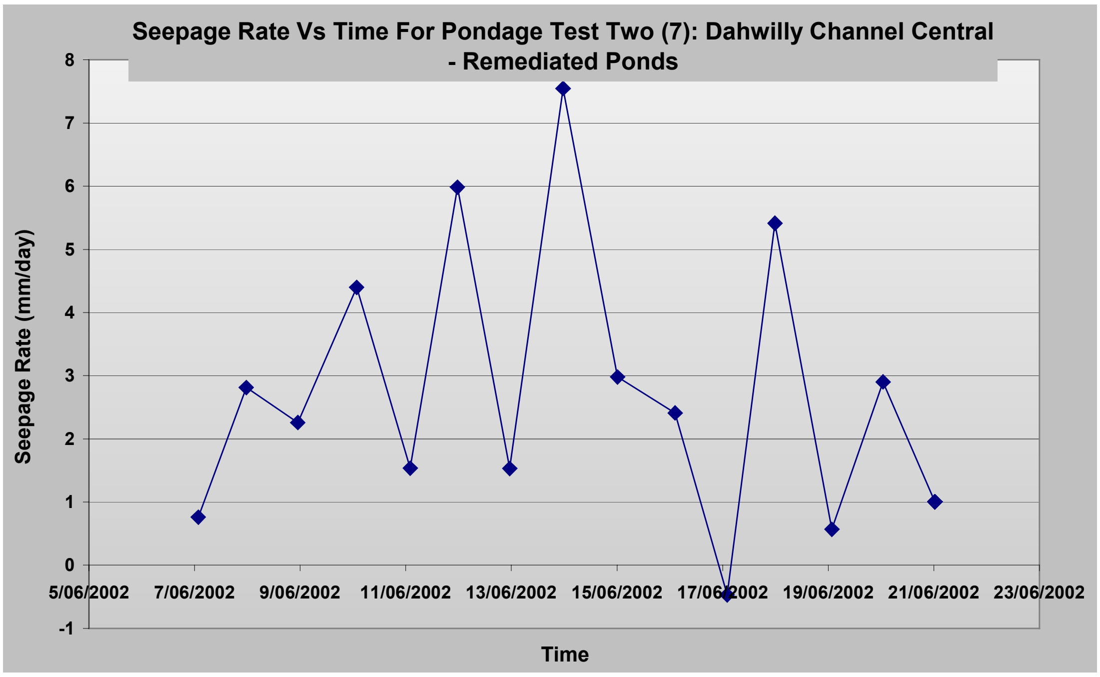
Seepage Rate Vs Time For Pondage Test Three: Dahwilly Central (Ponds 1-5)

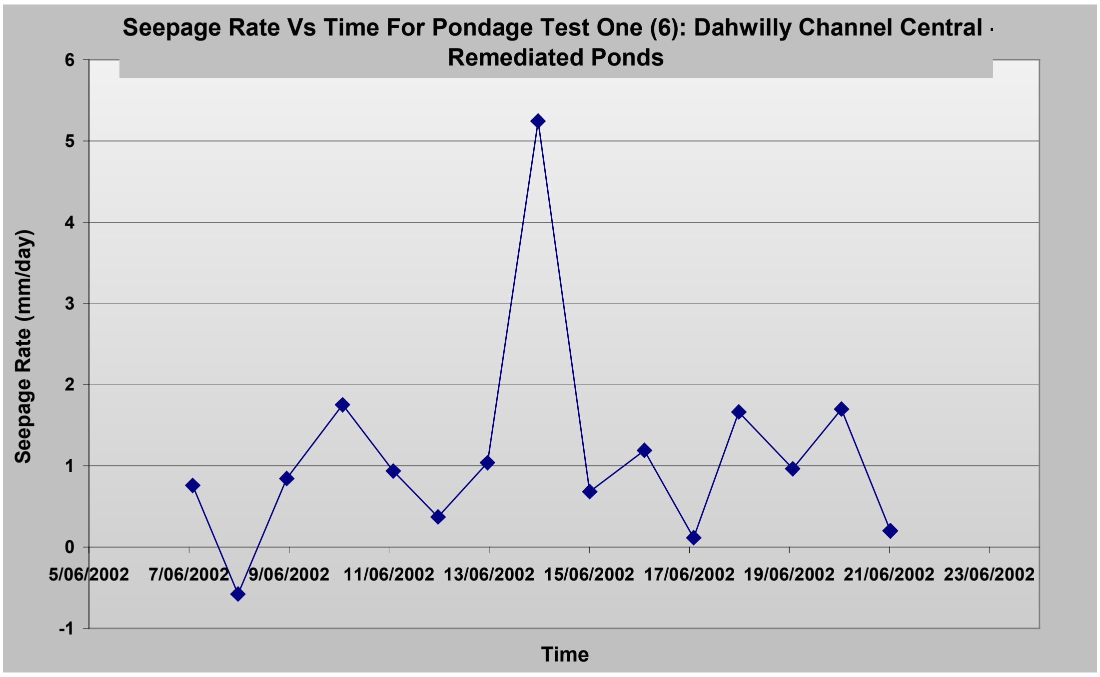


Seepage Rate Vs Time For Pondage Test Four: Dahwilly Central (Ponds 1-5)

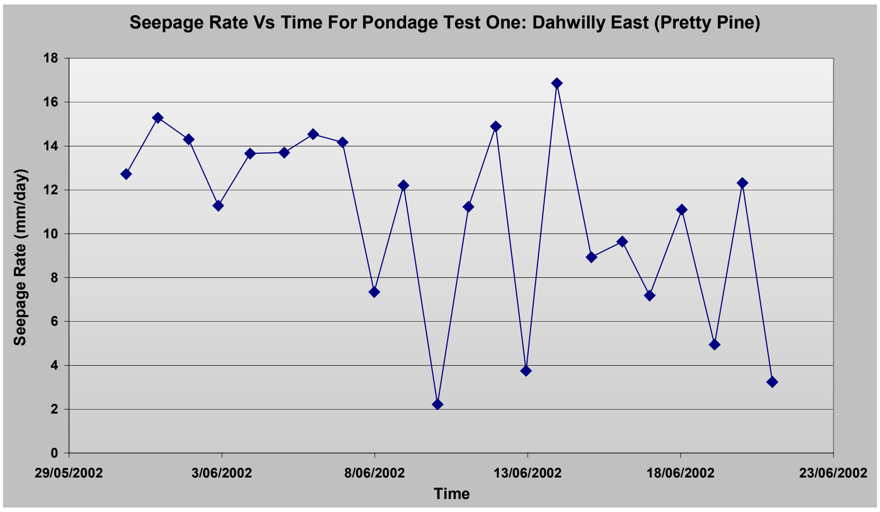


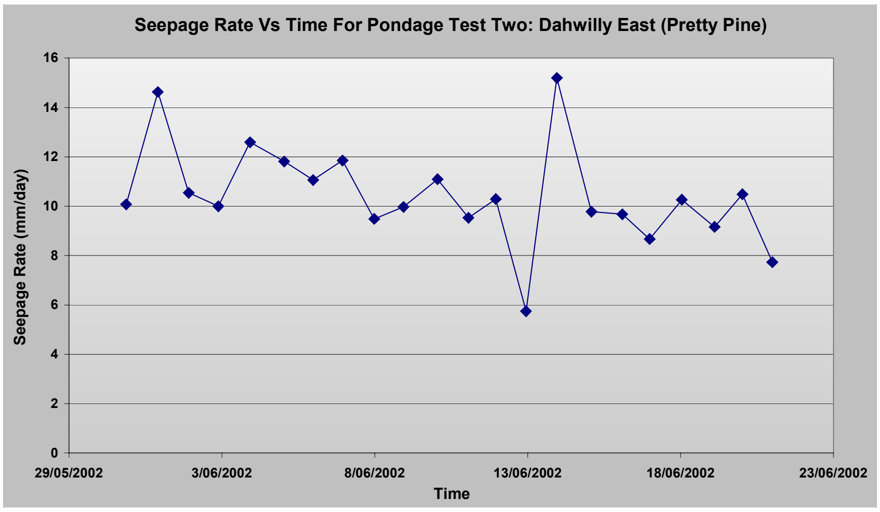
Seepage Rate Vs Time For Pondage Test Five: Dahwilly Central (Ponds 1-5)

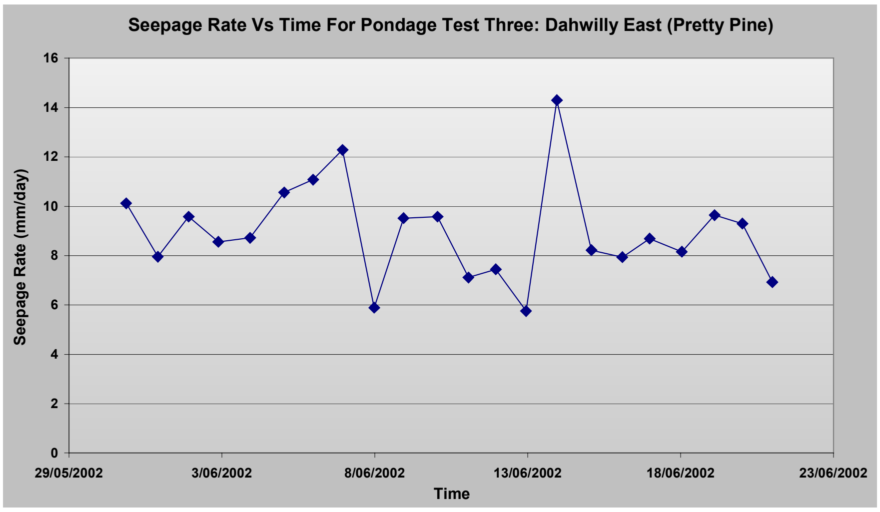

Seepage Rate Vs Time For Pondage Test Two (7): Dahwilly Channel Central - Remediated Ponds
Seepage Rate (mm/day)
8
7
6
5
4
3
2
1
0
-1
5/06/2002
7/06/2002
9/06/2002
11/06/2002
13/06/2002
15/06/2002
17/06/2002
19/06/2002
21/06/2002
23/06/2002
Time


Seepage Rate Vs Time For Pondage Test One (6): Dahwilly Channel Central - Remediated Ponds
Seepage Rate (mm/day)
6
5
4
3
2
1
0
-1
5/06/2002
7/06/2002
9/06/2002
11/06/2002
13/06/2002
15/06/2002
17/06/2002
19/06/2002
21/06/2002
23/06/2002
Time

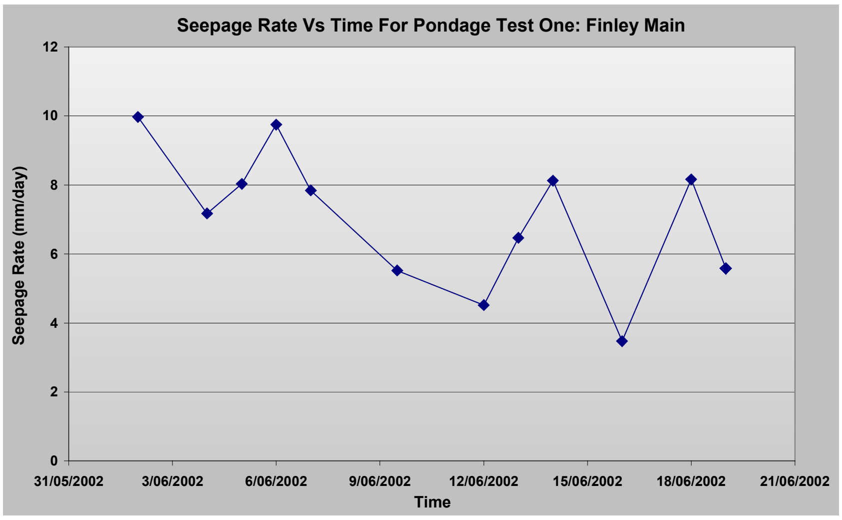
B.3.4 Dahwilly East Pondage Tests: 30th May – 21st June, 2002

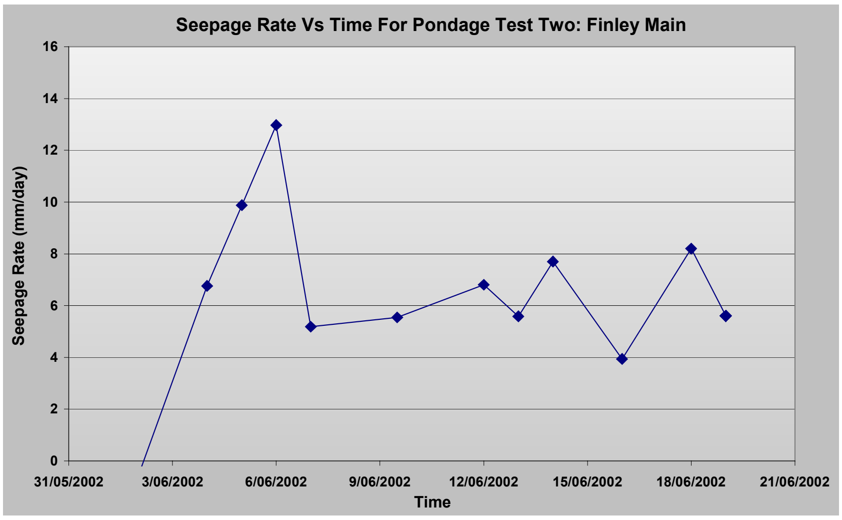


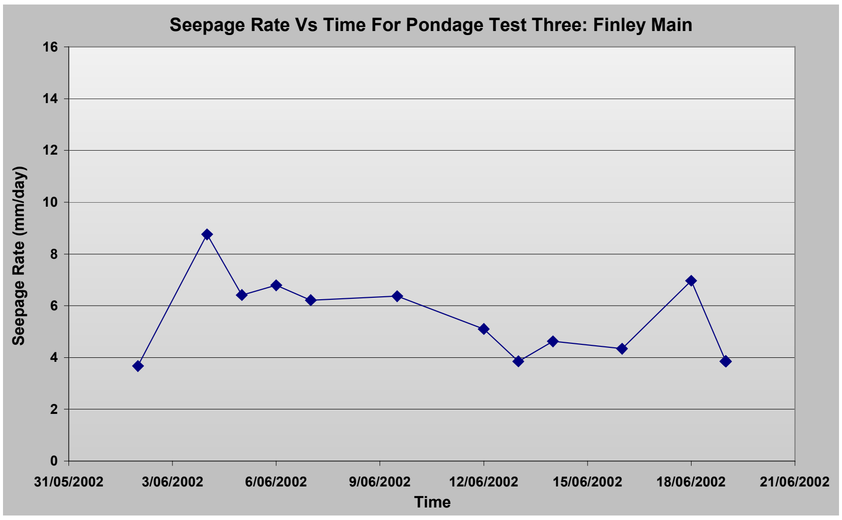




B.3.5 Finley Pondage Tests: 31st May – 19th June, 2002

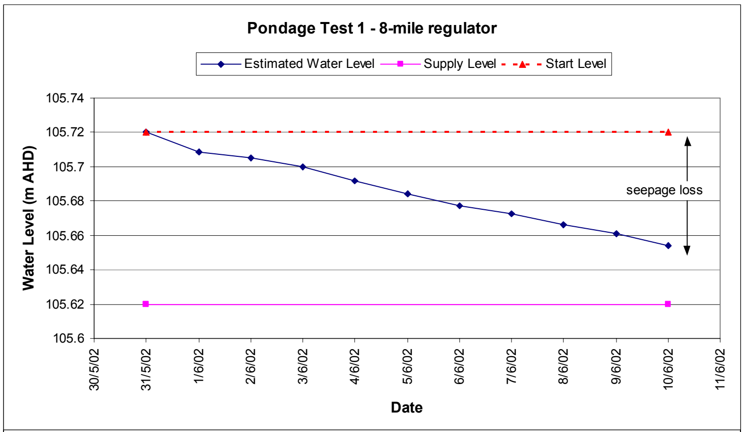


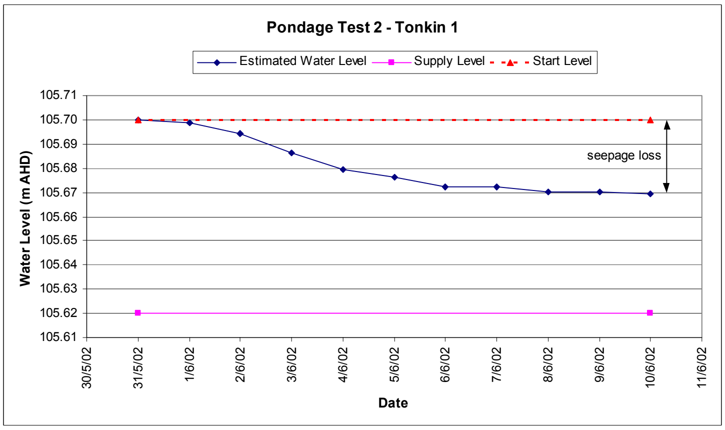


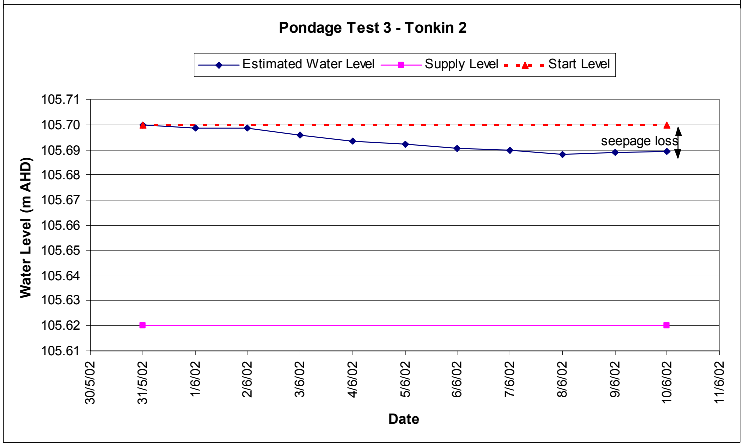


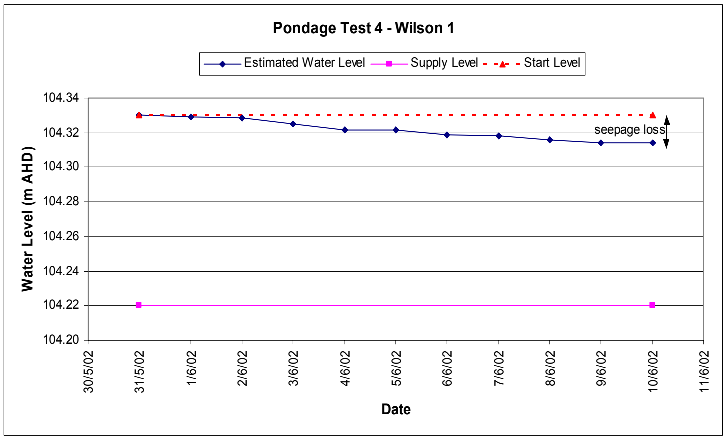
B.4 Goulburn Murray Water Pondage Test Results

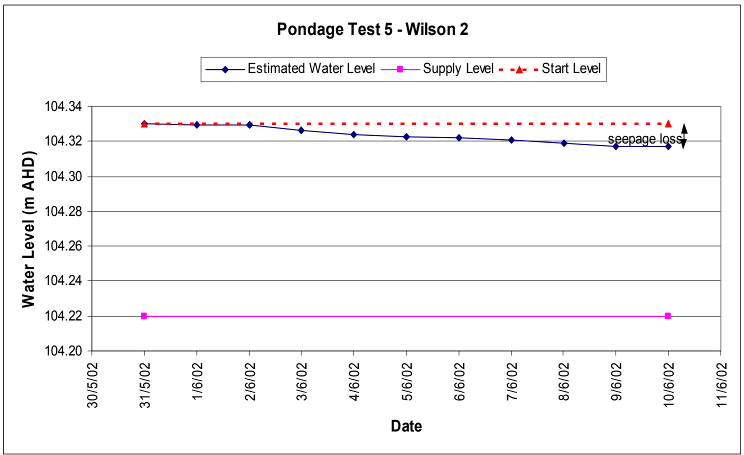
B.4.1 Waranga Western Channel

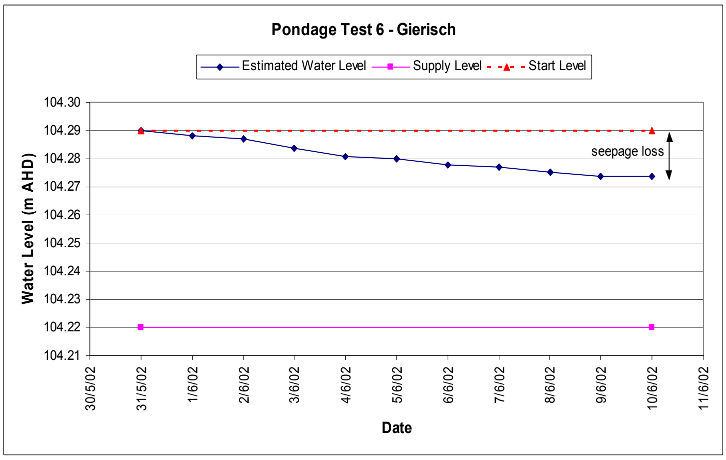


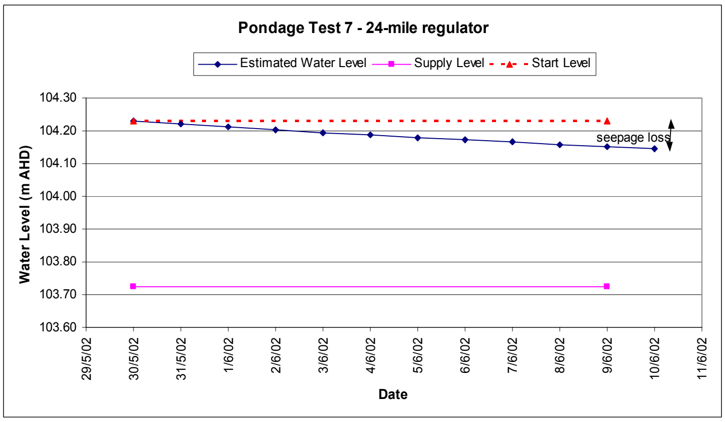


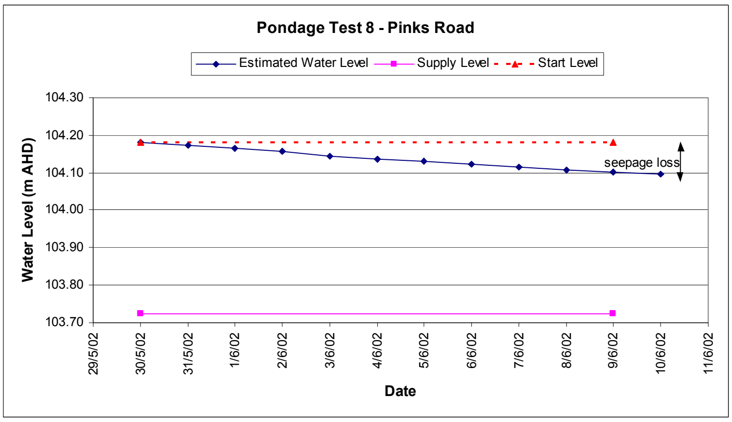


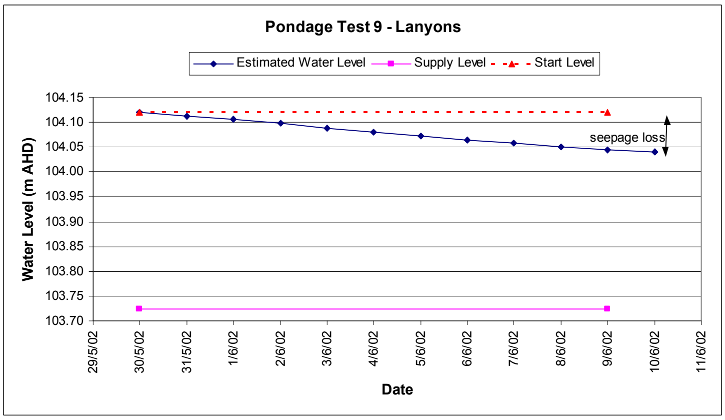


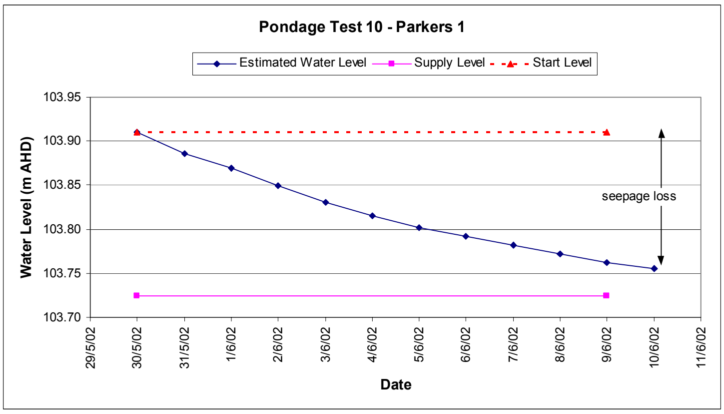


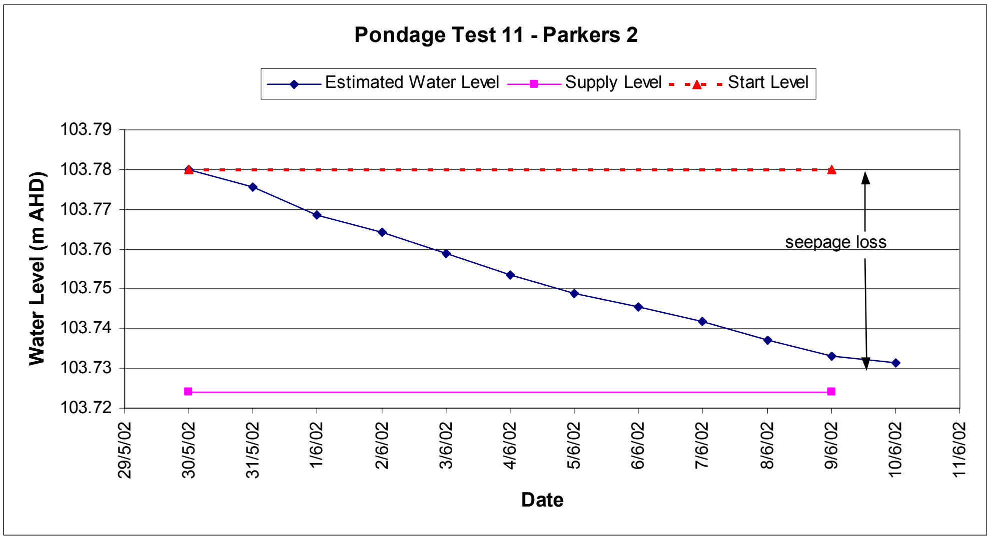



Pondage Test 7 - 24-mile regulator
Estimated Water Level
Supply Level
Start Level
seepage loss
Water Level (m AHD)
Date


Pondage Test 8 - Pinks Road
Estimated Water Level
Supply Level
Start Level
seepage loss
Water Level (m AHD)
Date


Pondage Test 9 - Lanyons
Estimated Water Level
Supply Level
Start Level
seepage loss
Water Level (m AHD)
Date


Pondage Test 10 - Parkers 1
Estimated Water Level
Supply Level
Start Level
seepage loss
Water Level (m AHD)
Date


Pondage Test 11 - Parkers 2
Estimated Water Level
Supply Level
Start Level
seepage loss
Water Level (m AHD)
Date

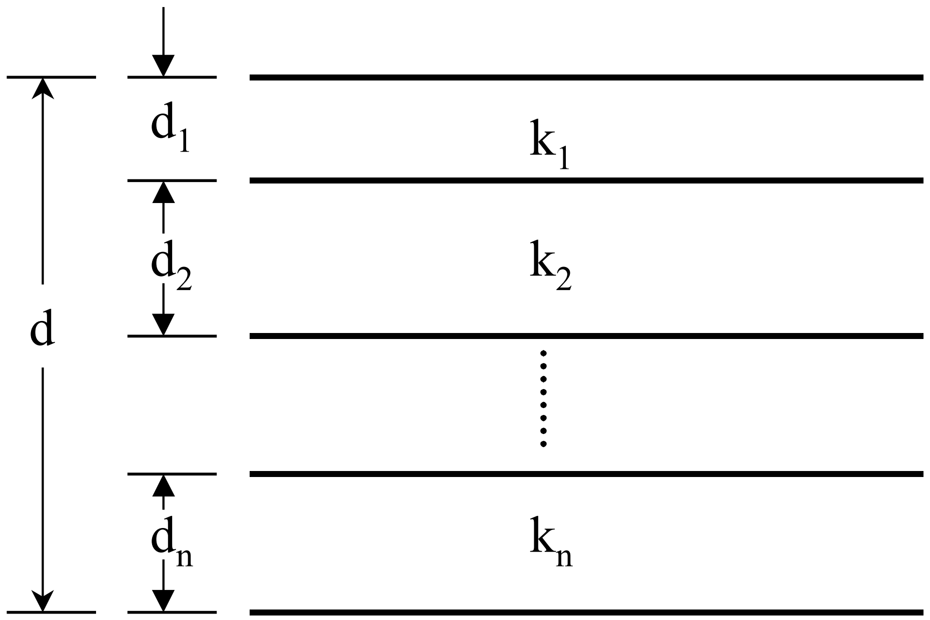
Appendix C Bulk Vertical Hydraulic Conductivity Calculations

Figure C-1 Example spreadsheet of bulk vertical hydraulic conductivity calculation for each pondage cell

Donald (P1-P3)	Lithology									Hydraulic Conductivity								
Depth Interval	POND 1			POND 2			POND 3			POND 1			POND 2			POND 3		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0 - 0.5	ClyS	ClyS	ClyS	ClyS	ClyS	ClyS	ClyS	ClyS	ClyS	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5 - 1	FS	FS	FS	MC	MC	MC	FS	MC	MC	2	2	2	1E-04	1E-04	1E-04	2	1E-04	1E-04
1 - 1.5	FS	FS	FS	MC	FS	FS	FS	FS	MC	2	2	2	1E-04	2	2	2	2	1E-04
1.5 - 2	FS	FS	FS	FS	FS	FS	FS	FS	FS	2	2	2	2	2	2	2	2	2
2 - 2.5	FS	FS	FS	FS	FS	FS	FS	FS	FS	2	2	2	2	2	2	2	2	2
2.5 - 3	FS	FS	FS	FS	FS	FS	SC	FS	FS	2	2	2	2	2	2	0.07	2	2
3 - 3.5	FS	FS	FS	FS	FS	FS	SC	FS	FS	2	2	2	2	2	2	0.07	2	2
3.5 - 4	FS	FS	FS	SC	FS	FS	SC	FS	FS	2	2	2	0.07	2	2	0.07	2	2
4 - 4.5	SC	SC	SC	SC	SC	SC	SC	FS	FS	0.07	0.07	0.07	0.07	0.07	0.07	0.07	2	2
4.5 - 5	SC	SC	SC	SC	SC	SC	FS	FS	FS	0.07	0.07	0.07	0.07	0.07	0.07	2	2	2
5 - 5.5	SC	SC	SC	SC	SC	SC	FS	FS	FS	0.07	0.07	0.07	0.07	0.07	0.07	2	2	2
5.5 - 6	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
6 - 6.5	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
6.5 - 7	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
7 - 7.5	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
7.5 - 8	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
8 - 8.5	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
8.5 - 9	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
9 - 9.5	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
9.5 -10	SC	SC	SC	SC	SC	SC	SC	SC	SC	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Donald (P1-P3)	Representative Number			EM31 Response				Near Surface (0-2m)				Whole Profile - Surface Weighted				Whole Profile - Evenly Weighted (Resistivity)			
Depth Interval	Pond 1	Pond 2	Pond 3	Effevtive Thickness (Weighting)	Pond 1	Pond 2	Pond 3	Effevtive Thickness (Weighting)	Pond 1	Pond 2	Pond 3	Effevtive Thickness (Weighting)	Pond 1	Pond 2	Pond 3	Effevtive Thickness (Weighting)	Pond 1	Pond 2	Pond 3
0 - 0.5	0.50	0.50	0.50	0.48	0.96	0.96	0.96	2.5	5.00	5.00	5.00	0.90	1.80	1.80	1.80	0.5	1.00	1.00	1.00
0.5 - 1	2.00	0.00	0.67	1.07	0.53	10681	1.60	2.5	1.25	25000	3.75	0.90	0.45	9000	1.35	0.5	0.25	5000	0.75
1 - 1.5	2.00	1.33	1.33	1.30	0.65	0.98	0.98	2.5	1.25	1.87	1.87	0.90	0.45	0.67	0.67	0.5	0.25	0.37	0.37
1.5 - 2	2.00	2.00	2.00	1.32	0.66	0.66	0.66	2.5	1.25	1.25	1.25	0.90	0.45	0.45	0.45	0.5	0.25	0.25	0.25
2 - 2.5	2.00	2.00	2.00	1.20	0.60	0.60	0.60					0.80	0.40	0.40	0.40	0.5	0.25	0.25	0.25
2.5 - 3	2.00	2.00	1.36	1.02	0.51	0.51	0.75					0.80	0.40	0.40	0.59	0.5	0.25	0.25	0.37
3 - 3.5	2.00	2.00	1.36	0.82	0.41	0.41	0.60					0.70	0.35	0.35	0.52	0.5	0.25	0.25	0.37
3.5 - 4	2.00	1.36	1.36	0.64	0.32	0.47	0.47					0.70	0.35	0.52	0.52	0.5	0.25	0.37	0.37
4 - 4.5	0.07	0.07	1.36	0.51	7.30	7.30	0.38					0.60	8.57	8.57	0.44	0.5	7.14	7.14	0.37
4.5 - 5	0.07	0.07	2.00	0.43	6.11	6.11	0.21					0.60	8.57	8.57	0.30	0.5	7.14	7.14	0.25
5 - 5.5	0.07	0.07	2.00	0.39	5.50	5.50	0.19					0.40	5.71	5.71	0.20	0.5	7.14	7.14	0.25
5.5 - 6	0.07	0.07	0.07	0.36	5.10	5.10	5.10					0.40	5.71	5.71	5.71	0.5	7.14	7.14	7.14
6 - 6.5	0.07	0.07	0.07	0.30	4.34	4.34	4.34					0.30	4.29	4.29	4.29	0.5	7.14	7.14	7.14
6.5 - 7	0.07	0.07	0.07	0.17	2.40	2.40	2.40					0.30	4.29	4.29	4.29	0.5	7.14	7.14	7.14
7 - 7.5	0.07	0.07	0.07									0.20	2.86	2.86	2.86	0.5	7.14	7.14	7.14
7.5 - 8	0.07	0.07	0.07									0.20	2.86	2.86	2.86	0.5	7.14	7.14	7.14
8 - 8.5	0.07	0.07	0.07									0.10	1.43	1.43	1.43	0.5	7.14	7.14	7.14
8.5 - 9	0.07	0.07	0.07									0.10	1.43	1.43	1.43	0.5	7.14	7.14	7.14
9 - 9.5	0.07	0.07	0.07									0.10	1.43	1.43	1.43	0.5	7.14	7.14	7.14
9.5 -10	0.07	0.07	0.07									0.10	1.43	1.43	1.43	0.5	7.14	7.14	7.14
				10	0.282	0.001	0.519	10	1.143	0.000	0.842	10	0.188	0.001	0.303	10	0.113	0.002	0.145

The vertical hydraulic conductivity for each pondage cell was calculated based on the following formula (after Freeze and Cherry, 1979). For each layer 'd' (as shown in the figure below) where different soil types were encountered within the one pondage cell, the average of the different soil types was used, as shown in the above example.



$$K_z = \frac{d}{\sum_{i=1}^{n} \frac{d_i}{K_i}}$$

Appendix D Summary of Project Brief for Remote Sensing in the Wimmera

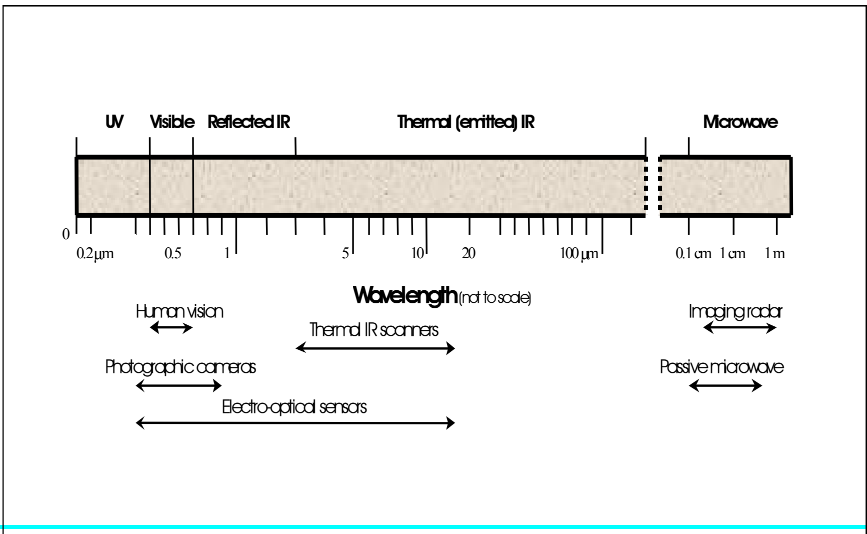
Background

The brief presented in this Appendix is the brief prepared for a planned remote sensing trial in the Wimera. This was not carried out due to budget constraints (refer Section 4.5). The brief is presented here as an indication of the issues requiring consideration when conducting remote sensing as part of a channel seepage investigation. It is not a prescriptive method for using this technique. The brief outlined the requirements for conducting an investigation into the feasibility of using remote sensing techniques for channel seepage identification and quantification. Remote sensing techniques can offer an efficient method to detect and locate seepage without interfering with channel operations. Remote sensing refers to any kind of data recording by a sensor which measures energy emitted or reflected by objects located at some distance from the sensor and includes aerial photography and satellite imagery.

All remote sensing techniques for channel seepage detection assume that channel seepage has a surface expression adjacent to the channel. This may be detected as increased soil moisture and / or vegetation vigour and water status. These techniques are limited to detecting seepage that migrates laterally through the channel banks, and/or re-surfaces near the channel toe. Remote sensing cannot account for seepage that moves vertically to the groundwater and does not re-surface. A key aspect of remotely sensed data is that it must be at a suitable resolution to allow definition of seepage zones. Typical seepage zones may be 10 – 20 m in width adjacent to a 10 – 20 m channel. Therefore ground resolutions of less than 10 m are required.
The proposed project was to be inter-related with the EM surveys and soil survey assessments. It was proposed that the results be brought into the proposed project using GIS.

Figure E-1 shows the major regions of the electromagnetic spectrum that are used in remote sensing. The regions most useful for channel seepage detection include visible, reflected (near) infrared and thermal infrared.

- **Figure E-1 Major regions of the electromagnetic spectrum pertinent to remote sensing**



Project Description

The project aims are to investigate and evaluate remote sensing techniques and spatial data analysis for the identification and quantification of channel seepage. The project should be conducted on selected pilot areas within the WMW channel system and in an area where seepage sites have been detected and quantified using other methods.

Task One – Identification of Channel Seepage
This task was to involve the identification of channel seepage using remotely sensed data analysis techniques to identify potential seepage sites. This would be followed by on ground verification of these sites and an evaluation of the accuracy of the technique/s implemented. The aim of the task was to evaluate the ability of remotely sensed imagery to detect known channel seepage sites.

Task Two – Quantification of Seepage
The second task was to involve the investigation of the potential of an integrated spatial data analysis approach for quantifying channel seepage. The spatial data analysis would combine results from Task One with those from the EM and Soil surveys, and pondage test data using GIS (Geographical Information Systems). The aim of this task was to determine the ability of integrated spatial data analysis to quantify channel seepage.

Methodology

Task One – Identification of Channel Seepage

Data source review and image acquisition
A review of available remotely sensed data was to be undertaken culminating in a comparison of spatial and spectral resolutions, and costs of acquisition and analysis. Previous data collected by WMW was to be assessed and published literature investigated.

The nature of channel seepage suggests that the source data should have high spatial resolution (10 m or less) and that it is multispectral (ie. has data collected from more than one distinct region of the electromagnetic spectrum). Distinct data from the infra-red region is expected to be the most beneficial as this area of the spectrum is strongly absorbed by water and will be able to most distinctly separate areas of varying soil moisture and plant water and growth status.

The review was also to investigate the optimum data collection time. It is expected that increased surface moisture and vegetation growth due to channel seepage would be particularly evident during late summer and early autumn when surrounding areas (apart from irrigation) would be distinctly drier. In addition, imagery from more than one date would be useful to remove the effects of crop irrigation and other seasonal variations. Thus the temporal dimension of the imagery was also to be investigated.

Remotely sensed image data sources may include:
- Digital infra-red aerial photography;
- Airborne high resolution sensor data; and,
- Satellite imagery.

Image analysis
Using high-level image analysis software (eg. ER MAPPER or ERDAS IMAGINE) multidate imagery was to be combined and analysed for the selected study area along with ground data. Automated image analysis and GIS techniques were to be developed where possible to identify and map potential channel seepage sites.

Accuracy assessment and evaluation
The accuracy of the developed remote sensing techniques was to be assessed by comparison to field surveys, with respect to:
- the percentage of sites identified as potential locations of channel seepage that are actually channel seepage locations (the converse of this is the error of commission, or over estimation);
- the percentage of channel seepage locations identified using the techniques (the converse of this is the error of omission, or under estimation); and
- The key characteristics of inaccurately detected sites were to be identified to allow the development of recommendations that may reduce these errors.

Task Two – Quantification of seepage

Spatial data from a number of sources, including Task One, was to be combined and analysed using GIS. Data sources were to include:
- airborne radiometric and electromagnetic data (EM data)
- soil survey assessments.
- channel flow and width
- pondage test data

The extent to which the input data could quantify seepage at known locations would be assessed by comparison to the pondage test data.

Trial Requirements

Budget
The budget for the pilot study was expected to be $15,000 to $20,000, allowing for approximately $5,000 to $10,000 in image costs.

Information Technology
Software requirements include high-end image analysis software such as ER MAPPER and / or ERDAS IMAGINE and advanced GIS software such as ArcInfo and Arcview including support of raster data formats. The imagery and GIS data required to be collated may need approx . 1 to 5 gigabytes.

Skills and experience
The required skills and experience to undertake this type of task would include:
- Geophysical interpretation (EM31 & EM34), soil data interpretation and analysis;
- Knowledge / familiarity with GIS and spatial analysis;
- Remote sensing data processing and analysis;
- Accuracy assessment and evaluation.

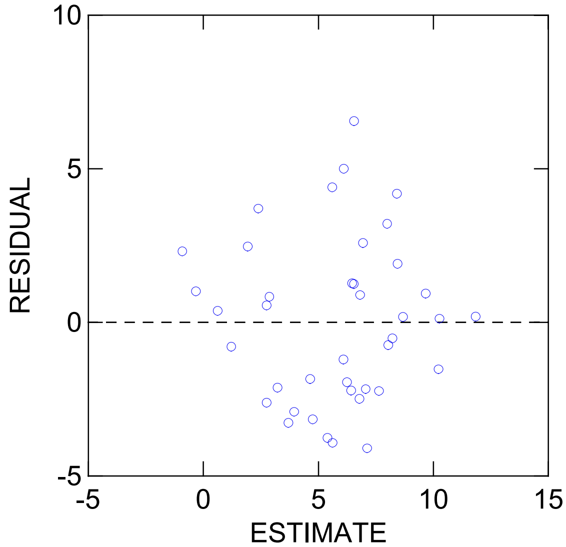
Appendix E Statistical Output from Regional Assessment Regression Analysis

Task 1 – Multiple Linear Regression With DTWT 5-10m

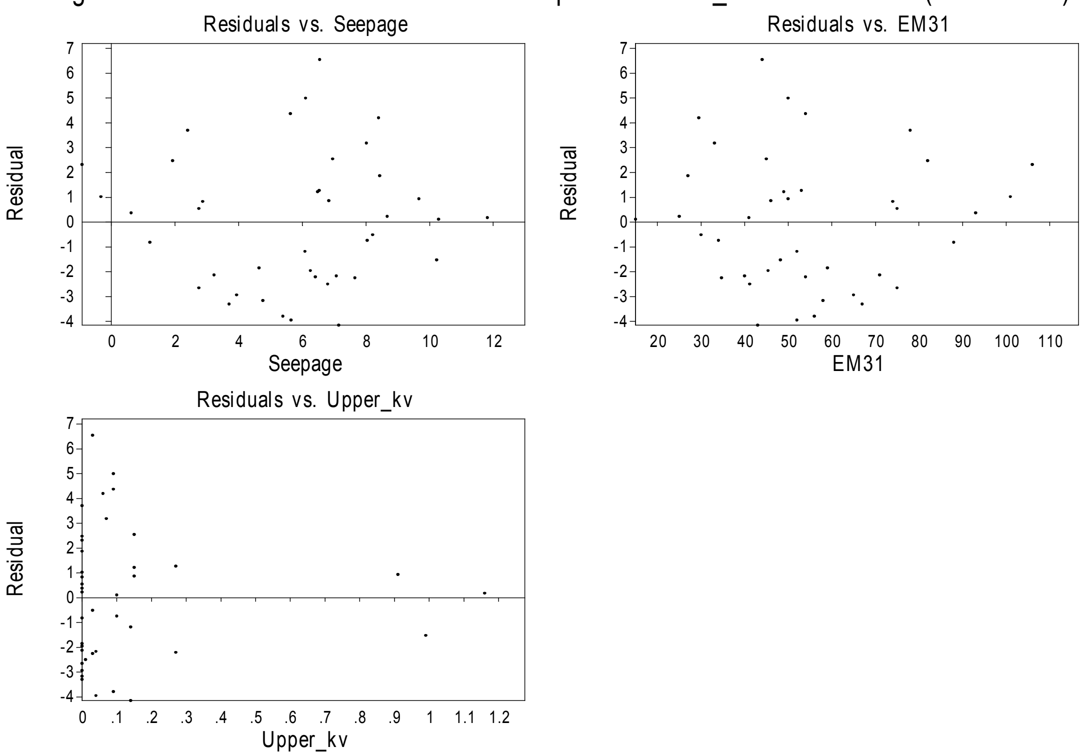
(All site but Finley, Lake View, Lake View West and Donald)

```
Dep Var: SEEPAGE   N: 40   Multiple R: 0.743   Squared multiple R: 0.552

Adjusted squared multiple R: 0.528   Standard error of estimate: 2.739 (0.48%
of mean)

Effect          Coefficient     Std Error      Std Coef Tolerance      t    P(2
Tail)

CONSTANT             11.623         1.294          0.000       .         8.985
0.000
EM31                 -0.118         0.021         -0.626      0.960    -5.573
0.000
UPPER_KV              4.352         1.666          0.294      0.960     2.613
0.013

                             Analysis of Variance

Source             Sum-of-Squares   df  Mean-Square     F-ratio       P

Regression              341.936      2      170.968      22.783       0.000
Residual                277.660     37        7.504
-------------------------------------------------------------------------------

*** WARNING ***
Case           32 has large leverage   (Leverage =        0.406)

Durbin-Watson D Statistic     1.450
First Order Autocorrelation   0.247
```

Plot of Residuals against Predicted Values



Regression on I:\WCMS\Wc01312\060-Reports\DAT00_01.10\Statistics (calibration)



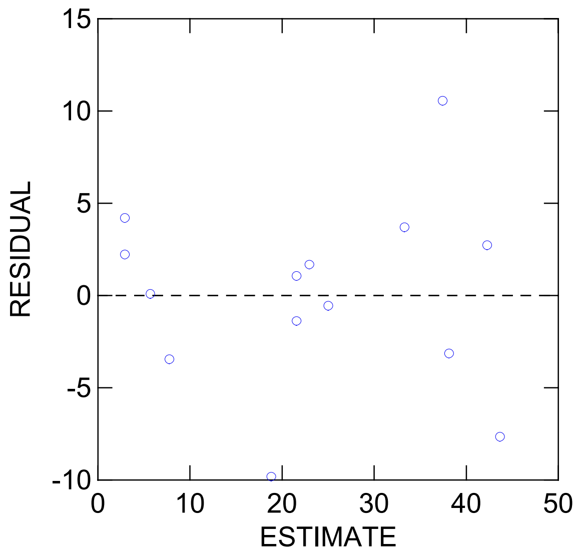
Note: Transformations of Upper_kv did not greatly improve the fit of the model and so were not followed any further.

Task 2 – Multiple Linear Regression With DTWT < 2m
(Lake View, Lake View West and Donald)

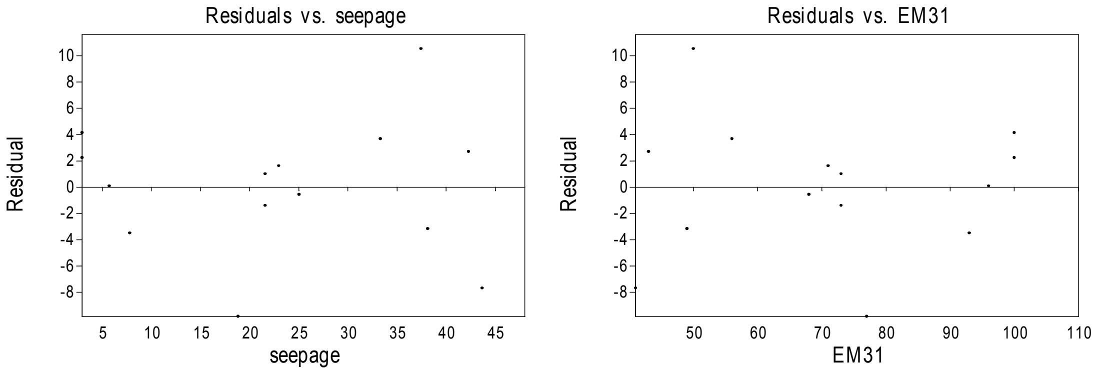
Note – no other variables were significant.

```
Dep Var: SEEPAGE   N: 14   Multiple R: 0.943   Squared multiple R: 0.889

Adjusted squared multiple R: 0.880   Standard error of estimate: 5.306 (0.23%
of mean)

Effect          Coefficient    Std Error     Std Coef Tolerance     t   P(2
Tail)

CONSTANT             71.961        5.178        0.000        .       13.897
0.000
EM31                 -0.690        0.070       -0.943      1.000     -9.797
0.000

                            Analysis of Variance

Source            Sum-of-Squares   df  Mean-Square     F-ratio       P

Regression             2702.405     1     2702.405      95.978       0.000
Residual                337.879    12       28.157
-------------------------------------------------------------------------------

*** WARNING ***
Case            5 is an outlier       (Studentized Residual =       2.626)

Durbin-Watson D Statistic     2.746
First Order Autocorrelation  -0.384
```

Plot of Residuals against Predicted Values



Regression on temp.sdy (calibration)

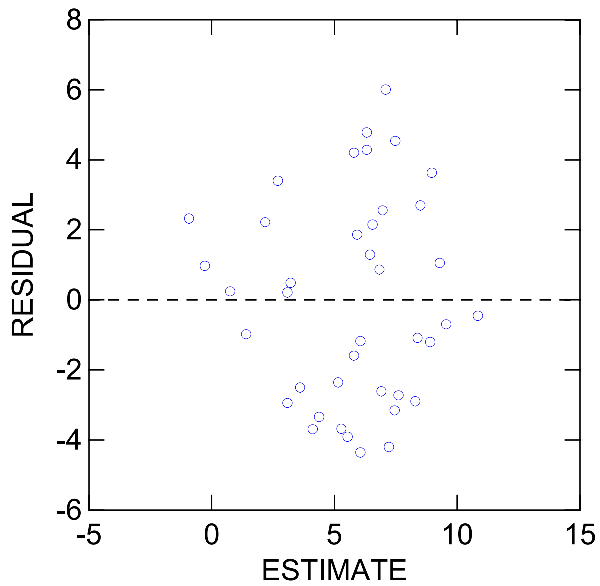


Note: No transformations required.

Task 3 –Regression of only EM31 With DTWT 5-10m

```
Dep Var: SEEPAGE    N: 40    Multiple R: 0.685    Squared multiple R: 0.469

Adjusted squared multiple R: 0.455    Standard error of estimate: 2.942 (51% of
mean)

Effect           Coefficient     Std Error      Std Coef Tolerance      t    P(2
Tail)

CONSTANT              12.788         1.304         0.000        .        9.807
0.000
EM31                  -0.129          0.022        -0.685      1.000    -5.796
0.000

                             Analysis of Variance

Source             Sum-of-Squares   df  Mean-Square     F-ratio       P

Regression              290.708     1      290.708      33.589       0.000
Residual                328.888    38        8.655
-------------------------------------------------------------------------------


Durbin-Watson D Statistic     1.348
First Order Autocorrelation   0.303
```

Plot of Residuals against Predicted Values



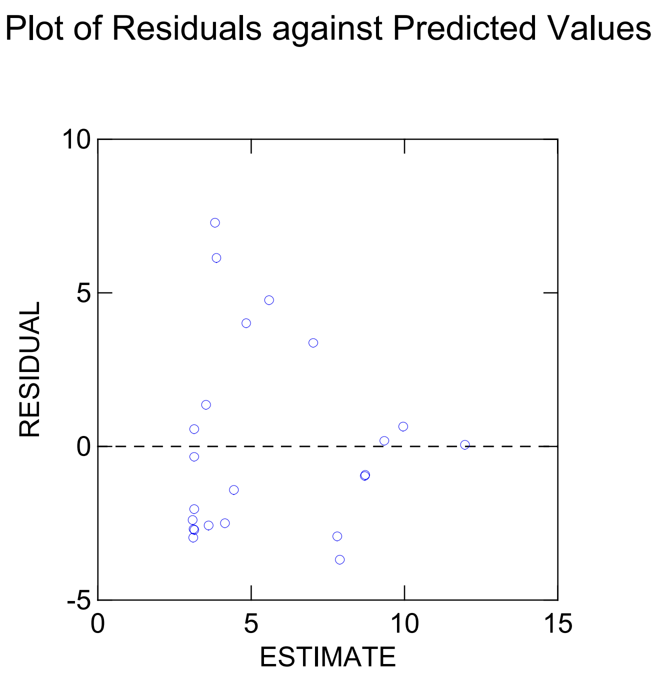
Task 4 –Prediction bands for equations with only EM31
Work saved in other excel spreadsheets.

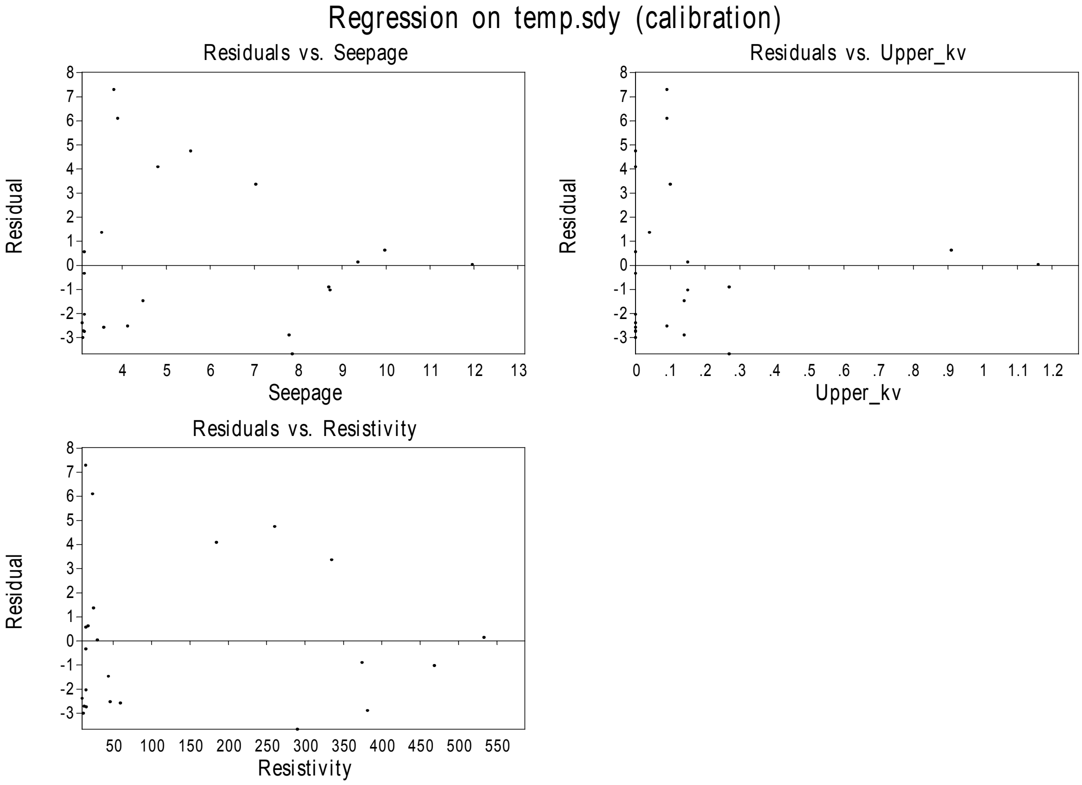
Task 5 – Multiple Linear Regression with Resistivity at 10m
All sites were used initially and Resistivity was not found to be significant, only DTWT. Therefore used the two groups used to predict with EM31.

DTWT 5-10m

```
17 case(s) deleted due to missing data.

Dep Var: SEEPAGE    N: 23    Multiple R: 0.660    Squared multiple R: 0.435

Adjusted squared multiple R: 0.379    Standard error of estimate: 3.284 (61% of
mean)

Effect            Coefficient     Std Error      Std Coef Tolerance       t    P(2
Tail)

CONSTANT                3.004          0.964          0.000        .         3.117
0.005
UPPER_KV                7.460          2.394          0.524       1.000      3.116
0.005
RESISTIVITY             0.010          0.004          0.408       1.000      2.430
0.025

                             Analysis of Variance

Source              Sum-of-Squares   df   Mean-Square     F-ratio       P

Regression                166.164     2        83.082       7.705       0.003
```

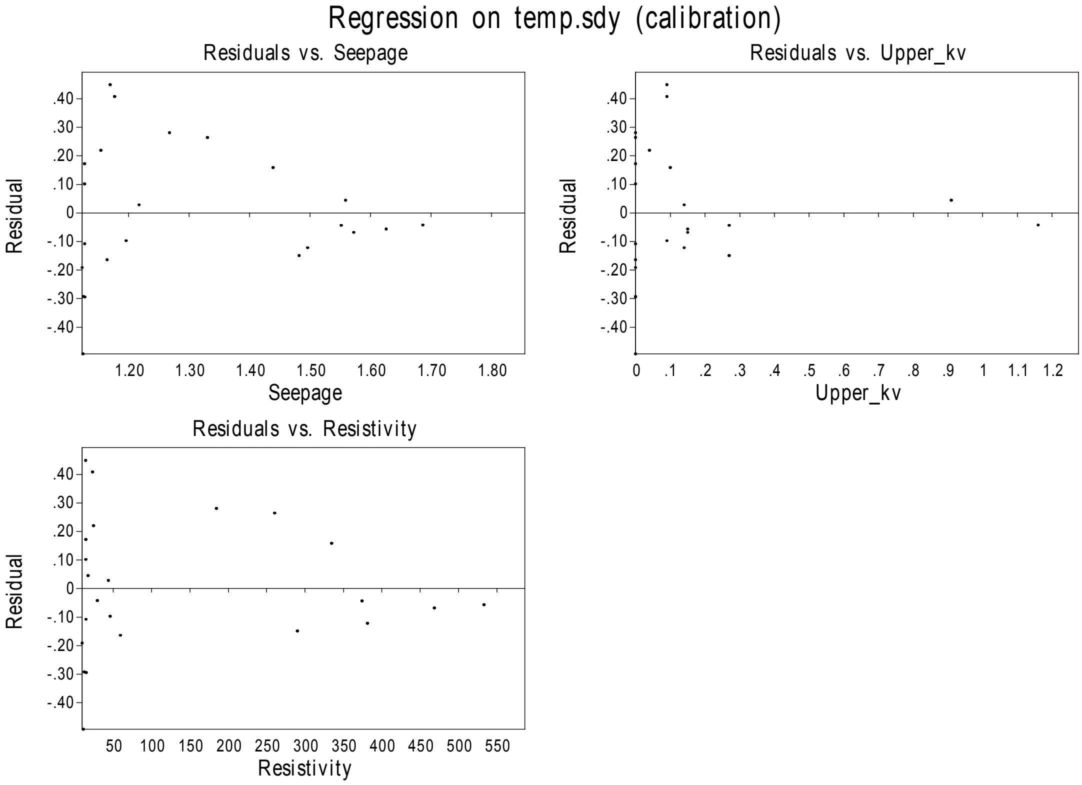
```
Residual                  215.646    20       10.782
-------------------------------------------------------------------------------

*** WARNING ***
Case           32 has large leverage   (Leverage =        0.597)

Durbin-Watson D Statistic     1.626
First Order Autocorrelation   0.170
```





Looked at transforms. Raised Seepage to the power of 0.2 and greatly improved the standard error. The new results are provided below:

```
REGRESSION MODEL RESULTS
~~~~~~~~~~~~~~~~~~~~~~~~

Dependent var: Seepage       N:     23    Mult. R:   0.647    Mult. R^2:
0.419
                                        Std error est.:   0.243 (19% of
mean)

Variable          Power      Coefficient       Std  Error          t-Stat
Prob(t)
Depndnt Var  0.2000
Constant       1.0000           1.1152           0.0714      15.62916
0.00000
Upper_kv       1.0000           0.4716           0.1776       2.65607
0.01516
Resistivity   1.0000       0.8250E-03          0.0003       2.75541
0.01220

                       Analysis of Variance
Source        Sum-of-Squares     df    Mean-Square     F-ratio

Regression             0.854      2          0.427       7.217
Residual               1.183     20          0.059
Total                  2.037     22
```



DTWT < 2m

(Only resistivity used because once any other variable was added it was no longer significant).

6 case(s) deleted due to missing data.

Dep Var: SEEPAGE   N: 8   Multiple R: 0.787   Squared multiple R: 0.619

Adjusted squared multiple R: 0.556   Standard error of estimate: 6.277 (27% of mean)

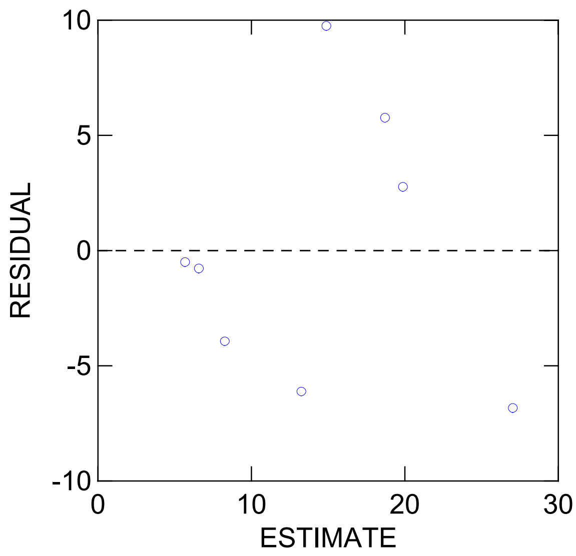
Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.662	5.278	0.000	.	-0.125	0.904
RESISTIVITY	1.714	0.549	0.787	1.000	3.124	0.020

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Regression	384.634	1	384.634	9.761	0.020
Residual	236.436	6	39.406		

Durbin-Watson D Statistic   1.045
First Order Autocorrelation   0.328

Plot of Residuals against Predicted Values

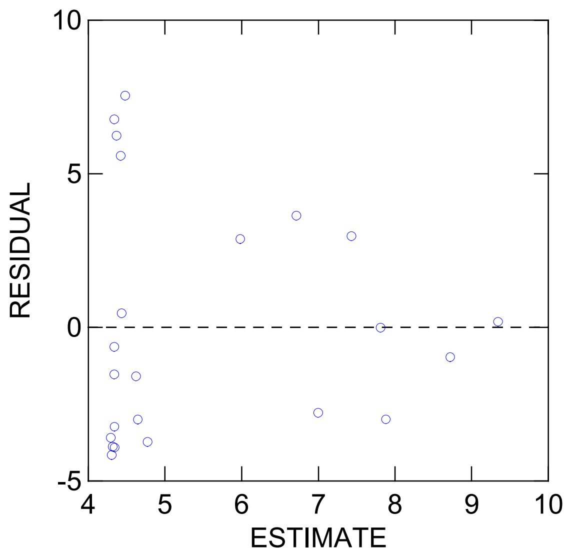


Looked at transforms but not enough data to see any trends.

Task 6 –Regression with only Resistivity at 10m for DTWT 5-10m

```
17 case(s) deleted due to missing data.

Dep Var: SEEPAGE    N: 23    Multiple R: 0.401    Squared multiple R: 0.161

Adjusted squared multiple R: 0.121   Standard error of estimate: 3.906 (68% of
mean)

Effect            Coefficient      Std Error      Std Coef Tolerance      t    P(2
Tail)

CONSTANT                 4.201          1.051          0.000        .         3.996
0.001
RESISTIVITY              0.010          0.005          0.401       1.000      2.007
0.058

                             Analysis of Variance

Source              Sum-of-Squares   df  Mean-Square     F-ratio       P

Regression                61.452      1       61.452       4.028       0.058
Residual                 320.357     21       15.255
-------------------------------------------------------------------------------


Durbin-Watson D Statistic     1.408
First Order Autocorrelation   0.274
```

Plot of Residuals against Predicted Values



I looked at transforms and found that raising seepage to the power of 0.2 greatly improved the model. The results are below:

```
REGRESSION MODEL RESULTS
~~~~~~~~~~~~~~~~~~~~~~~~

Dependent var: Seepage       N:     23    Mult. R:   0.463    Mult. R^2:
0.214
                                                     Std    error    est.:
0.276

Variable         Power       Coefficient        Std  Error          t-Stat
Prob(t)
Depndnt Var   0.2000
Constant       1.0000             1.1906             0.0743      16.02543
0.00000
Resistivity   1.0000        0.8133E-03             0.0003        2.39344
0.02611

                       Analysis of Variance
Source        Sum-of-Squares      df     Mean-Square      F-ratio

Regression             0.436       1           0.436       5.729
Residual               1.600      21           0.076
Total                  2.037      22
```

Regression on temp.sdy (calibration)