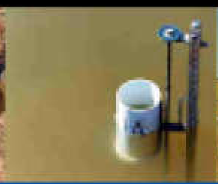
Open Channel Seepage & Control Vol 1.4 – Best Practice Guidelines for Channel Seepage Identification and Measurement

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January 2003

AUSTRALIAN NATIONAL COMMITTEE ON IRRIGATION AND DRAINAGE

Foreword

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

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

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

Each stage of the project is briefly described as follows:

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

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

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

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

The major outcomes from each of the Stages of the project work will be in the form of reports and Best Practice Guidelines Manuals. This report is one of the suite arising out of the project. It brings together all investigations made under Stage 1 of the project and presents these as a Best Practice Guidelines Manual. It has 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 and as such should be a extremely valuable reference document.

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

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Chairman
ANCID

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

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

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

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

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Executive Summary

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 surface 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 Rural Water Authority 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	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	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	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 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

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
	evaporation, rainfall and any other inflows or outflows.	sealed barrier should be utilised where 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.	other methods can be assessed. 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.	❑ The 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 carried during normal channel flow conditions ❑ The result does not provide an indication of the spatial variation of losses within the reach	width and 1.5-2m deep), 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.	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:

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
			❑ To obtain reliable results, tests usually require a skilled operator/technician ❑ Not practical for post-remediation measurement		*Idaho Seepage Meter* - 22 sites (4 individual tests 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	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).

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
			at channel surface)		
Ground-water Assessment	The use of groundwater 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.	There are three ways in which groundwater 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 techniques are 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.	Groundwater bores are 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	The costs of drilling and 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
		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 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.	However for large scale investigations reliance on groundwater techniques is costly as many wells and on-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.	across the channel which may not be representative of broader channel conditions.	
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: 1) 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	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	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	❑ 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:

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
	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	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 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.	channel operations ❑ The costs should continue to come down as new procedures emerge, and ❑ With adequate local 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		$250/km,(1 traverse only), $500/km for both sides of channel. For 6 kms (on each side of channel) over 3 sites: $435/km ❑ Multi-electrode resistivity surveying $900/km [Includes mobilisation, travel between sites, production and all equipment costs] Data processing costs: $220/km

Technique	Principle	Methodology	Applicability	Practical Implementation	Indicative Costs
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 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	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 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	❑ 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 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	The technique is relatively expensive and requires specialist technical input at the planning and data gathering, processing and interpretation stages. However this technology 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.	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 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
		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 ❑ Airborne high resolution sensor data; and/or ❑ Satellite imagery	surface expression as moist soil or associated vegetation adjacent the channel.		

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Introduction

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

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,
- 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 (Stage1) and remediation (Stage 2) and to develop a suitable user support system (Stage 3). The three projects are being coordinated by a Task Force comprising ANCID members.

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 and to evaluate the benefits and effectiveness of remedial works.

Aim of the Guidelines

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

Audience

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 Stage 3 user support system (USS) will provide the management tool to identify the business objective for conducting seepage identification or measurement. The guidelines are to be connected to the USS to allow detailed procedures to be assessed and input to the management process.

Using this Document

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 a way of thinking to assist users undertaking the most appropriate investigation to meet their particular channel need.

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 key 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.

PART 1:   GUIDELINE STRUCTURE

1 Derivation of Channel 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 the practical experience of water authorities, review of national and international literature, and three years of field trials assessing a range of different techniques. These investigations are described in the *Documentation of Seepage Measurement Trials* report (ANCID, 2003).

The key aspects of each of the key techniques, including the basic theory behind the technique, advantages, disadvantages and a summary assessment of the technique are discussed in Part 2 of the guidelines.

A brief summary of the information used to derive the guidelines is presented below.

1.1 RWA Survey

Surveys of 41 Rural Water Authorities (RWAs) across Australia provided a broad understanding of the current state of knowledge and experience with channel seepage measurement and remediation in Australia.

It appears from the survey that there is a somewhat ad-hoc way of dealing with channel seepage and in fact many channel seepage projects have been undertaken without any quantitative analysis of seepage itself. The survey has shown that on average 17.5% of water released into supply systems is unaccounted for and it is estimated that 4% of the water supplied is lost to seepage (ANCID, 2000b).

The most common technique used by RWAs for identifying and measuring channel seepage was piezometric survey of groundwater levels, ahead of estimation from records, aerial photographs and pondage tests. RWAs indicated that cost and speed were rated a higher priority than technical accuracy in channel seepage measurement.

Quantification of seepage on sites after remediation has been undertaken less commonly that initial measurement, especially when the initial assessments were obtained by pondage test and the Idaho seepage meter. Visual inspection was the most common method used to identify the significance of seepage and the effectiveness of remediation. Alternative methods were rarely used, especially after remediation had occurred.

1.2 Literature Review

A comprehensive review of the literature has identified different techniques which are considered useful for channel seepage quantification or identification. These comprise three categories:

- ***Direct and Point Measurement***: Inflow-Outflow, Pondage Test, Point Measurement
- ***Remote, non-invasive techniques:*** Geophysics, Remote Sensing

- ***Subsurface characterisation:*** Soil and Stratigraphic Classification and Groundwater Techniques, including Groundwater Level Monitoring; Mathematical Modelling; Hydrochemical and Isotope Mass Balance; Tracing Leaking Plumes.

Literature review of each of these techniques is described in ANCID (2000a) and a brief summary of the key techniques in Table 1-1 (a-c). Their application as a routine part of channel seepage management is presented in detail in Part 2 of the Guidelines. The literature review was the basic framework for establishing appropriate techniques to evaluate channel seepage under Australian operating conditions.

Table 1-1 Summary of Techniques

Technique	Principle
a) Direct Measurement	
Inflow-Outflow	This consists of measuring water flowing into and out of a channel over relatively long sections. Flows are measured between gauged sites Difference between quantities of water flowing into and out of section is attributed to seepage, after accounting for inflows, off-takes and known losses (eg, evaporation).
Pondage Tests	Seepage losses are estimated by measuring the drop in water level over time in an isolated reach of channel (or volume added to maintain a constant level) after accounting for evaporation and rainfall. Widely considered the most accurate means of measuring channel seepage, Can be used on both lined and unlined channels
Point Measurement (Channel Empty and Channel Full)	Point measurement refers to any technique (such as Idaho Seepage Meter, Infiltrometer) which measures infiltration / hydraulic conductivity at a given point, usually involving the application of water to the surface or hole within the channel and measuring the rate at which it drains away. Provides an indication of the distribution of losses along the channel Often used in conjunction with soil surveys to assign a seepage rate to a particular soil type.
b) Subsurface Characterisation	
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.
Groundwater Techniques	Groundwater levels measured 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. Useful for post-remediation assessment of watertable / salinisation impacts Hydro-chemical / isotopic concentration of seepage water can be used to define a plume and also the volume of water that has escaped from the channel
c) Remote Non-Invasive techniques	
Geophysical Techniques	Geophysical methods use electric circuits to measure the ground conductivity or resistivity and can detect the impact of low salinity channel water on the native groundwater near a channel. It essentially identifies differences based on: • Direct contrast of the salinity of the groundwater and the generally fresher channel water; • Indirect comparison of soil properties at a channel such as soil moisture content and soil type. Geophysical techniques can be used for rapid assessment of long channel sections, however care needs to be taken in the interpretation of results
Remote Sensing	Remote sensing techniques assume seepage will have a surface expression as moist soil or associated vegetation adjacent the channel.

1.3 Field Trials

Field investigations of a range of measurement techniques have been undertaken in SE Australia over a three year period (ANCID, 2003). Trials were carried out over selected sections for Murray Irrigation Ltd, Murrumbidgee Irrigation and Wimmera Mallee Water. In addition, the results of an investigation of a 50 kilometre length of the Waranga Western Channel in northern Victoria have been incorporated into the development of the guidelines.

Different techniques were evaluated at each site to:

- identify the locations of the greatest water losses from seepage;
- quantify the volume of water loss at test sites using direct measurement;
- compare the direct measurements with indirect techniques;
- determine the channel seepage mechanisms to assess the seepage impact;
- extrapolate the results beyond the test zones and interpret the seepage distribution; and,
- identify the areas in greatest need of channel remediation.

The trials focussed on developing the general principles which could be applied to measurement under the operating procedures of the managing water authority. An extensive range of tests was undertaken under a range of site conditions. The key site conditions including the geological profile in and around the channel, the local groundwater depth and salinity, and the channel cross-section and alignment were documented. Statistical and empirical evaluation of the data were used to derive relationships which can be used to evaluate the extent of channel seepage.

An important consideration in preparing and conducting the trials was to recognise that the techniques would have to cater for the operational needs of the water managers and how the results obtained from the technique would fit the management objective. That is, for a particular channel system the measurement technique depends on the purpose of the measurement, which is to some degree based on the scale.

The three years of field trials are described in detail in a summary report (ANCID, 2003).

2 Basic Issues Affecting Channel Seepage Identification and Measurement

The study has 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, so scale is a necessary consideration in the guidelines

2.1 Physical Conditions

Particular factors affecting seepage from earthen channels are:

- Soil Characteristics
- Hydraulic Characteristics
- Channel Water Characteristics
  - Suspended Sediment
  - Salinity and Sodium Adsorption Ratio

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. In addition, a very important factor is the presence of any thin silt horizons on the channel base resulting from sedimentation in 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 this may vary depending on channel dimensions and 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.

2.2 Seepage Mechanisms

The channel seepage investigations carried out to date have highlighted the importance of understanding the seepage mechanism and the resultant impacts. Seepage from surface earthen channels can be dominantly horizontal or vertical, or a combination of the two. The dominant mechanism at a site will affect the rate of seepage, the impact and the most appropriate remedial approach.

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.

1) Shallow surface mechanisms

Lateral leakage through preferred horizontal pathways is a major reason for channel remediation in Australia. In some circumstances, it can lead to perched water tables and local soil waterlogging and degradation. In addition, there could be bank instability from the saturation under particular soil conditions.

Under these circumstances, the rate of water loss from channels is not necessarily high but there can be a major impact on the channel operation and maintenance as well as the environmental conditions in the immediate vicinity of the channel.

Calculation of the relative rate of seepage from these conditions is not always possible, and may be of less significance than the impact on the soil conditions, especially waterlogging and salinisation. Locations can be easily detected by surface mapping and even by remote sensing. Remediation by applying cut-off walls, trenches and bank lining may be all that is needed in these circumstances and this can be a considerable saving compared to lining of the entire wetted perimeter of the channel.

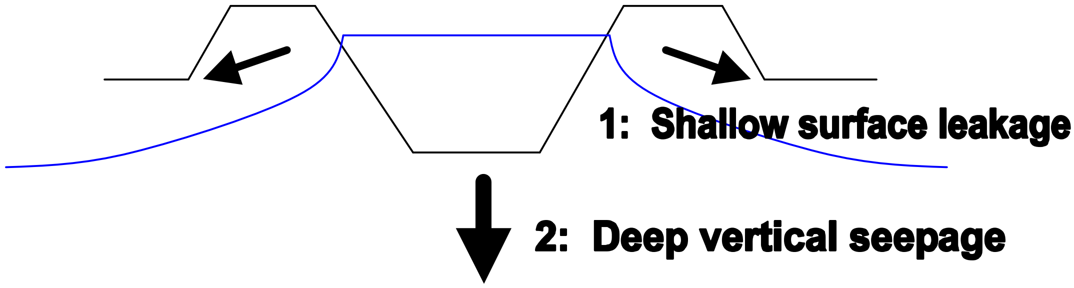
2) Vertical seepage

It is more difficult to identify the extent of leakage where there is no surface expression and the leakage is more likely to be governed by vertical seepage processes. However there are local and perhaps regional groundwater impacts from seepage from channels. These are perceived to be increased recharge and rising water tables. The impact of channel seepage on regional water tables needs to take into consideration the external groundwater flow systems before extensive remediation is undertaken. This is particularly the case in some irrigation areas where there are existing high water tables from regional irrigation which are also significant in affecting land degradation. Remediation of the entire channel section may be required or remediation may have no effect on adjacent land systems because high water tables may be due to external factors which may not be altered by channel works.

Under conditions of deep drainage, remedial works either for reduction of seepage or for maintenance of infrastructure need to consider carefully the effect of channel works on increasing seepage. Examples include deepening of channels and exposure of potentially high leakage pathways, or de-silting of the existing channel and re-opening seepage pathways which have been previously blocked.

The mechanisms are shown in Figure 2-1.

■ **Figure 2-1: Mechanisms of water loss from channels**



2.3 Issues of Scale

The trials conducted and the knowledge obtained from the RWA survey, the Task Force, and others involved in seepage evaluation, suggest that for most investigations the scale of the investigation is an important factor. Scale should be considered when the management needs for doing the project are being evaluated (eg extent of the project, expenditure, reason for the project, due diligence), 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:

a. **Local Scale**: Short (up to 400m in length) where anecdotal or other evidence exists for some leakage and a quick assessment is needed. This leads to the possibility of undertaking site specific measurements at a very local scale (eg point tests, groundwater monitoring, pondage tests).

b. **Intermediate to Large Scale**: Hundreds of metres to tens of kilometres. For investigations of this length, it is considered best to apply a combination of mapping channel characteristics (eg geophysics, remote sensing), identifying seepage rates at test sections (pondage tests), and interpolating between the test sections, including the use of statistical analysis.

c. **Macro Scale**: Tens of kilometres to entire systems. A similar approach to (b) when testing is undertaken, 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.

The basis for consideration of these scales is two-fold.

- A key operational need is often to identify the location of high seepage zones to set priorities in remediation expenditure. To be cost-effective in remediation programs, the measurement technique needs to be able to target channel sections in greatest need of works. Therefore the measurement technique may need to look at the distribution and rate of seepage across lengths of channel which may be local (a) or intermediate to large (b) scales.

- In contrast there are broad scale issues of quantifying losses within a system and estimating the cost of the lost resource. This could effectively be done at macro-scale (c) based on relatively simple water balance estimates, using inflow – outflow measurements. Knowledge of the system configuration and operation, including diversions, are needed. For this type of water resource analysis the detail of where, how and at what rate seepage is occurring may not necessarily be as important as the overall water balance. The question may then remain, if losses can be detected at large scale, is there a need for more detailed quantification at smaller scales (a,b).

For identifying the appropriate scale for the seepage investigations and therefore the scope of the work, key questions to ask are:

- Are locations of interest known (and how were they identified)?
- What is the distribution of seepage zones in these locations?
- Do we have to find out which sections are problematic?
- Is there a need to map the various zones of higher and lower seepage within the sections of interest?
- What length of the channel do we have to map?
- Is enough already known to commence some simple, inexpensive tests?

Once the scale has been identified, the selected technique will need to take into consideration the cost and the ability to extrapolate or interpolate the results. It is important that when test information is extrapolated to the entire section of interest in the channel in a large scale investigation, the test results are representative of the channel conditions over the total length which the extrapolation has been made.

For the different scales and management requirements, there are generic approaches to conducting a seepage investigation. These have been developed largely form the experience gained in the field trials and are described in section 4. It must be noted that in some circumstances there will be constraints on performing the techniques and these will need to be understood by examining the detailed description of each technique (see Part 2 of these Guidelines).

For example, in one case a planned pondage test on the Retreat Channel operated by Murray Irrigation was not conducted because of the size of the channel and the cost of earthworks which would have been required. In that case the preferred approach for this investigation was not adopted and alternative means were required to assess the seepage rate.

3 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.

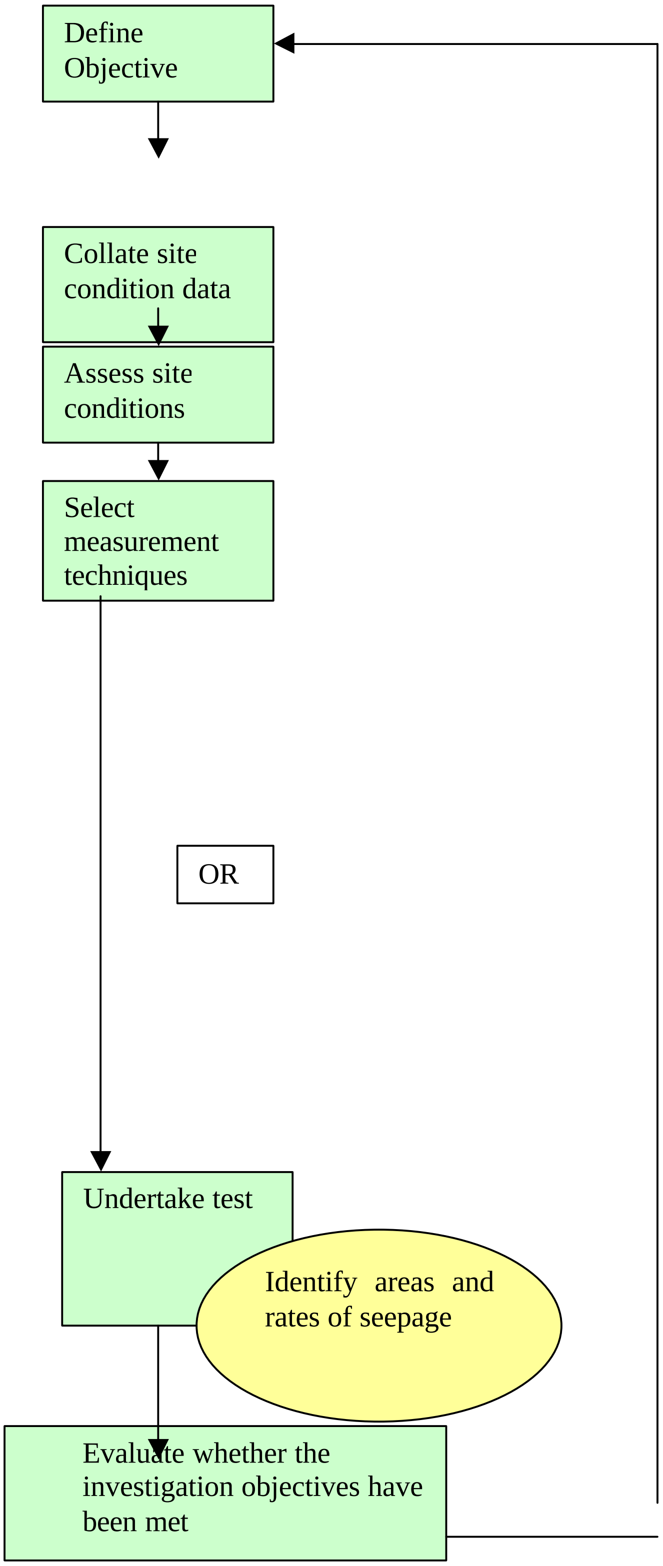
The logic presented in the guidelines is based on the conclusions drawn from the investigation work undertaken in the field trials. A framework was established by the literature review and the current practices of the RWAs, with the final guidelines largely developed from the practical experience of the field trials. They take into consideration the field conditions, the operational factors in the Australian water industry and the available technology. In addition, the trade off between costs and the accuracy of results are addressed. The investigations and trials conducted suggest that there are preferred techniques and procedures for most investigations.

The guidelines 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 key tasks:

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

The process suggested to thoroughly evaluate, plan and implement a project are shown in Figure 3-1.

■ **Figure 3-1: Process for Selecting the Seepage Measurement Approach for specific projects**



3.1 Define Objective

Purpose: This activity is required to define the reason why the work is being proposed. The purpose of the investigation must be clearly defined from the outset. Find out how the technical works would meet the business objective.

Some of the key drivers are:

- Water loss concerns
- Regional environmental concerns
- Local environmental concerns

Inputs: Interaction with the decision support tool to obtain ***business*** objectives for doing the work in the first place. This is likely to include the costs and benefits, and any community or political drivers for undertaking an investigation.

Description: This activity involves obtaining answers to the following key questions:

- Is the primary objective to identify relatively high seepage points or to measure the volume of seepage?
- Is it necessary to establish the rate of seepage – either the actual or the relative rate
- What magnitude of seepage loss is being considered to be unacceptable and why?
- What degree of confidence in the results is required?
- Over what length of channel is the information required – local scale or larger?
- What budget might be available?
- When is the information required?
- Is it essential/desirable to use in-house resources or can it be done by contractors?
- Is there likely to be any follow up monitoring after remedial works?

Responsibility / Decision Makers: This is a management function which would be expected to be driven by the organisation as part of its water management strategy. External Stakeholders may also provide input.

Output: A clear decision concerning the reasons for undertaking seepage investigations (eg asset management), budget considerations, scale of the operation (eg whole channel, specific channel lengths etc), need for accuracy, or relativity. A basic scope or terms of reference should be developed as a guide to future decision making. It would also require some assessment of whether there could be several iterations of investigations.

3.2 Collate Site Physical Condition Data

Purpose: To understand the factors which affect channel seepage and draw together what is known about the site already. These are a combination of the physical conditions at the site, as well as the hydraulics of the channel.

Inputs: Understanding of the factors which affect channel seepage. The sources of these data could be published or unpublished data from local government agencies or from agencies such as the Murray Darling Basin Commission (eg the Basin in a Box map series). Organisational knowledge of the channel dimensions and distribution.

Description of Activity: The above information is best assembled by mapping the key factors along the channel length. Maps can be developed displaying key factors likely to affect detection and measurement of seepage, including:

- Soils and Geology;
- Groundwater Depth and Quality
- Channel Depth and Capacity.
- Visual observations of seepage

Field work does not have to be undertaken to develop these maps, however the finest scale (covering the selected length) and best quality existing data should be used. Preparation of the maps in GIS format is valuable as they can then be used for later analysis with other data sources. The channel alignment is necessary on the maps.

In addition, the distribution of silt layers identified at the base of channels should be documented. If channel cross sections prepared, the silt layer thickness should be indicated. Further information to be collated which is fundamental includes:

- Channel elevation compared to surrounding natural ground levels, including the full supply level and design levels
- Channel construction and maintenance data

Responsibility: Generally project officer level.

Output: Spatial distribution of the key factors affecting channel seepage, including a summary of what is known and not known about the channel and seepage conditions. Identification of additional information that might be required.

3.3 Evaluation of Site Condition Information

Purpose: Interpret the known information about the site and provide preliminary assessment of the areas where seepage is most likely to occur, evaluation of the likely seepage mechanisms. Will assist in identifying the conditions so that appropriate techniques can be selected. Careful evaluation may lead to a concentration of effort into a particular location.

Inputs: Maps, site condition data, observations of seepage, anecdotal information

For this task, existing information is usually adequate, although if necessary some field data may be needed to assess the basic factors which might affect channel seepage.

Description of Activity: Assess areas that have characteristics which might lead to leakage from the earthen channel.

- Note features such as the distribution of highly permeable materials, including rock zones with fracturing or potential fracturing, extensive clay intervals,

- Review of anecdotal information and actual observations of leakage
- The distribution of any silt layers in the channel floor
- Identification of groundwater depth and salinity
- Evaluate the information to interpret possible leakage mechanisms and identify likely high seepage locations.

Responsibility: Best to be done by the project engineers. For specialised information, such as interpretation of existing aerial photos and some subsurface data analysis such as geophysics, specialists should be involved

Output: Basic knowledge of the material and water characteristics that will be important in selecting a measurement technique. Understanding of areas which may benefit from detailed testing, such as pondage test locations, areas for drilling etc.

This may also be a partly iterative activity, as information obtained from field investigations perhaps as parts of the seepage measurement program (eg drilling information, groundwater levels) may contribute to further understanding of site characteristics

3.4 Selection of a Technique

Purpose: This task is to identify the best technique for obtaining seepage data to meet the management objective. It is the basis for developing a work plan for the project, provide advice to management on costs and expected outcomes.

The trials work and information from operators has shown that there are two basic approaches to selection of techniques based on whether the investigations are local or larger scale programs. These are described in more detail in Section 4, but the following considerations are needed in assessing what techniques are to be applied

Inputs:

- Management decisions on project scope
- Identification of the scale of the project (say local site or broader scale)
- Descriptions of particular techniques, including the principle, the method, practical implementation, applicability and costs (See part 2 of these guidelines)
- Site condition data from previous task
- Operational factors related to conducting channel works including :
    - Cost;
    - Channel operating schedule and operational constraints; and,
    - Personnel / Resource constraints.

Description: The information obtained from the site condition assessment is to be used to determine which techniques can provided meaningful data on seepage within the operational conditions of the channel. The local or larger scale approaches need to be identified at an early stage.

The evaluation of the management issues should include the practical implementation issues for each technique which are described in Part 2. General considerations include:

Operational Constraints

Operational constraints may further reduce the number of approaches available. Key questions to consider include:

- Does the channel require continuous operation?
- Over what period is the channel shut down?
- What time is available for the investigation work?

Resource Constraints

Resource constraints may impose further restrictions on the options available. Important questions to ask include:

- Are the personnel and resources required to plan, conduct and analyse tests available in-house?
- Are there equipment and skilled technical personnel available for making measurements?
- If not can these be readily obtained outside of the organisation?

Accuracy / Cost Trade - Off

The ideal investigation often requires adjustment, with due consideration given to accuracy requirements and related cost constraints. Questions to ask are:

- Can the accuracy requirements be met within the available budget?
- Is allocation of additional funds warranted?
- Can the area to be assessed be fine-tuned (i.e. representative sub-areas studied)
- Can an extrapolative technique be employed to lower costs?
- Does the accuracy requirement need review?

Responsibility: This is generally a project manager/officer activity which makes a recommendation to management.

Output: A decision on the most suitable technique which can be practically implemented for the investigations needed for the particular channel. A recommendation to management on expected outcomes of the data to be obtained, how the data can be used, and costs and benefits.

This may be a staged recommendation, which may identify value in undertaking certain tasks, reviewing the results and making decisions to draw conclusions or to do further work.

3.5 Implementation of Seepage Measurement Techniques

Purpose: To undertake the seepage tests on site and document the distribution and/or rate of seepage from the channel

Inputs: Description of the preferred technique(s) including specifications, operational and any other constraints.

Description:

- Develop a work plan for the technique selected,
- Set up contracts and engage contractors to undertake the works (if required),
- Undertake the test(s) and collate test data,
- Undertake calculations for quantification, determine mechanisms,
- Extrapolate test information to entire section of interest (where appropriate)
- Report on the results, perhaps including preparation of maps displaying distributions of leakage zones, profiles of seepage impacts etc

Responsibility: Contractors, Project officers

Outputs: The type of output which can be obtained includes:

- Estimates of seepage rates
- Maps showing the distribution of high seepage zones
- Report on the work undertaken, including test results

3.6 Evaluation of the Results of the Testing

Purpose: The purpose of this task is to determine whether the seepage measurements can be used to achieve the seepage management objective.

Inputs: Seepage rate estimates, maps from measurement tasks; Management objectives

Description: The evaluation of the results covers:

- an assessment of the accuracy of the results,
- whether the results are consistent with expected results inferred from site condition assessment of existing data (eg groundwater monitoring data),

Responsibility: This task is a combined project manager/officer level task where conclusions and recommendations are reviewed by management.

Outputs: This could include an assessment of whether management objectives have been met and may result in identification of priority locations for remediation. Future directions and perhaps further work plans could be developed.

4 Recommended Procedures

4.1 General Requirement

The Rural Water Authority 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. While this may be the case, circumstances for specific investigations will vary and the best results will be obtained when the technique used is appropriate for the particular investigation. It is therefore recommended that the six step process presented in section 3 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
- 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.

Three scales were referred to in Section 2.3. Macro scale investigations are not detailed in these guidelines. Generally macro scale investigation are comprised of a water balance conducted at a regional or sub-regional level.

4.2 Local Scale, Site Specific Testing

The approach for conducting investigations at local scale, using the six step process described in section 3 is outlined below.

4.2.1 Define the Objective

Depending on the circumstances, particularly budget and time, specific tasks might be undertaken to provide a small amount of local site knowledge as a basis for further decision making. This is recommended only for small-scale projects at specific locations.

The reason for the investigation may be driven by the occurrence of recognised problems at a predetermined location, or it may be to fully evaluate a specified short length of channel for particular reasons. Usually this specific type of investigation would be in recognition of an identified or inferred local problem due to channel seepage. The scale of this type of predetermined action would be typically in the order of less than 200 – 400m.

The basic assessment of the scope of work will depend on the business needs of the organisation responsible for the channel. The main considerations in determining the scope of work for a local scale project (Figure 2) are:

- Has a seepage problem been identified and on what basis?
- Is the extent of seepage known in the section of interest?
- Is there a need to map the distribution of highest seepage zones and if so why?
- Is an estimate of seepage rate required and how accurately is it needed?

- Is there scope for further investigation work prior to selecting and undertaking measurement?

4.2.2 Collate Site Data

It is assumed that if decisions for action to be taken have been made, there is already some knowledge of the site conditions. The details would require collation, especially the main factors of soil types, channel characteristics and evidence of seepage. This knowledge may be the basis for the investigation in the first place.

In the event that there are no details, other than an inferred seepage problem, key data should be collated. If necessary, additional site data, such as soil information and depth to water table should be collated. This will be reflected in the project objectives.

4.2.3 Evaluate the Site Data

It is possible that the process of evaluating the data will have already been performed formally or intuitively to identify that there is a need for some action at the site. Regardless, it is recommended that a proper assessment of what is known is conducted to develop a conceptual understanding of the seepage mechanisms and to identify likely factors which would allow successful measurement. This will also overcome bias in the selection of a particular technique which may not be the most appropriate.

4.2.4 Selection of a Technique

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 (Figure 4-1).

For measurement of seepage rates at pre-determined sites the likely techniques which could be considered are:

- point tests;
- groundwater monitoring and modelling;
- pondage tests.

If there is a need for mapping of zones of different seepage or potential seepage, there is a need to use tools such as geophysics, and sub-surface methods along the length of interest along the channel such as soil and geological profiles, and groundwater observations, as well as surface observations. Estimates of the rate could be undertaken with those techniques listed above, once the mapping is complete.

In some cases, individual preferences are followed when selecting an appropriate technique for conducting seepage measurements. For example an individual asset engineer may be familiar with point tests in channels and consider that there could be enough knowledge from several tests to allow meaningful decisions to be made. This was a finding of the RWA survey. However it is recommended that such bias is avoided by going through the process outlined in these guidelines.

4.2.5 Implementation of Selected Technique

The different techniques recommended for the particular investigation should be conducted according to the procedures described in Part 2 of these guidelines and to the highest standards using appropriate contractors where necessary.

Any tendency for local scale investigations to be considered only worthy of limited investigation needs to be seriously considered, particularly as some of these types of investigations are a response to unwanted community concern or threatened litigation from adjacent landholders, or may have financial implications because of damage to the channel and related assets.

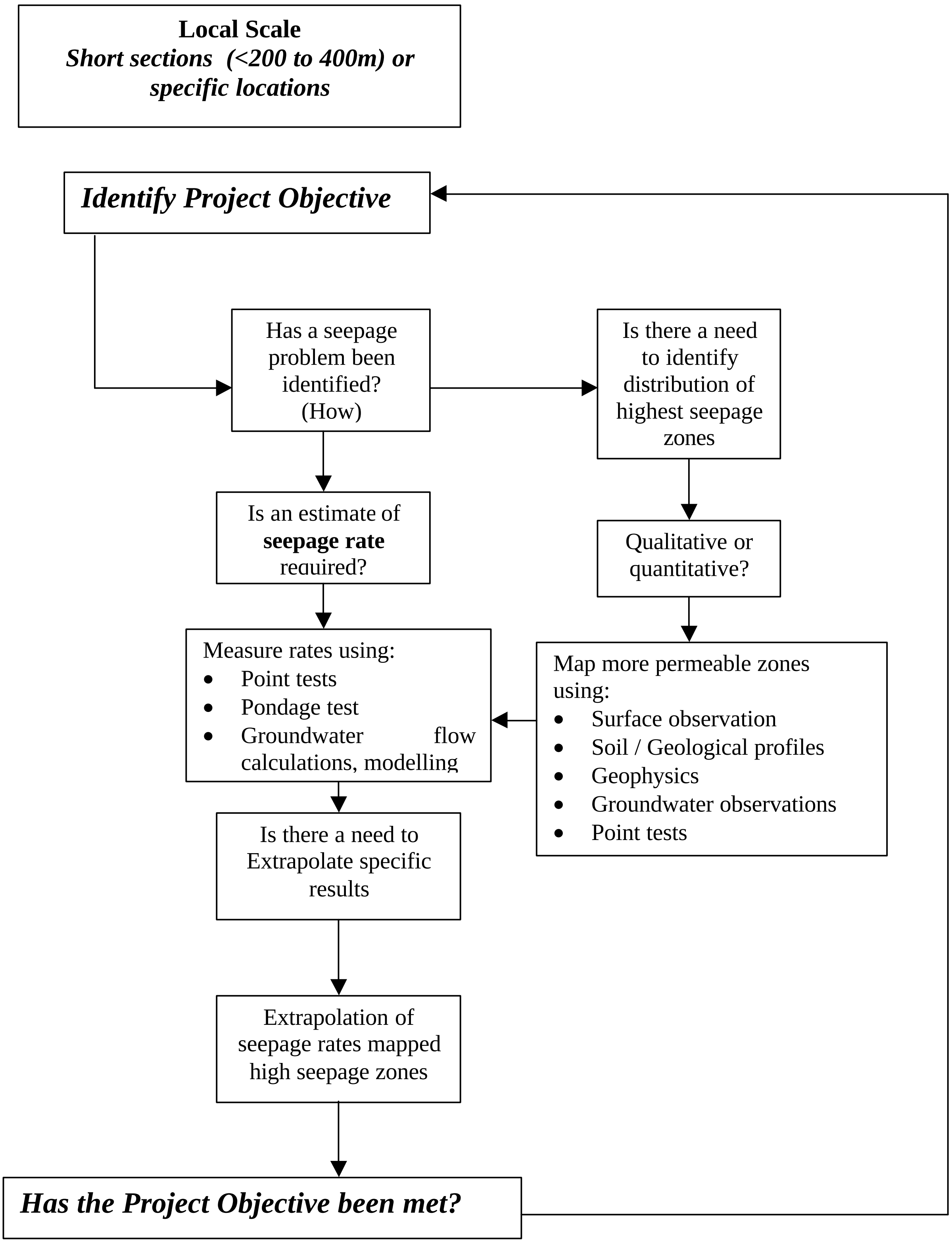
4.2.6 Evaluation of the Results of Testing

A local scale investigation may suit an immediate purpose of being seen to take some action at a particular location and provide some site specific management data. However, care must be taken in extrapolating the extent of any knowledge obtained at specific sites using techniques which only provide spatially limited data (eg point tests).

It is recommended that the basic framework described above is adopted to come to a perspective on what site specific work achieves. It is considered necessary to re-assess whether the needs of the investigation have been met by the work undertaken. Investigators are encouraged to maintain an open mind on the potential success of the technique used and to be mindful of possible techniques that may be more suitable for specific conditions and that actually address the needs of the investigation.

The approach to conducting local scale investigations is summarised in Figure 4-1.

■ **Figure 4-1: Local Scale Investigation Procedure**



4.3 Intermediate to Large Scale Approaches to Seepage Measurement

The trials conducted in this study and the case study of the Waranga Western Channel have indicted that for most channel seepage projects at intermediate to large scale (ie scales larger than a well defined local site), 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. (Remote sensing also has the potential to rapidly and cost effectively cover large areas, but this was not investigated in the trials associated with this project. It is applicable at the large to macro scale level of investigation).
- 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 the channel 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.

This method still presumes some existing knowledge of which parts of an RWA system might be targeted for investigation. Generally this information will be held within the organisation, based on flow records or visual observations of historical seepage. However, techniques such as remote sensing might be considered as a first cut approach to identifying areas susceptible to channel seepage at a regional level, allowing for limitations with this method (refer Part 2 of the guidelines).

In applying this routine procedure, the six stage process (section 3) needs to be implemented to refine the detailed work plan for the particular project (Figure 3-1).

4.3.1 Define Project Objective

The project objective for intermediate to large scale projects needs to be carefully defined at the outside so that costs incurred provide the most suitable answers. This may also have implications for channel rehabilitation or seepage remediation.

In order to define the objective in more detail the types of questions which are to be answered are:

- Is the primary objective to identify relatively high seepage points or to measure the volume of seepage?
- Is it necessary to establish the rate of seepage? – either the actual or relative rate.
- What degree of confidence in the results is required?
- Over what length of channel is the information required?
- What is the available budget?

At the end of this process there will be a clear definition of the reasons for undertaking the seepage investigation (eg asset management), budget considerations, scale of the operation (eg whole channel, specific channel lengths etc), need for accuracy, or relativity. This process will affect all future decision making.

4.3.2 Collate Site Data

It is important that information on depth to groundwater, background groundwater salinity, soil type and channel hydraulics are known or gathered), both at the site where the testing is conducted, and over the area the results are to be extrapolated.

This does not have to be at a detailed level in the initial stages, but should be sufficient to be able to propose a conceptual model of the seepage mechanism, to detect where changes in these parameters may impact on the mapping technique, and to assist in technique selection. Channel hydraulic information is required to help determine potential channel seepage mechanisms.

The sources of these data could be published or unpublished data from local government agencies or from agencies such as the Murray Darling Basin Commission (eg, the Basin in a Box map series). In addition there is likely to be organisational knowledge of the channel dimensions and distribution as well as hands on knowledge of site conditions. At this stage of an investigation, field work is usually not necessary, although in the absence of any data, or if there is conflicting data, some investigation work such as drilling may be needed.

4.3.3 Evaluate Site Data

The available data needs to be carefully evaluated to develop a conceptual understanding of the seepage mechanisms and to identify likely factors which would allow successful measurement. This will also overcome selection of an inappropriate technique. In the routine approach nominated here, this would include evaluating geological and soil data, groundwater water levels and salinity, lateral seepage occurrences.

In large scale studies also there is a need to have this information understood because of the possible variability in extrapolation from selected investigations sites to the entire channel. Therefore mapping of the conditions along the channel, preferably using a GIS application is considered to be a valuable activity.

4.3.4 Select Technique

The work conducted in the trials has shown that in most cases, geophysical techniques are effective in rapidly mapping sections of seepage along extensive channel systems. Coupled with appropriate soil and groundwater investigations, as well as local knowledge, geophysical techniques offer the potential to effectively map spatial variability of sub-surface conditions along major channels. This variability is the basis on which zones of significant seepage can be inferred.

Correlated against direct measurements of seepage rates (usually from pondage tests), a general relationship between the geophysical response and seepage rate can be established. This approach is considered to be superior both technically and economically to other techniques assessed for most projects, particularly those in which there are significant lengths of channel being investigated.

Therefore, if following the routine approach suggested here as being most likely to be successful for most investigations, the techniques to be applied are:

- map the distribution of lengths of the channel considered likely to be sites of seepage by using ground based geophysics,
- quantify the seepage rate using direct testing in sections of the channel using pondage tests.

One important conclusion from the trials is that the geophysical surveys work best when the conductivity measurement is focused at the depth where seepage has the greatest influence on groundwater salinity. Thus depending upon local and temporal conditions, different systems have performed better at different sites and at different times. The differences of each technique and the target depths are presented in Part 2 of these guidelines.

The particular geophysical method to be used depends on local conditions. In general, for a shallow watertable (surface to approximately 4m) EM31 (vertical dipole) should be suitable for detection of seepage impacts at the top of the watertable. For deeper watertables, a decision could be made to use EM31 to map inferred seepage based on soil properties in the unsaturated zone. However it must be ensured that seepage is controlled by the unsaturated zone and not surface clogging processes. Otherwise an instrument with deeper capability targeted to the top of the watertable should be selected.

The preferred geophysical seepage measurement technique is one that has a depth focus on and immediately below the watertable. Whether this is achieved using EM or resistivity is not highly important. However, generally it is easier to focus on a given depth with resistivity (EM provides an average across a range) and this can be achieved independent of knowledge of groundwater depth. The advantages and disadvantages of each of the techniques are discussed in more detail in Part 2 of the guidelines and these need to be assessed in light of the specific project objectives and the understanding of the site conditions (Stages 1 - 3 above).

Alternative Techniques:

Individual sites may for some reasons be better served by alternative mapping and seepage testing.

Remote Sensing Mapping Techniques aim at providing cost-effective means of assessing long sections of channel. Preliminary assessment of the technique suggests that it may be very useful in identifying those areas along channels where there is saturation at the ground surface from lateral seepage through channel walls and banks, but not where seepage is relatively deep and with no surface expression. Results are relatively limited to date, although there is potential if suitable frequencies are adopted. The use of remote sensing techniques is discussed in ANCID (2003) and in Part 2 of these guidelines.

Guidance on alternative seepage measurement techniques such as point tests or groundwater quantification, is presented in Part 2 of the guidelines

4.3.5 Undertake the Technique

4.3.5.1 Map Spatial Variability in Geophysical Response

The procedure to undertake a large scale investigation, using the routine recommended approach is to

- Undertake the geophysical survey over the section of interest, giving due consideration to factors such as appropriate timing of the survey and other important variables
- Plot geophysical survey results along the section and overlay with known site conditions (soils, geology, hydrogeology and channel hydraulic data). Based on these plots identify areas of suspected high, low and moderate seepage, assuming low conductivity / high resistivity equates to higher seepage.
- Soil bores could be drilled at appropriate intervals along the length of the geophysical survey to assist with interpretation of the geophysical survey. Conduct drilling across a range of low, moderate and high conductivity / resistivity sites;
    - Drill at least some bores into the watertable, and construct some as permanent groundwater observation bores;
    - Generally drilling should be conducted on the outside toe of the channel;
    - Logging and sampling of the bores should ideally be undertaken by someone trained in soil / geological classification and a consistent classification system should be followed.
    - Depending on the density of data collected, presenting the results in a geological long section should be considered so that a picture of soil variability is obtained..

4.3.5.2 Basic Seepage Quantification

The basic approach considered in the trials to be most effective in quantifying seepage is to undertake pondage tests. The measured seepage rates can be used as a calibration / correlation datum on which to assess the significance of other techniques.

1. Pondage tests are conducted at intervals over the entire length of the channel. The number of tests will depend on the length of channel surveyed and the variability of conditions along the channel. The following basic principles are recommended:
    - Pondage tests should be conducted across a range of low, moderate and high conductivity / resistivity sites so as to establish a regression equation which represents the range of geophysical response across the area.
    - Similarly, based on the soil drilling results, the pondage tests should be based on a range of different soil types and / or groundwater conditions.
    - Pondage tests must be conducted over areas of like conductivity / resistivity. That is they should not staddle areas of (significantly) different geophysical response, as this will complicate interpretation of the results and development of the regression equation.
    - Due to the cost of conducting pondage tests, it is recommended that at least two cells back to back should be conducted at each site for efficiency

purposes. Using available structures should also be considered to minimise bank construction costs.

- Pond length can be variable, but as a guide one pondage cell should generally not be more than 400-500m and not less than 50m.

By conducting pondage tests in this manner across the area of the geophysical survey, prediction of seepage rates outside of pondage test areas will be based on extrapolation between ponds rather than into entirely untested environments. This improves confidence in the predicted seepage. While pondage tests are expensive, they are a critical part of the interpretation process. It should be noted that while seepage rates determined from pondage tests are the most accurate means of measuring channel seepage they can sometimes lead to an underestimation of seepage compared to channel flowing conditions. This is due to the effects of clogging caused by siltation when the water is stationary, which are lessened when the channel is running (ANCID, 2000a). Therefore, it is recommended that where possible, geological and soil profiles should be examined as a sanity check on the pondage test results.

It is recommended that pondage tests are used as a basis for calibration of other techniques and that these are included in all but the simplest investigations. Certainly for large scale investigations, they are considered to be an essential part of the analysis for quantification.

Other direct measurements could also be applied to correlate against geophysical results. However because of the inherent variability of the results of point tests and the need for many results to provide representative values, they are generally not considered to be as effective as the pondage test technique (see Part 2). Furthermore, point tests are labour intensive in comparison with pondage tests.

4.3.5.3 Develop and Evaluate Relationship Between Seepage and Geophysical Response –

The following key steps should be conducted:

- Plot geophysical response against pondage test seepage. The average geophysical response (eg average conductivity) for the test section and the steady state seepage rate are used in establishing the relationships
- Outliers in particular should be assessed in light of all available information, including the conceptual seepage mechanism, test drilling results, channel hydraulics etc. If there are legitimate grounds for excluding outliers they should be removed.
- If from this data two or more different trends can be observed due to identifiable differences in sub-surface conditions, then two different regression equations should be generated.
- Fit a regression line(s) through the data.
- Statistical analysis should be conducted to determine the degree of confidence that can be placed in the derived relationship
- Using the derived relationship the channel length should be divided into seepage categories of various seepage rates based on geophysical response, with accompanying error estimates.

4.3.5.4 Interpretation and Extrapolation of Results beyond the Test Sections

The results of the completed tests need to be evaluated to interpret what they mean in terms of actual seepage beyond the test sections. In addition, investigations must assess how accurately the measurements reflect actual channel seepage rates or distributions and how can they be used in channel management, including after remediation.

4.3.5.4.1 Extrapolation of Seepage Measurements

Extrapolation involves taking the results of a more accurate method of assessment (particularly direct measurements) and applying them to other areas based on results of a more cost effective but perhaps less accurate method. The basic approach to extrapolation is discussed in the Literature Review (ANCID 2000a), with the following principles relevant:

- The technique upon which the extrapolation is based is applied locally, restricting the chance of significant variability in conditions over the area which the extrapolation is applied;
- As many tests as possible are conducted to clearly establish the relationship between the primary technique and the extrapolated technique;
- Sufficient information is known about the area over which the data is to be extrapolated to ensure the basis for the development of the relationship is not compromised.

Extrapolation is based also on the availability of detailed spatial knowledge which can be obtained quickly. The particular information of most relevance is extensive soil and geophysical mapping and geophysical survey mapping. This is the reason for evaluating the basic conditions along the entire channel length being considered (Step 2 above). There are a number of major ways in which extrapolation occurs.

4.3.5.4.2 Extrapolation of Geophysical Data

There is a general pattern of low average conductivity / high average resistivity relating to the highest seepage estimated from pondage tests (ANCID , 2003). On this basis, the mapped distribution of low conductivity / high resistivity zones can be inferred to be a general map of the zones of highest seepage. This has been found to be the case in field trials.

The relationship of EM results against the measured seepage rate from the ponds can be used to extrapolate the inferred seepage rate to other sections of channel. It must however be recognised that the estimated seepage is not absolute and that the rate is within error bands. For a specific channel a strong relationship may be recognised. In addition the extrapolation of the seepage measurements should be related to zones of similar geological conditions as identified in the trials.

One of the key questions to address is whether there is sufficient confidence in the derived relationship. In addition to the particular statistics of the regression line, this will largely depend on the project objectives. Further pondage tests or other testing may be required to further improve confidence in the relationship.

To date there has been no real spatial modelling / analysis of the EM data (eg using geostatistical methods such as kriging) in the trial work for this project although this may be an appropriate activity in future calibrations of geophysical results with seepage. This approach may be worth considering as a refinement of the calibration and extrapolation.

4.3.5.4.3 Extrapolation of Soil and Geological Information

The use of soil types and geological profiles to identify seepage zones or potential seepage zones is also an extrapolation technique. Based on the seepage rates for a particular type of soil (determined from a seepage meter, pondage tests etc), these rates are projected to all the soil types along the channel. The cheaper and more rapid method of soil surveying / mapping, effectively replaces the more expensive method of seepage meter testing or pondage test measurements.

The extrapolation of soil and geological information is based on a direct comparison of the rates related to the particular type of soil being used to infer that, where the same type of soil or geological profile exists, similar rates of seepage could be expected. In addition, groundwater monitoring data can also be extrapolated to similar soil and geological profiles and can be used to interpret relative seepage rates.

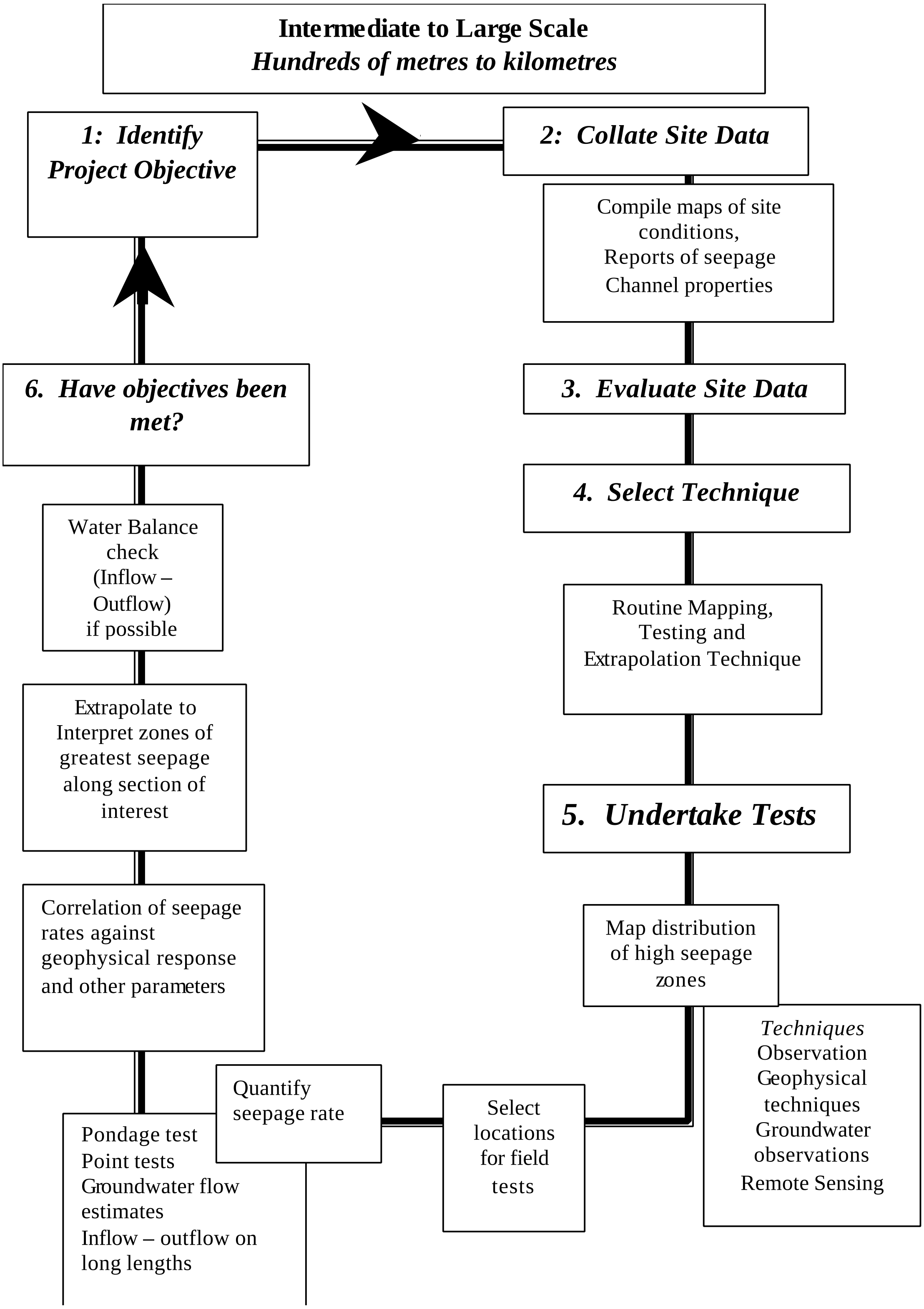
4.3.6 Evaluation of the Results of the Testing - Application of Results to Channel Management

The final aspect of seepage measurement and assessment is to review the actual distribution and rate of seepage measured and inferred from the tests at the various scales. The review needs to determine whether the management objectives identified early in the project definition have been met. Project review and evaluation also needs to take into account the need for additional work and refinement of the scale of testing to achieve management targets.

Figure 4-2 presents a summary of the approach to conducting intermediate to large scale channel seepage investigations.

This concludes Part 1 of the guidelines, which outlines a generic approach to conducting channel seepage assessment investigations. Part 2 describes the operation and evaluation of a range of the key seepage measurement techniques considered to be most applicable to Australian channel operators.

■ **Figure 4-2: Intermediate to Large Scale Procedure**



PART 2: DESCRIPTIONS OF TECHNIQUES

1 Introduction

This second part 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. As well as an understanding of how to actually undertake the tests, there are some basic project considerations which are needed.

1.1 Defining the Project Scope

The step by step approach to the investigation in Part1 should provide the basic framework for identifying the scope of the investigation. Before any on-ground works are undertaken the following four key tasks: should have already carried out:

1) Reason for doing the investigation including scale, extent, water management issues should have been identified
2) Key data affecting channel seepage should have been collated
3) Conditions at the site should be understood
4) Appropriate measurement technique or combination of techniques for the conditions and for the problem should be determined. This could be the local scale investigation or the generic broader scale investigation outlined in Part1 section 4.

1.2 Basic Planning

Planning needs to be thorough before any contracts are let and site works take place. Issues to be considered would be as follows:

- Decisions on resourcing – can in-house resources be used or are external contractors to be preferred?
- Which specialist consultants and contractors are likely to be involved? Drilling, EM /Resistivity work, some aspects of point testing and groundwater analysis and remote sensing are techniques needing specialist input,
- Is there sufficient budget to do the full project in one program or does it need to be staged?
- How long will tests be run and how long can they be run for, bearing in mind channel operational considerations?

1.3 Required Communications

Once the project has been planned, some basic activities will be needed before on-ground investigation works commence. Quite often this involves:

- Communication with adjacent landowners, for access to land, gathering of history of seepage, land loss, and clarifying the works to be undertaken on private property. A key issue is the control of stock during the tests.
- Coordination of operations and maintenance staff for programming works outside or within season and getting commitments to allow the testing to be done.

- Coordination of Field staff (internal and external) responsible for setting up and monitoring works.
- Coordination of contractors, for scheduling, clarifying scope of work, costs and deliverables, and setting up works.

1.4 Description of Techniques

The techniques are grouped according to:

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

Each of these has been considered in the project and many techniques have been trialed. In this part of the guidelines, each technique is described. Where relevant, examples are given to outline what these techniques entail, the outputs from measurement works and how they can be used. Each technique is described in the following way:

1.4.1 Principle

This outlines the basic understanding of how the technique is used to indicate and measure seepage from an earthen channel.

1.4.2 Methodology

This describes the set up, planning, operation, collection and analysis of data. It provides descriptions of the way in which results are presented and used, based largely on examples from the Trials program. Where calculations are undertaken to quantify seepage rates (eg pondage tests), worked examples are provided.

Detailed descriptions which can be applied as work briefs for contractors outline some of the practical and contractual issues that need to be considered in implementing the measurement techniques.

1.4.3 Applicability

- The applicability of a technique refers to the types of outcomes likely to be obtained and how these will meet the particular project objective. It embraces factors such as scale and the physical (soil, groundwater etc) conditions which may be applicable.
- This section also considers the applicability of the technique for post-remediation measurement and monitoring.

1.4.4 Practical Implementation

Description of the practical implementation of a technique identifies factors such as scale, timing of testing, and operational and physical constraints on undertaking the technique at a particular site.

1.4.5 Indicative Costs

A summary of indicative costs to set up, implement, monitor and analyse the information is provided. The costs related to interpretation and input to channel management are not included as these are pertinent to the individual channel operator.

Indicative costs for each of the techniques where available are based on costs from the ANCID trials. The costs for a given technique vary between Authorities due to the use of different sub-contractors, use of internal resources versus use of a sub-contractor, different internal accounting procedures (eg different charge rates for staff) and differences in channel and site characteristics (eg access, channel width etc). Where the work can be conducted in-house, the anticipated personnel time required is provided rather than a dollar cost, as this will vary from Authority to Authority, depending on internal charge rates.

2 Direct and Point Seepage Measurement Techniques

The techniques considered to be most likely to provide accurate measurements of the rate of seepage are Pondage and Inflow – outflow tests. In addition, point tests provide a way of quantifying seepage rates at specific locations in a channel.

2.1 Inflow-Outflow Method

2.1.1 Principle

The Inflow-Outflow method is considered to be 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 channel length being investigated.

This method is the only one which reflects actual operating conditions and permits measurement without interruption to system operations.

2.1.2 Methodology

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 the flow, rainfall, evaporation and diversions from the channel.

The level of the channel should be kept constant during test periods in order to eliminate the effect of bank and channel storage and changes to the wetted perimeter of the channel. All diversions must be measured accurately, and any inflow (eg, overland flow or rainfall) into the channel must be taken into account (preferably no diversions). Where practical, measures should be taken to eliminate as many parameters in the equation as possible, such as drainage inflows or diversion outflows. When tests are of long duration, or are to be repeated in the future, rating curves and tables can be prepared with water level recorders installed at the inflow / outflow gauging sites.

The basic equation for calculating seepage losses using the inflow-outflow method is presented below. **Figure 2-1** graphically displays these components.

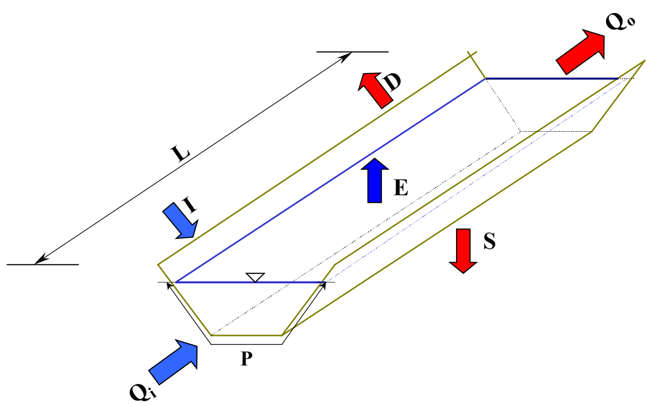
$$S = \frac{Q_i - Q_o - E - D + I}{P.L}$$

Where S = Seepage rate [length / time]
Q_i = Inflow rate [volume / time]
Q_o = Outflow rate [volume / time]
E = Evaporation along reach [volume / time]
D = Diversions along reach [volume / time]
I = Inflow along reach, eg, rainfall, runoff [volume / time]

P = Averaged wetted perimeter [length]
L = Length of canal reach [length]

In applying the equation, units must be consistent for all terms in the equation (preferred units are mm/day)

■ **Figure 2-1: Components of Inflow-Outflow Water Balance**



Discharge measurement can be conducted using a number of techniques. The two most common include:

- Use of a current meter to determine the average velocity. The discharge equals average velocity multiplied by the cross sectional area. This method is probably the most practical.
- Flumes or weirs with automatic recording gauges. If automatic gauges are not available, observations of volumes of water passing through such structures spaced at suitable intervals, with proper time lags between observations, are reasonably accurate. The best accuracy over a wide range of discharge can be obtained with the V-notch weir. Where regulating structures suitable for incorporating accurate measuring facilities are absent, temporary weirs or gauging sites can be established.

Climatic data can be obtained from the nearest weather station. For potentially more accurate results, a rain gauge and an evaporation pan can be established along the section of interest. Corrections from pan evaporation to evaporation from a shallow water body need to be applied.

Other details which need consideration in conducting the tests are:

- It is important that the water level is held constant for the duration of the survey. The channel should be operated at or as close to full supply level during the survey;
- All checks, wheels, gated structures and doors must remain unadjusted for the duration of the survey;
- Where identified all leaks through Dethridge outlets etc should be sealed prior to commencement of discharge measurements. Structures should be checked throughout the survey for leakage;

- Accurate cross section data must be available or obtained at the locations where discharge is calculated using the area / velocity method;
- All measurements should be conducted within a short a period as possible (ie several hours) to ensure constant conditions during the survey period.
- The water surface area along the section must be known in order to calculate evaporation;
- If a long section of channel is being investigated, installation of several rain gauges should be considered;
- Use of either on-site pan evaporation or local evaporation data from the nearest weather station will depend on the proximity of the nearest station to the site, and on the degree of accuracy required in the testing.

More detail of the method as well as specific references can be found in the Literature review (ANCID , 2000a).

2.1.3 Applicability

The method is often used to provide a first cut estimate of seepage losses in a system but can produce accurate results if accurate flow measurements are able to be obtained. There is a need for knowledge of any other possible losses such as outflow diversions. In addition, the accuracy decreases as the percentage of flow which is lost to seepage decreases, ie it is best suited to relatively high seepage sections of channel.

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 is a method more suited to high flow channels where losses are likely to be much higher than measurement error. It is not suited to small, low flow channels where measurement errors swamp the calculations.

The inflow-outflow method is perhaps best suited at a system level for initial identification of long sections of channel which may contain high losses within the section (ie at a regional level). It can assist in setting priorities for detailed seepage assessment of one channel over another, but not for isolating sections of channel (down to say kilometres) where the problem occurs.

In practice this appears to be how most RWAs presently use inflow – outflow ‘tests’.

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

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

Inflow –Outflow tests are suitable for remediation assessment provided that a long section of channel has been remediated, or if dealing with a short section where gauges of very high accuracy are installed immediately upstream and downstream of the remediated sections.

2.1.4 Practical Implementation

Key issues to consider in determining whether an Inflow-Outflow test is practical at a particular site are:

- 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 needs to be assessed
- 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,
- Should ideally contain suitable structures for incorporating measuring devices,
- Need to have all inflows and outflows metered or capable of being measured accurately, as the overall accuracy depends on accuracy of inflow and outflow measurements.

2.1.5 Indicative Costs

If existing structures are already in place for measuring flow to a suitable level of accuracy, then costs will be minimal. Costs will be restricted to monitoring of flow in the gauges over the period of the test. However, if flow is required to be measured using the velocity - area method of assessment, then contractors are likely to be required.

The cost of a recent inflow-outflow test conducted by a contractor for Murrumbidgee irrigation was $7,000 (including analysis and reporting, but not including cross section surveying costs). This was conducted on a 5 km section of channel over a period of 2 days. The actual discharge measurements were conducted over a period of 6 hours. This included discharge measurement from gauges, various off-takes and wheels, as well as velocity-area discharge measurements. This cost also included sealing of identified leakages around various structures. Costs will increase with increasing number of outflows (or inflows) along the investigated reach.

2.2 Pondage Tests

2.2.1 Principle

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 (or volume added to maintain a constant level) after accounting for evaporation, rainfall and any other inflows or outflows.

The basic principle is that this method is a direct way of recording the losses through the section of channel of interest. As such it is considered to be a datum on which other methods can be compared and calibrated against.

2.2.2 Methodology:

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, anecdotal information etc.

Any existing structures suitable for forming a sealed barrier should be utilised where 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, or slightly higher than, the level at which it usually flows during operation. As the water level in the channel section declines, the level 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. A variation of the normal pondage test consists of adding water to maintain a constant surface level. The volume of water added is measured and is considered the seepage loss (accounting for evaporation and rainfall). This method has the advantage of more accurately representing normal flow conditions but is very much dependent on accurate measurement of the pond depth.

The basic equation for calculating seepage losses using the pondage test method is presented below [modified after Frevert and Ribbens (1988) to allow for rainfall and evaporation]. Figure 2-2 displays these components.

$$S = \frac{WL(d_1 - d_2) - (EWL) + I}{PL(t_2 - t_1)}$$

Units must be consistent for all terms in the equation.

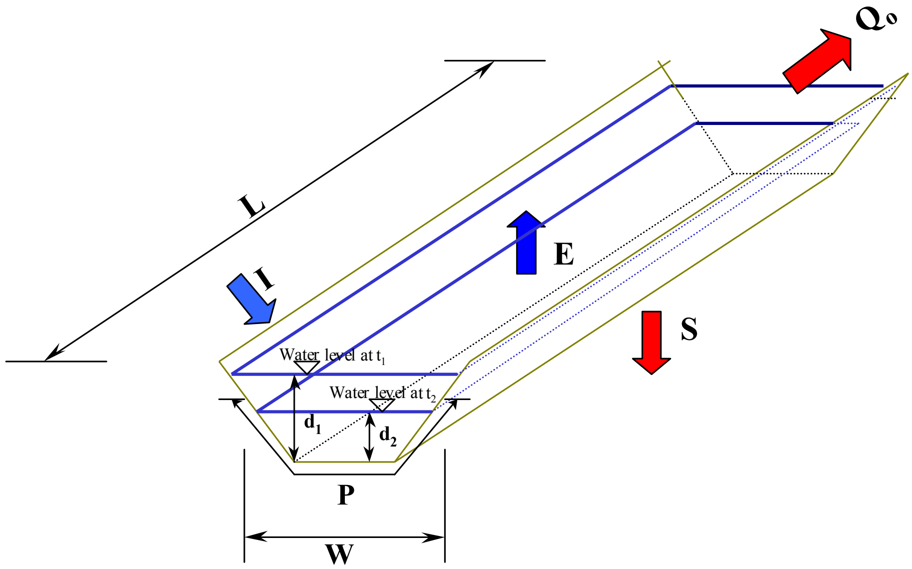
If the only inflow into the reach is rainfall (which is often assumed to be the case), the length of the reach drops out and the equation reduces to:

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

Where (for above 2 equations):

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

■ **Figure 2-2: Components of Pondage Test Water Balance**



2.2.2.1 Data to be Collected

Estimates of evaporation and rainfall can be obtained from the nearest weather station with evaporation data. However for more accurate results an evaporation pan and rainfall gauge are usually established adjacent to the ponds especially if the nearest weather station is a significant distance from the site.

As well as basic data concerning the soil and the basic channel hydraulic data, it is very important for the interpretation of the results that the extent of any silt layers lining the channel is known.

2.2.2.1.1 Site Survey

The site should be surveyed prior to channel filling to collect information on channel bed levels, channel cross sections and structure or bank details. At a minimum the survey should include the following:

- Full Supply level (FSL) should be surveyed prior to any pond construction works so that during the test the ponds can be filled to this level
- Reference pegs at each of the pondage banks surveyed for location.
- All hook gauges surveyed at the 0 or 1.0 metre mark on the gauges. The FSL and channel bed levels are also to be recorded at each gauge.
- Survey to define the channel cross section as accurately as possible at the pondage walls and approximately every 200m . The recommended number of points to be collected in each cross section are presented in Table 2-1. Each point in the cross section is to be surveyed for elevation and chainage. Note that discretion on the minimum number of points is required depending on the shape of the channel.
- If a pondage test is to be repeated at a site the following year, the survey should be completed again, due to potential changes to the channel cross section during channel operation and maintenance.

■ Table 2-1: Recommended Number of Survey Points to be included in Channel Cross Section

Survey Point
LHS Natural Surface (≈ 5m from toe of bank)
LHS Natural Surface at toe of bank
LHS Top of Bank – outside
LHS Top of Bank – inside
LHS Bed
Centre Bed
RHS Bed
RHS Top of Bank – inside
RHS Top of Bank – outside
RHS Natural Surface at toe of bank
RHS Natural Surface (≈ 5m from toe of bank)

Survey Definitions
Left Hand Side (LHS) – Left hand side based facing downstream
Right Hand Side (RHS) – Right hand side based facing downstream

All elevations are to be surveyed to AHD. It is beneficial to survey to AMG coordinates to allow consistency with other spatial techniques such as geophysics and groundwater bore locations for input to GIS mapping and analysis systems.

It is recommended that a site plan showing all survey channel data, particularly an electronic version, should be prepared to assist in the interpretation of not only the pondage test data, but other related testing information.

- **Figure 2-3: - Pondage test soil embankment construction**

- **Figure 2-4: Pond embankment showing temporary plastic liner installation**

2.2.2.2 Pond Set-Up and Construction

Tests can be individual ponds for a site specific investigation, or multiple ponds if data are required to extrapolate to other parts of the channel, using other data such as geophysical response for calibration. In these cases pond banks should be located so that individual ponds coincide with sections showing similar geophysical response. A minimum of 50m is recommended. Construction of the pondages back to back minimises the number of banks required to be constructed.

Pondage banks are required to be constructed in a way which minimises, and if possible prevents, seepage through or under the bank. A plastic liner is recommended. An excavator will be required for construction of the banks. Figure 2-3 and Figure 2-4, depicts two different stages of a pondage embankment under construction while the channel is full.

To avoid transporting soil into each site, landowner permission should be sought to source the soil from land adjacent to each temporary bank location. The hole initially generated from soil removal will be filled in once the temporary banks are dismantled at the completion of the tests. The soil should have sufficiently high clay content.

The banks should be track rolled with the excavator to provide some compaction and a membrane lining comprised of plastic or rubber is required to be placed on the banks. A soil cover is required over the membrane.

2.2.2.3 Installation of Monitoring Gauges

2.2.2.3.1 Hook Gauges

Two hook gauges are to be installed in each pondage section, one at the upstream and downstream end of each pondage (to eliminate potential wind effects). The hook gauges should be measured to millimetre accuracy. Data loggers can be installed in place of hook gauges for more accurate results and would remove the need for gauge monitoring during the test.

2.2.2.3.2 Rainfall Gauge and Evaporation Pan

Rainfall and evaporation must be measured to develop the water balance. A rain gauge should be set up on the middle of the pond bank. A class A evaporation pan should installed in middle of the pond or at the middle pondage for a series of ponds. It is best to allow the evaporation pan to float in the pond if possible. Specifications for setting up this equipment can be obtained from the Bureau of Meteorology.

2.2.2.4 Filling Methodology

To the degree possible, all the pondage tests within the section should start simultaneously, with water levels at Full Supply Level (FSL). To account for losses which occur during the initial wetting period of the soil, the methodology should either include:

- Filling the pondages above FSL and commencing the test when the first pondage level passes the FSL; or,
- Maintaining the pondage levels at FSL for half to one day, prior to commencement of the test.

To obtain a consistent initial level across the ponds, the banks should be constructed within one day, and a pump used to transfer water from the upstream section into the ponds, and from pond to pond. The methodology for setting up the tests will slightly vary different depending on whether conducted at the start or end of the irrigation season.

2.2.2.4.1 Filling Methodology at End of Channel Operation

The furthest downstream bank should be constructed first, working backwards towards the upstream bank. The water level in the most downstream pondage should be allowed to backup to the highest degree, as this will undergo the highest losses by the time the final pondage is constructed. A pump will probably be required to top up levels in the lower ponds prior to starting the test.

2.2.2.4.2 Filling Methodology at Beginning of Channel Operation

The downstream bank can be fully constructed prior to the release of the water (ie in dry conditions). The remaining banks can also be fully constructed, taking advantage of the dry conditions, however, to allow water to be transferred through the banks a suitably sized pipe should be installed towards the top of the bank. When the filling of the ponds is completed these pipes need to be adequately sealed. The use of these pipes will enable an equilibrium to be attained across all the ponds. (A portable pump may also be required to top up ponds)

The water being released to fill the ponds would require careful control. Once the test has commenced the flow coming down the channel will need to be virtually stopped. Overflow of the upstream bank cannot occur during the test. This makes the timing of the test crucial and operations personnel need to be fully aware of the intention and need to shut down the system for the test.

2.2.2.5 Checking of Site for all Possible Inflows and Outflows

During and after filling of the ponds, an inspection should be carried out of all the sealed structures, and along both banks of the test reach, to check for leakage and for other signs of water loss (eg stock, pumps etc). If such leakage or inflow sites are found, attempts should be made to either measure or eliminate them.

2.2.2.6 Pondage Test Operation

2.2.2.6.1 Duration of Test

- The typical duration of a pondage test is in the range of four to ten days.
- The duration of the test would be best determined during the test and would be dependent on the amount of measured seepage. Therefore the results should be assessed daily during the tests
- If rainfall during the test causes significant uncontrolled and unmeasured runoff into the ponds, the test will need to be cancelled or extended as this inflow will not be accounted for effectively in the water balance.

2.2.2.6.2 Monitoring During the Test

- Data measurements (water level gauges, pan evaporation and rainfall) should be taken daily;

- Accurate measurement of hook gauges can usually only occur effectively from inside the channel, which may require wading into the channel.
- At least two data measurements should be taken on the first day of the test.
- All water level measurements should recorded inside stilling wells to minimise short term variations in the channel water level (eg wind driven waves).
- Gauges at the upstream and downstream end of each pondage are to be read not more than 5 minutes apart.
- Data should be recorded on a spreadsheet similar to that shown in Figure 2-5 which can allow direct input for calculations.

2.2.2.7 Evaluation of Test Results

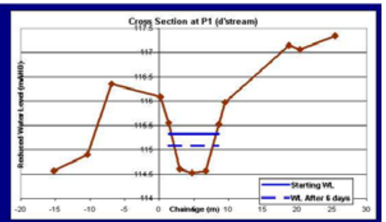
The field recorded data are inserted in the equations to calculate seepage and an estimate of seepage rate is determined. An example of the general output from the calculations is shown in Figure 2-5.

■ **Figure 2-5: Pondage Test calculation output**

PONDAGE ONE - Seepage Calculation Sheet: Donald Main Channel

X-SECTION P1 (D/S)

Survey Point	Ch (m)	RL's (m)	21/12/2000 11:45	21/12/2000 16:12	22/12/2000 8:37	25/12/2000 8:37	25/12/2000 16:30	26/12/2000 8:32	26/12/2000 14:35	27/12/2000 8:12	27/12/2000 14:16	28/12/2000 8:08	28/12/2000 14:45	29/12/2000 8:08	29/12/2000 14:17
Water Level			115.33	115.31	115.29	115.14	115.12	115.10	115.08	115.05	115.04	115.01	115.00	114.97	114.97
LNSO	-15.2	114.568													
LNS	-10.4	114.908													
LTO	-6.9	116.358													
LTI	0.2	116.088	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L-FSL	1.4	115.553	1.42	1.38	1.33	1.04	1.01	0.95	0.93	0.87	0.85	0.79	0.77	0.71	0.70
LB	3	114.613	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LC	3	114.613	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
C	4.8	114.518	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RC	4.8	114.518	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
RB	6.7	114.568	1.70	1.66	1.60	1.27	1.24	1.18	1.15	1.08	1.06	0.99	0.97	0.90	0.89
R-FSL	8.6	115.523	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RTI	9.5	115.973													
RTO	18.8	117.153													
RNS	20.4	117.058													
RNSO	25.4	117.338													
Wetted Perimeter			6.82	6.74	6.63	6.01	5.95	5.83	5.78	5.65	5.61	5.49	5.44	5.32	5.29
Water Width			6.44	6.37	6.27	5.73	5.67	5.57	5.53	5.41	5.38	5.27	5.23	5.12	5.09
Depth			0.81	0.79	0.77	0.62	0.60	0.58	0.57	0.53	0.53	0.50	0.48	0.46	0.45
WL Change				0.018	0.028	0.036	0.016	0.027	0.012	0.032	0.008	0.030	0.011	0.029	0.008

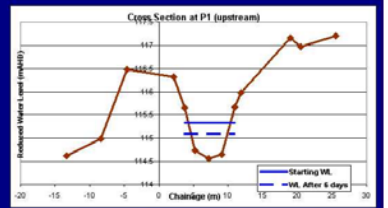


Water Levels For Plotting

Start		After 6 days	
1.4	115.33	1.4	115.08
8.6	115.33	8.6	115.08

X-SECTION P1 (U/S)

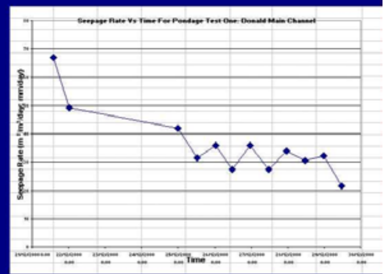
Survey Point	Ch (m)	RL's (m)	21/12/2000 11:45	21/12/2000 16:12	22/12/2000 8:37	25/12/2000 8:37	25/12/2000 16:30	26/12/2000 8:32	26/12/2000 14:35	27/12/2000 8:12	27/12/2000 14:16	28/12/2000 8:08	28/12/2000 14:45	29/12/2000 8:08	29/12/2000 14:17
Water Level			115.33	115.31	115.28	115.14	115.12	115.09	115.09	115.05	115.04	115.01	115.00	114.97	114.97
LNSO	-13.4	114.623													
LNS	-8.4	114.988													
LTO	-4.6	116.488													
LTI	2.1	116.313	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L-FSL	3.7	115.663	1.14	1.10	1.05	0.77	0.74	0.69	0.66	0.60	0.59	0.53	0.51	0.45	0.44
LB	5.2	114.738	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LC	5.2	114.738	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01
C	7.2	114.568	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
RC	9.1	114.648	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RB	9.1	114.648	1.44	1.41	1.35	1.04	1.00	0.95	0.92	0.85	0.84	0.77	0.75	0.69	0.67
R-FSL	11	115.668	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RTI	11.8	115.983													
RTO	19	117.158													
RNS	20.5	116.973													
RNSO	25.5	117.198													
Wetted Perimeter			6.49	6.42	6.31	5.72	5.65	5.54	5.50	5.37	5.33	5.21	5.17	5.05	5.02
Water Width			6.14	6.08	5.98	5.47	5.41	5.31	5.29	5.17	5.14	5.03	4.99	4.89	4.86
Depth			0.761	0.745	0.715	0.570	0.554	0.525	0.518	0.485	0.475	0.445	0.434	0.405	0.397
WL Change				0.016	0.030	0.037	0.016	0.029	0.007	0.033	0.010	0.030	0.011	0.029	0.008



Water Levels For Plotting

Start		After 6 days	
3.7	115.33	3.7	115.09
11	115.33	11	115.09

Time	21/12/2000 11:45	21/12/2000 16:12	22/12/2000 8:37	25/12/2000 8:37	25/12/2000 16:30	26/12/2000 8:32	26/12/2000 14:35	27/12/2000 8:12	27/12/2000 14:16	28/12/2000 8:08	28/12/2000 14:45	29/12/2000 8:08	29/12/2000 14:17
Time Change (days)		0.185	0.684	0.741	0.328	0.668	0.252	0.734	0.253	0.744	0.276	0.724	0.256
Wetted Perim. Summary													
DS Half of Pond	6.72	6.64	6.53	5.92	5.85	5.74	5.69	5.55	5.52	5.39	5.35	5.23	5.19
US Half of Pond	6.56	6.48	6.37	5.77	5.70	5.59	5.54	5.41	5.38	5.26	5.21	5.09	5.06
Water Width Summary													
DS Half of Pond	6.33	6.26	6.16	5.63	5.57	5.47	5.43	5.31	5.28	5.17	5.13	5.02	4.99
US Half of Pond	6.18	6.12	6.01	5.49	5.44	5.33	5.31	5.19	5.15	5.05	5.01	4.90	4.88
Change in WL Summary													
DS Half of Pond	0.000	0.018	0.029	0.036	0.016	0.028	0.011	0.032	0.009	0.030	0.011	0.029	0.008
US Half of Pond	0.000	0.017	0.029	0.037	0.016	0.029	0.008	0.033	0.010	0.030	0.011	0.029	0.008
Evap. During Period		0.004	0.003	0.004	0.005	0.003	0.002	0.005	0.002	0.004	0.002	0.005	0.002
Rainfall During Period		0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Seepage Summary (m)													
DS Half of Pond		0.069	0.049	0.042	0.032	0.035	0.032	0.036	0.025	0.034	0.030	0.032	0.022
US Half of Pond		0.064	0.050	0.042	0.032	0.037	0.023	0.036	0.029	0.034	0.031	0.032	0.022
Representative Time		21/12/2000 13:58	22/12/2000 0:24	24/12/2000 23:43	25/12/2000 12:33	26/12/2000 0:31	26/12/2000 11:33	26/12/2000 23:23	27/12/2000 11:14	27/12/2000 23:12	28/12/2000 11:26	28/12/2000 23:26	29/12/2000 11:12
Representative Time		21/12/2000 13:58	22/12/2000 0:24	24/12/2000 23:43	25/12/2000 12:33	26/12/2000 0:31	26/12/2000 11:33	26/12/2000 23:23	27/12/2000 11:14	27/12/2000 23:12	28/12/2000 11:26	28/12/2000 23:26	29/12/2000 11:12
Total Seepage (mm/day)		67	49	42	32	36	27	36	27	34	30	32	22



2.2.3 Applicability

- 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 benchmarked and assessed.
- Pondage tests can be undertaken at most locations and provide the channel seepage base data. However, care must be taken at locations where there is hard rock to secure the pond banks. In some very large channels, the amount of earth works may be cost prohibitive. Alternative methods of constructing secure banks would be worthwhile considering in future.
- The two main issues limiting technique usefulness are the inconvenience of conducting outside of channel operation times and the cost of bank installation. In the trials, the RWAs found it most convenient to undertake tests at the end of the season.
- The extent of pondage test work to be undertaken at a site depends on the objectives of the investigation.
    - If the investigation is aimed solely at determining the seepage rate along a specific length of channel, a single pond along the section of interest could be used.
    - While a long section can be tested at minimal cost (ie only two banks), if pondage tests are to be used to identify seepage within short-medium length sections then multiple banks will be required, which (especially for large channels) can be very expensive.
    - A minimum of 4 ponds is recommended for a section if pondage test results are to be used to correlate against other test results such as geophysical data, point test data or groundwater analyses and then used to extrapolate to larger lengths of channel.

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.

2.2.4 Practical Implementation

- 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 remain out of use during tests;
    - Installation cost of embankments to isolate reaches of the channel can be high, and sometimes prohibitive in very large channels;
    - Conditions do not reflect velocities and sediment loads carried during normal channel flow conditions; and,
    - The pondage test result does not provide an indication of the spatial variation of losses within the reach isolated and tested and therefore only represent a bulk figure for seepage.

The most appropriate time for conducting pondage tests is at the end or beginning of the water distribution season, so as to minimise disruption to the system. Of these two options, the ideal time is at the end of the water distribution season, immediately before the shut down of the system, as sub-surface conditions are closest to those encountered during operation. However, pondage tests can be conducted at the beginning of the season which can be an advantage if initial channel start up losses are of special interest.

2.2.5 Experience from the Trials

The set up for the trials was generally to install six back to back pondage sections, each of 150-300m length. In the trials these were predetermined locations based on inferred zones of high or low seepage. The results are an average of the seepage rate over the pond length and do not necessarily target areas which are the highest seepage zones.

The results of the trials suggests that under full scale investigation and operational programs, the location of the ponds could be targeted using geophysical indicators of high seepage. Where possible, pond banks should be located so that individual ponds coincide with sections showing similar geophysical response. A minimum of pond length of 100m is recommended.

Pondage tests were conducted successfully at a large number of sites in the trials. Six 150 - 300m length ponds were installed and monitoring occurred over a 2-week period at each site. A summary of the results of the pondage tests conducted is presented in Table 2-2.

- **Table 2-2 Pondage Test Summary**

Channel	Seepage Rate Range (mm/d)	Average Seepage Rate (mm/d)	Pondage Section
Donald	9 – 48	35	6
Toolondo	1 – 11	7	6
Rocklands	4 – 13	8	6
Tabbita	6 – 10	7	6
Lake View	7 – 9	8	4
Dahwilly	4 – 16	10	6
Finley	4 – 7	4	6
Waranga Western	1 - 13	5	11

The sites tested were considered by the respective RWAs to be high seepage sites. The rates of seepage determined were variable along each channel. The range of rates along the channel sections appeared to be consistent with the geological profile at each site and the perceived significance of the seepage problem. However there were anomalies identified in several locations.

It appears that while pondage test seepage rates are the most accurate means of measuring channel seepage, they may still lead to an underestimation of seepage compared to channel flowing conditions. For example, at Dahwilly in SE NSW, the geological profile is very sandy. It was expected that the rates of seepage would be high, although pondage test results from the selected sites suggested low rates of seepage. This is due to the effects of clogging caused by siltation when the water is stationary (ANCID, 2003).

2.2.6 Indicative Costs

The most significant cost of pondage tests is the bank construction. The next largest cost is personnel time for monitoring during the tests. The cost estimates below assume that the RWA has the required equipment available for the tests, including hook gauges, rainfall gauge and evaporation pan.

- *Bank Construction / Removal*:
    - Earthmoving contractor costs - These costs will vary considerably depending on the availability of a suitable local clay source. Approximate costs for bank construction and removal in the ANCID trials are listed below. These were for channels between 10-20m width (at FSL) and 1.5-2m deep:
        - Wimmera Mallee Water : $1000 per bank for 7 banks;
        - Murray Irrigation: $715 per bank for 10 banks; and,
        - Murrumbidgee Irrigation: $780 per bank for 7 banks (including importing clay) and $560 per bank for 5 banks (using on-site soil).

      The difference between Authorities are attributable to different channel sizes, economies of scale for different number of banks constructed and different charges rates of internal personnel.
    - Supervision by RWA personnel: Generally a least half a day would need to be allowed for supervision of bank construction.
    - Plastic lining: Plastic lining is recommended on all pondage banks, but essential if the bank is not constructed with a suitable percentage of clay material. The cost of this for one pondage bank is relatively minor (eg $50-$100/bank). Additional personnel (two recommended) will be required to lay this plastic. About one hour per bank should be allowed.
- *Cross-Section and Hook Gauge Surveying* – A least one cross section per 200m, or one at the upstream and downstream ends of the pond is recommended. Typical costs in this study for the cross section surveying for 6 cells (every 200m) ranged from $600 (Murray Irrigation), $1,200 (Wimmera Mallee Water) to $2,000 (Murrumbidgee Irrigation). The variation is largely attributed to internal charge-out rate differences and/or the use of external contractors.
- *Set-up Costs* – These activities (including installing hook gauges, rainfall gauge and evaporation pan) can be conducted by RWA staff. This is likely to take half to one day.
- *Monitoring Costs* – This can be conducted by RWA staff. Monitoring costs will depend on the number of cells at the site and the distance of bank spacing. Excluding travel time to the site, the daily time required on site for one cell is likely to be around 15 minutes. During this study the typical time required for monitoring six cells at one site was about half to one hour, including measurement of water levels, rainfall and evaporation. Monitoring should be conducted once per day and a test duration of at least seven days is recommended.

2.3 Point Measurement

2.3.1 Principle

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. The infiltration rate has a direct relationship to the seepage at that point. Each point test is a unique value and when individual values are collated they can be useful for identifying seepage 'hotspots' and relative seepage potential.

2.3.2 Method

Point tests can be undertaken at times when the channel is either operating or not running. The techniques which have been applied to channels around the world are:

1. ***Channel Operating Techniques***

   Seepage Meters
   Barrel Tests
   Well Permeameter

2. ***Channel Empty Techniques***

   Constant Head Permeameter
   Double Tube Method
   Disc Permeameter, Infiltrometer
   Ring Infiltrometers
   Two-Stage Borehole Permeameter

These techniques have been described in detail in the literature review (ANCID , 2000a).

All point testing methods involve introducing water into a hole on the base of the channel and measuring the rate at which it infiltrates the channel substrate. In these cases it is presumed that the water used for measurement is similar in chemical make-up to the water that normally runs in the channel. The infiltration rate has a direct relationship to potential seepage. Therefore results are used to infer the point distribution of seepage potential at a point. To obtain a broad coverage of the infiltration variability, many point tests are usually required.

In Australia, the most commonly used techniques are those where relevant equipment is available and there are experienced operators to undertake the field tests and analyse the field data to provide a valid infiltration rate. These are:

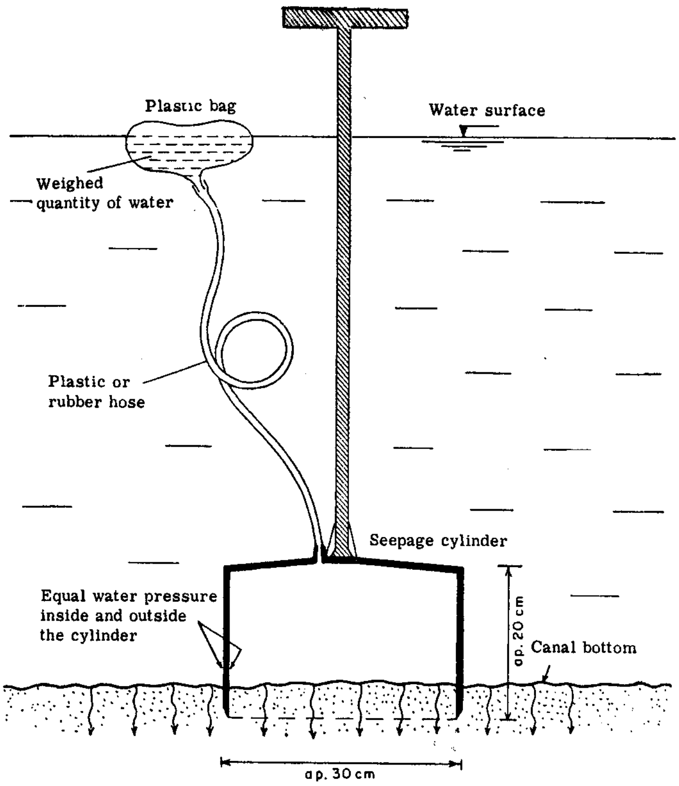
- Idaho Seepage Meter (operating channel),
- Ring Infiltrometers (channel empty),
- Disc Infiltrometer (channel empty).

These techniques are considered to be the most appropriate for current operations in Australia and are the recommended point tests in these guidelines. Direct results of the use of these techniques in Australian conditions are obtained from the project trials (ANCID, 2003) with supporting information in the Literature Review.

2.3.2.1 Seepage Meters (channel running conditions)

Seepage meters are essentially cylindrical infiltrometers modified for use under water. The seepage meter method involves the use of a water tight bell housing embedded into the channel bed where the water lost per unit area through the base of this bell is the seepage loss from the channel. Although many kinds are in use, most involve the insertion of a relatively small ring structure (covered by a water tight bell) into the channel bed. The structure is typically 30-60cm in diameter and is connected by a hose or some other type of tube to a water supply reservoir which allows the rate of loss of water from the bell to be measured. The meters generally used, or referred to in the literature, are based on either a variable or a constant head. Figure 2-6 presents a simple version of a constant head seepage meter. It consists of a watertight bell connected by a hose to a flexible (plastic) bag floating on the water surface. By keeping the water bag submerged, it will adapt itself to the shrinking volume so that heads on the areas within and outside the bell are equal. This type of meter is described in more detail later in the section.

- **Figure 2-6: Seepage Meter With Submerged Plastic Bag**



The seepage meter commonly used in Australia is a constant head unit referred to as an Idaho Seepage Meter (Figure 2-7), which operates using a reservoir (rather than a floating bag) from which seepage can be calculated directly from the rate of fall of water in the reservoir. The work is best conducted by contractors who have the appropriate equipment.

- **Figure 2-7: Installation of Idaho Seepage Meter**

2.3.2.2 Ring Infiltrometers (dry channel conditions)

Single and double ring infiltrometers are devices for determining the rate of infiltration into soil. Single ring infiltrometers are a simple device used for gaining a rough estimate of infiltration rates (Figure 2-8). Single ring infiltration rates can be affected by 'edge' effects. To help eliminate the effect of lateral spreading, a double ring infiltrometer can be used, which is a ring infiltrometer with a second larger ring around it. Both the inner and outer rings are filled with water, which causes essentially vertical flow through the inner ring into the soil. The relative accuracy of either method is not clearly documented.

Ring infiltrometers are normally metal rings with diameters from 30 – 100 cm and a height of about 20cm. The ring is driven into the ground about 5 – 10 cm, water is applied inside the ring with a constant head device, and intake measurements are recorded until a steady infiltration rate is observed. For a double ring infiltrometer, both rings have water applied to them (to a depth of about 15cm), the head (water level) is recorded, and measurements are taken inside the inner ring. If a constant head device is not available to add water to the hole, a constant head can be maintained by adding water and recording the volume of water added at approximately10 minute intervals for a period of one hour (depending on soil type).

The ring infiltrometer can be conducted as a falling head test, and measurements of the drop in water level can be taken at regular intervals, rather than the use of a device to maintain a constant water level in the rings. The infiltrometer does not provide a seepage rate but allows the variability in hydraulic conductivity and by implication the potential for seepage to be identified.

■ **Figure 2-8 Ring Infiltrometer In Use In Dry Channel**

2.3.2.3 Disc Permeameter (dry channel conditions)

The disc permeameter is an instrument developed and commonly used in Australia to measure the hydraulic conductivity of soil at (or near to) saturation. A disc covered with a semipermeable membrane (typically 0.2 m in diameter) is placed on a surface and the subsequent infiltration of water allows calculation of the hydraulic conductivity of that surface.

The test requires a specialist in undertaking this type of work, including the interpretation of the hydraulic conductivity. This measurement method can only be used in empty channels or in areas that are not currently inundated. The method can be used on an undisturbed channel bed. The disc should be mounted on an approximately level surface and thus the approach would be less useful on the side walls of channel beds.

When the disc permeameter is used to measure the hydraulic conductivity of soils, soil profiles are often excavated to the required depth of around 30 cm. This method would allow measurements of soil properties beneath the surface of the channel if it were required. The analysis assumes homogeneity of soil properties.

2.3.3 Applicability

A direct seepage measurement is obtained from point tests undertaken under channel full conditions using the Idaho or other type of seepage meter. The channel empty conditions operate under different hydraulic and soil saturation conditions and provide a measure of soil hydraulic conductivity from which seepage rates can be calculated. Channel empty techniques measure the hydraulic conductivity of the channel soils, which can then be used in mathematical groundwater equations to determine the seepage rate. The presence of silt layers at the channel base can have a strong influence on the interpretation of measurements.

In general point tests are best suited for determining the distribution of seepage losses or potential losses (i.e., relative seepage). However, the frequency distribution of seepage rates is usually positively skewed. That is, a high percentage of the seepage occurs through a relatively small percentage of the channel. Therefore many measurements are required to obtain a reliable estimate of the mean. Taking too few samples tends to produce biased estimates of the total seepage rate and the number of measurements required to accurately estimate the actual seepage is generally prohibitive.

Due to variable and sometimes erratic values obtained in measurements and the large number of tests required to sufficiently determine the average seepage rate, point tests are not considered reliable for absolute quantitative purposes. However they provide a restricted amount of information on seepage distributions.

While these tests provide valuable information on individual locations, soil variability can lead to the need for a large number of point measurements being necessary to adequately map the seepage zones over a significant channel length.

Rarely would point measurement techniques be used as a stand alone method, but often a soil survey can help guide where to take measurements, how many to take, identification of likely hotspots and extrapolation of results. Point measurement techniques can be used in conjunction with soil surveys to assign a seepage rate to a particular soil type. With this approach however there needs to be adequate understanding of surface and sub-surface soil profiles.

Point tests are not sufficiently reliability for absolute quantification of channel losses 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). They are:

- Generally not reliable for direct (absolute) quantification of channel seepage losses due to the variable nature of soil/channel bed liner. They are most useful for determining relative seepage rates.
- Typically a high percentage of seepage occurs through a relatively small percentage of the channel. Therefore numerous point measurements are required to obtain a reliable estimate of the mean.
- To obtain reliable and meaningful results, tests usually require a skilled operator/technician so generally tests will not be able to be conducted in-house.
- In principle, suitable for measuring local seepage rates in channels without artificial lining. They are not practical for a post-remediation assessment, other than for clay lined channels or parts of channels.

2.3.4 Practical Implementation

Generally point tests are quickly and easily installed and are most useful for locating short sections of a channel where seepage is excessive. Seepage meters should be installed with the least possible disturbance of the bed material. Disturbance of the soil during insertion of the meter can cause indicated seepage rates to be higher or lower than actual due to potential leakage around the bell and / or changes in the soil bed structure. Installation of infiltrometers and permeameters also have the potential to disturb the channel base during installation.

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.

Dry channel measurement techniques are time consuming. A single measurement may take several hours depending on the hydraulic conductivity and the moisture condition of the channel bed.

2.3.5 Experience from the Trials

Comparison of the representative seepage rates for each pond derived from channel empty point tests (Disc Permeameter and Ring Infiltrometer) and channel full point tests (Idaho Seepage Meter) have either not compared favourably with the pondage test seepage rates or have been inconclusive. The point test results do not typically cover large enough segments of the channel, either laterally or vertically to be representative of the larger ponded section. Surface sediment layers which were not the most restrictive layers also significantly adversely affected some trials.

The results do not preclude the use of point tests for some aspects of channel seepage assessment (eg for qualitative purposes such as isolating hotspots). However using point test data is limited by the variability in the soil, and the results indicated that significantly higher numbers of tests were required to characterise the channel. The number of tests required to adequately characterise the seepage over a defined length of channel will be financially prohibitive.

2.3.6 Indicative Cost

Generally point measurement techniques will need to be conducted by an operator outside of the RWA, with suitable expertise in the particular equipment being used. The greatest variable influencing the cost of point measurement is the density of testing. The cost of testing will also depend on the duration of individual tests, which will be a function of the time required to reach steady state infiltration (which in turn will be a function of the soil type or clogging layer in the base of the channel).

Sub-contractor costs are provided below for infiltration tests conducted during the ANCID study. Note however that none of these tests were conducted at sufficient density to adequately describe seepage within the reaches they were conducted over. Therefore to properly characterise a reach, testing at a greater density than conducted in these studies will be required.

- *Idaho Seepage Meter* - For Idaho tests at 22 sites (4 individual tests at each site, over the channel cross section) along approximately 800m of channel, the total subcontractor cost (including reporting) was $6,200. The testing was conducted over four days (plus travel time).
- *Ring Infiltrometer* – For 29 individual ring infiltrometer tests, over approximately 600m of channel, the total subcontractor cost (including reporting) was $5,000. The testing was conducted over three days (plus travel time).

- *Disc Permeameter* – For 24 disc permeameter tests, over approximately 600m of channel, the total subcontractor cost was $4,000 (including reporting). The testing was conducted over three days (plus travel time).

3 Subsurface Characterisation

Subsurface characterisation of the area around a channel provides a large amount of information on which assessments of the sites of seepage can be made. The techniques to consider are:

- Soil and Geological Profile Classification.
- Groundwater Assessment, including Water Level Monitoring; Mathematical Modelling; and Hydrochemical investigations

3.1 Soil and Geological Profile Classification

3.1.1 Principle

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. Soil categories (based on texture) can be assigned seepage categories based on the distribution of soils within channel zones of higher and lower seepage. However, the use of material properties and distributions alone is not effective in calculating seepage rates.

3.1.2 Method

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 determine seepage through changes in soil type (this can be conducted at a regional scale, using available soil maps and published data on seepage rates, or at a local scale involving local soil mapping and seepage testing)

Site characterisation is an important component of any channel seepage investigation and site stratigraphy is probably the most important aspect requiring characterisation. Interpretation of test results from all measurement techniques will be underpinned by the conceptual understanding of the site, and therefore it is important that this is established as accurately as possible. For example from the trials the Tabbita site is clearly dominated by stiff clay soil profiles and when this is taken into consideration with the low seepage rates from pondage tests, confirms that the seepage rates are consistent with the ground conditions.

Soil and geological profiling can be undertaken by limited review of available data from soil and geological maps. While these are typically produced at regional scales, they provide a preliminary assessment of the ground conditions.

Subsurface profiling on a site specific basis requires site inspection, local mapping of soil types and drilling. The typical technique to obtain site specific subsurface information is outlined in Section 3.1.2.1 below.

Information on the sub-surface is collected via drilling bores. The key issues to be addressed in developing a drilling program for a channel seepage investigation are essentially where and how many bores to drill, what type of drilling to use, what depth to drill to, and how to log the materials recovered by drilling. All of these issues will be tightly constrained by cost. The approach adopted in this study is described below:

3.1.2.1 Bore Locations

- Bores drilled immediately adjacent to the outside toe of the channel banks (or as close as practical to the bank) provide the closest information about the channel conditions. While drilling in the channel may also be of assistance to determine the stratigraphy directly beneath the channel, this is generally not practical due to the considerable expense of drilling from a barge or boat, unless in dry channel conditions. However interpolation between drilling results on either side of the channel is necessary to determine conditions directly beneath the channel.
- Bores should be located so as to sufficiently define significant changes in soil conditions and stratigraphy. Some indication of the variability can be obtained from geophysical surveys (see section 4). The greater variability at the site, the greater the number of bores required to characterise the site.
- Near channel drilling coincides with the most obvious location of the EM31 and EM34 surveys adjacent the channel bank and provides supporting data for geophysical interpretations. The selection of drilling sites along the channel will depend on the study objectives and the extent of other works being conducted:
- If the investigation is to rely on subsurface profiling as the main technique to identify seepage paths, it is recommended that bores are placed at regular intervals along the length of channel of interest.
- If there is additional information already available, particularly geophysical survey data, bores should be located at sites to cover the range of geophysical response at the site, as well as in locations representing changes in geophysical response, which potentially represent changes in geology.

3.1.2.2 Depth

- Channel seepage impacts on the upper profile, particularly the top 2-3 metres, although in the trials drilling was typically to 4-5m, which coincides with the approximate penetration depth of EM31. When resistivity surveys were used in the final year of the trials, the drilling was increased to 10m. Drilling should be at least 2m into the water table.
- The depth of drilling may be limited by the type of drill rig employed, which in turn may be controlled by cost constraints. Even drilling to several metres will provide valuable information regarding potential seepage paths and mechanisms.
- The depth of drilling will be governed by project objectives:
- For projects where soil profiles are likely to be the sole basis for identifying potential seepage paths, or to support pondage test data alone, extensive drilling to 4-5m is likely to provide the most useful information.
- For projects where groundwater monitoring is a key seepage measurement tool, the minimum depth of drilling will depend on the depth to water table.
- For projects where geological and soil data are used to support geophysical interpretation, the drilling will need to cover the penetration depth of the

geophysical tool. For EM31 this is 4-5m, EM 34 and Resistivity this is around 10m. (see Section 4).

3.1.2.3 Type of Drilling

- The drilling technique needs to be appropriate for the likely strata to be encountered. Suitable drilling equipment needs to be able to drill through to the required depth and through the site materials. Qualified drillers should be used with knowledge of local conditions and appropriate equipment. For example, in areas of hard rock, auger rigs suitable for softer materials are unlikely to be successful. This is an important limitation.
- Most drilling methods will cause disturbance of the sample and care must be taken in the logging of the strata profile. While an undisturbed sampling technique such as split spoon sampling will yield greater accuracy, such a method would be too costly for most channel investigations.

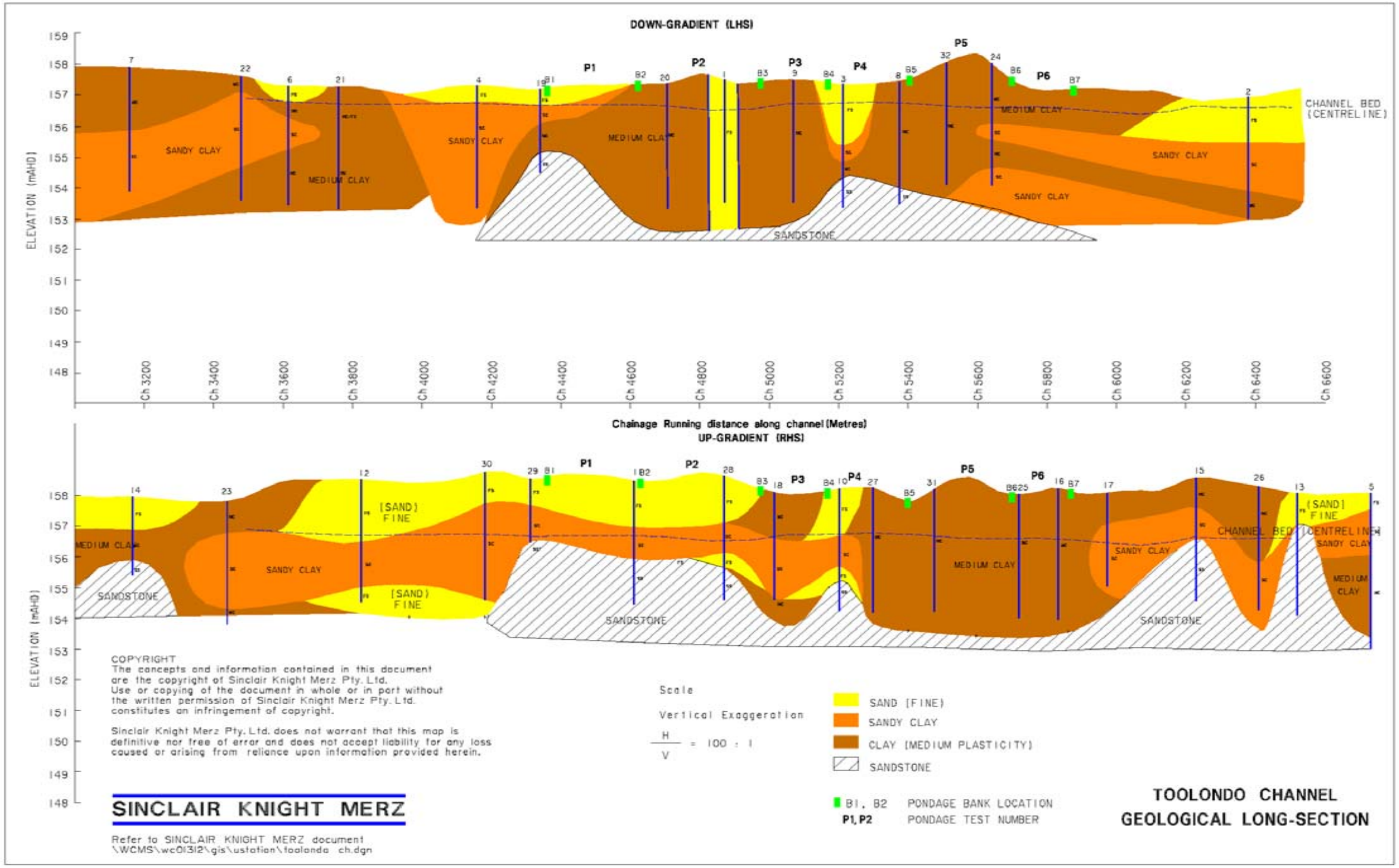
3.1.2.4 Logging

- Ideally a geologist or soil scientist should be available to log the bores. One of the most important aspect of logging is consistency which is best achieved by logging to recognised standards. The Unifed Soil Classification System is considered to be the most appropriate logging system. Numerous other systems exist, including the Northcote system which is often used by soil and agricultural scientists.

3.1.2.5 Interpretation of Subsurface Profiles

- The raw data are best used when incorporated into cross sections along the length of the channel (Figure 3-1). It is recommended that a qualified geologist undertakes geological interpretations of the extent and/or level of uncertainty in correlations between bores.
- As shown on the example of a geological profile (Figure 3-1), it is useful to show the locations of the centreline of the channel so that a comparison of the materials in the walls and the base of the channel can be made. If pondage tests are conducted, showing the location of banks and ponds helps when comparing lithology with measured seepage rates.

■ **Figure 3-1 Geological Cross Section at Toolondo Channel**



3.1.3 Applicability

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. On its own, the geological profile will not provide estimates of seepage rates. In addition, detailed subsurface profiles are limited by the separation of bores. Inevitably there are data gaps and a need for interpretation between the data points.

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. However for more detailed assessment or quantification, any correlations made between soil type and seepage potential based on typical hydraulic conductivity estimates for the particular materials are likely to be of limited accuracy or value.

3.1.4 Practical Implementation

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. In addition, mapped soil data is relevant to surface layers whereas a channel is usually cut several metres into the profile where soil types may be different.

Drilling of soil investigation bores can be done simply by using suitable drilling equipment able to penetrate the site materials to the required depth. Qualified drillers should be used with knowledge of local conditions and appropriate equipment. For example, in areas of hard rock, auger rigs suitable for softer materials are unlikely to be successful. This is an important limitation.

As an addition, the strata profile should be logged carefully by a qualified geologist.

Selected soil bores, where possible, should also be converted to groundwater observation wells. This will depend on the nature of the project, but in most cases it is considered that water level information at a minimum provides a large amount of significant information. This is a relatively straight forward part of a subsurface investigation program.

In terms of interpretation, there are limitations on the assumptions which can be made. In particular,

- Seepage rates within the one broad soil type can vary significantly
- Many measurements are required to obtain reliable estimate of mean hydraulic conductivity of a particular soil type.
- Other significant factors influencing seepage are not allowed for (eg, groundwater levels, clogging layer at channel surface)

3.1.5 Experience from the Trials

The drilling and identification of the subsurface stratigraphy generally provided good back up to the interpretation of zones of greater permeability and the inferred higher seepage rate from them. For example, zones of low seepage measured by pondage tests, (eg Tabbita) were dominantly clayey sequences. In contrast some of the more permeable sections of the Donald Channel displayed higher average seepage rates.

The drilling data at Donald also showed differences in the profiles on either side of the channel, which was also detected by different geophysical profiles (ANCID , 2003).

An important observation at Dahwilly demonstrates the need for caution in interpreting seepage rates based solely on geological profiles. In this location, a very sandy profile, which was inferred to seep at high rates was observed to have low seepage rates because of the presence of a silt layer in the channel which added an additional stratigraphic layer of low permeability.

Attempts to calibrate average soil types based on actual soil survey of the channel, with point or pondage tests may allow estimates of seepage rates to be inferred if a sufficiently strong relationship is developed between soil type and seepage (eg pondage test, point measurement etc). However this requires averaging of the soil materials and interpreted correlations between bore locations. Attempts in the trial investigations to generate average hydraulic conductivity based on soil properties and correlate with pondage tests results were not successful. It is more useful to use an intuitive approach to identifying seepage pathways based on stratigraphic cross sections.

3.1.6 Indicative Costs

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. In the project trials the drilling was primarily conducted by the EM31 surveying contractor. This was approximately \$1200 - \$1500/day and these relatively low costs were due to the fact that the contractor was already on-site (for the EM survey). Further, due to the type of rig used, drilling was limited to around 4-6m and shallower in hard rock. The disadvantage of conducting drilling at the same time as the EM survey is that the bore placement is determined at the discretion of the EM contractor on-site. The preferred methodology is to locate the bores based on the EM results, which involves coming back at a later time.

Typical drilling costs at one 'site' in the ANCID study (approximately 2 km of channel), were \$4,500 - \$6,000. This includes:

- 10 soil bores to 7m (including backfilling);
- 3 permanent groundwater bores installed and cased to 12m;
- Drill rig operator and qualified geologist; and,
- Other expenses (Meals, accommodation etc).

For estimating variations to the above scenario, a rate of \$40-\$50 per metre for soil bore drilling should 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).

3.2 Groundwater Assessment

Seepage from channels has the potential to impact on the local groundwater system. Evaluating the impact of seepage on the groundwater is commonly used by RWAs to identify leakage zones adjacent to channels. While this method is expensive and only provides individual point information, it is a valuable tool in understanding the seepage mechanism.

3.2.1 Principle

The use of groundwater monitoring wells to identify and estimate channel seepage is based on the principle that if water is introduced to a soil profile and reaches the water-table, there can be changes in the hydraulic and chemical conditions within the aquifer. In areas where the channel water level is above the level of the groundwater, there will be a hydraulic gradient between the channel and the aquifer, providing a driving head for seepage to migrate away from the channel. Conversely if the groundwater levels are very high and above the channel water level, groundwater will discharge into the channel.

Seepage from the channel water into an aquifer will result in an increase in the water stored in the aquifer and therefore a rise in groundwater level. Groundwater observations bores allow the watertable (piezometric level) to be measured and monitored. When compared with channel running times, the trends in the groundwater levels can provide an indication of seepage, and it may be possible to estimate seepage rates in some circumstances. In addition samples can be recovered for chemical analysis which can provide information on chemical changes in the groundwater in the aquifer resulting from the introduction of water from the channel.

Groundwater observation bores provide a permanent record of the response of the aquifer to seepage from channels, and this can be useful for post remediation seepage analysis.

3.2.2 Methodology

There are three ways in which groundwater information can be used. These are in order of complexity and level of input:

- Identifying seepage using water levels in groundwater monitoring bores
- Calculating seepage 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, data collection and monitoring.

3.2.2.1 Groundwater Monitoring Bore Set Up

Groundwater monitoring is best conducted using a series of piezometers located at right angles to the centre line of a channel. This enables assessment of the spread of seepage water into the aquifer in a direction away from the channel. A minimum of two and preferably at least three groundwater observation bores in each transect is recommended. One well is required as close to the channel as possible to provide the best indication of the presence of seepage. The bore furthest away from the channel may not be affected by seepage and may provide an indication of the natural background aquifer condition on which the channel seepage impact is superimposed.

The observation bores should be constructed with screens and become permanent installations. Drilling needs to be conducted by an experienced drilling contractor adhering to standard drilling and bore construction standards.

A critical issue is the depth of the bores and the location of the screens to monitor the parts of the aquifer which are likely to be affected - ie: the bores must be shallow enough to actually monitor the water table. In some instances, it can be useful to install "nested" bores which monitor piezometric levels at different depths to identify if there is a strong vertical hydraulic gradient developed by seepage.

3.2.2.2 Collection of Aquifer Data

The range of data obtained from the installation and monitoring of wells which is relevant to channel seepage identification and measurement is typically:

- water level (piezometric level) in the bores - the most common parameter,
- soil profile information including observations of material type (lithology) and saturation (see previous section)
- hydraulic conductivity estimates from groundwater pumping tests or slug tests
- groundwater salinity from field monitoring instruments
- groundwater compositions, from samples tested for a range of parameters including natural and artificial tracers

All bores should be surveyed for location and elevation.

3.2.2.3 Monitoring Water Levels

Water levels in the bores in the immediate vicinity of a channel can provide direct evidence that seepage has affected the groundwater system. Observation of groundwater levels in transects located at right angles to the centre line of a channel provides data to determine the flow lines and equipotential lines of seepage water away from the channel

The hydrograph showing the change in water level with time compared with the duration of the channel provides a direct comparison of the period over which possible seepage impacts could be occurring. If piezometers are monitored at close intervals in the period around channel shut down, the results can be used to identify those locations where there is a high groundwater level adjacent to the channel, and to detect how rapidly the water levels respond (drop).

The best period of observation is during the rise in watertable when a channel is put back into operation or during the fall of the watertable at the end of the irrigation season. Evaporation losses from the watertable can generally be ignored when the watertable is deeper than 1.5m, and other outflow from the groundwater to the natural drainage can be accounted for. (Monitoring at these times should also be complemented by monitoring during the water distribution season, but at a lower frequency).

3.2.2.4 Seepage Estimation

The quantity of seepage can be calculated from the water level information when the hydraulic conductivity of the aquifer is determined or a reasonable estimate can be made. Quantification of seepage rates can be done by using simple analytical equations or in some circumstances by using complex numerical groundwater models. They have been found to yield reliable estimates of channel seepage, when the required field data such watertable elevations, soil and aquifer characteristics, and the hydraulic conditions under which seepage occurs are collected.

The use of these approaches requires records of water levels both adjacent to the channels and at distance away from the channel so that the hydraulic gradient can be estimated. In addition an understanding of the aquifer hydraulic conductivity and the variability of the aquifer properties is required. This can be estimated based on the textural properties of the material identified during the drilling of the bores, but is preferably obtained by aquifer pumping tests or slug tests. These tests require an experienced groundwater specialist to undertake the test and interpret the results of aquifer properties.

Analytical Calculations:

Seepage rates can be calculated by estimating the groundwater flow through a vertical plane arising from a hydraulic gradient between the water in the channel and the aquifer. It assumes that the materials between the channel and the groundwater is saturated. Under this assumption, flows can be calculated using the Dupuit Forcheimer equation for steady flow in an unconfined aquifer. The solution for flow in the direction of the hydraulic gradient on one side of the channel is given by:

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

Where
h_2 is the head in the channel,
h_1 is the head in the observation well,
K is the hydraulic conductivity
L the distance between the edge of the channel and the observation bore.

An alternative technique which may have applicability is to evaluate the rise in water level and use an inferred property of the aquifer known as the storage coefficient to estimate the volume of water which has entered the aquifer. Basically:

$$\textit{Inflow} = \textit{Storage} \times \textit{Increase in Water Level in well}$$

Simple analytical approaches to seepage quantification such as these are difficult because they generally require assumptions on the general properties of aquifers as shown above, and the impact of thin low permeability sediment channel sediments cannot be easily accounted for. However for relative estimates they may be useful.

Numerical Analysis

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

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

This approach requires a modelling specialist, and also requires adequate water level monitoring of bores and channel levels, as well as geological information.

Hydrochemical Methods

Groundwater chemistry information can provide valuable information of channel seepage although this has generally had limited application. Hydrochemistry may be used to estimate either the rate of seepage from a water body (quantitative assessment), or to indicate where seepage may be higher than average (qualitative assessment). It is not considered to be readily applicable to routine channel seepage investigation and is only briefly described in these guidelines. The methods are described in detail in the Literature Review (ANCID, 2000a).

In a practical sense, the most useful technique is to trace the seepage plume from the channel into the surrounding groundwater system. This method relies on the hydrochemical / isotopic concentration of a tracer in the water leaking from the channel to be different from its concentrations in the surrounding soil / groundwater. Types of tracers include conservative chemical tracers (eg, chloride [Cl]), and isotopic tracers (eg, the stable isotopes of water, deuterium ^{2}H, and oxygen-18, ^{18}O). Analyses of selected tracers are required from a series of monitoring wells. For adequate definition of the plume, a minimum transect is required. For better spatial definition of the plume, multiple transects will be required.

The simplest form of tracer to monitor channel seepage is the total dissolved solids concentration of the groundwater. Monitoring of groundwater levels and salinity can provide a reasonable indication of the area and extent of seepage, provided there is sufficient contrast between the salinity of the groundwater and the salinity of the channel water. These data can also be input to detailed hydraulic and solute transport numerical models. The salinity (and [Cl] concentration) of channel water may vary slightly from month to month and year to year, however generally channel water will be significantly fresher than that in the soil water (unsaturated zone) and that in the groundwater around and beneath the channel. Hence, the distance travelled by seepage from the channel should be readily discernible from measurements of total salinity (ie TDS), or by using the electrical conductivity of the groundwater as an approximation of TDS. Preferably a chemical component of the water, usually [Cl] can be used. The groundwater should be collected from a network of bores around the channel. Ideally, the locations and screen depth for the bores should be such that they allow reasonable definition of the freshwater plume.

Isotope and tracer investigations could be used in very detailed studies, although this is complex and requires specialist input. Outputs from these types of studies, combined with water balance estimates, can lead to estimates of seepage rates.

The tracers selected could be naturally occurring or enhanced artificially. The difficulty with artificial enhancement is that flow in the channel limits the residence time to allow sufficient volumes of dosed water to seep into the aquifer and be detected.

3.2.3 Applicability

Groundwater techniques are applicable for both the identification and quantification of seepage rates. They are mostly applicable, especially when attempting any quantification, at local scale.

There are significant advantages in applying groundwater techniques to identifying and estimating seepage. These are:

- Groundwater measurements reflect actual operating (dynamic) conditions and provide a direct identification of channel seepage – it measures all channel water which seeps to the groundwater;
- 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;
- Measurements and samples can be undertake on routine basis to provide and assessment of time variability in seepage impacts under varying channel operating conditions;
- Can be used as a "sanity check" on the results of other work; and,
- The data collected to apply the approach provides knowledge on the seepage processes for the given channel setting (eg it can provide understanding of seasonal seepage processes).

However for large scale investigations the reliance on groundwater techniques is costly as many wells and extensive and on-going monitoring of water levels is required. In addition, to quantify the seepage rates, a large number of assumptions need to be made regarding the soil properties, and these assumptions can lead to wide variability in the estimates, particularly for using analytical methods.

The extent of groundwater investigations conducted will depend on the management issues to be investigated. Different combinations of investigation methods may be undertaken, and these may be used as the basic investigation or as a supplement to other works. The types of typical tasks, the information obtained (ie the purpose that can be met) and the most appropriate scale for these types of activities are shown in the following table: 3.1.

Table 3.1: Groundwater Technique Investigation Methods

Extent of Investigation	Information Obtained	Applicable Scale
Single Point Piezometric Investigation • Drilling adjacent to channel only (single bores) • Monitoring of groundwater and channel water levels during channel running period	• Indication of impact of channel if water levels rise during channel running period and fall in closed down period • Applies to a particular point only – limited ability to extrapolate and needs geological data to support • No indication of rate	• As it is single point it could be applied along any length of channel • For short channel lengths, numerous wells would be required to obtain spatial variation for detailed identification of high seepage zones
Transect Piezometric Investigation • Drilling along transect • Monitoring of groundwater and channel water levels during channel running period • Numerical calculations (and/or modelling)	• Indication of impact of channel if water levels rise during channel running period and fall in closed down period • Extent of impact away from the channel can be determined • Quantification of seepage rates possible through analytical or numerical modelling techniques with assumed aquifer properties • Modelling could show presence of a low permeability zone and could be used to test the possible impacts of remediation strategies • Results apply to a particular transect only – limited ability to extrapolate and needs geological data to support	• Best for detailed investigations along short lengths. • Requires significant extrapolation and high cost for large scale investigation • Useful along remediated sections where elevated water tables are of concern (ie, post-remedial monitoring of changes in watertable due to lining)
Hydrochemical Methods (combined with transect piezometric studies)	• Mapping of the extent of plume can be based on contrasting groundwater and channel water salinity • Detailed hydrochemical and isotopic studies can provide understanding of seepage mechanisms, extent and rates, but are expensive, complex and require specialist inputs	• Best for detailed investigations along short lengths. • Requires significant extrapolation and high cost for large scale investigation

3.2.4 Practical Implementation

Groundwater bores are easily installed, although they can be very expensive, especially as the depth to water table increases. In rocky areas, the cost and the ease of drilling may be prohibitive unless suitable drilling rigs (eg hammer drilling) are used. Siting of bores can 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 (K), which can be difficult to accurately determine and may require specialist technical input. This also requires a considerable amount of investigation work and assumptions made in the evaluation. Therefore, although solution techniques may yield reasonably accurate answers, the amount of work to achieve this may not be justified by the project requirements or expectations. The project objectives must be carefully considered before undertaking groundwater investigations.

To be effective, there is a need to measure soil hydraulic conductivities, which requires personnel competent in performing hydraulic conductivity tests, soil survey crews, and experienced supervising personnel competent in hydrogeology. The detailed field work required to characterise flow paths and hydrogeological conditions in the vicinity of the channel is likely to involve considerable time and expense and require significant expertise.

A mathematical approach to estimating channel seepage has many advantages over direct measurement, particularly in terms of seepage prediction, eg, at different times of the year, under variable operating conditions or changed groundwater conditions. Most mathematical approaches account for the significant effect of groundwater on the seepage process, which other techniques tend to largely ignore. However, the amount of data required to adequately characterise a reach of channel (including a large number of piezometers and numerous hydraulic conductivity measurements) is likely to render this means of seepage measurement as impractical for most purposes. The most useful application of a mathematical approach in routine works may be as a "sanity check" on the results of other work.

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

The main shortfall of trying to determine seepage rates using piezometric or hydrochemical groundwater data alone is that it is concentrated on a slice across the channel which may not be representative of broader channel conditions. If the results from one transect of bores are to be extrapolated along a section of channel, the assumption is being made that hydraulic conductivity (and other groundwater conditions) are uniform along the channel, which may not be a reasonable assumption. The method does not enable any spatial analysis of zones of higher or lower seepage. Therefore it suffers from the same limitation as point measurement - that is many measurements are required to obtain a reliable estimate of the mean;

Hydrochemical methods can be easily adopted if monitoring wells are installed and groundwater samples are able to be recovered. Interpretation requires specialist inputs, especially if detailed studies and techniques (eg isotopes) are applied.

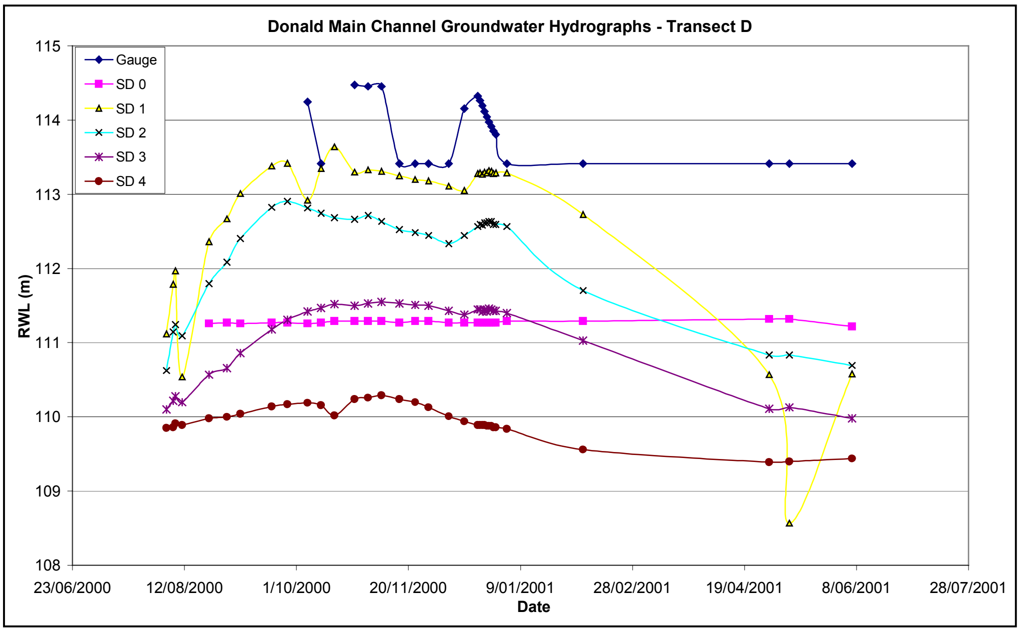
3.2.5 Experience from the Trials

Groundwater observations were made in the trials from formally constructed observation bores, as well as observations on saturation of the soils made while drilling soil bores. The latter are useful observations to indicate the occurrence of seepage, although they do not provide adequate data on elevation or trends to be useful in quantification or examining impacts related to channel operations.

Groundwater monitoring bore transects including both single wells and nested sites were installed at the Tabbita site and at the Donald channel during the trial program.

The recorded water levels in the wells in the transects at both locations show that during the channel running period, the groundwater levels were affected by seepage.

- **Figure 3-2: Groundwater Hydrographs for Donald Main Channel**



For an example, the groundwater bore hydrographs and channel gauge heights at a bore transect at the Donald Main Channel (Figure 3-2) indicate that during times of channel running, the groundwater levels in the bores nearest the channel are elevated, and the groundwater elevation decreases away from the channel. The water levels are based on fortnightly to monthly monitoring. Where the gauge line is flat, the channel was not in operation. The near channel bores (SD1, 2 in Figure 3.2) rise 1-2m in a matter of weeks after the filling of the channel, with the rate dependent on distance from the channel. Bores greater than 50m from the channel (eg SD0) generally display less than 0.5-1m rise in groundwater level.

Attempts to estimate the seepage rate from the groundwater information indicated that there is uncertainty in the calculated rates. This is because there are no reliable estimates of the hydraulic properties, particularly the hydraulic conductivity.

The use of hydrochemical data is based on an investigation of groundwater salinity at the Donald Main Channel, Victoria, (SKM, 1998). This work showed a strong correlation between groundwater salinity and distance from the channel (ie as the distance increases, the salinity increases). This relationship was deemed to be a result of mixing of low salinity channel water with high salinity groundwater, with the influence of the channel water decreasing with distance away from the channel. This was consistent with the results from isotope sampling studies.

3.2.6 Indicative Costs

The costs of evaluating groundwater impacts includes the cost of drilling and bore construction which can range widely depending on materials. The range of costs for drilling and bore construction could range from around $60-70 /metre to as much as $120/ metre. Other significant costs are the costs of monitoring which would be required daily at the commencement of channel running, and continuing on a regular say twice weekly to weekly basis during the running period and monthly for the non-running period. These can be internal costs.

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 require specialists. Costs for modelling will vary with the scale of the modelling 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.

4 Remote Non-Invasive Techniques

The techniques previously described in Part 2 of these guidelines assist in identification of seepage distribution and rate by directly measuring a physical property at a single location. For example, groundwater monitoring of water levels in a bore allows a direct measure of the watertable, and infiltration tests are direct measures of the soil properties at a point.

In contrast, the techniques described in this section, Geophysics and Remote Sensing, use high density sampling of sub-surface and near-surface properties to provide essentially continuous data along the channel.

4.1 Geophysical Surveys

4.1.1 Principle

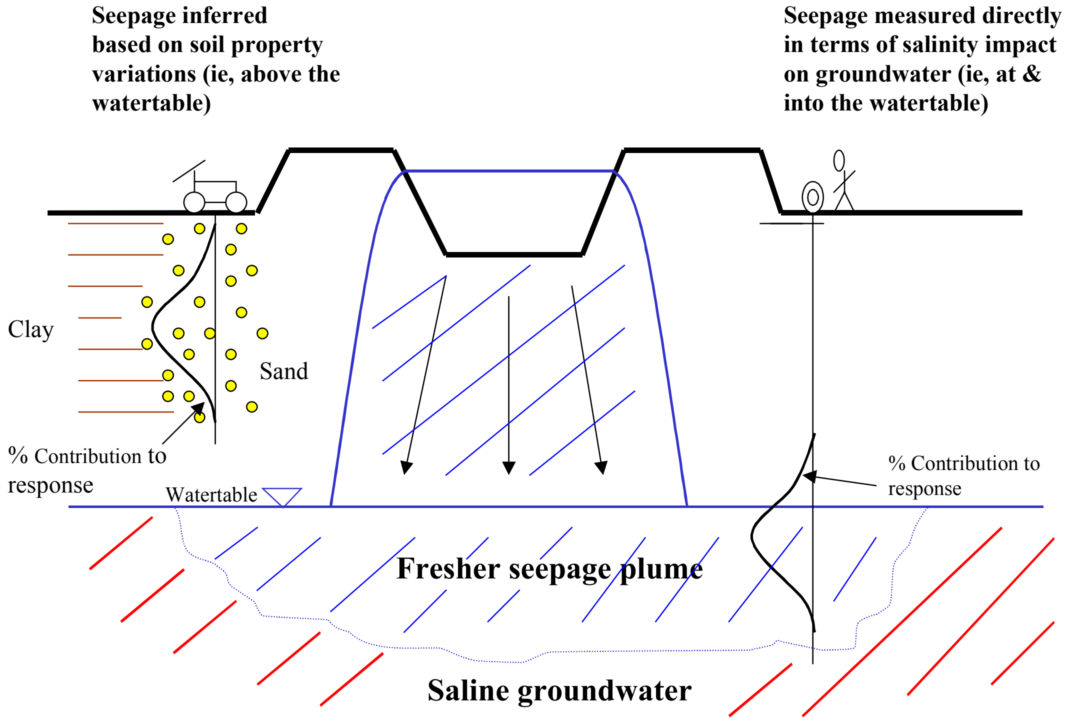
Geophysical techniques applied to seepage measurement primarily depend upon measuring a contrast in terrain conductivity (or resistivity) in the sub surface profile around the channel. They can be used in one of two ways:

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 4-1 visually depicts how these two different approaches can be used to identify or infer 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 beneath or adjacent to the channel. In many cases this is a reasonable assumption, however the unsaturated zone is not necessarily the controlling influence on seepage. For example, over time most Australian channels tend to silt up and the resulting surface clogging layer is often more restrictive than the unsaturated zone. Therefore unsaturated zone lithology may not be related to seepage rates, as seepage is controlled by the thickness and conductance of the clogging layer. Nevertheless, it was found that the inferred method of identifying contrasts in soil properties (ie, where the watertable was deeper than the penetration depth of the geophysical equipment) was successful at most sites conducted during the trials (ANCID, 2003). There is less risk however in using the direct method of seepage detection, because as the name implies it is not inferred, but direct.

■ **Figure 4-1 Comparison of how geophysical techniques can be used to identify channel seepage (LHS – inferred from soil property variations, RHS – direct measurement of salinity impact on watertable)**



Two possible limitations of the direct method of seepage detection are:

1) In a relatively non-saline groundwater environment the fresh seepage water will not contrast with the native groundwater. This is not expected to be a problem in most Australian conditions; and,
2) Groundwater salinity may vary along the channel and this needs to be allowed for in interpretation.

4.1.2 Methods

4.1.2.1 Technique Selection

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. These techniques achieve different depths of penetration (the depth to which the instrument set up allows readings to be obtained) and have different depth focuses (depth interval from which the bulk of the response is derived). Therefore the different geophysical methods measure the conductivity (or resistivity) of different parts of the sub-surface profile.

Geonics EM techniques record the average conductivity across a certain depth interval. The depth of penetration and the focus of the interval are dependent on the type and dipole orientation of the instrument. For example, the depth of penetration for EM34 with a 10m coil spacing and in vertical dipole is around 20m, so the conductivity measurement from available tools is an average across this depth. In contrast, existing resistivity tools (as used in the trials; ANCID, 2003) measure the resistivity (and indirectly its inverse, conductivity) of the profile at a range of depths. This provides information on the change in resistivity through the profile. The depth of penetration of resistivity techniques can be varied by the addition or removal of dipole arrays.

The depth to watertable therefore influences the property being measured by a given geophysical technique. For a given geophysical technique, when the watertable is deep, unsaturated zone soil properties may be measured, whereas when the watertable is shallow, the same technique may be measuring changes in the groundwater resulting from seepage.

Therefore, it is very important that the depth to watertable at the site is known before selecting a particular geophysical technique. This is to add confidence to the interpretation by recognising whether the geophysical responses are direct measurements of seepage impact in the groundwater or inferred seepage zones based on interpreted soil properties.

Preferred Geophysical Techniques

- The preferred technique for geophysical channel seepage assessment is *directly detecting the impact of seepage on the groundwater*. This means that the instrument must focus on the zone immediately above and several metres below the watertable:
    - For a *shallow watertable* (surface to approximately 5m) *EM31* is suitable for direct seepage detection.
    - For *watertables deeper than 5m*, *EM34* (in ***vertical*** dipole mode) or *resistivity* can be used. However, particularly for deeper watertables, it is easier to focus on a given depth with resistivity and this can be achieved independent of knowledge of groundwater depth. The significant advantage of resistivity is that it provides a profile of the resistivity beneath the channel. The disadvantage is that resistivity technology for channel seepage assessment is relatively new and therefore more expensive.

- EM31 (vertical dipole) adjacent the channel can be used effectively in areas with deeper watertables, although it does not directly measure the seepage impact on the watertable. It has been effective in the trials (ANCID, 2003). This is due to fact that the upper soil layers are the most influential on channel seepage and the relatively shallow depth focus of EM31 measures these upper soil layer properties. The method infers zones of likely channel seepage by identifying materials in the unsaturated zone most susceptible to seepage. A decision to use EM31 in deeper watertable area might be based on:
    - Cost and required accuracy – If a potentially slightly lower level of accuracy is considered acceptable then EM31 represents a cheaper alternative than EM34 or resistivity; or,
    - Lack of alternatives – EM34 or resistivity contractors are not readily available.

It this method is used however, it must be made certain that seepage is controlled by the unsaturated zone and not surface clogging processes. Otherwise errors will potentially be introduced to the assessment process.

The preferred geophysical techniques for seepage detection are summarised in Table 4-1.

- **Table 4-1 Recommended Geophysical Technique for Seepage Detection and Measurement**

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

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

A more detailed description of each of the techniques described in Table 4-1 and how they can be used in seepage measurement, including examples from the trials program, is presented below. These techniques are best undertaken by specialist geophysical contractors who possess the appropriate tools, including software for analysis and documentation.

4.1.2.2 EM Systems

Ground conductivity can be obtained with frequency domain electromagnetic instruments such as the Geonics EM38, EM31 and EM34 meters. EM38 depth penetration is less than a metre and dominated by near surface conductivity changes. Previous trials showed that it was not an appropriate system for this work and hence EM38 is not recommended for seepage assessment (SKM, 1998).

4.1.2.2.1 Field Operation

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

Geonics EM34 systems can be used at various intercoil spacings and orientations so as to vary the effective depth of exploration, in contrast to Geonics EM31 systems which have a fixed coil spacing. EM34 is a slower technique than EM31, as the required coil spacing means that the coils must be carried by hand. An EM34 unit in operation (horizontal dipole) is shown in Figure 4-2.

EM31 during the trials were undertaken on a quad bike and at some site also on-channel (Figure 4-3). A digital outlet is linked to a data storage device and the results all linked to GPS location data. Sampling can be set by time or by distance travelled, and measurements can be taken as close as every ten centimetres along a transect line. In the trials a reading was taken approximately every 5m. Various multi-coil, multi-frequency systems are also under development, which enable conductivity depth resolution.

The details of these systems are described in the Literature Review (ANCID, 2000a) and the Technical Report on the Project trials (ANCID, 2003).

■ **Figure 4-2 EM34 In Use (in horizontal dipole mode)**

■ **Figure 4-3 EM31 Mounted on Quad Bike and on Boat**

4.1.2.2.2 Qualitative Versus Quantitative Seepage Assessment using EM results

Geophysical tools can be applied in two ways:

- ***Mapping the distribution of high and low seepage zones***

  As a mapping activity only, detection of seepage (or inferred zones of likely seepage) can be achieved with geophysical techniques alone as geophysics is an effective tool for mapping the distribution of zones of relatively higher or lower seepage. Greater confidence can be obtained by confirmation with geological investigations.

- ***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. More likely, the relative seepage rate is able to be identified by the correlation of geophysics with other data, particularly pondage tests.

As with all other techniques, the level of investigation needs to meet the project objectives and budget and the level of confidence required. These two applications of geophysical surveys are described in further detail below, as they relate to EM assessment:

Qualitative Assessment – Mapping Seepage Zones
Geophysical surveys using EM31 and EM34 have shown promising results in mapping the extent of seepage zones along channels, based on both direct and inferred seepage detection (ANCID, 2003). Mapping of relative seepage occurrences is valuable in identifying the extent of the seepage problem, and the areas of the channel with the greatest problems. Comparison of the EM with direct measurement, especially with pondage tests, is considered to provide the best assessment of the relative significance of the EM readings in mapping the distribution of the highest seepage zones along a channel.

The geophysical mapping is complemented by direct measurement to evaluate the rate of seepage, although point tests could be also be used. In addition, soil and geological strata information can provide a greater level of confidence in this qualitative assessment.

> ***The use of EM mapping is extremely valuable for indicating lengths of channel which are most likely to be seeping at the highest rate. It is suggested that mapping is the first task to be conducted in an investigation and it can provide the basic framework on which to locate other work such as pondage tests, groundwater and soil bores.***

Quantitative Analysis of Seepage
Good correlations have been obtained between pondage test seepage rates and the average EM conductivity of the sub-surface profile along the pond. In general, EM conductivity values can be correlated against the pond seepage rates with correlation coefficients as high as 0.9 for sections of channel which have been measured. Care must be made in interpreting trends local scale because there may only be a narrow range of seepage rates and /or conductivity values. Too much emphasis on trends under these circumstances can lead to invalid interpretations.

The general relationship between seepage rate and conductivity measurement can be used to attempt to quantify the possible seepage rate. This has been done by a statistical analysis of the data. This work is described in detail in the Project Trials Report (ANCID , 2003), although the relationships obtained are included in the guidelines to provide channel managers with a tool which may provide some preliminary estimates of possible channel seepage rates. The relationships are not definitive and there are limitations on the extent to which conclusions may be drawn.

> ***It must be stressed that these trends and confidence limits are general and are based on data sets derived from locations where there are different soil and groundwater properties. While the trends are valid, the width of the***

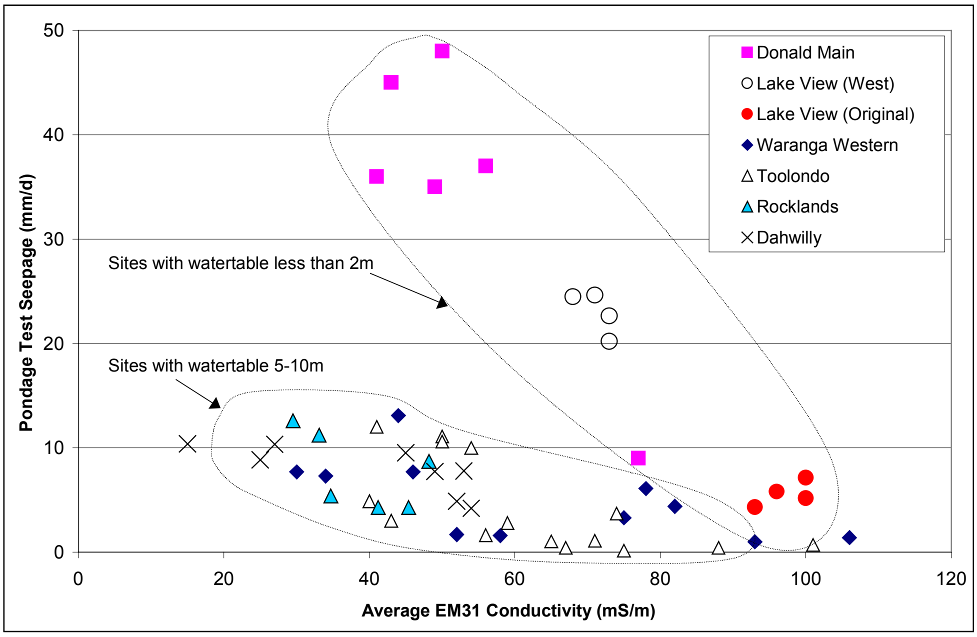
error bands indicates that at best they can provide give a range of possible magnitudes of seepage.

Detailed quantification will require more detailed site specific testing to identify any local trends which can be extrapolated beyond the immediate test sites. However it needs to be noted that in some locations, there is a very limited range of readings and relying solely on developing a correlation coefficient may be misleading.

Figure 4-4 presents EM31 conductivity plotted against pondage test seepage for the majority of the test sites in the trial program, representing a total of 57 ponds. Based on this data, there appear to be two categories based on depth to watertable. These two trends concur with the understanding of the EM31 inferring seepage based on soil type for the deeper watertable site and directly detecting seepage for the shallow watertable site. The details of the data and interpretation are provided in ANCID (2003).

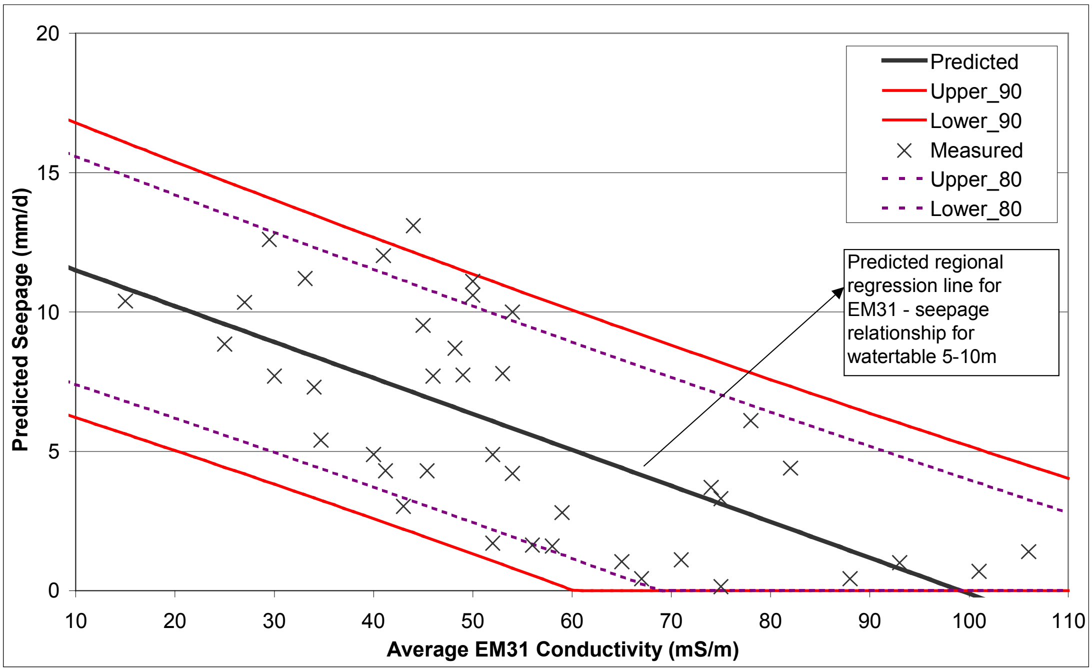
Using the two different populations, the limited information suggests that within each population, there may be a general trend. Confidence limits based on each trend may allow estimation of a likely range of seepage from a pond with a particular average EM31 response.

■ **Figure 4-4 General plot of EM conductivity against measured seepage**



The trend line seepage based on EM31 response when the watertable depth is 5-10m is shown in Figure 4-5 with surrounding 80% and 90% confidence limits.

■ **Figure 4-5 Trend line for Watertable depths of 5-10m**

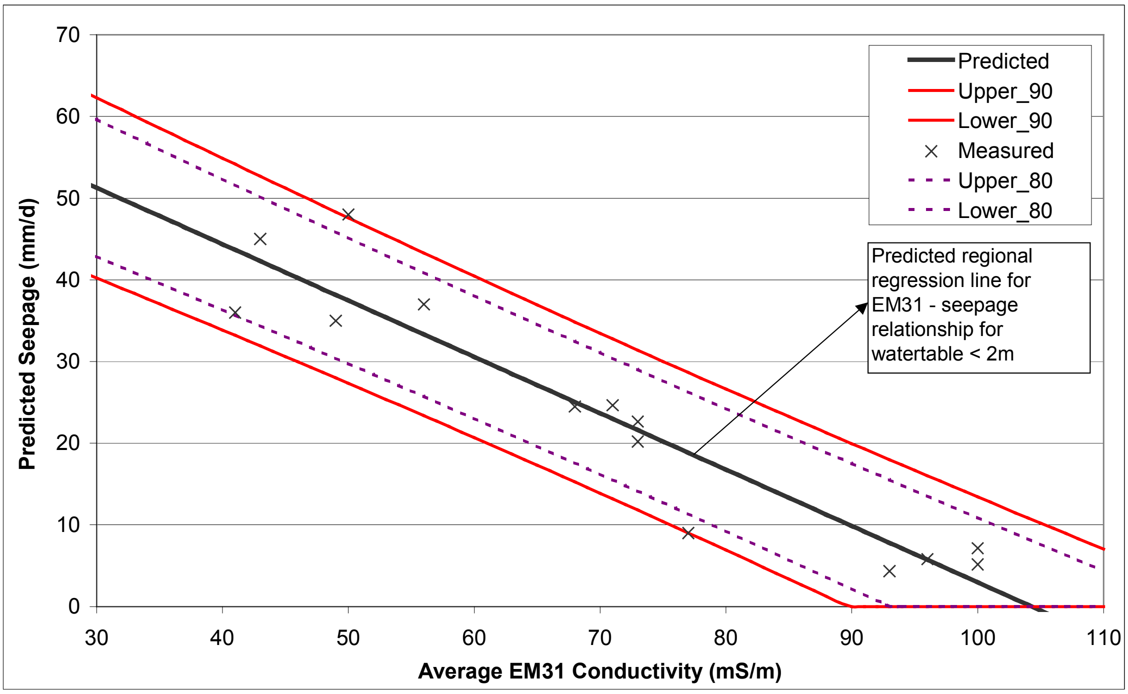


Applying this figure, these bands suggest that if an average EM31 measurement represents a certain stretch of channel, we would be 80% confident that the seepage rate in that section would lie within the confidence bands at that average EM31 value. The 80% intervals are narrower than the 90% intervals, as there is less certainty in pinning the value down to its 'true' seepage rate. This figure shows that the prediction equation is accompanied by quite broad prediction intervals.

For example, an EM31 survey with an average response of 30 mS/m, would suggest a seepage value of 10 mm/d. Using the prediction bands, we would be 80% confident that the seepage in that section would be between 5 – 13 mm/d and 90% certain that it was between 4 – 14 mm/d. These bands are quite wide, however they indicate that the prediction equation is a useful tool for broadly classifying seepage rates (eg into low, medium and high categories).

Figure 4-6 presents prediction bands (80% and 90%) for estimating seepage based on EM31 response when the watertable is less than 2m. While the prediction intervals are actually broader in magnitude (approximately 20 mS/m and 15 mS/m for the 90% and 80% intervals respectively) than for the prediction bands for the deeper watertable scenario, relative to the seepage range covered by the equation, they are actually narrower. This pattern is based on limited data.

■ **Figure 4-6 Trend line for Watertable less than 2m**



Quantification of seepage rates can be made by assessing the relationships between pondage tests and average EM response over a pond length. A preliminary approximation can be obtained using the relationships described above, recognising that the accuracy of rates inferred have limitations.

Confirmation with site specific testing is strongly recommended. This would include targeting pond locations to areas inferred to be high seepage based on geophysical results and comparing the results. The results of distributions based on EM results can be complemented by soil and groundwater investigation.

4.1.2.2.3 Implications of EM results for Remediation

There is a general correlation between EM results and seepage measured by pondage tests. It is thus assumed that the lowest conductivity usually is an indicator of zones of highest seepage and is a guide to channel managers of locations in need of remediation. The relationship is not unique to all areas investigated and before extensive channel works programs are conducted it is highly recommended that the correlation be locally verified by direct measurement. Being able to assign approximate seepage rates to conductivity response for the region will assist in refining this process.

These figures will also assist in improving the decision making process as to the EM response which represents a cut-off criterion for determining which areas of channel are the highest seepage sections in a particular area.

Drilling at sites where channel refurbishment is proposed is often undertaken to provide greater definition of the lateral and vertical extent of materials for excavation. It also assists in definition of high seepage areas by obtaining more strata information for comparison with EM results, additional information on the relationship between conductivity and material type. In addition detection of the watertable during this drilling assists in clarifying the locations of greatest seepage.

4.1.2.3 Resistivity Surveys

Resistivity surveys provide a depiction of resistivity (and indirectly its inverse, conductivity) variation through the profile. They are therefore ideally suited to the direct method of seepage detection, where seepage induced changes in the watertable are targeted. The significant advantage is that it is not necessary to know the exact depth to watertable prior to conducting the survey.

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

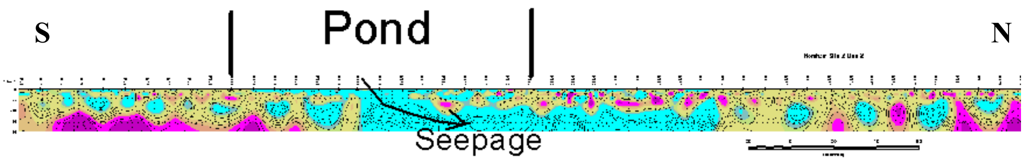
The advantage of resistivity systems is that a single transmitting dipole can be used with a number of receiving dipoles. These dipoles positioned at increasing distance from the transmitting electrodes can be used to calculate the depth and conductivity relationships of the sub-surface. This allows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

In the trials a multi electrode array was built in what is commonly referred to as a dipole-dipole configuration. A pair of current electrodes separated by a distance x are followed by a series of receiver electrodes all separated by the same distance. The closest receiver electrodes sample the resistivity in the near surface (around one third to half x) and the more distant electrodes 'see' deeper into the ground. Using an array of receiver dipoles allows the possibility for a resistivity section to be created. In the trials the array was immersed (floating) on the channel. Contact of electrodes in the water and thus to the underlying ground was good and the array could be towed at speeds of around five to eight kilometres per hour while data was collected. This allowed data collection of two kilometre sections in around 20 minutes. The set up used in the trials is shown in Figure 4-7.

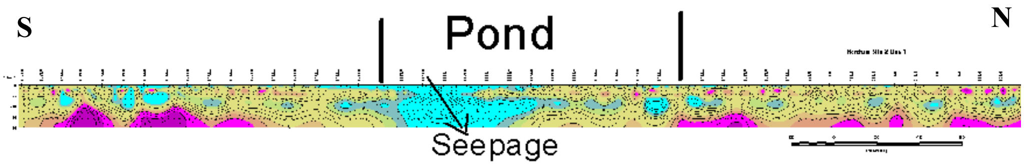
■ **Figure 4-7 Resistivity Configuration Used in the Trials**

Resistivity profiles were prepared which can then be used to identify seepage plumes. An example from the trials is shown in Figure 4-8.

■ **Figure 4-8 Resistivity section (Blue = high; red = low) under pond on Toolondo Channel from (a) south-north and (b) north-south traverse. Arrows show probable seepage zone under pond.**



(a)



(b)

4.1.2.4 Important Geophysical Survey Variables

The work conducted in the trials suggests that local conditions such as depth to watertable, soil type, salinity of the groundwater, channel operations and rainfall all have some effects on the data for sections of channel. Very local conditions such as high water use vegetation immediately adjacent to the channel also appears to affect the results. All of these need to be considered when planning or undertaking an EM investigation, and accounted for in the analysis of results.

The effectiveness of EM as a seepage mapping technique can be influenced by the site conditions, which can vary with time at the same site. Repeat tests under essentially the same conditions showed very similar results (ANCID , 2003). However under slightly different conditions, while the same overall trends were obtained, slight variations can occur.

Rather than be a source of uncertainty, all these sources of information can be complementary and improve the interpretation of the EM results. Some of the key variables are briefly discussed below:

- *Survey timing* – The timing of the geophysical survey will depend on the method of seepage detection being used. If seepage is being inferred from soil properties then the timing of the survey is not critical and can be conducted whether the channel is running or empty. However if direct measurement of seepage is used, the survey must be conducted while the channel is running, and preferably after it has been running for a least one month (depending on depth to watertable and vertical hydraulic conductivity), to ensure seepage has impacted the groundwater.
- *On-channel versus on-land* – During the trials, on-channel (ie, in a boat) EM31 surveys:
  - Did not work at one site where the watertable was beyond the range of the EM31 and returned similar (reasonable) results to the on-land survey at another site (Waranga).
  - Did work at sites with a shallow watertable; and,
  - Were partially successful when the watertable was located at the edge of the depth penetration capacity of the EM31.

  Further work is required in this area, but the evidence collected in this investigation suggests on-channel EM31 surveys should only be conducted where the geophysical technique can penetrate into the watertable, and ideally target the top of the watertable. However, there is some conflicting evidence, as demonstrated by the trial results summarised above. Overall however, the most consistent results were returned on-land and this is considered the safest option. A possible limitation of on-land surveying, may be at sites which contain significant land salinisation immediately adjacent to the channel. Therefore, if the budget allows, it is recommended that both on-land and on-channel surveys be conducted. Resistivity surveys can be conducted on-channel because of their greater depth penetration capacity.
- *Off-set distance and location for on-land surveys* – The best off-set distance for on-land surveys is generally immediately adjacent to the outside toe of the down slope side of the channel. because the soil type next to the channel is most likely to be representative of the soil type beneath the channel and immediately adjacent the channel will be the zone of greatest seepage impact on the watertable. Away from the channel this impact will be diluted. However at sites without a steep gradient or high transmissivity, an average of survey traverses up to 50m on each side of the channel was found to improve the correlation between seepage and the geophysical survey at most sites.

  Traverses on either side of the channel are recommended, however if budget is a significant constraint, a traverse on the down-slope side of the channel should be preferred.

- *Groundwater salinity*- For direct measurement of seepage impacts on groundwater salinity, for channels where groundwater salinity changes significantly along the length of the channel, interpretation will need to take this into account.
- *Other variables* – Other variables which may need to be accounted for in the interpretation of geophysical survey results include:
  - Trees – In two surveys tree plantations adjacent the channel appeared to interfere with the survey results. The postulated mechanism is that the trees are consuming the seeped water and therefore the observed impact (in the geophysical survey) on the native groundwater is lessened.
  - Rain – Rainfall did not interfere with the surveys conducted in these trials. However it is possible that surveys conducted after heavy rainfall on light to moderate soil types (ie which allowed significant infiltration) could interfere with the conductivity / geophysical response and therefore should be avoided. Surveys inferring seepage based on shallow soil properties or direct measurement in shallow watertable environments would be most effected.

4.1.3 Applicability

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. Detection of seepage can be achieved with geophysical techniques alone, however even though general trends have been inferred from the limited data available, quantification requires integration of geophysical methods with other techniques, in order to calibrate the results.

- 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 calibration, they can provide reasonable estimates for seepage quantification.
- The application and extent of investigation will be dependent on the immediate needs of the investigations. With the availability of resistivity techniques, it is possible to obtain a multiple level distribution of seepage. This is in contrast to the EM31 and EM34 techniques which have a single measurement representing a thickness of the sub-surface profile.
- In order to map and quantify seepage, using local relationships from back to back ponds in a single location is satisfactory if estimates close to this location are required, and sub-surface conditions do not vary considerably between the ponds. However if the purpose of the investigation is to predict seepage over a long section of channel, pondage tests covering a range of sub-surface conditions should conducted. If from this data two or more different trends can be observed

due to identifiable differences in sub-surface conditions, then two different regression equations should be generated. If such trends cannot be picked then all ponds should be used to generate the regression equation, excluding any obvious outliers, where there are grounds to do so.

- Pondage tests selected for calibration should be over areas of like conductivity / resistivity. This infers that the geophysical survey must be completed *prior* to the pondage tests and the pondage tests are to be located based on the survey results.

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.

4.1.4 Practical Implementation

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.

A disadvantage of resistivity surveys is that they require substantially more post data-processing than EM surveys which is costly, requires higher levels of specialist technical input and potentially greater time to deliver final information and reports.

4.1.5 Experience from the Trials

A large number of geophysical investigation techniques were undertaken in the trials and these are fully documented in the Project Trials Report (ANCID , 2003). Relevant examples demonstrating the use of the techniques are shown below. In particular, the experience gained in:

- Comparison of different techniques at the same site;
- Use of EM as a mapping tool and comparison with direct measurements; and,
- Repeatability.

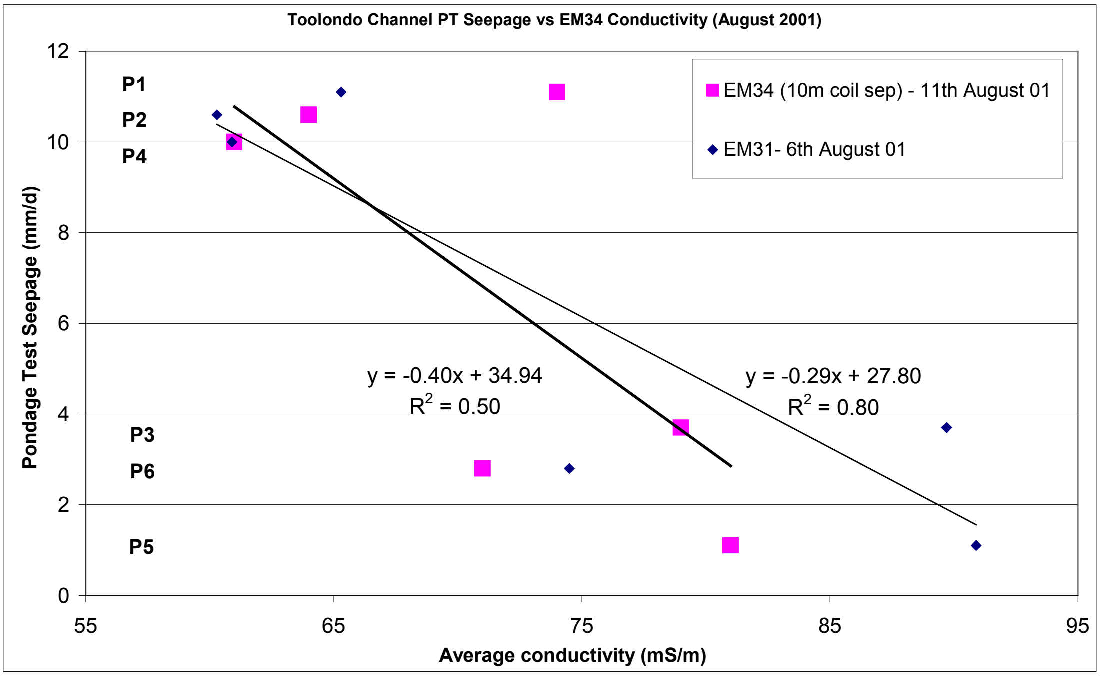
4.1.5.1 Comparison of Techniques at the Same Site

Comparison of the results of different EM techniques are shown using the results of trials at the Toolondo channel, which used both EM31 and EM34 (refer Figure 4-9). The surveys were conducted within 5 days of each other, so it can be assumed groundwater conditions were essentially identical and the differences reflect the responses of the different techniques.

Within this narrow range of measurements the trends are generally similar when plotted against the pondage tests results, with the higher conductivity areas coinciding with lower seepage zones. Differences appear to be slight. The EM31 conductivities, representing shallower depth profiles, were slightly higher than the EM34 results for the low seepage ponds, whereas the EM34 conductivities were marginally higher than the EM31 in the three higher seepage rate ponds.

It appears that even though the target depths of the EM31and EM34 are different, EM responses are similar for the bulked soil and water profiles. This limited information suggests that even in this case where the watertable is around 7m deep, the EM31 responses appear to adequately detect the lower salinity and lower clay impacts in the higher seepage zones (P1,2,4) and lower impact on the profile in the low seepage zones.

■ **Figure 4-9 EM34 and EM31 Survey Results (August 2001) – Toolondo Channel**

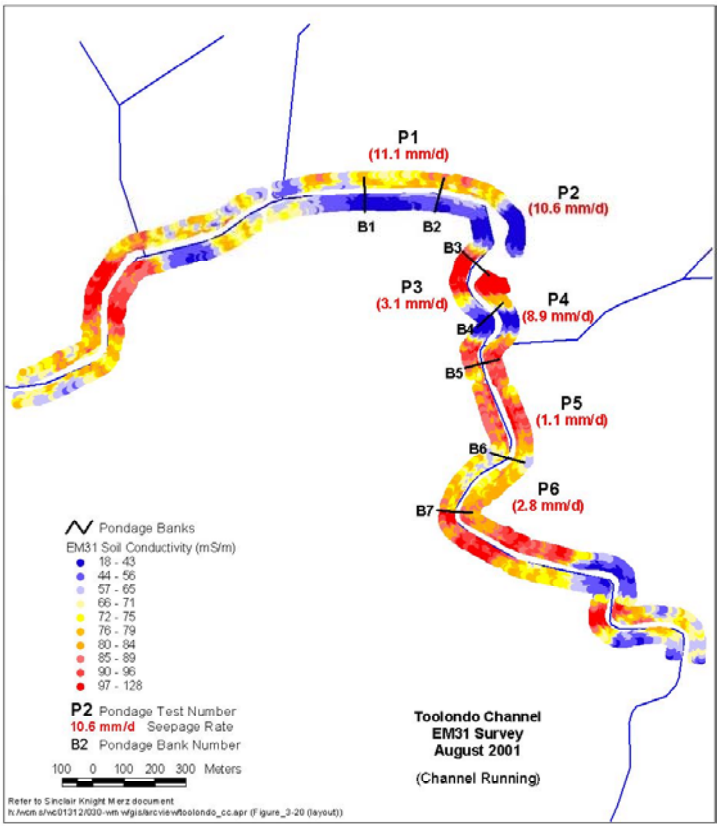


4.1.5.2 EM Mapping and Quantification

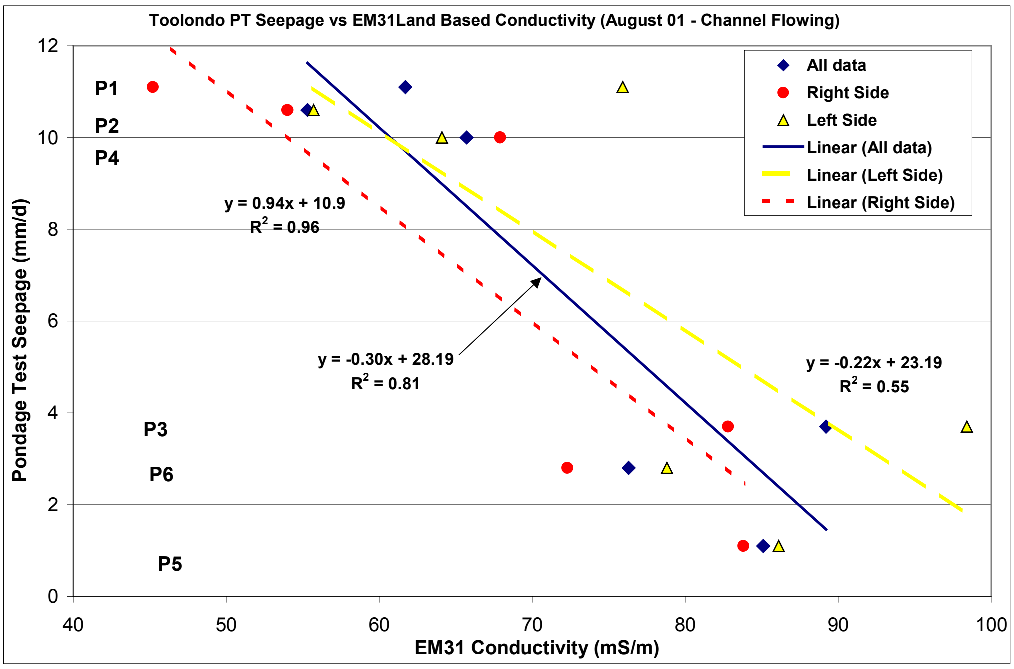
The main approach in the trials was to compare the distribution of EM conductivities from survey lines alongside and within channels. There is a general trend at all sites of lower conductivity relating to higher seepage, although this strength of the correlation varies between locations (Figure 4-10).

The distribution of the EM results for the Toolondo channel in Western Victoria are shown in Figure 4-11, along with the measured base rate seepage estimates obtained from pondage tests. The figure shows clearly that in this case the lengths of pond where low conductivities are identified tend to have higher pond seepage rates. Therefore in its simplest form, an EM survey provides an indication of the areas on either side of a channel where there may be seepage.

■ Figure 4-10 Toolondo EM31 Land Survey



■ Figure 4-11 Correlation of Seepage Measurements and EM31 results for Toolondo Channel



4.1.5.3 Repeatability

Repeatability testing shows that the average conductivities in each pondage section from the Donald Main channel in western Victoria varies between two surveys (Table). The Results from a September 2001 survey consistently returned higher conductivities than the October 1999 survey.

- **Table 4.2 Comparison of Donald Main Channel EM34 Results: October 1999 and September 2001**

Pond	Seepage (mm/d)	Av. Sept 2001 Conductivity (mS/m)	Av.Oct1999 Conductivity (mS/m)	Variation (mS/m)
P1	32	51	28	23
P2	29	44	25	19
P3	28	39	22	17
P4	35	49	42	7
P5	48	49	36	13
P6	9	66	54	13

The differences are primarily due to the much more elevated and fresh groundwater mound present in the October 1999 survey due to 6 months of prior channel operation. The channel had only been running four weeks (at reduced capacity) at the time of the September 2001 survey, possibly only enough to flush some of the accumulated surficial salts down into the profile. The October 1999 survey was therefore conducted under a sub-surface environment dominated by seeped water and a flushed (ie relatively salt free) profile, while the September 2001 survey was conducted in a environment probably only just beginning to flush salts through the profile (ie relatively salt rich).

4.1.6 Indicative Costs

Approximate costs for the three types of geophysical surveys undertaken in these trials are provided below:

- EM31 Surveys:
  - Wimmera Mallee Water: For 6 kms, on-land including 4 traverses on each side of channel (over 3 sites): $400/km (includes mobilisation, data processing and mapping).
  - Murray Irrigation: For 8 kms, on-land including 4 traverses on each side of channel (over 4 sites): $340/km (includes mobilisation, data processing and mapping).
  - Murrumbidgee Irrigation: On-land including 4 traverses on each side of channel, on each side of channel, the unit cost ranged from $650/km (3km section) to $800/km (1 km section). (includes mobilisation, data processing and mapping). On-channel survey cost was $330/km for a 3 km section.
- EM34 Surveys:
  - Wimmera Mallee Water: For 4 kms over 2 sites: $250/km (1 traverse only on one side of the channel) ie, $500/km for both sides of channel (excludes mobilisation).

- Murray Irrigation: For 6 kms (on each side of channel) over 3 sites: $435/km (includes mobilisation).

- Multi-electrode Resistivity Surveying – The follow costs were for resistivity surveying across 11 sites (approximately 2km each in length) in the Wimmera, Murray and Murrumbidgee Irrigation areas:
  - Resistivity towed array surveys: $900/km [Includes mobilisation (from Adelaide), travel between sites, production and all equipment costs]
  - Data processing costs: $220/km.

  Note that resistivity surveying costs are difficult to quantify given that the technique is relatively new. Costs are likely to come down as the technique is refined, the equipment becomes commercially available and subsequently competition is introduced.

4.2 Remote Sensing

Remote sensing techniques can offer an efficient method to detect and locate seepage without interfering with channel operations. Remote sensing refers to any kind of data recording by a sensor which measures energy emitted or reflected by objects located at some distance from the sensor and includes aerial photography and satellite imagery.

4.2.1 Principle

Remote sensing techniques are considered to have the potential to provide a cost-effective means of assessing long sections of channel seepage by evaluating soil moisture, vegetation vigour and soil profile properties especially in dry periods during which channels are operating.

In particular, Airborne Night Thermal Infrared imagery can provide an indication of shallow soil saturation resulting from lateral seepage occurring along channels which may be a precursor to water logging and soil degradation from soil salinisation.

There are currently no documented studies of remote sensing being used to ***quantify*** channel seepage; although it has been used for ***detecting*** and/or ***predicting*** channel seepage in NSW (McGowen, et al. 2001) and in the USA (Nellis, 1982).

4.2.2 Method

All remote sensing techniques for channel seepage detection assume that channel seepage has a surface expression adjacent to the channel. This may be detected as increased soil moisture and / or vegetation vigour and water status. These techniques are limited to detecting seepage that migrates laterally through the channel banks, and/or re-surfaces near the channel toe.

A key aspect of remotely sensed data is that it must be at a suitable resolution to allow definition of seepage zones. Typical seepage zones may be 10 – 20 m in width adjacent to a 10 – 20 m channel. Therefore ground resolutions of less than 10 m are required. The regions most useful for channel seepage detection include visible, reflected (near) infrared and thermal infrared.

The remote sensing data can be evaluated in conjunction with other spatial data such as with the EM surveys and soil survey assessments. This can be done using GIS.

Several attempts to incorporate remote sensing data into channel seepage studies have been somewhat ad-hoc and unsuccessful. Most importantly, this is a specialist task and needs careful planning of the details of the data to be obtained, in what format and in what range of the spectrum. An experienced specialist is needed to provide guidance and define the program and the expected outputs prior to any data gathering work.

As this technique has not been adequately tried, as with all channel seepage investigations, the general approach will depend on project requirements. This will be to use remotely sensed data analysis techniques to identify potential seepage sites. This would be followed by on ground verification of these sites (using say drilling, groundwater monitoring) and an evaluation of the accuracy of the technique/s implemented. The aim of the task was to evaluate the ability of remotely sensed imagery to detect known channel seepage sites.

At this stage there is little evidence that spatial data analysis would able to quantify seepage. However it may be worthwhile considering combining the results from seepage measurement such as pondage test results, and using GIS to compare actual seepage with areas mapped by remote sensing.

In detail, there are some key activities involved in any remote sensing investigation of channel seepage.

Data Source Review and Image Acquisition

A review of available remotely sensed data, including published literature, needs be undertaken culminating in a comparison of spatial and spectral resolutions, and costs of acquisition and analysis.

The nature of channel seepage suggests that the source data should have high spatial resolution (10 m or less) and that it is multispectral (ie. has data collected from more than one distinct region of the electromagnetic spectrum). Distinct data from the infra-red region is expected to be the most beneficial as this area of the spectrum is strongly absorbed by water and will be able to most distinctly separate areas of varying soil moisture and plant water and growth status.

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. This would imply that this is the optimum data collection time. 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;
- Airborne high resolution sensor data; and/or,
- Satellite imagery.

Automated image analysis and GIS techniques should be developed where possible to identify and map potential channel seepage sites. Software requirements include high-end image analysis software such as ER MAPPER and / or ERDAS IMAGINE and advanced GIS software such as ArcInfo and Arcview.

Accuracy assessment and evaluation
The accuracy of the developed remote sensing techniques needs to be assessed by comparison to field surveys, with respect to:

- the percentage of sites identified as potential locations of channel seepage that are actually channel seepage locations
- the percentage of channel seepage locations identified using the techniques
- The key characteristics of inaccurately detected sites to make recommendations that may reduce these errors.

Spatial data from a number of sources such as :

- electromagnetic data (EM data)
- soil survey assessments.
- airborne radiometric
- channel flow and width
- pondage test data

should be combined and analysed using GIS. The extent to which the input data could quantify seepage at known locations would be assessed by comparison to the pondage test data.

4.2.3 Applicability

- Remote sensing techniques offer considerable potential for rapid identification of seepage zones (but not quantification) of large lengths of a channel system.
- The techniques are best suited to investigation where the primary aim is identification of land degradation associated with channel seepage. Remote sensing techniques rely on the detection of differences in soil / moisture properties in the upper surface. Therefore it has significant potential if there are known surface effects of channel seepage. Conversely, they should not be used if it is known that the seepage mechanism is predominantly vertical, such as is likely to occur at sites with a deep watertable.
- Remote sensing will be most useful in environments where lateral seepage is predominant. For example sites with a high watertable, shallow impermeable layer or bank seepage - these environments represent conditions most likely to facilitate lateral seepage and cause the seepage to have a surface expression.
- It offers a promising means of providing a first-cut identification tool for targeting potential seepage sites, although a drawback is that it assumes seepage will have a surface expression as moist soil or associated vegetation adjacent the channel.
- The method does not interfere with channel operations.
- For this method to be cost effective, it needs to be conducted at a suitably large scale. Costs are likely to come down and resolution likely to improve as the technology develops, and will therefore become an increasingly attractive option.

4.2.4 Practical Implementation

The technique is relatively expensive and requires specialist technical input at the planning and data gathering, processing and interpretation stages. However this technology has the potential to rapidly acquire data over long distances of channel, and along with geophysics is likely to be a key part of future large scale channel seepage investigations.

Care needs to be taken in the interpretation. For example, sites which have moist soils not caused by seepage can be misinterpreted as seepage sites (eg, drainage lines, topographic lows etc). The interpretation benefits from integration with other investigation techniques.

4.2.5 Indicative Costs

Remote sensing costs for specific channel seepage investigations were not obtained from direct trials in the project. A significant proportion of the costs are required for post-collection data processing and it is recommended that any project proposed obtains cost estimates from specialist contractors.

The following rough costs are provided for *data collection only.* Note that it is unlikely that resolutions of greater than 10m will be suitable for channel seepage detection purposes. It is probable that a spatial resolution of less than 10m would be required.

- Landsat Imagery (25m cells) 25km x 25km = $550
- Spot Imagery (10m cells, black and white only) - 25km x 25km = $325
- There may be local opportunities for data collection: eg in Victoria, there is the Daedalus multispectral scanner which has 11 bands. This is flown by DNRE in near infrared mode during fire season and in multispectral (11 bands) mode otherwise. As a rough guide, the cost for this in a 25km x 25 km area may be about $2500 at 10 m resolution and about $3000 for 5m resolution. The data collection costs of suitable quality airborne infra-red data (3-5m resolution) for three lengths of channel in the Wimmera (approximately 10-20km each) were quoted approximately at $11,000.

Data processing costs including integration with the stakeholder's GIS system are in addition to the above costs.

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