Project I10004

Open Channel Seepage & Control

Vol. 1.5 - Channel Seepage Identification & Measurement

Final Report

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Contents

Abbreviations

ANCID - Australian National Committee on Irrigation and Drainage

DPIE - Department of Primary Industries and Energy

EM - Electromagnetic

G-MW - Goulburn-Murray Water

LWA - Land and Water Australia

MDBC - Murray Darling Basin Commission

MI - Murrumbidgee Irrigation

MIL - Murray Irrigation Limited

RWA - Rural Water Authority

SI & E - Strategic Investigation and Education

SKM - Sinclair Knight Merz

SRW - Southern Rural Water

WWC - Waranga Western Channel

WMW - Wimmera Mallee Water

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.

This document presents a summary of the research and investigations into the knowledge and application of improved channel seepage measurement techniques (*Stage 1*). This report has been prepared to summarise all work undertaken, to highlight the successes against the originally conceived objectives and to present the key outcomes which are expected to be of benefit to the whole water industry, both across Australia and internationally.

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. In addition, the majority of the technical work associated with this project was undertaken by staff at Sinclair Knight Merz in Melbourne and their efforts and assistance are also gratefully appreciated and acknowledged. Without this valued support and interest, the project and this report would not have been possible.

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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 control.

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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).

This document presents a summary of the research and investigations into the knowledge and application of improved channel seepage measurement techniques (Stage 1). This report has been prepared to summarise all work undertaken, to highlight the successes against the originally conceived objectives and to present the key outcomes which are expected to be of benefit to the whole water industry, both across Australia and internationally.

Stage 1 of a suite of three ANCID channel seepage projects was focussed on development of best practice guidelines for identifying and quantifying channel seepage. Development of the guidelines required the undertaking of a number of tasks. The first two activities provided a platform for the entire project, and involved undertaking a national and international literature review on channel seepage measurement and a national survey of Rural Water Authorities (RWAs) to gather information on existing channel seepage assessment processes. Following these preliminary tasks, three years of field trials were undertaken in four RWAs, trialing various techniques identified in the literature review as well as some less developed approaches to seepage measurement. The results of these trials, including an understanding of the accuracy of each technique, were thoroughly documented. Based on the results of the literature review, the national survey and three years of trials, the Guidelines on techniques for quantifying channel seepage were prepared. A workshop was conducted to discuss and allow feedback on the draft Guidelines prior to them being finalised.

The Stage 1 project also involved one task which was not directly related to the development of the Guidelines. This involved the development of a standard set of terminologies and units related to the topic of channel seepage. These were incorporated into a second edition of the ANCID *Rural Water Industry Terminology and Units* booklet.

E.2 Literature Review

The Literature Review is a comprehensive summary and evaluation of all available techniques for measuring and identifying channel seepage. In the report on the review, each of these techniques is discussed in terms of theory, methodology, advantages and disadvantages of each technique. It was based on approximately 40 primary and 50 secondary references from Australia and overseas. The literature review forms a very valuable reference tool for anyone undertaking channel seepage assessment.

Only in respect to geophysics did the trials significantly advance knowledge and practical understanding beyond that identified in the literature review. Therefore, the *Documentation of Seepage Measurement Trials* report (*ANCID, 2003*) and *Best Practice Guidelines for Channel Seepage Identification and Measurement* (*ANCID, 2003*) should be used in conjunction with the Literature Review to obtain a complete and up to date assessment of the theory and application of geophysical techniques for channel seepage assessment. The literature review was used as the starting point for selecting techniques for the trials. It was also used extensively in development of the Guidelines.

E.3 RWA Survey

In order to provide a point of reference of current RWA practice with respect to seepage assessment and assist in setting the direction of the trial program, a national survey of 41 different RWAs or Irrigation Districts / Areas across Australia was undertaken. The survey was designed to compile information on :

- Total water supplied by each RWA;
- An estimate of seepage losses in the channel distribution systems, and total system losses, *ie*, unaccounted for water;
- Effect of seepage losses (monetary loss of water and land degradation);
- Importance of channel seepage issues to the RWA;
- Accuracy of (*ie*, confidence in) seepage estimates;
- Criteria by which the Authority selects a seepage measurement technique;
- Estimate of money spent addressing channel seepage issues; and,
- Seepage measurements techniques (techniques used, perceived accuracy, cost and satisfaction with outcome).

Estimates were provided by RWAs of unaccounted water losses (average of 17.5%) and on average they estimated that 4% was lost through seepage. The discrepancy between unaccounted for water and seepage loss estimates suggests that actual seepage may be higher than the 4% estimated. The survey appeared to indicate a divide in priority between RWAs with respect to the importance of channel seepage issues, with over 40% of authorities rating channel seepage as a high or very high priority, yet by contrast 50% of authorities had undertaken no on ground seepage measurement works.

An increase in the amount of seepage assessment did not result in clear gains in understanding of seepage rates, suggesting that inappropriate methods are being used for channel seepage measurement. The survey indicated that channel seepage remediation projects are often undertaken without quantitative seepage assessment. Qualitative techniques are the main means by which seepage sites are targeted for remediation. These are less than ideal approaches to selecting remediation sites and are unlikely to provide the best return for funds expended.

A key outcome of the survey was identification of the importance of cost and speed to RWAs in channel seepage assessment, with technical accuracy considered of lesser importance. This shaped the trial program and development of the Guidelines. The survey indicated that there was strong demand for seepage measurement guidelines, with the majority of authorities believing that there is insufficient information and/or expertise on techniques for seepage identification and measurement.

E.4 Trial Program

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* 1-2 km).
- 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.

The following concluding remarks are made regarding each of the trialed techniques:

Pondage Tests: 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 conducted across all sites (totalling 81 ponds) returned seepage rates ranging from 0.1 mm/d to 48 mm/d. 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.

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 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.

Point Tests: 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).

Groundwater Techniques: 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.

Remote Sensing: Remote sensing techniques:
1. Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage;
2. Will be most useful where lateral seepage is predominant;
3. Should primarily be regarded as a seepage identification tool and not for seepage quantification;
4. Require a suitable spatial resolution to allow definition of seepage zones (< 10m suggested);
5. Are best conducted in the infra-red range of the electromagnetic spectrum; and,
6. Are generally best collected during late summer and early autumn.

Geophysical Techniques - These trials have demonstrated that geophysical techniques offer the best solution for rapid identification and measurement of channel seepage. They are well suited to use at an RWA level, in that they are fast and relatively cost effective, and when calibrated against direct measurement techniques, can provide a reasonably accurate quantitative assessment of seepage rates.

Understanding of the application of geophysics to identify and measure channel seepage has been significantly advanced through these trials. In particular, progression in the following areas has been achieved:
- Understanding of the mechanisms by which geophysical techniques detect seepage. In particular the distinction between directly measuring seepage as it impacts the watertable and indirect measurement of unsaturated zone soil properties. This important distinction is not made in previous literature relating to geophysics and channel seepage.
- Identification of the best types of geophysical techniques for channel seepage assessment for different environments (with depth to watertable being the key variable influencing selection).
- Improved understanding of the key variables which impact on geophysical surveys.
- Identification of the best time to conduct surveys in terms of channel operation, most appropriate offset distance for surveys, and the suitability and accuracy of on-channel surveys compared to on-land surveys.
- Improved understanding of the repeatability of geophysical surveys.
- Understanding of the degree of accuracy that can be achieved using geophysics for quantifying channel seepage, and statistical assessment of this accuracy both at a local level and using a combination of the results to undertake a regional assessment encompassing a range of site conditions.

The most practical and useful output arising from the Stage 1 trials is a preferred methodology for using geophysics for identifying and measuring channel seepage. This is based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. This preferred methodology also includes a table to assist in selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

This preferred methodology is very similar in approach to recent international channel seepage research (*Hotchkiss et al, 2001*). This paper also describes the development of geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the geophysical response and measured seepage and then extrapolation to new areas. This independent and simultaneously conducted research confirms that geophysics is emerging as a widely regarded technique that is one of the best ways forward in terms of rapid and relatively cost effective identification and measurement of channel seepage.

Another key outcome arising from this work is the potential of on-channel resistivity for rapid seepage assessment. Surveys were conducted in the final year of trials at eight sites, and the results showed significant promise, with good correlations against pondage tests observed at most sites. The main advantage of on-channel resistivity over traditional electromagnetic techniques is that data is gathered at multiple depths beneath the channel, which enables a depth profile of conductivity beneath the channel to be developed. Not only does this have significant advantages in terms of output presentation and visualisation of seepage mechanisms, but importantly it means that the critical depth immediately above and below the watertable can be targeted. In contrast fixed array surveys, even when they are selected appropriately according to the watertable depth, provide a cumulative response from the surface depth interval and are less discriminatory in their measurement, allowing potentially greater error. Costs of resistivity are at present higher than EM surveys but are expected to decrease if this technique becomes more widely used (at present there are no commercial operators of this equipment on the market). More resistivity trials are needed to increase the existing data set upon which conclusions are based. One specific area requiring investigation is the issue of near surface resolution of the equipment, which affects accuracy in shallow watertable environments. It is anticipated that this could easily be resolved by varying the array spacing (from linear to exponential, with more closely spaced arrays near the boat).

One cautionary note is warranted regarding the use of geophysics for channel seepage assessment. The geophysical survey should be carried out by a suitably qualified contractor and the geophysical results should be interpreted with sufficient bore hole data, proper calibration against a direct seepage measurement techniques, should be interpreted by someone with relevant geophysical experience and if the results are to be used quantitatively, the seepage-geophysical relationship derived should be subject to proper statistical analysis, in order to determine the degree of confidence in the prediction equation.

E.5 Channel Seepage Guidelines

The Guidelines for channel seepage measurement have been successfully completed, including industry review through a workshop process. The Guidelines are a significant step forward in management of channel seepage issues. They provide RWAs with best practice procedures for identifying and quantifying channel seepage. They fill a gap in understanding in channel seepage assessment clearly identified in the national RWA survey (*ANCID, 2000b*). Through a circular six step process, the Guidelines enable users to make a serious evaluation of suitable procedures which meet individual needs and objectives. The most significant aspect of the Guidelines is their recommendation that, (for intermediate to large scale investigations), geophysical techniques offer the best solution for rapid identification and measurement of channel seepage for RWA purposes. They are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates. A preferred methodology for using geophysics for identifying and measuring channel seepage is outlined in the Guidelines, based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. The Guidelines also provide information on selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

The preferred methodology based on geophysical assessment outlined in the Guidelines offers the potential for significant efficiency gains in channel seepage management. The procedure provides a basis for highly targeted channel seepage remediation initiatives, which have the potential to greatly improve the economics of remediation projects. These water savings will minimise the loss of a resource of which the real economic value is being increasingly realised, reduce contributions to groundwater recharge and associated land salinisation, and increase the available water which could be returned to the environment.

E.6 Terminology and Units Booklet

The *Second Edition* of the ANCID "*Rural Water Industry Terminology and Units*" booklet was updated with terms and units used in channel seepage, as well as other minor changes. It was completed and available in April, 2001 and formally released at the 2000 ANCID Annual Conference held in Toowoomba, Queensland. The document can be accessed and down loaded from the ANCID web site (*www.ancid.org.au*) and from the CD included at the back of this document. The booklet will continue to provide a valuable reference document to help to ensure common terminology and units are used in the Australian rural water industry.

E.7 Recommendations

It is recommended that, for most investigations, RWAs should adopt the preferred technique as outlined in the conclusions of the *Documentation of Seepage Measurement Trials* report (*ANCID, 2003a*) and the *Best Practice Guidelines for Channel Seepage Identification and Measurement* (*ANCID, 2003b*). This methodology relies on geophysics to identify seepage, and pondage tests and soil bores to calibrate and interpret the geophysical response. Although the Stage 1 project has resulted in this recommended assessment methodology, this does not mean that further research is not required in the area of geophysics. Key recommendations arising from the Stage 1 project are listed below:

- *Development of a national database*. It is 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.
- *Establishment of geophysics seepage relationship.* 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.
- *Cheaper and more convenient way of calibrating geophysical surveys.* The main deterrent to RWAs from widespread adoption of geophysics is the operational inconvenience and expense of the pondage tests required to calibrate the geophysical survey. A means of calibrating geophysical surveys where pondage tests are extremely difficult or cannot be conducted needs to be explored. A cheaper means of bank construction (possibly using some type of transportable barrier such as appropriately designed sheet piling) would greatly reduce the cost of pondage tests, as these represent a significant part of the costs.
- *Further testing of on-channel fixed array surveys*. Further testing of the relative merits of on-channel fixed array surveys compared to adjacent channel fixed array surveys are required.
- *Remote sensing trials*. Remote sensing trials 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.
- *Dissemination of results*. The key remaining part of Stage 1 is to ensure that the information in the Guidelines is properly disseminated and marketed to RWAs.

1 Introduction

This document presents a summary of the research and investigations into the knowledge and application of improved channel seepage measurement techniques. The project has received significant funding from the Murray Darling Basin Commission (MDBC) and this report has been prepared to summarise all work undertaken, to highlight the successes against the originally conceived objectives and to present the key outcomes which are expected to be of benefit to the whole water industry, both across Australia and internationally.

All investigations and reports associated with this project have been developed to assist water supply managers, operations and maintenance staff and technical consultants to provide the most appropriate and cost effective method to identify and measure channel seepage. As such this summary report should be an extremely valuable reference document.

1.1 Acknowledgments

This project would not have been possible without the interest and generous investment of the MDBC through its Strategic Investigation and Education (SI & E) program and additional significant investment by the following organisations:

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

There has also been wide industry interest in this study and significant input has been provided by a wide and diversified range of people and this interest and input is very much appreciated.

1.2 Background

As the driest inhabited country in the world, Australia is dependent on its water resources. Development of Australia was viable through the development of vast networks of water supply infrastructure to service irrigation and stock and domestic needs. 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). Preliminary estimates indicate that, for Queensland, New South Wales and Victoria, this loss could amount to close to 300 GL/annum.

Seepage from earthen channels has therefore become an important issue in Australia for several reasons:

- The loss of an economically valuable resource;
- Management of channel assets,
- The contribution to groundwater recharge, associated induced water logging and land salinisation which affects the environmental and community amenity, and
- The need to retain more water within our waterways to halt environmental decline.

With strategic issues such as the Murray Darling Basin Cap, and the need to return water to the environment, the water industry is, more than ever before, faced with challenges in managing the available water resources in a sustainable way.

In response to concerns over the lack of information available on seepage from earthen 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 MDBC, Land and Water Australia (LWA), the Commonwealth Department of Primary Industries and Energy (DPIE) and 16 other industry organisations. The workshop brought together 90 stakeholders and experts in the field of channel seepage from throughout Australia. It was organised to address concerns raised by the water industry over the lack of technical information and standards for dealing with channel seepage.

The workshop recognised the urgent need to produce best practice standards and guidelines to assist the water industry in dealing with water distribution system efficiency issues as related to seeping channels.

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.

Workshop recommendations seen as necessary to support the rural water industry were to:

- Establish an industry Task Force to co-ordinate channel seepage investigation and remedial action;
- Develop standard terms and methodologies related to channel seepage;
- Refine the science of channel seepage assessment and reduction;
- Develop standard guidelines to assist with channel seepage measurement, impact assessment and remedial works;
- Develop a decision support system; and
- Develop a rapid method of assessing zones of high seepage in various geological profiles.

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

Each stage of the total project is briefly described as follows (noting that Stages 2 and 3 are still in progress at the time of preparing this report):

Stage 1 - This project was to 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 been completed and Stages 2 and 3 are scheduled for completion in December, 2003. This report focuses on Stage 1, "*Development of Guidelines for the Quantification and Monitoring of Seepage from Earthen Channels*".

1.3 Objectives

The following are the specific objectives developed for Stage 1 looking into improving the understanding and science of channel seepage:

- *Undertake and document national and international literature reviews on channel seepage measurement;*

- *Supplement the information gathered at the October 1998 ANCID Channel Seepage Workshop held at Moama, undertake a survey of the key RWAs throughout Australia and gather documentation on:*

  - *i) methods used for selecting the appropriate seepage measurement techniques at each site;*
  - *ii) setting up and undertaking seepage measurement trials; and*
  - *iii) evaluating the results of those trials.*

- *Develop a standard set of terminologies and units related to the whole topic of channel seepage and have these incorporated into a second edition of the ANCID "Rural Water Industry Terminology and Units" booklet;*

- *Select techniques that will be trialed at a number of representative sites within Victoria and New South Wales to cover a range of soil types, water salinities and hydrogeological conditions. Techniques chosen are to include rapid and detailed assessment techniques;*

- *Undertake and document these trials including an understanding of the accuracy of each technique;*

- *Prepare and publish guidelines on the techniques for quantifying and monitoring the extent of channel seepage.*

- *Prepare and publish the second edition of the "Rural Water Industry Terminology and Units" booklet;*

- *Conduct a workshop to discuss the draft guidelines; and*

- *Distribute these guidelines and booklets to at least 50 stakeholders.*

1.4 Structure of this Report

The structure of the report is based around the above nine objectives. Each objective is discussed in terms of background, methodology, results, conclusions and where appropriate, recommendations. The detail of each objective is discussed, including a description of how the objective has been satisfied. A discussion section at the end of the report discusses in further detail what has been learned as a result of the project and the implications of this gained knowledge.

The Executive Summary for each of the report outputs from this project (Stage 1) are also included, and are attached as Appendices to this report.

2 Objective 1 – Channel Seepage Literature Review

Prepare a literature review on channel seepage measurement

2.1 Background

The first step in a project of this nature was to ensure that the project was built upon the existing body of knowledge of channel seepage measurement, and that no 're-inventing of the wheel' was undertaken. To this end a comprehensive national and international literature review of earthen channel seepage measurement and identification techniques was undertaken.

2.2 Methods

The literature review was based on approximately 40 primary and 50 secondary references from Australia and overseas. Most of the techniques discussed represent a summary of the available literature, however some parts, including aspects of the geophysical survey, hydrochemical and isotopic sections, also include direct contributions from experts in these fields. Some of the ideas expressed therefore may not have been specifically trialed for channel seepage applications, but represent techniques with potential for channel seepage measurement.

2.3 Results

The range of methods identified in the review were subdivided into the following ten categories:

- Inflow-Outflow Measurement;
- Pondage Tests;
- Point Measurement (channel empty and channel full);
- Mathematical Modelling
- Soil Classification;
- Groundwater Techniques;
- Geophysical Techniques;
- Remote sensing
- Hydrochemcical / Isotopic Mass Balance; and,
- Tracers and Isotopes.

Each of these techniques are discussed in terms of theory, methodology, advantages and disadvantages. Key references for each technique are provided at the end of each section. Each technique was also assessed in terms of its application as either a:

- Primary technique (*ie*, direct) for the quantification of channel seepage;
- Primary means of identifying (qualitative) areas where channel seepage occurs;
- Technique which provides a means of estimating channel seepage through a relationship with one other technique; or,
- Technique which provides a means of estimating channel seepage through a relationship with two or more other techniques.

The conclusion of the report presents a summary of all techniques in tabular form and discusses the factors that need to be considered in selection of a particular technique, including the purpose of the survey, technical constraints, cost and required accuracy of the investigation. Also discussed in the report is the important topic of extrapolation of seepage measurement results.

The list below is extracted from the final column of the main summary table in the literature review. It provides a concise summary of the applicability of each technique for channel seepage measurement:

- **Inflow-Outflow** - Best suited to long sections of channel which contain appreciable seepage, from which there are no diversions, and which contain suitable structures to incorporate measuring devices. When conducted properly, this method can be considered fundamentally the most direct, and potentially accurate method available.
- **Pondage Tests** - Widely considered the most accurate means of measuring channel seepage and generally regarded as the best technique against which other methods can be assessed. Main difficulty is that the test must be conducted outside of normal channel operation, and non-flow conditions introduce some inaccuracies.
- **Point Tests** - Point tests are best suited for determining the distribution of seepage losses (*ie*, relative seepage). Due to variable and sometimes erratic values obtained in measurements and the large number of tests required to sufficiently determine the average seepage rate, they are not considered reliable for absolute quantitative purposes. Often used in conjunction with soil surveys to assign a seepage rate to a particular soil type.
- **Theoretical Mathematical Modelling** - Theoretical mathematical models have been found to yield reliable estimates of channel seepage, when the required field data is collected. The technique is best suited for seepage prediction purposes, such as seasonal variation, variable operating conditions or changed groundwater conditions. Modelling of channel seepage may be useful in intensive site investigation studies.
- **Soil Classification** - The regional approach to estimating losses based on published seepage rate data for a given soil type is a useful method for providing a first cut estimate of seepage losses from a system. However accuracy is likely to be relatively low. A local approach involving an actual soil survey of the channel and an attempt to calibrate soil types based on point or pondage tests is likely to significantly improve the accuracy of this technique.
- **Groundwater Techniques** - The attraction of this method is that it provides a permanent seepage assessment tool, which amongst other things is useful for assessment of the effectiveness of remedial measures. The main shortfall of the method is that it is concentrated on a slice across the channel, which may not be representative of broader conditions. Installation of numerous transects to improve accuracy will be expensive. The method may not be appropriate where a significant percentage of the seepage does not reach the groundwater.
- **Geophysical Techniques** - Use of geophysics for channel seepage assessment is an emerging area. The attraction of these techniques is the potential for rapid assessment of long channel sections. However care needs to be taken in the interpretation of results. While there are several examples of geophysical techniques being used for detection of high seepage zones, references to use for quantification are scarce. However, provided results are locally calibrated, seepage quantification from geophysical techniques is possible.
- **Remote Sensing** - Remote sensing techniques offer considerable potential for rapid identification of seepage zones (but not quantification). Major drawback associated with this technique is that it assumes seepage will have a surface expression as moist soil adjacent the channel. Despite this disadvantage, it offers a promising means of providing a first-cut identification tool for targeting potential seepage sites. Assessment needs to be conducted at a suitably large scale if the technique is to be cost effective.

- Hydrochemical and Isotopic Techniques:
  - Mass Balance - The traditional hydrochemical / isotopic mass balance approach is unlikely to have significant application to channel seepage measurement due to relatively

short time of residence of water in the channel. Some potential for use of this method under PT conditions if seepage rates are low.
- Tracing the Seepage plume - Use of naturally occurring tracers may be valuable if information is obtained on the seepage plume over a sufficiently long time period, and an area large enough to account for spatial and temporal changes in seepage. CFC dating of g/water has the most potential, as this detects relatively recent seepage. Major disadvantage with artificially increased tracers is high cost of doping the water. Best use of enriched isotopes may be at a small scale and time intervals, to investigate spatial seepage rate variation.

The literature review contains a summary of the main texts reviewed for survey. A section of the report was used to describe the main factors influencing seepage rates in earthen irrigation channels, including soil characteristics, depth of water in and wetted perimeter of the channel, depth to groundwater and channel water characteristics.

2.4 Conclusions

The literature review is a comprehensive summary and evaluation of all available techniques for measuring and identifying channel seepage. It therefore forms a very valuable reference tool for anyone undertaking channel seepage assessment. Only in respect to geophysics did the trials *significantly* advance knowledge and practical understanding beyond that identified in the literature review. In other words, the Literature Review should be considered an up to date document for all techniques, *except* geophysical techniques, as the trials work undertaken in this project has progressed understanding of the use of geophysics for channel seepage identification and measurement. Therefore, the Documentation of Seepage Measurement Trials report (ANCID, 2003a) and Best Practice Guidelines for Channel Seepage Identification and Measurement (ANCID, 2003b) should be used in conjunction with the Literature Review to obtain a complete and up to date assessment of the theory and application of geophysical techniques for channel seepage assessment.

The literature review was used as the starting point for selecting techniques for the trials. It was also used extensively in development of the guidelines.

The literature review was successfully completed and is available for distribution. A number of CDs containing the review have already been distributed at various ANCID conferences and forums and to the participating funding agencies / organisations. The literature review can also be accessed and down-loaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document.

The Executive Summary of the Literature Review is contained in *Appendix A* of this report.

3 Objective 2

Survey the key Rural Water Authorities throughout Australia and gather documentation on current trials, methods and evaluation of seepage measurement trials

3.1 Background

A key aspect of developing national channel seepage guidelines was to determine the important channel seepage issues within RWAs across the country. In order to develop a meaningful strategy for assessing channel seepage, there was a need to know current RWA standing with respect to seepage measurement, and in fact whether seepage was (or was perceived to be) an important issue within the RWA. Therefore this task was conducted immediately after the literature review and prior to commencement of the trials.

3.2 Methods

Significant effort was expended in maximising the return rate of the surveys, including phone calls prior to and after issue of the survey, a variety of forms of media replying options, compilation of an easy to complete survey form and further follow-up phone calls to later respondents.

The survey was sent to 41 different RWAs or Irrigation Districts / Areas across Australia. The list of authorities was supplied by ANCID and is considered to be representative of rural water management authorities providing water for irrigation purposes across Australia.

The questions within the survey were designed to compile information on the following areas:

- Total water supplied by the RWA;
- An estimate of seepage losses in the channel distribution systems, and total system losses, *ie* unaccounted for water;
- Effect of seepage losses (monetary loss of water and land degradation);
- Importance of channel seepage issues to the RWA;
- Accuracy of (*ie*, confidence in) seepage estimates;
- Criteria by which the RWA selects a seepage measurement technique;
- Estimate of funds spent addressing channel seepage issues; and,
- Seepage measurements techniques (techniques used, perceived accuracy, cost and satisfaction with outcome).

Of the surveys forwarded to the RWAs, 90% were returned. The survey was not seen as applicable to 32% of the RWAs as channels did not form a significant part of their distribution network. As a result, of the 41 surveys sent out, 24 (58%) provided information on channel seepage from earthen channels. The majority of these were from the eastern States, reflecting the distribution of water resources within Australia.

3.3 Results

A summary of the results of the survey is presented below:

Water Supply, Size of Channel	☐ The majority of rural water RWAs surveyed supply less than 100 GL/yr.
Network and Seepage Rates	☐ On average, 17.5% of released water is lost through unaccounted for processes. ☐ On average 4% of total water supplied by all RWAs surveyed is estimated to be lost via seepage. ☐ An estimated 320 GL of water is lost each year from the RWAs who responded. ☐ The average length of earthen channel per GL of water supplied is 3.85 km. This result is skewed, however, by one RWA which has 54 km channel / GL supplied. When this result is removed the overall average drops to 1.45 km / GL water supplied.
Significance of Channel Seepage	☐ Two-thirds of all RWAs surveyed have a reasonable or higher confidence in their estimate of seepage. ☐ Of the RWAs surveyed, 42% rate channel seepage as a high or very high priority.
Channel Seepage Costs & Issues	☐ Measurement of channel seepage is most commonly considered the area where additional resources need to be applied. ☐ 25% of RWAs have undertaken assessment of seepage at 3 or more sites. ☐ 50% of RWAs have undertaken no on ground seepage measurement works at all. ☐ Extensive seepage investigations are generally only undertaken by water RWAs delivering greater than 160 GL/Yr. ☐ There is a weak correlation between increased investigation and higher confidence in channel seepage estimates. ☐ The priority given to channel seepage appears dependent mostly on the perceived cost of the impacts of channel seepage. ☐ Loss of water is considered the most significant cost consequence of channel seepage. ☐ It is estimated that 46% of RWAs do not know the extent of land degradation associated with channel seepage. A further 25% believe it to be less than 1 Ha. ☐ Of the RWAs surveyed, 16% indicated that they are spending more on channel seepage identification, measurement and remediation than the estimated cost of water lost and other impacts of seepage from the channel. ☐ The average expenditure on channel seepage identification, measurement and remediation is approximately 60% of the estimated cost of water lost and other impacts of seepage from the channel. ☐ Remediation works accounts for 61% of the monies spent on channel seepage, with monitoring and investigation contributing 35%.
Channel Seepage Measurement Techniques	☐ Cost and speed are considered the most important criteria in channel seepage assessment. ☐ Technical accuracy is considered of lesser importance. ☐ Seepage identification (visual, piezometers) rather than quantification techniques dominate channel seepage assessment methods.
Channel Seepage Remediation	☐ The majority of RWAs do less than 5 km of remediation works per year.
Demand for Guidelines	☐ The majority of RWAs believe that there is insufficient information and/or expertise on techniques for seepage identification and measurement. ☐ There is a strong demand for guidelines on channel seepage identification and measurement.

3.4 Conclusions

The RWA survey was successfully completed. A number of CDs containing the review have already been distributed at various ANCID conferences and forums. The Executive Summary of the survey is contained in *Appendix B* of this report.

A summary of some of the key conclusions from the survey were:

- Estimates of unaccounted water losses from RWAs were identified: average across RWAs of 17.5%, of which 4% was estimated to be lost via seepage. (Totalling 320 GL/yr).
- Over 40% of RWAs surveyed rated channel seepage as a high or very high priority.
- 50% of RWAs had undertaken no on ground seepage measurement works.
- An increase in the amount of seepage assessment did not result in clear gains in understanding of seepage rates and losses, suggesting a lack of success, and a lack of direction in channel seepage measurement. Either the techniques being employed, or the implementation of the techniques appears to be inappropriate. The fact that seepage identification techniques (visual and piezometers) rather than quantification techniques dominated channel seepage assessment suggested that inappropriate methods are largely being employed.
- Pondage tests are universally regarded as the most accurate method of assessing channel seepage, however only one quarter of RWAs (six) use pondage tests for seepage measurement.
- The loss of water was considered the most significant cost consequence of channel seepage, but almost 50% of RWAs did not know the extent of land degradation associated with channel seepage.
- Cost and speed were considered the most important criteria in channel seepage assessment, with technical accuracy considered of lesser importance.
- Ten RWAs indicated they had not conducted any on-ground seepage assessment works in the past decade, and yet five of these indicated they had reasonable or better confidence in their estimate of seepage. To be reasonably confident in a seepage estimates based only on system records suggests a certain degree of ignorance of channel seepage issues.
- Channel seepage remediation projects are often undertaken without quantitative analysis of seepage. Qualitative techniques (particularly visual inspection and piezometric surveys) are the main means by which seepage sites are targeted for remediation. These are less than ideal approaches to selecting remediation sites and are unlikely to provide the best return for dollars expended. This failure to clearly establish cost-benefit aspects of remediation contradicted RWA assertions that the value of water lost is the major motivator for channel seepage investigations.
- The survey indicated that there was strong demand for seepage measurement guidelines, with the majority of RWAs believing that there is insufficient information and/or expertise on techniques for seepage identification and measurement.

To assess the impact of the outcomes of the Stages 1 investigation, consideration should be given to conducting a similar survey in several years (*eg*, 2005).

4 Objective 3 – Updating of ANCID Terminology and Units Booklet

Develop a standard set of terminologies and units related to the whole topic of channel seepage and have these incorporated into a second edition of the ANCID "Rural Water Industry Terminology and Units" booklet

4.1 Background

The rural water industry in Australia embraces engineers, agriculturalists, educationalists, farmers, equipment manufacturers and suppliers, administrators and various other disciplines. A wide range of terminology is used to describe the processes required to deliver water to farms, remove surface and sub-surface drainage water and provide for plant growth. While some terms are self explanatory, or are commonly used within the water or agricultural industries worldwide, others have developed locally to describe particular features or procedures. In these instances the meaning of some terms may not be clear or may even be contrary to the understanding of persons from other regions. Some expressions, such as "irrigation efficiency", can have legitimate differences in meaning according to the particular context or component of the irrigation system being considered so that clear definition is necessary. The rapid growth and application of electronic technology in recent years has introduced many additional expressions from the information technology industry to describe equipment and processes

In 1997 ANCID Executive suggested that a document be produced that sets out preferred units of measurement and common definitions for various rural water industry infrastructure components and scientific processes in Australia.

ANCID subsequently researched and produced a guideline which is intended to be used for the preparation of technical papers, presentations, publications and correspondence for nationwide dissemination within Australia.

The document was originally prepared by consultants Hydro Environmental Pty Ltd and Sinclair Knight Merz (SKM). During the course of preparation of *Edition 2*, the draft document was referred to a number of persons and organisations including:

- Participants in a MDBC Irrigation Forum in March 1998, and
- The ANCID Executive which has representation in all States of Australia.

The guidelines therefore serve as a valuable reference of appropriate terminology to ensure consistency and equal levels of understanding in terms and units used in the rural water industry.

This objective arose out of a perceived deficiency in the guidelines where they were relatively silent in terms used for water supply efficiency and particularly channel seepage measurement and control. Given the channel seepage measurement project was likely to expose many of the terms used in this area of science and engineering, it was therefore considered appropriate to update the ANCID Guideline of Terminology and Units.

4.2 Methods

The methodology basically involved:

- Listing and obtaining definitions of new terms and units uncovered as part of the Literature Review of Channel Seepage Identification and Measurement (*Refer Objective 1*).
- Adding in new terminology and units, sorting and editing these into the original document entitled "*Rural Water Industry Terminology and Units*" and compiling as a "*Second Edition*".
- Releasing the updated version (*Edition 2*) to the water industry for comment. This was done by direct letter to each of the RWAs, having it available on the ANCID Web site and by advertisement and "invitation to comment" at the ANCID 2001 Annual Conference in Toowoomba, Queensland.

4.3 Results

The *Second Edition* of the ANCID "*Rural Water Industry Terminology and Units*" was updated with terms and units used in channel seepage. It was completed and available in April, 2001 but had a formal release at the 2001 ANCID Annual Conference held in Toowoomba, Queensland.

The document can be accessed and downloaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document. In all, 500 hard copies were printed and many have already been forwarded to water authorities and other interested organisations and individuals. Hard copies are still available from ANCID as follows:

The Secretary,
ANCID
C/o Goulburn-Murray Water
PO Box 165
TATURA, VICTORIA, AUSTRALIA, 3616

4.4 Conclusions

As in the first release of the document valuable inputs were sought and received through a number of sources throughout the rural water industry and comments were incorporated into the document where appropriate. The resulting updated guidelines have therefore been reviewed by the Australian water industry.

The guidelines will continue to provide a valuable reference document to help to ensure common terminology and units are used in the Australian rural water industry.

5 Objective 4 – Selection of Techniques and Sites

Select techniques that will be trialed at a number of representative sites within Victoria and New South Wales to cover a range of soil types, water salinities and hydrogeological conditions.

5.1 Background

A key component of the study was to consult with the project partners (Wimmera Mallee Water, Murray Irrigation and Murrumbidgee Irrigation) to select the sites and techniques which would be used in the trials. This was a task that had to be undertaken before the trials could commence (*Objective 5*).

5.2 Methods

Site Selection

Early in the trials program considerable attention was given 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 on 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.

The sites represented areas where Authorities had previously experienced channel seepage problems, and overall, consideration was given to ensure a range of soil types, geological and hydrogeological conditions were represented by the sites.

Technique Selection

The most important criteria for selecting techniques suitable for channel seepage measurement and identification are cost and accuracy. From the Rural Water Authority (RWA) survey (ANCID, 2000b) it was observed that RWAs rank cost as the most significant factor in selecting seepage investigation techniques, with technical accuracy of lesser importance. 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 required 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 electromagnetic 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 seepage in either a more cost effective or accurate way than pondage tests, and,
(b) identification of seepage in a more accurate or cost effective way than visual inspection.

In all cases there is a trade off between cost and accuracy.

5.3 Results

Site Selection

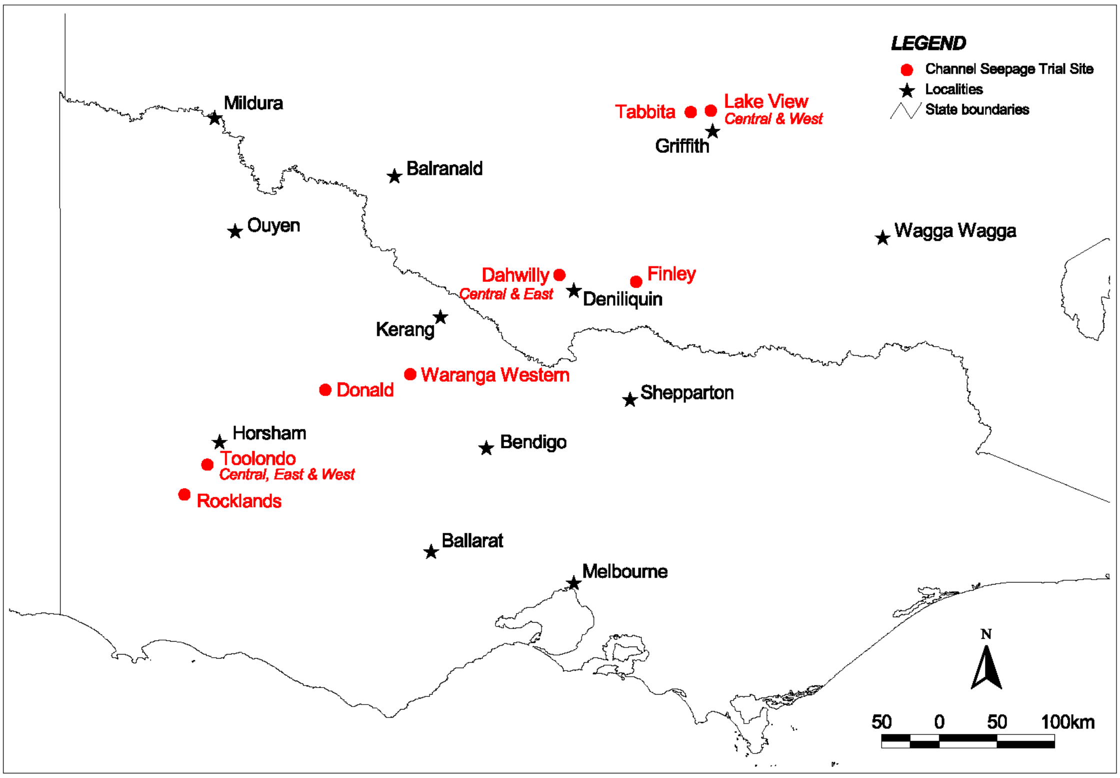
Based on the site visits, three sites were selected in each Authority to trial a range of channel seepage techniques:

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

Subsequently, MIL 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 was also deleted from the program due to the size of the channel and associated cost of conducting pondage tests (however an EM31 survey was conducted at this site). MI also removed Mirrool Creek branch canal from its trials program, choosing to devote more resources into assessing the two remaining channels.

Figure 5-1 presents the location of the channel seepage measurement trial sites. All of the sites lie within the Murray Basin. With the exception of the Rocklands and Toolondo channels, which traverse the flanks of the Grampians ranges in the Southern Wimmera, 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).

■ Figure 5-1 Trial Site Regional Location Map



Technique Selection
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 following techniques:

- Pondage Tests
- Point measurement (channel full and empty)
- Geophysical Techniques
- Groundwater Techniques
- Soil Classification
- Remote Sensing

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 identification and measurement. The technique selected was geophysics.

5.4 Conclusions

In consultation with the partnering RWAs, trial sites were selected which covered a range of physical conditions. The techniques were selected based on the literature review, the RWA survey and the primary objectives of the study. In the final year of the project the focus was solely on geophysics.

Further detail on the selection of the techniques and trial sites is included in the *Documentation of Seepage Measurement Trials* (ANCID, 2003) report which is completed and available for distribution. The *Documentation of Seepage Measurement Trials* report can also be accessed and down-loaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document.

The Executive Summary of the *Documentation of Seepage Measurement Trials* (ANCID, 2003) report is contained in **Appendix B** of this report.

6 Objective 5 – Trial Program

Undertake and document these trials including an understanding of the accuracy of each technique

6.1 Background

The seepage measurement trials formed the major part of the project. The purpose of the trials was to determine the most appropriate technique (considering accuracy, cost and ease of interpretation) for identifying and measuring channel seepage in a range of different environments. The primary aim of the trials was to provide information which could contribute to development of the guidelines.

6.2 Methods

A trial program (based on the techniques selected – refer *Objective 3*), within each RWA was devised at the beginning of each year, in consultation with that Authority. Each year of the three year program was built upon the previous year. This culminated in the third and final year of trials focussing purely on one technique, geophysics. The consultant partnered with the RWAs to:

- Identify the appropriate technique at a particular site;
- Prepare work specifications to be completed by the RWAs (or their contractors);
- Provide technical advice as required during the running of the trials; and,
- Analyse trial data and document results.

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. The method by which the pondage test was 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 were the baseline means of assessment in this study. Therefore where terms such as 'accurate' or 'successful / unsuccessful' are used to describe a technique, this refers to comparison with pondage test data, which were assumed to be sufficiently accurate for the purposes of this investigation.

Table 6-1 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. 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 to enable comment to be made on the usefulness of this technique. Channels which were initially included in the program, but removed for various reasons, are listed at the bottom of the table.

■ **Table 6-1 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)

6.3 Results

Brief conclusions regarding trial outcomes for each of the techniques is presented below:

6.3.1 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.

6.3.2 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.

6.3.3 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.

6.3.4 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 site 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.

6.3.5 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, a 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.

6.3.6 Geophysics

6.3.6.1 Background

Geophysical techniques were identified in the literature review as having potential for channel seepage identification and quantification. In addition, geophysical techniques fit the criteria for the type of technique RWAs require for channel seepage assessment. The national RWA survey (ANCID, 2000b) 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. This suggested 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. Geophysical trials eventually became the primary focus of the investigation as the results from early in the trials indicated that they were the most appropriate technique for relatively accurate but cost effective assessment of channel seepage.

6.3.6.2 Methodology

Based on the literature review, the geophysical techniques selected were EM and resistivity. EM techniques essentially average the conductivity over a depth (to provide one number representative across that depth) whereas resistivity techniques are multi-channelled, which provides depth distinction. In total the following surveys were conducted:

- 16 EM31 surveys across 12 different sites
- 6 EM34 surveys across 4 different sites
- 8 resistivity surveys across 8 different sites

Details of which surveys were done at particular sites are contained in Table 6-1 in this report.

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. Comparison of the average geophysical response and pondage test seepage involved plotting the two variables against each other, and analysis of the trends.

The following variables were tested during the trials:

- The influence of 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);
- Repeatability of surveys;
- Channel operation (*ie*, timing of the survey);
- Transferability of correlations between seepage rates and conductivity at different locations; and,
- Difference in results between EM and resistivity.

An attempt was also made to undertake a statistical assessment of regional relationships across all sites, incorporating key parameters such as depth to watertable, groundwater salinity and soil type.

6.3.6.3 Results

6.3.6.3.1 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.

6.3.6.3.2 Comparison of Trialed Geophysical Techniques

Accuracy, cost and speed, availability of operators and data processing are key criteria against which geophysical techniques should be compared. The three techniques trialed in this investigation (EM31, EM34 and resistivity) are discussed in terms of each of these criteria.

Accuracy - Generally direct measurement should be considered more accurate 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. If the EM equipment is selected to suit the watertable depth, it can provide results similar to the accuracy of resistivity surveying.

EM31 was shown to be quite robust in the trials. For channels where there is a shallow watertable (*eg*, surface to 3-4m), EM31 can be used for direct measurement of seepage, and when the watertable is deep, EM31 infers seepage from near surface soil properties, which was shown to be 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. Resistivity surveying costs are difficult to quantify given that the on-channel application of the technique is relatively new but 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. 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 and conduct the surveying.

Data Processing - Data processing requirements for EM surveying are minimal. In comparison, data processing requirements for resistivity surveying are much higher.

6.3.6.3.3 Critical Geophysical Survey Variables

- *Survey timing* – If direct seepage measurement is used, the survey must be conducted while the channel is running (preferably for 2-3 weeks prior to survey).

  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.

- *Off-set distance and location* – 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.

Traverses on both sides of the channel are recommended, but a traverse on the down-slope side should be the priority.

6.3.6.3.4 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.

6.3.6.3.5 Regional Assessment of Key Relationships

For all of the sites used in the final year of analysis, multiple and simple linear regression were 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 a significant explanatory variable, but of secondary importance compared to the influence of the geophysical variable (EM31 or resistivity).

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. 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 concluded that there is currently insufficient confidence in the regression equations for their use to predict seepage at new sites without local calibration (with 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 10m depth slice was adopted as the variable for use in the model. The analysis indicated only a moderately fitting regression equation, which could not be used with the same degree of confidence as the EM31 based equations. It is anticipated that a more accurate analysis could be conducted using the depth at and just below the watertable. However, for the purpose of a consistent approach, the 10m depth slice was selected. There also appeared to be some inaccuracies in the near surface resistivity data, contributing to selection of the 10m depth slice for regional analysis.

6.3.6.3.6 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*? - 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.

6.3.6.3.7 Preferred Methodology

Based on the trials conducted in this investigation, and the methodology outlined in the Best Practice Guidelines for Channel Seepage Identification and Measurement (ANCID, 2003b) 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 to 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). If 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 (based on geophysical results) to assist with interpretation of the geophysical survey;

5d.. Conduct pondage tests – The number of pondage tests will depend on the length of the section and variability of conditions. Pondage tests should be conducted across the range of geophysical response so as to establish a regression equation representative of the entire survey area and should also cover the range of soil types.

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

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

6.3.6.3.8 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.

In summary, at only one site (Dahwilly East) no relationship was observed between EM34 and pondage tests. This 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 magnitude.

6.3.6.3.9 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. 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.

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 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 at this site using a technique targeting the top of the watertable.

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 EM31 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 margin 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. This would preclude EM31 on-channel use when the watertable is deeper than approximately 4-5m.

6.3.6.3.10 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.

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 have dominated 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.

6.3.6.3.11 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. G-MW required quantification of sections with existing seepage problems and identification 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.

Based on the results of the pondage tests, the regression relationship between EM31 and pondage tests and the drilling program, the areas recommended for remediation were finalised. High risk sites were defined as either priority one or priority two 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 presented a good example of the integration of geophysical, geological and pondage test data to determine areas of highest seepage risk.

6.3.6.4 Conclusions

The conclusions to the geophysical trials form the major part of the conclusions to Objective 5 and the reader is therefore directed to these conclusions (refer Section 5.4).

6.3.6.5 Recommendations

The recommendations to the geophysical trials form the major part of the recommendations to this objective and the reader is therefore directed to these recommendations (refer Section 5.5).

6.4 Conclusions

Trials were conducted in four RWAs from 2000 to mid 2002. They were focussed on the following channel seepage identification and measurement techniques:

- Pondage tests,
- Point measurement (channel full and empty),
- Geophysical,
- Groundwater,
- 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.

The following concluding remarks are made regarding each of the techniques trialed:

Pondage Tests: 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 conducted across all sites (totalling 81 ponds) returned seepage rates ranging from 0.1 mm/d to 48 mm/d. 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.

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 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.

Point Tests: 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).

Groundwater Techniques: 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.

Remote Sensing: Remote sensing techniques:

- Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage;
- Will be most useful where lateral seepage is predominant;
- Should primarily be regarded as a seepage identification tool and not for seepage quantification;
- Require a suitable spatial resolution to allow definition of seepage zones (< 10m suggested);
- Are best conducted in the infra-red range of the electromagnetic spectrum; and,
- Are generally best collected during late summer and early autumn.

Geophysical Techniques - These trials have demonstrated that geophysical techniques offer the best solution for rapid identification and measurement of channel seepage. They are well suited to use at an RWA level, in that they are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates.

Understanding of the application of geophysics to identify and measure channel seepage has been significantly advanced through these trials. In particular, progression in the following areas has been achieved:

- Understanding of the mechanisms by which geophysical techniques detect seepage. In particular the distinction between directly measuring seepage as it impacts the watertable and indirect measurement of unsaturated zone soil properties. This important distinction is not made in previous literature relating to geophysics and channel seepage.
- Identification of the best types of geophysical techniques for channel seepage assessment for different environments (with depth to watertable being the key variable influencing selection).
- Improved understanding of the key variables which impact on geophysical surveys.
- Identification of the best time to conduct surveys in terms of channel operation, most appropriate offset distance for surveys, and the suitability and accuracy of on-channel surveys compared to on-land surveys.
- Improved understanding of the repeatability of geophysical surveys.
- Understanding of the degree of accuracy that can be achieved using geophysics for quantifying channel seepage, and statistical assessment of this accuracy both at a local level and using a combination of the results to undertake a regional assessment encompassing a range of site conditions.

The most practical and useful output arising from the Stage 1 trials is a preferred methodology for using geophysics for identifying and measuring channel seepage. This is based on calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. This preferred methodology also includes a table to assist in selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

This preferred methodology is very similar in approach to recent international channel seepage research (Hotchkiss *et al*, 2001). This paper also describes the development of geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the geophysical response and measured seepage and then extrapolation to new areas. This independent and simultaneously conducted research confirms that geophysics is emerging as a widely regarded technique that is one of the best ways forward in terms of rapid and relatively cost effective identification and measurement of channel seepage.

Another key outcome arising from this work is the potential of on-channel resistivity for rapid seepage assessment. Surveys were conducted in the final year of trials at eight sites, and the results showed significant promise, with good correlations against pondage tests observed at most sites. The main advantage of on-channel resistivity over traditional EM techniques is that data is gathered at multiple depths beneath the channel, which enables a depth profile of conductivity beneath the channel to be developed. Not only does this have significant advantages in terms of output presentation and visualisation of seepage mechanisms, but importantly it means that the critical depth immediately above and below the watertable can be targeted. In contrast fixed array surveys, even when they are selected appropriately according to the watertable depth, provide a cumulative response from the surface depth interval and are less discriminatory in their measurement, allowing potentially greater error. Costs of resistivity are at present higher than EM surveys but are expected to decrease if this technique becomes more widely used (at present there are no commercial operators of this equipment on the market). More resistivity trials are needed to increase the existing data set upon which conclusions are based. One specific area requiring investigation is the issue of near surface resolution of the equipment, which affects accuracy in shallow watertable environments. It is anticipated that this could easily be resolved by varying the array spacing (from linear to exponential, with more closely spaced arrays near the boat).

One cautionary note is warranted regarding the use of geophysics for channel seepage assessment. The geophysical survey should be carried out by a suitably qualified contractor and the geophysical results should be interpreted with sufficient bore hole data, proper calibration against a direct seepage measurement technique, should be interpreted by someone with relevant geophysical experience and if the results are to be used quantitatively, the seepage-geophysical relationship derived should be subject to proper statistical analysis, so that the degree of confidence in the prediction equation can be well understood and appreciated.

The key remaining part of the Stage 1 trial with respect to geophysics is to ensure that the information regarding the use of geophysics for channel seepage assessment is properly disseminated and marketed to RWAs. The national survey (ANCID, 2000b) indicated that RWAs tend to use assessment techniques with which they are familiar. There is therefore significant inertia which must be overcome to get RWAs to change existing channel seepage assessment practices, which are not necessarily based on good science.

A full description of the results and conclusions arising from the trials is contained in a single document entitled *Documentation of Seepage Measurement Trials (ANCID, 2003a)*. This document can be accessed and down-loaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document. The Executive Summary of the

Documentation of Seepage Measurement Trials (ANCID, 2003a) report is contained in *Appendix C* of this report.

6.5 Recommendations

In summary, geophysics offers a promising way forward for future channel seepage identification and measurement. It is recommended that RWAs should adopt the preferred technique as outlined in the conclusions of the Trials report and the Guidelines Manual. This methodology relies on geophysics to identify seepage, and pondage tests and soil bores to calibrate and interpret the geophysical response. Although the trials investigation has resulted in this recommended assessment methodology using geophysics, this does not mean that further research is not required. Key recommendations arising from the trials are listed below:

- *Development of a national database*. 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. It is therefore recommended that a national database be established to record all channel seepage related 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, soil type, geology and channel hydraulic information.
- *Establishment of geophysics seepage relationship.* 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.
- *Cheaper and more convenient way of calibrating geophysical surveys.* The main deterrent to RWAs from widespread adoption of geophysics is the operational inconvenience and expense of the pondage tests required to calibrate the geophysical survey. A means of calibrating geophysical surveys where pondage tests are extremely difficult or cannot be conducted needs to be explored. A cheaper means of bank construction (possibly using some type of transportable barrier) would greatly reduce the cost of pondage tests, as these represent a significant part of the pondage test procedure.
- *Fine tuning of resistivity technique*. Resistivity surveys showed significant promise, as they allowed targeting of the seepage impacts on the watertable. 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 trials to overcome these problems are recommended. Investigation into means of reducing resistivity data processing time (and thus costs) are also suggested.
- *Further testing of on-channel fixed array surveys*. Further testing of the relative merits of on-channel fixed array surveys compared to adjacent channel fixed array surveys are required.
- *Remote sensing trials*. Remote sensing trials 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 can be used to assist in calibration of such trials.

7 Objective 6

Prepare and publish guidelines on the techniques for quantifying and monitoring the extent of channel seepage

7.1 Background

In many respects the guidelines were the ultimate objective of the Stage 1 project. The purpose of producing the guidelines was to promote a technically sound, systematic approach to addressing channel seepage identification and measurement. The primary audience of the document is personnel (managers, engineers and technical officers) within Australian RWAs, although they will also be useful to other natural resources managers, academics and consultants.

The guidelines are to be linked to the channel seepage user support system (Stage 3) which provides a structured management tool for channel managers.

7.2 Methods

The primary aim of the guidelines was to document the best practice techniques for identifying, quantifying and monitoring:

1) The extent of channel seepage
2) The effectiveness of remedial works in reducing channel seepage

To achieve this objective, the guidelines needed to detail:

- the best techniques to identify and measure seepage in various environments
- the most appropriate techniques to meet project objectives
- how to go about conducting the work
- how to assess the results

The guidelines were developed from the outcomes of previous tasks, including the literature review, RWA survey, and the three years of seepage measurement trials.

A key aspect arising from the national survey which shaped the development of the trials and the guidelines was that RWAs rank cost as the most significant factor in selecting seepage investigation techniques, with technical accuracy of lesser importance. This finding was the reason why some techniques were not included in the trial program and were not recommended as appropriate techniques for RWAs in the guidelines. Conversely this shaped other techniques (in particular geophysics) in becoming the focus of the trial program and are the recommended technique in the guidelines.

The guidelines are prepared in two Parts. The first part (Part 1) provides background to the project and how the guidelines were derived. It is aimed at bringing out a range of important issues and approaches to assist users towards developing the most appropriate investigation to meet their particular channel seepage issue.

An important section in Part 1 is the introduction of a six step process which allows readers to identify the key factors they need to address when undertaking a seepage measurement investigation. In addition, Part 1 introduces the concept of recommended generic investigation procedures which are related to the scale of the investigation.

Part 2 describes the operation and evaluation of a range of the particular techniques considered to be most applicable to Australian channel operators. It is recommended that readers progress through Part 1 before going to the detailed descriptions of various techniques.

7.3 Results

A summary of the content of the guidelines is provided below.

PART I

Some basic parameters affect the location and rate of channel seepage, how it impacts local amenities and how it can be remediated. These are related to the soil and water conditions in the vicinity of the channel and the mechanisms by which seepage occurs. These factors were an important input to the development of these guidelines.

The particular physical factors affecting seepage from earthen channels are, soil characteristics, hydraulic and channel water characteristics. It is also important to understand the seepage mechanism and the resultant impacts. Seepage from earthen channels can be dominantly horizontal or vertical, or a combination of the two. Basic understanding of site conditions can be used to derive some idea of the mechanism which can provide a guide to the investigation technique to be applied.

The scale of the investigation is also an important factor. Scale should be considered when management needs for undertaking the project are being evaluated and they are to be reconsidered in finalising the selection of the technique. Three scales of investigation are considered appropriate in the selection of a technique:

- Local Scale: Short (up to 400m in length);
- Intermediate to Large Scale: Hundreds of metres to tens of kilometres; and,
- Macro Scale: Tens of kilometres to entire systems.

The guidelines are designed to enable users to make a serious evaluation of suitable procedures which meet individual project needs and objectives. They are based around the need to generate the detailed knowledge required to undertake measurement of seepage and how to interpret the results to meet a channel management objective. It is a circular process involving the following six key tasks:

TASK	ACTIVITY
1. Define Objective	Understand the reasons for doing the investigation.
2. Collate Site Physical Condition Data	Collate key data affecting channel seepage.
3. Assessment of Site Conditions	Understand the conditions at the site.
4 Selection of Measurement Techniques	Select the appropriate measurement technique for the conditions and for the problem.
5. Implementation of Tests	Conduct tests and estimate seepage rates and distribution.
6. Interpret Results	Evaluate if the test results answer the question raised in the management process, *ie*, meet the defined objective.

Recommended Procedures

The RWA survey conducted as part of the Stage 1 investigation identified that RWAs consider cost and speed of investigations to be the most important criteria in channel seepage assessment. This was a guiding factor in development of the trial program and the recommended techniques described in the guidelines. However, circumstances for specific investigations will vary and the best results will be obtained when the technique used is appropriate for the particular investigation. Therefore it is recommended that the six step process described above be adopted in selecting the test(s) to be conducted. A fundamental issue related to the selection of the technique is the scale of the investigation. The guidelines therefore present separate procedures for:

- Local scale or specific sites where the focus may be on addressing a particular, previously identified issue; and,
- Larger scale investigations where business objectives suggest a need for investigation even though the specific distribution and rate of seepage is not known. This may form the basis for more detailed investigation at a later date.

Local Scale Investigations (up to 400m)

The types of techniques which would be used in local investigations will depend on whether there is a need for measurement of seepage rates at specific locations or if there is the need to map zones of higher permeability and then identify the rates. For measurement of seepage rates at pre-determined sites the likely techniques which could be considered are:

- Pondage tests;
- Point tests; and,
- Groundwater monitoring (and potentially modelling, depending on project objectives).

If there is a need for mapping of zones of relative seepage or potential seepage, there is a need to use a tool such as geophysics, and sub-surface methods such as geological profiling and groundwater observations, as well as surface observations. Estimates of the rate could then be undertaken with those techniques listed above, once the mapping is complete.

Intermediate to Large Scale Investigations (400m up to tens of kilometres)

The trials conducted in this study indicated that for most channel seepage projects at intermediate to large scale, the most appropriate approach is to:

- Rapidly and cost effectively identify zones of highest seepage by a mapping process such as geophysics or remote sensing. Geophysics is the preferred technique in most situations.
- Quantify the seepage rate, preferably using pondage tests, although for particular purposes point tests or groundwater investigations may be undertaken.
- Extrapolate the results to areas beyond the test sections to the length of channel of interest. This involves being able to compare the conditions at the test sections with the broader area of interest.
- Where possible undertake a verification using a water balance (*eg*, Inflow – Outflow) along the length of interest.

This provides a rapid and relatively inexpensive routine technique which provides an indication of the extent and magnitude of seepage along a channel. It can be applied at any scale. It becomes more cost effective with larger lengths of channel and there is also more opportunity for meaningful verification.

Macro Scale Investigations (tens of kilometres up to entire systems)
A similar approach to intermediate to large scale is recommended, but for some investigations, water balance estimates (*eg*, Inflow – Outflow) may be sufficient. Remote sensing techniques may also be useful at this regional level of investigation.

PART II

Part 2 of the guidelines provides a description of how to go about conducting seepage measurements using the techniques considered most relevant to Australian conditions and operations. The techniques are grouped into the following categories:

- Direct and Point Measurements;
- Subsurface Characterisation; and
- Remote Non- Invasive Techniques.

Each technique is discussed in terms of:

- Principle
- Methodology
- Applicability
- Practical Implementation
- Indicative Costs

7.4 Conclusions

The guidelines have been successfully completed, including review through the workshop process (*Objective 8*) and are contained in: *Guidelines for Channel Seepage Measurement* (ANCID, 2003). The Executive Summary of the Guidelines is contained in *Appendix D* of this report.

The guidelines are a significant step forward in the management of channel seepage issues. They provide RWAs with best practice procedures for identifying and quantifying channel seepage. They fill a gap in understanding of channel seepage assessment clearly identified in the national RWA survey (ANCID, 2000b). Through a circular six step process, the guidelines enable users to make a serious evaluation of suitable procedures which meet individual needs and objectives. The most significant aspect of the guidelines is their recommendation that, (for intermediate to large scale investigations), geophysical techniques offer the best solution for rapid identification and measurement of channel seepage for RWA purposes. They are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates. A preferred methodology for using geophysics for identifying and measuring channel seepage is outlined in the guidelines, based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. The guidelines also provide information on selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

The preferred methodology based on geophysical assessment outlined in the guidelines offers the potential for significant efficiency gains in channel seepage management. The procedure provides a basis for highly targeted channel seepage remediation initiatives, which have the potential to greatly improve the economics of remediation projects. These water savings will minimise the loss of a resource of which the real economic value is being increasingly realised, reduce contributions to groundwater recharge and associated land salinisation, and increase the available water which could be returned to the environment.

Given that the national survey (ANCID, 2000b) indicated that geophysical techniques are not currently widely used by RWAs for channel seepage assessment, the challenge ahead is in changing RWA practice to adopt, or at least trial this new approach. The guidelines will need to be well distributed and promoted to achieve this change in direction.

While the Guidelines have been completed, a deliberate decision has been taken to only release limited numbers of hard copies. However it is available in digital form to anyone interested (either on CD or by download from the ANCID web site). The reason for this is related to the Stage 3 project which involves the preparation of a User Support tool to assist decision making with channel seepage measurement and control. The Stage 3 project is planned to effectively link all three stages into a web based user support system. The required linking, once known, may facilitate the need to make minor changes to the format of the Channel Seepage Measurement Guidelines document released under this Stage 1 project. However, the content is expected to remain unchanged.

8 Objective 7

Prepare and publish the second edition of the "Rural Water Industry Terminology and Units" booklet

8.1 Background

This objective relates closely to *Objective 2* outlined in detail earlier.

8.2 Methods

Refer *Objective 2*.

8.3 Results

The Second Edition of the ANCID *Rural Water Industry Terminology and Units* booklet was updated with terms and units used in channel seepage. It was completed and became available in April, 2001 but had a formal release at the 2001 ANCID Annual Conference held in Toowoomba, Queensland.

The document can be accessed and downloaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document. In all, 500 hard copies were printed and many have already been forwarded to water authorities and other interested organisations and individuals. Hard copies are still available from ANCID as follows:

The Secretary,
ANCID
C/o Goulburn-Murray Water
PO Box 165
TATURA, VICTORIA, AUSTRALIA, 3616

8.4 Conclusions

The *Rural Water Industry Terminology and Units* booklet will continue to provide a valuable reference document to help to ensure common terminology and units are used in the Australian rural water industry.

9 Objective 8

Conduct a workshop to discuss the draft guidelines

9.1 Background

The need for increased research and investigation into channel seepage had its genesis at a specially convened workshop held in Moama in October, 1998. It arose out of interest and concern in the rural water industry over the lack of reliable information on how to identify, measure and deal with channel seepage.

Coinciding with the release of the project results, it was considered appropriate to hold a follow-up workshop to present the outcomes, in this case of the Stage 1 works looking into channel seepage identification and measurement. In particular, the workshop was an ideal forum for review and comment on the contents of the *Best Practice Guidelines for Channel Seepage Identification and Measurement*, which is the key output from this project (Stage 1).

9.2 Methods

The following steps were involved in organising and implementing activities necessary to meet this objective:

- Given that the original workshop on channel seepage was held in Moama in New South Wales and the fact that Moama was relatively equidistant from the key personnel interested in the project, the follow-up workshop was also convened in Moama, at the Rich River Golf and Country Club.
- Once the draft Guidelines Manual was available, a copy was placed on the ANCID web site for download and review by anyone interested, and in particular for those planning to attend the workshop.
- Letters of invitation were sent to those members of the water industry, consultants and contractors who attended the October, 1998 workshop. In addition, invitations were sent to all water authorities seeking their interest in sending relevant personnel to the workshop to participate in the review.

9.3 Results

- The workshop was held as planned on Monday 14 October, 2002.
- About 40 participants attended the workshop.
- Participants had had access to the Guidelines Manual prior to the workshop (via the ANCID web site) and additional hard copies of the Manual were available at the workshop, all of which were taken.
- Valuable feedback was obtained from those attending the workshop. Participants were requested to again review the Guidelines Manual and provide follow-up comment.
- Follow-up comment was provided but only from two people.
- A summary report on the workshop was prepared, a copy being attached as *Appendix E*.

9.4 Conclusions

The workshop represented a valuable opportunity for those interested in channel seepage to obtain an update on the project as well as be able to participate in the format and contents of the Guidelines Manual for channel seepage identification and measurement.

Outputs from the workshop were fed into the final draft of the Guidelines Manual and also to the report on the seepage trials.

10 Objective 9

Distribute the guidelines and booklets to at least 50 stakeholders

10.1 Background

Given that the original ANCID "*Are Your Channels Leaking*" conference held in Moama in October, 1998 indicated a gap in the knowledge base in the rural water industry in issues dealing with channel seepage, and given the interest shown in advancing that knowledge, an important objective of the project was to ensure that the water industry was fully consulted and kept up to date with the project work. More particularly, it was important that they have access to the outputs from the project.

10.2 Methods

Given that ANCID was given the task to oversee the project, the opportunity was taken to use ANCID's contacts in the rural water industry and more particularly to use their Annual Conferences as vehicles to promote the work on the project, to give short presentations on progress and to make available reports in both hard copy and digital form to anyone who was interested.

These conferences attracted attendees from not only around Australia but also overseas. Displays were prepared for each conference and presentations were given at each of three conferences held in Griffith (2002), Bunbury (2001) and Toowoomba (2000). All reports and CDs (50 at Toowoomba) were given out at the conferences.

In addition, presentations were given at the 2002 Hydrology and Water Resources Symposium held in Melbourne.

Reports were handed out at these conferences and also placed on the ANCID web site for download.

10.3 Results

Reports on the project have been disseminated in both hard copy and digital format to a wide variety of interested groups and agency personnel.

11 Discussion

Stage 1 of a suite of three ANCID channel seepage projects was focussed on development of best practice guidelines for identifying and quantifying channel seepage. Development of the guidelines required the undertaking of a number of tasks:

- An international **literature review** on channel seepage measurement and a **national survey of RWAs** gathering information on existing channel seepage assessment processes. These two tasks provided a platform for the entire project.
- Various seepage measurement techniques identified in the literature review, as well as some less developed approaches, were trialed in a three year **field trial program** conducted across four RWAs.
- Based on the results of the literature review, the national survey and three years of trials, the **guidelines** on techniques for identifying and quantifying channel seepage were prepared. A workshop was conducted to provide industry review of the draft guidelines prior to them being finalised.

Literature Review

The literature review is a comprehensive summary and evaluation of available techniques for measuring and identifying channel seepage. It therefore forms a very valuable reference tool for anyone undertaking channel seepage assessment. Only in respect to geophysics did the trials significantly advance knowledge and practical understanding beyond that identified in the Literature Review. In other words, the Literature Review should be considered an up to date document for all techniques, except geophysical techniques, as the trials work undertaken in this project has progressed understanding of the use of geophysics for channel seepage identification and measurement. Therefore, the Trials Report (ANCID, 2003a) and Best Practice Guidelines (ANCID, 2003b) should be used in conjunction with the Literature Review to obtain a complete and up to date assessment of the theory and application of geophysical techniques for channel seepage assessment.

RWA Survey

The national survey provided a valuable point of reference of current RWA practice with respect to seepage assessment and assisted in setting the direction of the trials program. Estimates were provided by RWAs of unaccounted water losses (average of 17.5%) and on average they estimated that 4% was lost via seepage. The discrepancy between unaccounted for water and seepage loss estimates suggests that actual seepage may be higher than the 4% estimated. The survey appeared to indicate a divide in priority between RWAs with respect to the importance of channel seepage issues, with over 40% of authorities rating channel seepage as a high or very high priority, yet by contrast 50% of authorities had undertaken no on ground seepage measurement works.

Interestingly, an increase in the amount of seepage assessment did not result in clear gains in understanding of seepage rates and losses, suggesting a lack of success in channel seepage measurement. Either the techniques being employed, or the implementation of the techniques appears to be inappropriate. The fact that seepage identification techniques (visual and piezometers) rather than quantification techniques dominated assessment suggests that inappropriate methods are largely responsible for this occurrence.

Channel seepage remediation projects are often undertaken without quantitative analysis of seepage. Qualitative techniques are the main means by which seepage sites are targeted for remediation. These are less than ideal approaches to selecting remediation sites and are unlikely to provide the best return for dollars expended. This failure to clearly establish cost-benefit aspects of remediation contradicted RWA assertions that the value of water lost is the major motivator for channel seepage investigations.

A key outcome of the survey was identification of the importance of cost and speed to RWAs in channel seepage assessment, with technical accuracy considered of lesser importance. This shaped the trial program and development of the guidelines. The survey indicated that there was strong demand for seepage measurement guidelines, with the majority of authorities believing that there is insufficient information and/or expertise on techniques for seepage identification and measurement. To assess the impact of the outcomes of the Stages 1 investigation, consideration should be given to conducting a similar survey in several years (*eg*, 2005).

Trial Program

Trials were conducted in four RWAs from 2000 to mid 2002. They were focussed on pondage tests, point measurement, geophysical techniques, groundwater techniques, soil classification and remote sensing. Inflow-outflow tests were not included in the trials as they were deemed not sufficiently accurate for measuring losses over short sections of channel but are still useful at a regional assessment level. Due to the intensity of data collection and level of specialist input required, mathematical modelling was also not trialed, but could be a useful technique for specialist, non-RWA investigations. Similarly, due to the high cost and expertise required, hydrochemical techniques were considered generally not practical solutions for RWAs and no trials were undertaken.

Being the most accurate means of channel seepage assessment, pondage tests were conducted across all sites and were the baseline technique against which other methods were assessed. At sites where pondage tests were repeated, a good degree of repeatability was observed. RWAs wishing to obtain accurate seepage quantification should undertake pondage tests, and the accuracy of other techniques should be assessed against pondage tests. The main difficulty with such tests is that they can be difficult to tie in with channel operations, and particularly during drought periods RWAs may be reluctant to conduct tests, from both a cost and public perception perspective. However, despite the drought period through which these trials were conducted, pondage tests were able to be undertaken through careful planning at the end and start of channel run seasons.

Sub-surface characterisation is a critical part of the site characterisation phase of a channel seepage investigation. However the density of sampling and permeability testing required for quantifying seepage, 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. Similarly the 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, and should generally be limited to determining the distribution of seepage losses.

Use of groundwater bores for quantitative analysis of seepage is not considered accurate or cost effective for typical RWA channel seepage investigations. Bores are essentially a type of point test and hence do not address the question of where the channel is seeping. Therefore a high density of bore transects would be required for meaningful identification of local areas of seepage. Hence this technique may be useful for local scale investigations but is unlikely to be accurate for intermediate to large scale investigations. 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.

Remote sensing techniques were not trialed in the program and it is recommended that given the potential of this technique for rapid assessment of long sections of channel, carefully planned field trials in Australian conditions should be undertaken. Remote sensing techniques have been heralded as an excellent tool for seepage assessment, but it does not seem to be clearly understood that they will generally only be useful where the primary aim is identification of land degradation associated with channel seepage (*ie*, where lateral seepage predominates). Many of the channels in the trials showed significant seepage rates, but no surface expression, because seepage processes were predominantly vertical. Further, remote sensing techniques should primarily be regarded as a seepage identification tool and not for seepage quantification.

One of the main outcomes arising from the Stage 1 trials is that geophysical techniques offer one of the best solutions for rapid identification and measurement of channel seepage. They are well suited to use at an RWA level, in that they are fast and relatively cost effective, and when calibrated against direct measurement techniques, can provide a reasonably accurate quantitative assessment of seepage rates. Understanding of the application of geophysics to identify and measure channel seepage has been significantly advanced through these trials. In particular, progression in the following areas has been achieved:

- Understanding of the mechanisms by which geophysical techniques detect seepage. In particular the distinction between directly measuring seepage as it impacts the watertable and indirect measurement of unsaturated zone soil properties. This important distinction is not made in previous literature relating to geophysics and channel seepage.
- Identification of the best types of geophysical techniques for channel seepage assessment for different environments (with depth to watertable being the key variable influencing selection).
- Improved understanding of the key variables which impact on geophysical surveys as they relate to seepage detection.
- Identification of the best time to conduct surveys in terms of channel operation, most appropriate offset distance for surveys, and the suitability and accuracy of on-channel surveys compared to on-land surveys.
- Improved understanding of the repeatability of geophysical surveys.
- Understanding of the degree of accuracy that can be achieved using geophysics for quantifying channel seepage, and statistical assessment of this accuracy both at a local level and using a combination of the results to undertake a regional assessment encompassing a range of site conditions.

The most practical and useful output arising from the Stage 1 trials is a preferred methodology for using geophysics for identifying and measuring channel seepage. This is based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. This preferred methodology also includes a table to assist in selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

This preferred methodology is very similar in approach to recent international channel seepage research (Hotchkiss *et al*, 2001). This paper also describes the development of geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the geophysical response and measured seepage and then extrapolation to new areas. This independent and simultaneously conducted research confirms that geophysics is emerging as a widely regarded technique that is one of the best ways forward in terms of rapid and relatively cost effective identification and measurement of channel seepage.

Another key outcome arising from this work is the potential of on-channel resistivity for rapid seepage assessment. Surveys were conducted in the final year of trials at eight sites, and the results showed significant promise, with good correlations against pondage tests observed at most sites. The main advantage of on-channel resistivity over traditional electromagnetic techniques is that data is gathered at multiple depths beneath the channel, which enables a depth profile of conductivity beneath the channel to be developed. Not only does this have significant advantages in terms of output presentation and visualisation of seepage mechanisms, but importantly it means that the critical depth immediately above and below the watertable can be targeted. In contrast fixed array surveys, even when they are selected appropriately according to the watertable depth, provide a cumulative response from the surface depth interval and are less discriminatory in their measurement, allowing potentially greater error. Costs of resistivity are at present higher than EM surveys but are expected to decrease if this technique becomes more widely used (at present there are no commercial operators of this equipment on the market).

More resistivity trials are needed to increase the existing data set upon which conclusions are based. One specific area requiring investigation is the issue of near surface resolution of the equipment, which affects accuracy in shallow watertable environments. It is anticipated that this could easily be resolved by varying the array spacing (from linear to exponential, with more closely spaced arrays near the boat).

One cautionary note is warranted regarding the use of geophysics for channel seepage assessment. The geophysical survey should be carried out by a suitably qualified contractor and the geophysical results should be interpreted with sufficient bore hole data, correct calibration against a direct seepage measurement techniques, should be interpreted by someone with relevant geophysical experience and if the results are to be used quantitatively, the seepage-geophysical relationship derived should be subject to proper statistical analysis, in order to determine the degree of confidence in the prediction equation.

Guidelines

The Guidelines are a significant step forward in management of channel seepage issues. They provide RWAs with best practice procedures for identifying and quantifying channel seepage. They fill a gap in understanding in channel seepage assessment clearly identified in the national RWA survey (ANCID, 2000b). Through a circular six step process, the guidelines enable users to make a serious evaluation of suitable procedures which meet individual needs and objectives. The most significant aspect of the guidelines is their recommendation that, (for intermediate to large scale investigations), geophysical techniques offer the best solution for rapid identification and measurement of channel seepage for RWA purposes. They are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates. A preferred methodology for using geophysics for identifying and measuring channel seepage is outlined in the guidelines, based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. The Guidelines also provide information on selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

The preferred methodology based on geophysical assessment outlined in the Guidelines offers the potential for significant efficiency gains in channel seepage management. The procedure provides a basis for highly targeted channel seepage remediation initiatives, which have the potential to greatly improve the economics of remediation projects. These water savings will minimise the loss of a resource of which the real economic value is being increasingly realised, reduce contributions to groundwater recharge and associated land salinisation, and increase the available water which could be returned to the environment.

Given that the national survey (ANCID, 2000b) indicated that geophysical techniques are not currently widely used by RWAs for channel seepage assessment and that RWAs tend to use assessment techniques with which they are familiar, the challenge ahead is in changing RWA practice to adopt, or at least trial this new approach. The content and message of the guidelines will need to be well distributed and promoted to achieve this change in direction. It is likely that there will be significant inertia which must be overcome to get Authorities to change existing channel seepage assessment practices, which are not necessarily based on good science.

Links to Stage 3 Project

An important step in the dissemination and promotion of the Stage 1 project is the incorporation of the Stage 1 results (in particular the Guidelines) into the Stage 3 project. The Stage 3 project is planned to link all three stages into a web based user support system. This will provide widespread access to the guidelines though the medium of the Internet. Importantly it will also facilitate more user friendly access to the Stage 1 information without the deterrent of the user having to wade through several reports.

12 Conclusion and Recommendations

12.1 Conclusions

Stage 1 of a suite of three ANCID channel seepage projects was focussed on development of best practice guidelines for identifying and quantifying channel seepage. Development of the guidelines required the undertaking of a number of tasks. The first two activities provided a platform for the entire project, and involved undertaking a national and international literature review on channel seepage measurement and a national survey of RWAs to gather information on existing channel seepage assessment processes. Following these preliminary tasks, three years of field trials were undertaken in four RWAs, trialing various techniques identified in the literature review as well as some less developed approaches to seepage measurement. The results of these trials, including an understanding of the accuracy of each technique, were thoroughly documented. Based on the results of the literature review, the national survey and three years of trials, the Guidelines on techniques for quantifying channel seepage were prepared. A workshop was conducted to discuss and allow feedback on the draft Guidelines prior to them being finalised.

The Stage 1 project also involved one task which was not directly related to the development of the Guidelines. This involved the development of a standard set of terminologies and units related to the topic of channel seepage. These were incorporated into a second edition of the ANCID *Rural Water Industry Terminology and Units* booklet.

12.1.1 Literature Review

The literature review is a comprehensive summary and evaluation of all available techniques for measuring and identifying channel seepage. Each of these techniques is discussed in terms of theory, methodology, advantages and disadvantages of each technique. It was based on approximately 40 primary and 50 secondary references from Australia and overseas. The literature review forms a very valuable reference tool for anyone undertaking channel seepage assessment.

Only in respect to geophysics did the trials *significantly* advance knowledge and practical understanding beyond that identified in the literature review. Therefore, the *Documentation of Seepage Measurement Trials* report (ANCID, 2003) and *Best Practice Guidelines for Channel Seepage Identification and Measurement* (ANCID, 2003) should be used in conjunction with the Literature Review to obtain a complete and up to date assessment of the theory and application of geophysical techniques for channel seepage assessment. The literature review was used as the starting point for selecting techniques for the trials. It was also used extensively in development of the guidelines.

12.1.2 RWA Survey

In order to provide a point of reference of current RWA practice with respect to seepage assessment and assist in setting the direction of the trial program, a national survey of 41 different RWAs or Irrigation Districts / Areas across Australia was undertaken. The survey was designed to compile information on :

- Total water supplied by the RWA;
- An estimate of seepage losses in the channel distribution systems, and total system losses, *ie*, unaccounted for water;
- Effect of seepage losses (monetary loss of water and land degradation);
- Importance of channel seepage issues to the RWA;
- Accuracy of (ie, confidence in) seepage estimates;
- Criteria by which the Authority select a seepage measurement technique;

- Estimate of money spent addressing channel seepage issues; and,
- Seepage measurements techniques (techniques used, perceived accuracy, cost and satisfaction with outcome).

Estimates were provided by RWAs of unaccounted water losses (average of 17.5%) and on average they estimated that 4% was lost via seepage. The discrepancy between unaccounted for water and seepage loss estimates suggests that actual seepage may be higher than the 4% estimated. The survey appeared to indicate a divide in priority between RWAs with respect to the importance of channel seepage issues, with over 40% of authorities rating channel seepage as a high or very high priority, yet by contrast 50% of authorities had undertaken no on ground seepage measurement works.

An increase in the amount of seepage assessment did not result in clear gains in understanding of seepage rates, suggesting that inappropriate methods are being used for channel seepage measurement. The survey indicated that channel seepage remediation projects are often undertaken without quantitative seepage assessment. Qualitative techniques are the main means by which seepage sites are targeted for remediation. These are less than ideal approaches to selecting remediation sites and are unlikely to provide the best return for dollars expended.

A key outcome of the survey was identification of the importance of cost and speed to RWAs in channel seepage assessment, with technical accuracy considered of lesser importance. This shaped the trial program and development of the guidelines. The survey indicated that there was strong demand for seepage measurement guidelines, with the majority of authorities believing that there is insufficient information and/or expertise on techniques for seepage identification and measurement.

12.1.3 Trial Program

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 1-2 km).
- 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.

The following concluding remarks are made regarding each of the trialed techniques:

Pondage Tests: 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 conducted across all sites (totalling 81 ponds) returned seepage rates ranging from 0.1 mm/d to 48 mm/d. 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.

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 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.

Point Tests: 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).

Groundwater Techniques: 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.

Remote Sensing: Remote sensing techniques:

- Are best suited to investigations where the primary aim is identification of land degradation associated with channel seepage;
- Will be most useful where lateral seepage is predominant;
- Should primarily be regarded as a seepage identification tool and not for seepage quantification;
- Require a suitable spatial resolution to allow definition of seepage zones (< 10m suggested);
- Are best conducted in the infra-red range of the electromagnetic spectrum; and,
- Are generally best collected during late summer and early autumn.

Geophysical Techniques - These trials have demonstrated that geophysical techniques offer the best solution for rapid identification and measurement of channel seepage. They are well suited to use at an RWA level, in that they are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates.

Understanding of the application of geophysics to identify and measure channel seepage has been significantly advanced through these trials. In particular, progression in the following areas has been achieved:

- Understanding of the mechanisms by which geophysical techniques detect seepage. In particular the distinction between directly measuring seepage as it impacts the watertable and indirect measurement of unsaturated zone soil properties. This important distinction is not made in previous literature relating to geophysics and channel seepage.
- Identification of the best types of geophysical techniques for channel seepage assessment for different environments (with depth to watertable being the key variable influencing selection).
- Improved understanding of the key variables which impact on geophysical surveys.
- Identification of the best time to conduct surveys in terms of channel operation, most appropriate offset distance for surveys, and the suitability and accuracy of on-channel surveys compared to on-land surveys.
- Improved understanding of the repeatability of geophysical surveys.
- Understanding of the degree of accuracy that can be achieved using geophysics for quantifying channel seepage, and statistical assessment of this accuracy both at a local level and using a combination of the results to undertake a regional assessment encompassing a range of site conditions.

The most practical and useful output arising from the Stage 1 trials is a preferred methodology for using geophysics for identifying and measuring channel seepage. This is based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. This preferred methodology also includes a table to assist in selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

This preferred methodology is very similar in approach to recent international channel seepage research (Hotchkiss et al, 2001). This paper also describes the development of geophysical techniques that can be compared to some form of direct seepage measurement, derivation of a relationship between the geophysical response and measured seepage and then extrapolation to new areas. This independent and simultaneously conducted research confirms that geophysics is emerging as a widely regarded technique that is one of the best ways forward in terms of rapid and relatively cost effective identification and measurement of channel seepage.

Another key outcome arising from this work is the potential of on-channel resistivity for rapid seepage assessment. Surveys were conducted in the final year of trials at eight sites, and the results showed significant promise, with good correlations against pondage tests observed at most sites. The main advantage of on-channel resistivity over traditional electromagnetic techniques is that data is gathered at multiple depths beneath the channel, which enables a depth profile of conductivity beneath the channel to be developed. Not only does this have significant advantages in terms of output presentation and visualisation of seepage mechanisms, but importantly it means that the critical depth immediately above and below the watertable can be targeted. In contrast fixed array surveys, even when they are selected appropriately according to the watertable depth, provide a cumulative response from the surface depth interval and are less discriminatory in their measurement, allowing potentially greater error. Costs of resistivity are at present higher than EM surveys but are expected to decrease if this technique becomes more widely used (at present there are no commercial operators of this equipment on the market). More resistivity trials are needed to increase the existing data set upon which conclusions are based. One specific area requiring investigation is the issue of near surface resolution of the equipment, which effects accuracy in shallow watertable environments. It is anticipated that this could easily be resolved by varying the array spacing (from linear to exponential, with more closely spaced arrays near the boat).

One cautionary note is warranted regarding the use of geophysics for channel seepage assessment. The geophysical survey should be carried out by a suitably qualified contractor and the geophysical results should be interpreted with sufficient bore hole data, proper calibration against a direct seepage measurement techniques, should be interpreted by someone with relevant geophysical experience and if the results are to be used quantitatively, the seepage-geophysical relationship derived should be subject to proper statistical analysis, in order to determine the degree of confidence in the prediction equation.

12.1.4 Channel Seepage Guidelines

The guidelines for channel seepage measurement have been successfully completed, including industry review through a workshop process. The guidelines are a significant step forward in management of channel seepage issues. They provide RWAs with best practice procedures for identifying and quantifying channel seepage. They fill a gap in understanding in channel seepage assessment clearly identified in the national RWA survey (ANCID, 2000b). Through a circular six step process, the guidelines enable users to make a serious evaluation of suitable procedures which meet individual needs and objectives. The most significant aspect of the guidelines is their recommendation that, (for intermediate to large scale investigations), geophysical techniques offer the best solution for rapid identification and measurement of channel seepage for RWA purposes. They are fast and relatively cost effective, and when calibrated against direct measurement techniques can provide a reasonably accurate quantitative assessment of seepage rates. A preferred methodology for using geophysics for identifying and measuring channel seepage is outlined in the guidelines, based around calibrating geophysical data against a direct form of measurement (preferably pondage tests) and extrapolation to untested areas. The guidelines also provide information on selection of the most appropriate geophysical technique for a given site, based on depth to watertable.

The preferred methodology based on geophysical assessment outlined in the guidelines offers the potential for significant efficiency gains in channel seepage management. The procedure provides a basis for highly targeted channel seepage remediation initiatives, which have the potential to greatly improve the economics of remediation projects. These water savings will minimise the loss of a resource of which the real economic value is being increasingly realised, reduce contributions to groundwater recharge and associated land salinisation, and increase the available water which could be returned to the environment.

12.1.5 Terminology and Units Booklet

The ANCID *"Rural Water Industry Terminology and Units"* Second Edition booklet was updated with terms and units used in channel seepage, as well as other minor changes. It was completed and available in April, 2001 and formally released at the 2001 ANCID Annual Conference held in Toowoomba, Queensland. The document can be accessed and down loaded from the ANCID web site (www.ancid.org.au) and from the CD included at the back of this document. The booklet will continue to provide a valuable reference document to help ensure common terminology and units are used in the Australian rural water industry.

12.2 Recommendations

It is recommended that, for most investigations, RWAs should adopt the preferred technique as outlined in the conclusions of the *Documentation of Seepage Measurement Trials* Report (ANCID, 2003a) and the *Best Practice Guidelines for Channel Seepage Identification and Measurement* (ANCID, 2003b). This methodology relies on geophysics to identify seepage, and pondage tests and soil bores to calibrate and interpret the geophysical response. Although the Stage 1 project has resulted in this recommended assessment methodology, this does not mean that further research is not required in the area of geophysics. Key recommendations arising from the Stage 1 program are listed below, and they mainly relate to further refinement of geophysical techniques:

- *Development of a national database*. 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 distances 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.
- *Establishment of geophysics seepage relationship.* 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, greater numbers of pondage tests could be conducted which would significantly improve the regression equations resulting from these relationships.
- *Cheaper and more convenient way of calibrating geophysical surveys.* The main deterrent to RWAs from widespread adoption of geophysics is the operational inconvenience and expense of the pondage tests required to calibrate the geophysical survey. A means of calibrating geophysical surveys where pondage tests are extremely difficult or cannot be conducted needs to be explored. On small to medium channels where pondage tests cannot be conducted for operational reasons, point tests using the Idaho meter could be used, although this could be expensive to ensure proper calibration. For very large channels where pondage tests cannot be conducted due to the very high expense of bank construction, alternative means of calibration need to be devised. As described above, a cheaper means of bank construction (possibly using some type of transportable barrier) would greatly reduce the cost of pondage tests, as these represent a significant part of the costs.
- *Fine tuning of resistivity technique*. The resistivity surveys undertaken in the final year of the trials were the culmination of the geophysical investigations. 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.
- *Further testing of on-channel fixed array surveys*. 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.
- *Remote sensing trials*. Remote sensing trials 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.

- *Dissemination of results*. The key remaining part of Stage 1 is to ensure that the information in the guidelines is properly disseminated and marketed to RWAs. Given that the national survey (ANCID, 2000b) indicated that geophysical techniques are not currently widely used by RWAs for seepage assessment and they tend to use assessment techniques with which they are familiar, there will be significant inertia which must be overcome to get Authorities to change existing channel seepage assessment practices, which are not necessarily based on good science. The guidelines will need to be well distributed and promoted to achieve this change in direction.

13 References

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Appendix A Executive Summary from Literature Review

Executive Summary

The Australian National Committee of Irrigation and Drainage (ANCID), in conjunction with the Murray Darling Basin Commission (MDBC), have initiated a project to investigate channel seepage measurement. This report summarises the outcomes of a literature review into channel seepage identification and quantification, which is one part of the overall project.

Seepage Factors
There are many variables that have an influence on the loss of water by seepage from earthen irrigation channels. These factors act simultaneously and some are interacting so that it is difficult to segregate and separate the effects of individual parameters. The principal variables which influence seepage from irrigation channels can be grouped into three broad categories:

- Soil characteristics;
- Hydraulic characteristics such as depth of water in the channel, wetted perimeter of the channel and depth to groundwater; and,
- Channel water characteristics.

Soil characteristics – One of the most important characteristics influencing channel seepage is the permeability of the layers forming, or lying immediately below the wetted perimeter of the channel.

Hydraulic characteristics (depth of water in the channel, wetted perimeter of the channel and depth to groundwater) – Generally seepage losses increase with greater water depth in the channel and as the difference in elevation between water level in the channel and watertable increases (until an equilibrium is reached). The significant depth below the channel bed within which the nature of the soil affects seepage losses has been found to be approximately five times the bed width of the channel. Laterally, at a distance of approximately ten times the bed width of the channel, the effect of seepage losses on the original watertable elevation is minimal, although may vary depending on channel dimensions & local hydrogeology.

Channel water characteristics - Material suspended in channel water is carried by seepage water into the pores in the soil in which the channel is constructed. If the water contains considerable amounts of suspended material, the seepage rate may be reduced in a relatively short time. Even small amounts of sediment will have a sealing effect over a long period of time.

Primary Outcomes
The primary outcomes from the review are summarised in **Table E.1**. This analysis forms the principal starting point for ongoing investigations into channel seepage measurement. **Table E.1** provides a synopsis of the information provided by each technique and its application as either a:

- Primary technique (i.e., direct) for the quantification of channel seepage;
- Primary means of identifying (qualitative) areas where channel seepage occurs;
- Technique which provides a means of estimating channel seepage through a relationship with one other technique; or,
- Technique which provides a means of estimating channel seepage through a relationship with two or more other techniques.

■ Table E.1: Channel Seepage Assessment Summary Table

Technique	Direct Measure of Seepage	Indicator of Where Seepage is Occurring	Secondary Measure of Seepage	Tertiary Measure of Seepage
Inflow – Outflow	Requires very accurate flow measurements. Useful for long channel sections and indicative seepage assessment	NA	NA	NA
Pondage Test	Provides accurate measurements if conducted properly. Widely considered the standard for channel seepage quantification	Only useful for pinpointing seepage if pondage sections are very short	NA	NA
Point measurement (channel full & empty)	NA	Useful for identifying seepage 'hotspots' and relative seepage potential	Numerous tests required for accurate assessment – extrapolation required contains some inaccuracies	Can be used in conjunction with soil surveys and geophysical techniques to extrapolate seepage rates
Mathematical Modelling	NA	If full range of parameters collected, model will predict where seepage is likely to occur	Requires input from groundwater surveys and physical parameter testing, eg, hydraulic conductivity	NA
Soil Classification	NA	Correlations can be made between soil type and seepage potential – provide rough indication of high seepage zones	Can provide estimate of seepage rate if sufficiently strong relationship developed between soil type and seepage (eg pondage test, point measurement etc)	NA
Groundwater Techniques	Semi-direct method – only detects seepage which migrates to groundwater. Extrapolation required along channel length	Changes in groundwater level can provide indication of significant seepage points	Only detects seepage which migrates to groundwater: requires inputs of aquifer hydraulic properties	NA
Geophysical Techniques	NA	Resistivity, Electromagnetics and Self Potential have best demonstrated history of channel seepage detection	Can provide an estimate of seepage rate provided a sufficiently strong relationship can be developed between geophysical response and pondage tests	Can provide seepage estimate provided sufficiently strong relationship can be developed between geophysical response and secondarily measured seepage, eg, soil type, point measurement etc
Remote Sensing	NA	A primary means of identifying seepage sites – air photos and thermal infrared most applicable	NA	NA
Hydrochemical / Isotopic Mass Balance	Combined with pondage tests provides an accurate direct measure of seepage but only useful in low (< 20 mm/d) seepage rate environments	NA	NA	NA
Tracing Leaking Plume	Semi-direct method - only detects seepage which migrates to groundwater. Many bores required to adequately define seepage plume	Provides an indication of seepage flow paths	Only detects seepage which migrates to groundwater: requires aquifer hydraulic properties and water chemistry input	NA

Overview of Techniques

A comprehensive review of the literature has identified nine different techniques which are considered useful for channel seepage quantification or identification. **Table E.2 a-c** summarises the key aspects of each technique, including the basic theory behind the technique, advantages, disadvantages and a summary assessment of the technique.

Table E.2a: Summary of Techniques Assessed – Direct Measurement & Point Tests

Technique	Principle	Significant Advantages	Significant Disadvantages	Summary Assessment
Direct Measurement Inflow-Outflow	Based on water balance approach. Method consists of measuring water flowing into and out of channel section. Difference between quantities of water flowing into and out of section is attributed to seepage, after accounting for inflows and known losses (eg, evaporation). Accuracy depends on accuracy of inflow and outflow measurements.	☐ Only method which reflects actual operating conditions ☐ Has a sound physical basis (mass balance) and requires few assumptions ☐ Permits measurement without interruption to system	☐ Difficult to obtain flow measurements of sufficient accuracy ☐ Determining potential inflows-outflows between gauged sites is difficult ☐ Must be conducted over relatively long sections and therefore does not provide an indication of spatial variation of losses	Best suited to long sections of channel which contain appreciable seepage, from which there are no diversions, and which contain suitable structures to incorporate measuring devices. When conducted properly, this method can be considered fundamentally the most direct, and potentially accurate method available.
Pondage Tests	Applies a water balance to an isolated reach of channel to determine seepage losses. Seepage losses constitute the drop in water level over time in the channel (or volume added to maintain a constant level) after accounting for evaporation and rainfall.	☐ Universally considered the most accurate way of determining channel seepage ☐ Test procedures relatively simple and do not require highly skilled personnel ☐ Can be used on both lined and unlined channels.	☐ Channel must remain out of use during tests ☐ Installation cost of embankments to isolate reaches of the channel can be high ☐ Conditions do not reflect velocities and sediment loads of operating conditions ☐ Does not provide indication of spatial variation of losses within the reach isolated	Widely considered the most accurate means of measuring channel seepage - regarded as the best technique against which other methods can be assessed. Main difficulty is that the test must be conducted outside of normal channel operation, and non-flow conditions introduce some inaccuracies.
Point Measurement (Channel Empty and Channel Full)	Point measurement refers to any technique which measures infiltration / hydraulic conductivity at a given point, usually involving the application of water to the surface or hole within the channel and measurement of the rate at which it drains away.	☐ Provides an indication of the distribution of losses along the channel ☐ Generally relatively quick to conduct ☐ Can be used to identify where in the channel cross section seepage is occurring ☐ Relatively cheap compared to other methods of seepage measurement.	☐ Majority of literature concludes these techniques are not reliable for direct quantification of channel seepage losses ☐ A high percentage of seepage occurs through a relatively small percentage of the channel. Therefore many point measurements are required to obtain a reliable estimate of the mean.	Point tests are best suited for determining the distribution of seepage losses (i.e., relative seepage). Due to variable and sometimes erratic values obtained in measurements and the large number of tests required to sufficiently determine the average seepage rate, they are not considered reliable for absolute quantitative purposes. Often used in conjunction with soil surveys to assign a seepage rate to a particular soil type.

■ **Table E.2b: Summary of Techniques Assessed – Mathematical Modelling, Soil Classification and Groundwater Techniques**

Technique	Principle	Significant Advantages	Significant Disadvantages	Summary Assessment
Theoretical Mathematical Modelling	Theoretical mathematical models use equations based on the physics of unsaturated and groundwater flow to predict seepage rates. Inputs generally required to these equations include: channel characteristics, watertable elevations, soil and aquifer characteristics, and the hydraulic conditions under which seepage occurs. The accuracy of the modelling depends largely on how well the soil, watertable and boundary conditions can be characterised.	☐ Reflects actual operating (dynamic) conditions ☐ Does not interrupt channel operation ☐ Allows for seepage prediction ☐ Accounts for the significant effect of hydrogeology on seepage processes ☐ Provides an understanding of the seepage process	☐ Detailed field work required to characterise flow paths and hydrogeological conditions involves considerable time, expense, and expertise. ☐ Amount of data required to adequately characterise a reach often renders this technique impractical for most purposes.	Theoretical mathematical models have been found to yield reliable estimates of channel seepage, when the required field data is collected. The technique is best suited for seepage prediction purposes, such as seasonal variation, variable operating conditions or changed groundwater conditions. Modelling of channel seepage may be useful in intensive site investigation studies.
Soil Classification	Soil type is one of the most influential variables effecting seepage rate. This method assumes seepage is primarily a function of hydraulic conductivity, which is in turn a function of the soil texture. Soil categories (based on texture) are assigned seepage rates - based on the distribution of soils within a channel the total seepage rate for a section can be calculated. The approach can be applied at a regional scale, using existing soil maps and published seepage rate data, or at a local scale, using field tests to determine seepage rates and local mapping of soil types.	☐ Is based on one of the most influential variables upon which channel seepage is based ☐ Relatively quick and cheap ☐ Seepage losses over a large region can be estimated.	☐ Other significant factors influencing seepage are not allowed for (eg, groundwater levels, clogging layer at channel surface) ☐ Seepage rates within the one soil type can vary significantly ☐ Many measurements required to obtain reliable estimate of mean hydraulic conductivity of a particular soil type - may lead to under-estimation of seepage	The regional approach to estimating losses based on published seepage rate data for a given soil type is a useful method for providing a first cut estimate of seepage losses from a system. However accuracy is likely to be relatively low. A local approach involving an actual soil survey of the channel and an attempt to calibrate soil types based on point or pondage tests is likely to significantly improve the accuracy of this technique.
Groundwater Techniques	Observation of groundwater levels in a series of piezometers located at right angles to a channel can be used to estimate seepage by subtracting groundwater flow before channel influence from groundwater flow after channel influence. The seepage rate can be estimated from groundwater flow equations, provided the hydraulic conductivity (K) of the aquifer is determined with sufficient accuracy.	☐ This method is a semi-direct measurement of channel seepage – it measures all channel water which seeps to the groundwater ☐ Provides a permanent tool for seepage measurement ☐ Can be used for post remediation seepage analysis. ☐ After capital outlay ongoing costs are minimal	☐ Installation of groundwater bores can be expensive ☐ Seepage rate will be sensitive to K, which can be difficult to accurately determine and may require specialist technical input ☐ Extrapolation of results from one transect of bores assumes K is uniform along the channel ☐ Requires estimate of pre-channel groundwater levels which may be difficult to obtain	The attraction of this method is that it provides a permanent seepage assessment tool, which amongst other things is useful for assessment of the effectiveness of remedial measures. The main shortfall of the method is that it is concentrated on a slice across the channel, which may not be representative of broader conditions. Installation of numerous transects to improve accuracy will be expensive. The method may not be appropriate where a significant percentage of the seepage does not reach the groundwater.

■ **Table E.2c: Summary of Techniques Assessed – Geophysical Techniques, Remote Sensing and Hydrochemical and Isotopic Methods**

Technique	Principle	Significant Advantages	Significant Disadvantages	Summary Assessment
Geophysical Techniques	Use of geophysical methods to detect channel seepage is essentially based around the detection of differences between: • Salinity of groundwater and the generally fresher channel water; • Soil moisture content; and, • Soil type. Detection of seepage can be achieved with geophysical techniques alone, however quantification requires integration of geophysical methods with other techniques, in order to calibrate the results.	☐ Some geophysical techniques offer potentially the fastest means of seepage assessment ☐ Can provide continuous spatial assessment ☐ Does not interrupt channel operations ☐ Costs should continue to come down as new procedures emerge ☐ With adequate local calibration can provide a reasonable estimate for seepage quantification	☐ Interpretation can be difficult and will vary from area to area ☐ Interpretation may require subsurface investigation ☐ Can be relatively expensive ☐ Technical expertise may be required to conduct and analyse survey results	Use of geophysics for channel seepage assessment is an emerging area. The attraction of these techniques is the potential for rapid assessment of long channel sections, however care needs to be taken in the interpretation of results. While there are several examples of geophysical techniques being used for detection of high seepage zones, references to use for quantification are scarce. However, provided results are locally calibrated, seepage quantification from geophysical techniques is possible.
Remote Sensing	Remote sensing techniques for channel seepage detection assumes seepage has a surface expression adjacent the channel, and are based around the difference between the properties of moist and dry soils, or differences in vegetation density or health. The part of the electromagnetic spectrum most useful for seepage detection are the near infrared (NIR) and thermal infrared (TIR) wavelengths.	☐ Potential for rapid assessment of large areas of channel system ☐ Does not interfere with channel operations ☐ Costs likely to come down and resolution likely to improve as the technology develops	☐ Relatively expensive ☐ Requires specialist technical input at the data gathering, processing and interpretation stages ☐ Sites which have moist soils not caused by seepage are likely to be identified as seepage sites (eg, drainage lines, topographic lows etc) ☐ Seepage only detected if has surface expression.	Remote sensing techniques offer considerable potential for rapid identification of seepage zones (but not quantification). A drawback is that it assumes seepage will have a surface expression as moist soil or associated vegetation adjacent the channel. However, it offers a promising means of providing a first-cut identification tool for targeting potential seepage sites. To be cost effective needs to be conducted at a suitably large scale
Hydrochemical and Isotopic Methods	There are two ways hydro-chemistry / isotopes may be used for channel seepage assessment: *Mass Balance* A hydrochemical / isotopic mass balance approach, relies on measuring the concentration of a conservative chemical or isotope (tracer) in the channel water and in the other inflow and outflow components. The method combines the use of a water balance and chemical / isotopic mass balance (i.e., 2 equations) allowing estimation of two unknown components (seepage plus either inflow, outflow, evaporation or rainfall). *Tracing the Seepage Plume* This method uses the hydro-chemical / isotopic concentration of seepage water to define a volume of water that has escaped from the channel over a known period of time. (i.e., rate = volume / time)	*Mass Balance* ☐ Seepage rate plus another component can be calculated – if a component of the water balance is not well known (eg, evaporation or inflow) this can be considered a variable during the method (i.e., allows a check on the mass balance) *Tracing the Seepage plume* ☐ Provides an indication of seepage flow paths, assist in determining the area affected by seepage ☐ Small scale & short time interval trials using enriched isotopes can be used to investigate spatial variation in seepage – provides a duplicate estimate of seepage (water balance & mass balance)	*Mass Balance* ☐ Mean residence time of channel water is too short for conventional use of this method. ☐ Even when combined with PTs, little to be gained when compared to simple water balance approach, except when seepage rates are low ☐ It may be difficult to pond the channel for sufficient time. *Tracing the Seepage plume*] Large no. piezometers required to define plume Mixing occurs between seeped water & groundwater making plume volume estimation difficult High chemical/ isotopic sampling / dosing costs. High degree specialist technical input required	*Mass Balance* The traditional hydrochemical / isotopic mass balance approach is unlikely to have significant application to channel seepage measurement due to relatively short time of residence of water in the channel. Some potential for use of this method under PT conditions if seepage rates are low. *Tracing the Seepage plume* Use of naturally occurring tracers may be valuable if information is obtained on the seepage plume over a sufficiently long time period, and an area large enough to account for spatial and temporal changes in seepage. CFC dating of gw has the most potential, as this detects relatively recent seepage. Major disadvantage with artificially increased tracers is high cost of doping the water. Best use of enriched isotopes may be at a small scale and time intervals, to investigate spatial seepage rate variation.

Appendix B Executive Summary from Rural Water Authority Survey

Executive Summary

The Australian National Committee of Irrigation and Drainage (ANCID), in conjunction with the Murray Darling Basin Commission (MDBC), have initiated a project to investigate channel seepage measurement. This report summarises the outcomes of a survey of 41 rural water authorities (RWAs) representative of the rural water industry in Australia (24 of the 41 surveys were useful for analysis purposes). The key outcomes from the survey are summarised below.

Water Supply, Size of Channel Network and Seepage Rates

- The majority of rural water authorities surveyed supply less than 100 GL/yr.
- On average, 17.5% of released water is lost through unaccounted for processes.
- On average 4% of total water supplied by all RWAs surveyed is estimated to be lost via seepage.
- An estimated 320 GL of water is lost each year from the authorities surveyed.
- The average length of earthen channel per GL of water supplied is 3.85 km. This result is skewed, however, by one RWA which has 54 km channel / GL supplied. When this result is removed the overall average drops to 1.45 km / GL water supplied.

Significance of Channel Seepage

- Two-thirds of all authorities surveyed have a reasonable or higher confidence in their estimate of seepage.
- Of the authorities surveyed, 42% rate channel seepage as a high or very high priority.

Channel Seepage Costs & Issues

- Measurement of channel seepage is most commonly considered the area where additional resources need to be applied.
- 25% of authorities have undertaken assessment of seepage at 3 or more sites.
- 50% of authorities have undertaken no on ground seepage measurement works at all.
- Extensive seepage investigations are generally only undertaken by water authorities delivering greater than 160 GL/Yr.
- There is a weak correlation between increased investigation and higher confidence in channel seepage estimates.
- The priority given to channel seepage appears dependent mostly on the perceived cost of the impacts of channel seepage
- Loss of water is considered the most significant cost consequence of channel seepage
- It is estimated that 46% of authorities do not know the extent of land degradation associated with channel seepage. A further 25% believe it to be less than 1 Ha.
- Of the authorities surveyed, 16% indicated that they are spending more on channel seepage identification, measurement and remediation than the estimated cost of water lost and other impacts of seepage from the channel.
- The average expenditure on channel seepage identification, measurement and remediation is approximately 60% of the estimated cost of water lost and other impacts of seepage from the channel
- Remediation works accounts for 61% of the monies spent on channel seepage, with monitoring and investigation contributing 35%.

Channel Seepage Measurement Techniques

- Cost and speed are considered the most important criteria in channel seepage assessment.
- Technical accuracy is considered of lesser importance.
- Seepage identification (visual, piezometers) rather than quantification techniques dominate channel seepage assessment methods.

Channel Seepage Remediation

- The majority of authorities do less than 5 km of remediation works per year.

Demand for Guidelines

- The majority of authorities believe that there is insufficient information and/or expertise on techniques for seepage identification and measurement.
- There is a strong demand for guidelines on channel seepage identification and measurement

A significant feature of the survey results was the apparent inconsistencies within and between surveys. This suggests that understanding of channel seepage issues and the approach to addressing them is ad-hoc for many authorities. Perceptions of seepage loss rates were often unsupported by seepage assessment studies. In addition a significant number of authorities who were undertaking assessment were finding that their assessment was not improving their confidence is seepage estimates. This suggests a lack of direction in the application of assessment methodologies.

Channel seepage remediation projects are often undertaken without quantitative analysis of seepage. The failure to clearly establish cost-benefit aspects of remediation contradicts the priority that the value of water lost is the major motivator for channel seepage investigations. The reliance on qualitative techniques such as visual inspection and piezometric surveys confirms this inconsistency. This is further supported by 70% of RWAs who acknowledge that there is insufficient information and expertise to assess channel seepage. However a clear outcome of the survey was the desire of RWAs to overcome these knowledge gaps and develop a more systematic approach to channel seepage assessment.

Appendix C Executive Summary from Documentation of Seepage Measurement Trials

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:

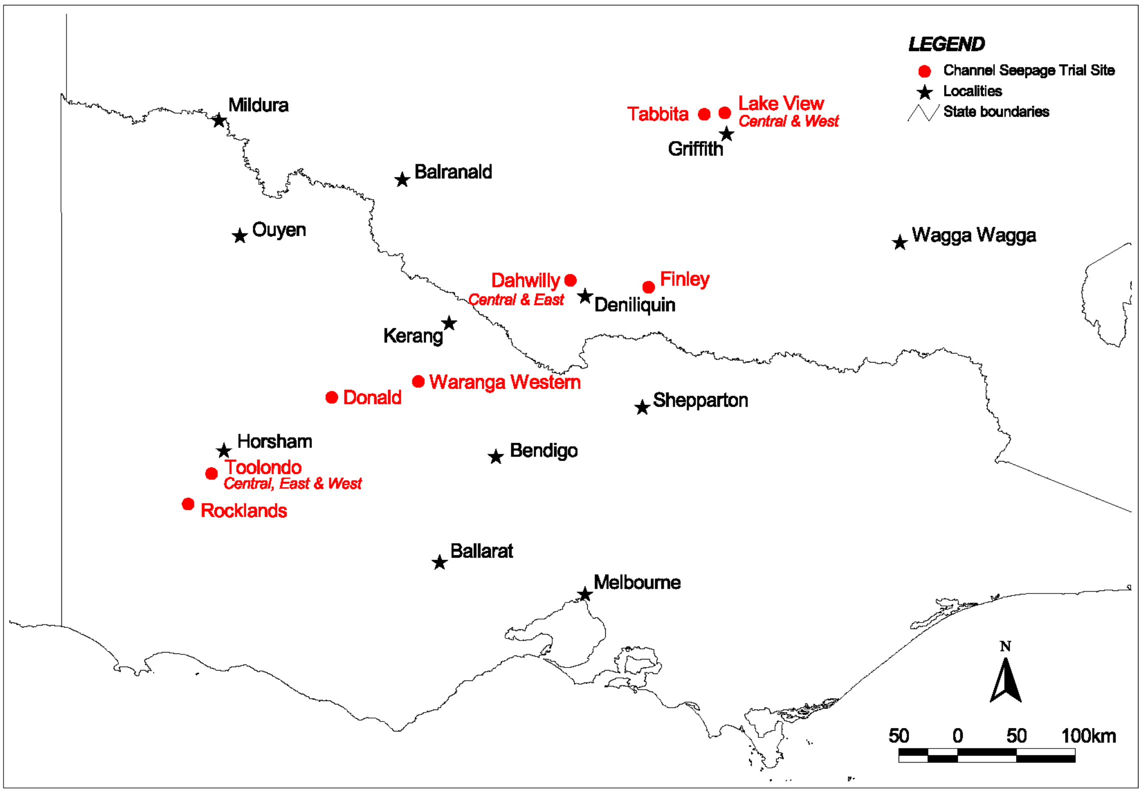
- Identification of test site locations;
- Gathering available information on test sites;
- Measuring rates of seepage at test sites using direct measurement techniques - pondage tests were used for this purpose;
- Comparison of the direct measurement technique with indirect techniques; and,
- Extrapolation 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**			**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. 0	-	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 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

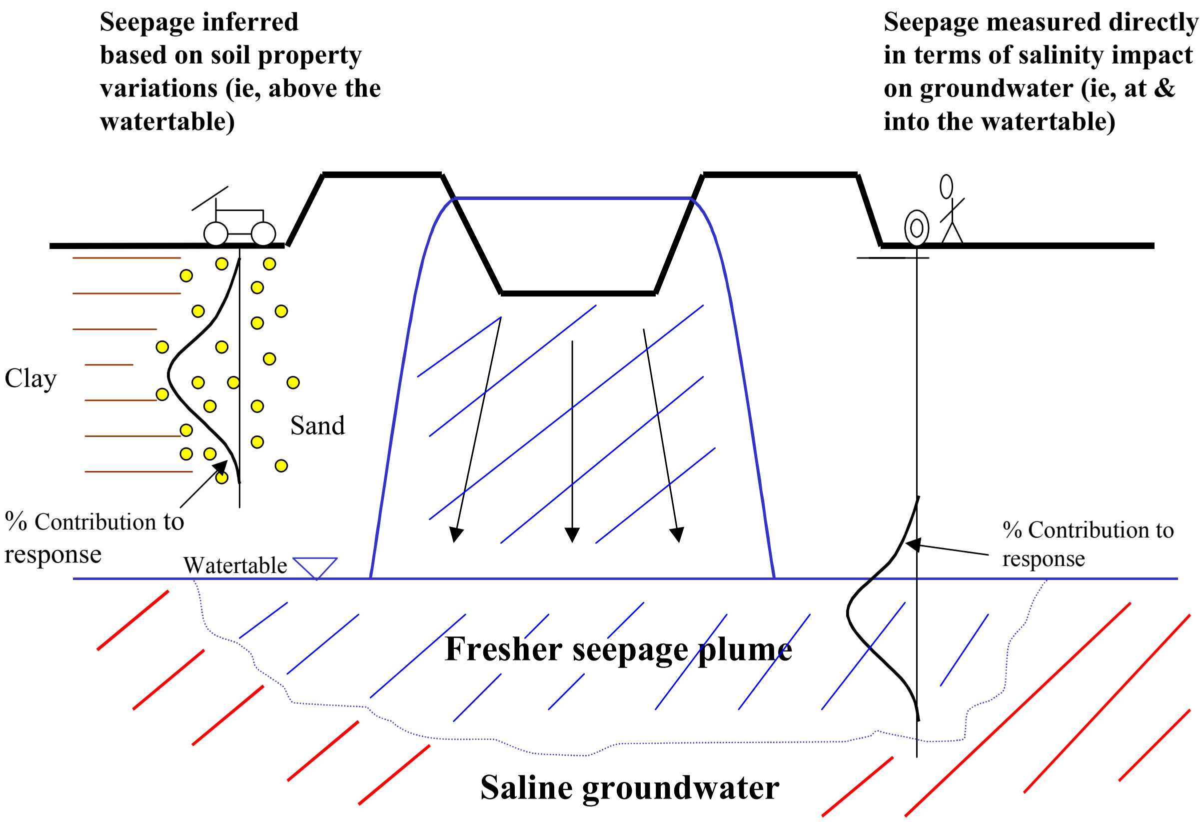
Geophysical techniques applied to seepage measurement primarily depend upon measuring a contrast in terrain conductivity (or resistivity) in the sub surface profile around the channel. They can be used in one of two ways:

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 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.

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. 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 in a channel seepage investigation. 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.

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.

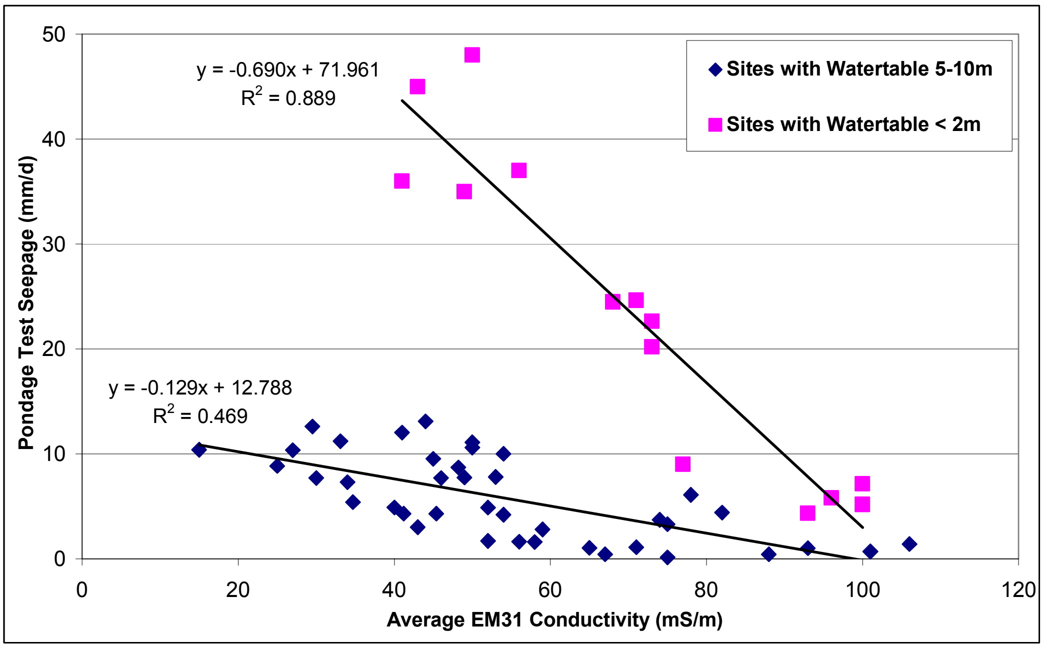
Based on distinct trends between sites with shallow and deeper watertables, the sites were split into two data sets based on depth to watertable, in order to improve the accuracy of the fitted regression model. This is most clearly illustrated in Figure E-3, which shows EM31 data for all sites divided 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. (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.

- **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:

3. *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.
4. *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:

6. *Define project objective* – The key issue that needs to be addressed is identification of the primary reason the work is being undertaken.
7. *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.
8. *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.
9. *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.

10. *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.

7. *Evaluation* – Evaluate whether investigation objectives have been met.

- **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]

Watertable Depth (m)	Recommended Technique [1]	Detection Method[2]	Approximate Depth of Penetration (m)[3]	Depth Focus (m)[4]
	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. 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 (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 fixed depth focus).

International Developments in Geophysics and Channel Seepage Measurement

Since the writing of the Literature Review conducted as part of this project (ANCID, 2000a), a US paper was published relating to international developments in channel seepage measurement using geophysics (Hotchkiss et al, 2001). The paper describes work which 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.

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 soil properties in the unsaturated zone.

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, 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 have dominated 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.

Appendix D Executive Summary from Guidelines for Channel Seepage Measurement

Executive Summary

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:

- The loss of an economically valuable resource;
- Management of channel assets;
- The contribution to groundwater recharge, associated induced water logging and land salinisation which affects the environmental and community amenity; and,
- The need to retain more water within our waterways to halt environmental decline.

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). This document outlines guidelines for improving channel seepage management by providing water supply agencies with knowledge and techniques to identify and measure seepage from earthen channels.

The guidelines are intended to be for practical use in undertaking channel seepage investigations across the Australian water industry. They are prepared as a tool for engineers and field technicians for Water Authorities to select and apply techniques appropriate to their particular channel system. The guidelines are to be linked to the channel seepage user support system (in progress) which provides a structured management tool for channel managers.

The guidelines are prepared in two parts. Part 1 provides background to the project, information on how the guidelines were derived and presents a six step process identifying the key factors that need to be addressed when undertaking a seepage measurement investigation. It also introduces recommended generic investigation procedures for channel seepage assessment. Part 2 describes the operation and evaluation of a range of the key techniques considered to be most applicable to Australian channel operators.

PART I

Derivation of Seepage Measurement Guidelines

To develop guidelines for application across the Australian Water industry, an extensive program has evaluated existing knowledge of seepage identification and measurement from a review of national and international literature (ANCID, 2000a), the practical experience of water authorities (ANCID, 2000b), and three years of field trials assessing a range of different techniques (ANCID, 2003a).

These investigations have shown that there are some basic parameters affecting the location and rate of channel seepage, how it impacts local amenities and how it can be remediated. These are related to the soil and water conditions in the vicinity of the channel and the mechanisms by which seepage occurs. These factors have been an important input to the development of these guidelines. In addition, the extent of the seepage is a fundamental factor in the approach to identification and measurement of seepage, and therefore scale is a necessary consideration in the guidelines.

The particular physical factors affecting seepage from earthen channels are, soil characteristics, hydraulic and channel water characteristics. It is also important to understand the seepage mechanism and the resultant impacts. Seepage from earthen channels can be dominantly horizontal or vertical, or a combination of the two. Basic understanding of site conditions can be used to derive some idea of the mechanism which can provide a guide to the investigation technique to be applied.

The scale of the investigation is also an important factor. Scale should be considered when management needs for undertaking the project are being evaluated and they are to be reconsidered in finalising the selection of the technique. Three scales of investigation are considered appropriate in the selection of a technique:

- Local Scale: Short (up to 400m in length);
- Intermediate to Large Scale: Hundreds of metres to tens of kilometres; and,
- Macro Scale: Tens of kilometres to entire systems.

Approach to Seepage Measurement Investigations

These guidelines are designed to enable users to make a serious evaluation of suitable procedures which meet individual project needs and objectives. They are based around the need to generate the detailed knowledge required to undertake measurement of seepage and how to interpret the results to meet a channel management objective. It is a circular process involving the following six key tasks:

TASK	ACTIVITY
1. Define Objective	Understand the reasons for doing the investigation.
2. Collate Site Physical Condition Data	Collate key data affecting channel seepage.
3. Assessment of Site Conditions	Understand the conditions at the site.
4. Selection of Measurement Techniques	Select the appropriate measurement technique for the conditions and for the problem.
5. Implementation of Tests	Conduct tests and estimate seepage rates and distribution.
6. Interpret Results	Evaluate if the test results answer the question raised in the management process, ie, meet the defined objective.

Recommended Procedures

The RWA survey conducted as part of the Stage 1 ANCID channel seepage investigation identified that RWAs consider cost and speed of investigations to be the most important criteria in channel seepage assessment. This was a guiding factor in development of the trial program and the recommended techniques described in these guidelines. However, circumstances for specific investigations will vary and the best results will be obtained when the technique used is appropriate for the particular investigation. Therefore it is recommended the six step process described above be adopted in selecting the test(s) to be conducted. A fundamental issue related to the selection of the technique is the scale of the investigation. These guidelines therefore present separate procedures for:

- Local scale or specific sites where the focus may be on addressing a particular previously identified issue; and,
- Larger scale investigations where business objectives suggest a need for investigation even though the specific distribution and rate of seepage is not known. This may form the basis for more detailed investigation at a later date.

Local Scale Investigations
The types of techniques which would be used in local investigations will depend on whether there is a need for measurement of seepage rates at specific locations or if there is the need to map zones of higher permeability and then identify the rates. For measurement of seepage rates at pre-determined sites the likely techniques which could be considered are:

- Point tests;
- Groundwater monitoring (and potentially modelling); and
- Pondage tests.

If there is a need for mapping of zones of relative seepage or potential seepage, there is a need to use a tool such as geophysics, and sub-surface methods such as geological profiling and groundwater observations, as well as surface observations. Estimates of the rate could then be undertaken with those techniques listed above, once the mapping is complete.

Intermediate to Large Scale Investigations
The trials conducted in this study indicated that for most channel seepage projects at intermediate to large scale, the most appropriate approach is to:

- Rapidly and cost effectively identify zones of highest seepage by a mapping process such as geophysics or remote sensing. Geophysics is the preferred technique in most situations.
- Quantify the seepage rate, preferably using pondage tests, although for particular purposes point tests or groundwater investigations may be undertaken.
- Extrapolate the results to areas beyond the test sections to the length of channel of interest. This involves being able to compare the conditions at the test sections with the broader area of interest.
- Where possible undertake a verification using a water balance (eg, inflow – outflow) along the length of interest.

This provides a rapid and relatively inexpensive routine technique which provides an indication of the extent and magnitude of seepage along a channel. It can be applied at any scale. It becomes more cost effective with larger lengths of channel and there is also more opportunity for meaningful verification.

PART II

Part 2 of the channel seepage measurement guidelines provides a description of how to go about conducting seepage measurements using the techniques considered most relevant to Australian conditions and operations. The techniques are grouped into the following categories:

- Direct and Point Measurements;
- Subsurface Characterisation; and

- Remote Non- Invasive Techniques.

Table E-1 presents a summary of these techniques. Each technique is discussed in terms of:

- Principle
- Methodology
- Applicability
- Practical Implementation
- Indicative Costs

Table E-1: Summary of Seepage Measurement and Identification Techniques

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
Inflow-Outflow	The Inflow-Outflow method is a direct measurement of losses. It is based on a water balance approach measuring water flow at either end of a channel section, taking into account additional inflows and losses along the investigated length.	The method is based on selecting a channel or length of channel and measuring the rates of water flowing into and out of the section. The difference between inflow and outflow is attributed to seepage, after accounting for inflows (eg rainfall) and known losses (eg, evaporation). Accuracy in the results depends on accuracy of inflow and outflow measurements, including flow, rainfall, evaporation and diversions from the channel. Discharge measurement can be conducted using a number of techniques. The two most common include: ❑ A current meter to determine the average velocity. (Discharge equals average velocity multiplied by the cross sectional area). ❑ Flumes or weirs with automatic recording gauges	The method is often used to provide a first cut estimate of seepage losses in a system. The accuracy decreases as the percentage of flow which is lost to seepage decreases. The inflow-outflow method can be conducted at various scales, from an entire irrigation system, to an isolated section of channel. However, measurements are suited to long sections of a channel which contain appreciable seepage, from which there are no diversions, and which contain suitable structures to incorporate measuring devices. It can assist in setting priorities for detailed seepage assessment of one channel over another, but not for prioritising sections of channel (down to km scale).	It is often difficult to obtain flow measurements of sufficient accuracy, particularly for short sections of channel, channels with low flows or low seepage rates. The feasibility of keeping levels in the channel constant for the duration of the test also needs to be assessed. There is the need to determine potential inflows and outflows between gauged sites, which may be difficult.	If existing structures are already in place for measuring flow to a suitable level of accuracy, then costs will be minimal. However, if flow is required to be measured using the velocity – area method of assessment, then contractors are likely to be required. As an indication of ballpark costs, a recent inflow-outflow test conducted by a contractor for an RWA in the Murray Basin was $7,000. This was conducted on a 5 km section of channel over a period of two days.
Pondage Tests	A pondage test uses a water balance to determine seepage losses in an isolated reach of channel. Seepage losses constitute the drop in water level over time in the pond after accounting for evaporation, rainfall and	The method relies on the construction of pond banks within a section of channel. The exact location of the banks depend on the project objectives, and ideally could be based upon the results of other work such as geophysical surveys, soil mapping, anecdotal information etc. Existing structures suitable for forming a sealed barrier should be utilised where	Pondage tests provide accurate measurements and are widely considered the standard for channel seepage quantification. As pondage tests are the most accurate means of measuring channel seepage they are the best technique against which other methods can be assessed.	The main difficulty with pondage tests is that the test must be conducted outside of normal channel operation, and non-flow conditions introduce some inaccuracies. This means that: ❑ The channel must	The most significant cost of pondage tests is the bank construction – this cost will vary considerably depending on the availability of a suitable clay source. During the trials (for channels between 10-20m width and 1.5-2m deep),

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
	any other inflows or outflows.	possible to minimise the number of barriers required to be constructed. To conduct a pondage test a section of channel is blocked off with embankments at each end, and the section filled with water to the level at which it usually flows during operation. Water level decline is measured by a staff or hook gauge, or water level recorder. The time between measurements is also recorded, necessary corrections for evaporation and rainfall made, and the resulting seepage loss rate computed.	The two main issues limiting the usefulness of this technique are the inconvenience of conducting outside of channel operation and the cost of bank installation. Conducting tests at the end of the season is generally most convenient. Pondage tests are probably the most useful (and accurate) post-implementation measurement technique. The only difficulty may be in obtaining a suitable seal between banks and remediated sections.	remain out of use during tests ❑ Installation cost of embankments to isolate reaches of the channel can be high ❑ Conditions do not reflect velocities and sediment loads carried during normal channel flow conditions ❑ The result does not provide an indication of the spatial variation of losses within the reach	bank construction and removal costs ranged from \$560 to \$1000 per bank. Other costs include cross-section and hook gauge surveying: surveying costs in this study for 6 cells (every 200m) ranged from \$600 to \$2000. Daily monitoring is required and can be conducted by RWA staff.
Point Measure-ment	A point test refers to any technique which measures seepage at a given point. It usually involves the application of water to the surface or hole within the channel and measurement of the rate of water loss.	Point tests can be undertaken when the channel is either operating or not running, depending on the particular technique used. To obtain a broad coverage of the infiltration variability, many point tests are usually required. In Australia, the techniques most applicable to channel seepage measurement are: ❑ Idaho Seepage Meter (operating channel) ❑ Ring Infiltrometers (channel empty) ❑ Disc Infiltrometer (channel empty)	Point tests are not sufficiently reliability for absolute quantification of channel losses due to the variable nature of (soil/channel bed liner) and are best suited for determining the distribution of seepage losses (ie. relative seepage), and then generally over short lengths of channel (eg defining a hotspot). ❑ Typically a high percentage of seepage occurs through a relatively small percentage of the channel. Therefore numerous point measure-ments are required to obtain a reliable estimate of the mean. ❑ To obtain reliable results,	Seepage meters should be installed with the least possible disturbance of the bed material Many measurements are required to obtain a reliable estimate of the mean so that the point test method requires a large number of tests to obtain a representative seepage rate over a given length of channel	Generally point measurement techniques will need to be conducted by an operator, with suitable expertise in the equipment being used. The greatest variable influencing the cost of point measurement is the density of testing. Sub-contractor costs for infiltration tests conducted during the ANCID study are provided as a rough guide to cost estimation: *Idaho Seepage Meter* - 22 sites (4 individual tests

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
			tests usually require a skilled operator/technician ❑ Not practical for post-remediation measurement		at each site, over the channel cross section): $6,200. *Ring Infiltrometer*: 29 individual tests: $5000. *Disc Permeameter:* 24 individual tests: $4000.
Subsurface Character-isation	Soil type is one of the most influential variables effecting seepage rate. Using soil and geological information to assess actual or potential seepage assumes that seepage is primarily a function of hydraulic conductivity, which is in turn a function of the soil texture.	Sub-surface profiling of soils and geological conditions can be conducted in a channel seepage investigation for various reasons, including: ❑ As part of site characterisation ❑ To help define seepage mechanisms; and / or ❑ To assign seepage rates to soil types and hence estimate seepage through changes in soil type Soil and geological profiling can be undertaken by limited review of available data from soil and geological maps. Sub-surface profiling on a site specific basis requires site inspection, local mapping of soil types and drilling. Key issues to be addressed in developing a drilling program for a channel seepage investigation are where and how many bores to drill, type of drilling to use, what depth to drill to, and how to log recovered materials.	Using soil and geological profiles in channel seepage investigations is valuable in providing a picture of the conditions where seepage is more likely to occur, but on its own will not provide estimates of seepage rates. Estimating losses based on application of a seepage rate for a given soil type is a useful method for providing a first cut estimate of zones of seepage loss from a system. Care should be taken in interpretation, in that: ❑ Seepage rates within the one broad soil type can vary significantly ❑ Many measurements are required to obtain a reliable estimate of mean hydraulic conductivity of a soil type. ❑ Significant factors influencing seepage are not allowed for (eg, ground-water levels, clogging layer at channel surface)	Regional scale maps are readily available over most areas to obtain general knowledge of site soil and geological properties. However care has to be taken if investigations rely only on these maps because of the details of map scale. ❑ Drilling of soil investigation bores should be undertaken with: suitable drilling equipment, able to penetrate to the required depth. ❑ Qualified drillers, preferrably with knowledge of local conditions should be used	Costs of drilling of soil bores will vary considerably depending on the type of drilling contractor / drilling rig used and whether an additional person is on-site for logging of the bores. For rough estimation of costs, a rate of $40-$50 per metre for soil bore drilling could be used. For groundwater observation bores the costs can range from an indicative cost of around $70/metre to around $120 per metre (excluding mobilisation).
Ground-	The use of groundwater	There are three ways in which groundwater	Groundwater techniques are	Groundwater bores are	The costs of drilling and

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
water Assessment	assessment to identify and estimate channel seepage is based on the principle that if water is introduced to a soil profile and reaches the watertable, there will be changes in the hydraulic and chemical conditions within the aquifer. When compared with channel running times, the trends in the ground-water levels can provide an indication of seepage, and it may be possible to estimate seepage rates. Groundwater bores also provide a permanent record of aquifer response to seepage, which can be useful for post remediation seepage analysis.	information can be used: ❑ Identifying seepage using water levels in groundwater monitoring bores ❑ Calculating seepage rates using analytical and numerical techniques ❑ Using the chemical properties of the channel water and groundwater to identify the extent and rate of seepage All methods or combinations of methods are based around the establishment of a representative monitoring bore network to provide access to the groundwater system. Groundwater assessment is generally best conducted using a series of piezometers located at right angles to the channel. The quantity of seepage can be calculated from the water level information when the hydraulic conductivity of the aquifer is determined. Quantification of seepage rates can be done by using simple analytical equations or in some circumstances by using complex numerical groundwater models. Simple analytical approaches to seepage quantification such as these are difficult because they generally require assumptions on the general properties of aquifers, and the impact of thin low permeability sediment channel sediments cannot be easily accounted for. However for relative estimates they may be useful. Groundwater modelling can incorporate all of the factors which affect seepage into the analysis and is valuable if there is a need to understand the details of the flow	applicable for both the identification and quantification of seepage. They are mostly applicable, especially when attempting any quantification, at local scale investigations. The advantages in applying groundwater techniques to seepage assessment include: ❑ They reflect actual operating (dynamic) conditions and provide a direct identification of channel seepage – it measures all water which seeps to the groundwater ❑ Observation bores provide permanent tools for measuring the effects of channel seepage and can be used for post remediation seepage analysis ❑ Channel operations are not interrupted ❑ All sizes of channel can be studied ❑ Allows assessment of time variability in seepage impacts under varying channel operating conditions. However for large scale investigations reliance on groundwater techniques is costly as many wells and on-	easily installed, although they can be expensive, especially as depth to watertable increases. Siting of bores may be influenced by field conditions, but for best information, the bore adjacent to the channel should be as close as possible. To use piezometric information for estimating seepage, the rates predicted for a given channel depends largely on how well the aquifer conditions can be characterised. Seepage rate is sensitive to the hydraulic conductivity, which can be difficult to accurately determine and may require specialist technical input. The main shortfall of trying to determine seepage rates using piezometric or hydro-chemical groundwater data alone is that it is concentrated on a slice across the channel which may not be representative of broader channel conditions.	bore construction will vary considerably. A cost range for estimating purposes only is from \$70/m to \$120/ m.(excl. mobilisation). Other costs include bore monitoring, which can be undertaken by the RWA. It recommended that for detailed estimates of seepage rates using groundwater information, experienced groundwater specialists are used. If numerical models are to be used, this will also require specialists. Costs will vary with the scale of the investigation, but a simple modelling project might be undertaken for around \$5000. Chemical techniques are highly specialised and would need specific scope of work and cost estimates.

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
		mechanisms at particular areas. Groundwater chemistry information may be used for quantitative or qualitative assessment. However this has generally had limited application and is not considered to be readily applicable to routine channel seepage investigation.	going monitoring is required. In addition, to quantify seepage, a large number of assumptions need to be made regarding aquifer properties, which can lead to wide variability in seepage estimates.		
Remote Non-Invasive Techniques	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: 3) Directly measuring the conductivity of the groundwater, and identifying the conductivity contrast of fresher seepage water as it dilutes saltier native groundwater. This will cause a decrease in electrical conductivity (or an increase in its inverse, resistivity). 4) Identifying contrasts in soil properties and	The geophysical methods most likely to be applied to channel seepage detection and which have most relevance to Australian water industry operations and conditions, are electromagnetics (specifically EM31 and EM34) and resistivity 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* (*on-channel*) can be used. 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. If this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes. Otherwise	Use of geophysics for channel seepage assessment is an emerging area. The attraction is the potential for rapid assessment of long channel sections, however care needs to be taken in the interpretation of results. Detection of seepage can be achieved with geophysical techniques alone, however quantification requires integration with other techniques. The benefits of using geophysical techniques are: ❑ They offer potentially the fastest means of seepage assessment ❑ They can provide essentially continuous spatial assessment ❑ They do not interrupt channel operations ❑ The costs should continue to come down as new procedures emerge, and ❑ With adequate local	❑ Geophysical surveys should be conducted while the channel is in operation, or immediately after the end of the channel operating season. There is no interruption to channel operations. ❑ Experienced contractors should be used to undertake the survey - a clearly defined brief should be prepared for the work.	Approximate costs for the three types of geophysical surveys undertaken in these trials are provided below. It is important to note that the unit costs per kilometre were for very short sections of channel (1-3 km) and costs would be significantly lower for longer channel sections. ❑ EM31 Surveys: For on-land surveys, including 4 traverses on each side of channel (over 3 sites): $400/km to $800/km. On-channel survey costs: around $330/km. ❑ EM34 Surveys: For 4 kms over 2 sites: $250/km,(1 traverse only), $500/km for both sides of channel. For 6 kms (on each side of channel) over 3 sites:

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
	inferring the likelihood of seepage through more permeable materials in the zone above the watertable	errors will potentially be introduced to the assessment process. Geophysical techniques can be used in two ways for seepage assessment: ❑ *Mapping the distribution of high and low seepage zones* – This can be achieved with the geophysical technique alone, however greater confidence can be obtained with geological investigations and/or limited direct or point testing. ❑ *Quantification of seepage rates* - Quantification requires integration of geophysical methods with other techniques in order to calibrate the results. Geophysics can be used to provide an estimate of seepage rate, provided a sufficiently strong relationship can be developed between geophysical response and pondage tests. Important variables which need to be considered when conducting a geophysical channel seepage investigation include survey timing, on-channel versus on-land, off-set distance and location for on-land surveys and other potential influences such as trees and rainfall.	calibration, they can provide reasonable estimates for seepage quantification It must be recognised that for geophysical surveys: ❑ Interpretation can be difficult and will vary from area to area ❑ Interpretation may require sub-surface investigation ❑ Can be relatively expensive; and ❑ Technical expertise is required to conduct and analyse survey results		$435/km ❑ Multi-electrode resistivity surveying $900/km [Includes mobilisation, travel between sites, production and all equipment costs] Data processing costs: $220/km
Remote Sensing	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	Remote sensing techniques for channel seepage detection assume that 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	❑ Remote sensing techniques offer considerable potential for rapid identification of seepage zones (but not quantification) of large lengths of a channel system (without interfering with	The technique is relatively expensive and requires specialist technical input at the planning and data gathering, processing and interpretation stages. However this technology	Costs will vary widely depending on the source data used. As an indication of the likely data collection costs, suitable quality airborne infra-red data (3-5m

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
	Remote sensing techniques infer channel seepage based on soil moisture, vegetation vigour and soil profile properties adjacent the channel. In particular, Airborne Night Thermal Infrared imagery can provide an indication of shallow soil saturation resulting from lateral channel seepage, which may be a precursor to water logging and soil degradation. There are currently no documented studies of remote sensing being used to *quantify* channel seepage, only for *detecting* seepage locations	through the channel banks, and/or re-surfaces near the channel toe. A key aspect of remotely sensed data is that it must be at a suitable spatial resolution to allow definition of seepage zones. Ground resolutions of less than 10 m are required. The regions most useful for channel seepage detection include visible, reflected (near) infrared and thermal infrared. Source data should also be 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. Remote sensing data is best evaluated in conjunction with other spatial data such as EM surveys and soil survey assessments. 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 seasonal variations such as irrigation or excess rainfall. Remotely sensed image data sources may include: ❑ Digital infra-red aerial photography	channel operations. ❑ The techniques are best suited to investigation where the primary aim is identification of land degradation associated with channel seepage. They should not be used if it is known that the seepage mechanism is pre-dominantly vertical, such as is likely to occur at sites with a deep watertable. ❑ Remote sensing is 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. 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.	has the potential to rapidly acquire data over long distances of channel, and along with geophysics is likely to be a key technique in future large scale channel seepage investigations.	resolution) for three lengths of channel (10-20km each) were quoted at around $11,000. Data processing costs, including integration with a GIS system are in addition to these costs and likely to be in the order of $5,000 - $10,000.

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
		❑ Airborne high resolution sensor data; and/or ❑ Satellite imagery			

Appendix E Notes of the ANCID Channel Seepage Project Workshop held in Moama on Monday 14 October, 2002.

ANCID CHANNEL SEEPAGE PROJECT WORKSHOP OUTCOMES
RICH RIVER GOLF CLUB – MOAMA
Monday 14th October, 2002

OPENING

John Mapson as Chair of the ANCID Task Force overseeing the three stage channel seepage investigation project opened the workshop and welcomed all present. In all the workshop attracted 40 participants and as such was well attended.

John gave a brief overview of the background of the project highlighting the funding partners being the Murray Darling Basin Commission (MDBC), Land and Water Australia (LWA), Wimmera Mallee Water (WMW), Murray Irrigation (MIL), Murrumbidgee Irrigation (MI) and, late in the project, Goulburn Murray Water. He referred to the October 1998 Workshop which was the genesis for the research and investigation work which has built up to this current workshop which is looking at the products from Stage 1 of the project.

John overviewed the agenda for the day and highlighted that the session proposed to be as interactive as possible where as much feed back on the guidelines for measuring channel seepage were requested.

OVERVIEW OF ANCID PROJECT

Peter Jackson briefly explained how, following the October 1998 Workshop, the research work focussed at better understanding of channel seepage and how to fix it were broken up into 3 clear Stages. Stage 1 deals with the identification and measurement of seepage; Stage 2 deals with the remedial works appropriate to address seeping channels and Stage 3 is aimed at developing a User Support System to take water agencies through the social, economic and environmental issues for justifying expensive works for addressing channel seepage. He added that the Workshop program was focused on Stage 1 project being seepage identification and measurement.

Peter then gave a brief background to Stage 1 and a very general overview of the methodology. He highlighted the reports that have already been prepared on the project and stated that they are all located on ANCID'S Website (*www.ancid.org.au*).

REPORT ON THE TECHNICAL WORK AND SEEPAGE TRIALS

Steve Parsons from Sinclair Knight Merz (SKM), gave a presentation looking at the detailed methodology of the work undertaken under Stage 1 and, in particular, focused on the seepage trials carried out and their results.

The issues which arose from Steven's presentation were summarised as follows;

- The depth of the water table is a key issue. It appears to influence many of the results on the pondage tests and the EM work.

- Higher seepage rates appear to produce more accurate EM results.

- Relating EM 31 results to pondage tests needs to be carried out with caution and extrapolating the results is dangerous unless there is sufficient data available for this purpose.

- More work is required to better understand the EM process.

- For all the work undertaken geophysics appears to have the greatest potential for mapping seepage in a cost-effective way.

- Pondage testing represents the best and most accurate way to assess seepage over given lengths of channel.

- The water balance and inflow/outflow assessments are best applied to very long reachs of channel.

THE BEST PRACTICE GUIDELINES MANUAL

Paul Bolger from SKM gave a presentation on the contents of the Best Practice Guidelines Manual for use in identifying and measuring channel seepage. He worked through the structure of the Guidelines Manual and how the individual trials or processes were included and what they involved. He summarised the whole process by a cyclic six step process starting with setting the objectives and ending with a position on the investigative work that should be taken. The key issues that arose from Paul's presentation are summarised as follows:

- There are various ways to map seepage from the channel and these are explained in the Guidelines Manual. However, EM applications would appear the most cost effective even though more work is required to improve the accuracy of these assessments.

- Having assessed one reach of channel, it is possible to extrapolate seepage rates to longer lengths of channel provided soil conditions and other geological processes are similar.

- Changing soil type is one of the key issues affecting the inaccuracy of the estimates. The best EM results were found from surveys which ran along the toe of the channel banks as compared to inside the channel and further away from the channel. This appeared as some what of a contradiction to Derek Poulton who commented that the work he was familiar with showed that the results along the toe of the channel were not as good as in the channel itself or further away.

- Peter Alexander commented that it was dangerous to extrapolate the results in different soil types and that there was a need to relate the soil types and geology to the seepage rates. It was agreed from this discussion that there was a need as part of the investigation loop to quantify the soil types over the length of the channel sections to be assessed as this was key information in determining seepage rates in a fast and economical way. There appeared a need to develop a relationship between the geological conditions and the seepage rates. Other issues which would affect such a relationship were possible levels of silt in the beds of the channels (providing a seal) and the degree of channel maintenance (which may remove this silt layer).

- Derek Poulton commented that, in the Waranga Western Channel case study, there were complex systems in place with fractured sandstone overlying *Parilla* sands in places. This was very patchy and made the results of the EM surveys very difficult to interpret.

Anthony Brinkley then gave a brief presentation on the proposed user support system and how the outputs from the Stage 1 project and the Stage 2 remedial project would feed into this Stage 3 work.

CASE STUDIES

The after lunch sessions dealt with looking at three case studies which were based on actual channel seepage problems. Those present were broken up into groups of about six and worked through each of the three case studies using the six Step Guidelines Procedure to fully appraise how each of the problems would be dealt with. The results from each of the groups were fed back and it appeared that the guidelines in general provided a logical process of working through the problems in the six clear stages with each group looking in detail at the information that would be collected as part of the investigations. Some of the issues which arose out of the reporting back process as summarised as follows:

- There is a need to look at overall catchment issues and, in particular, whole of catchment water balance issues to asses the impact of natural processes in play and how these might influence high water tables in areas where channel seepage is thought to be the problem. Other issues in play could be the use of pesticides, local and regional groundwater levels, soil physiology, and root decay all which could affect crop degradation which could be wrongly attributed to channel seepage.

- Investigations should often focus on issues like targeting 20% of a length of channel where 80% of the problems are occurring. This is a clear area where the economics will produce the best results of the least amount of work and cost. The EM survey appears a valuable method of determining where work should be planned which could also be valuable in seeking government funding for rehabilitation projects.

- The comment was made by John Mapson that sheet piling could be designed for easy installation to create pondage banks rather than spending up to $6,000 per bank with earth works, compaction *etc*. Sheet piling could be designed with rubber seals and with paddle and flap valves to allow channels to continue to run and which would be easily and quickly shut off when pondage results are to be done. This meeting could also be fitted with appropriate valving to allow passage of water from one pond to another. This matter was considered worthy of more investigation.

- There was an obvious need to think about setting up a national wide database which could be built with information on EM results and other information collected from any agency undertaking channel seepage control works so that, over time, large amounts of data can be collected to better prove up the processes being investigated.

OPPORTUNITIES FOR RESISTIVITY

PHD student David Allen gave a short presentation on the work he was doing on channel seepage using resistivity techniques.

David explained that the bed of a channel he was investigating was assessed using eco-sounding techniques from a boat which provided an effective way of carrying out this kind of survey.

The points that arose from David's presentation are summarised as follows:

- Derek Poulton commented that given the emphasis on the EM work, it was extremely important to standardise on a suitable technique for collecting EM 31 data and pondage test data. This information would then be fed into a large database mentioned earlier which anyone could get access to.

- Steven Harding commented that the User Support System appeared to have a strong economic focus. Kevin Devlin responded by commenting that the original brief sort a tool to prepare a business case on channel seepage control works. It was to produce an argued multi-objective outcome and have a rigorous decision process overseeing it, picking up environmental, social and economic issues whilst also looking at engineering measurement and remediation issues. Anthony Brinkley commented that the DSS looked at various multi-objective decisions but most systems were very data hungry and a clear vision was not available at the moment as to what the final product of Stage 3 would finally look like.

- Derek Poulton commented that in regard to watertable transects for seepage measurement, you don't necessarily need to have salinity measurements. It was important, however, to have good estimates of the specific yields of the groundwater system.