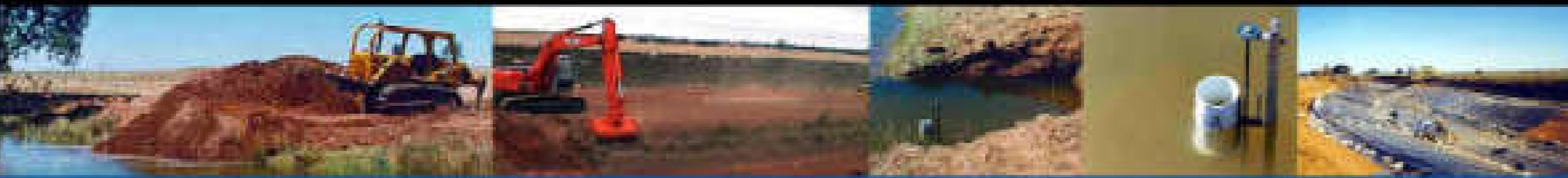
Open Channel Seepage & Control

Vol 1.1 Literature Review of Channel Seepage Identification and Measurement



An ANCID initiative funded by the Murray Darling Basin Commission, the Land and Water Resources Research & Development Corporation & the Rural Water Industry

August 2000

AUSTRALIAN NATIONAL COMMITTEE ON IRRIGATION AND DRAINAGE

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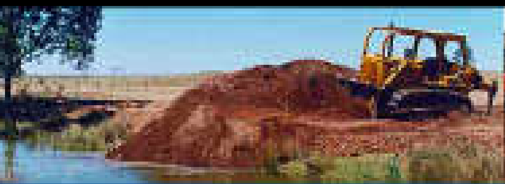

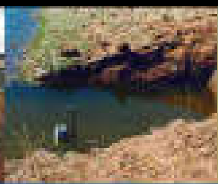
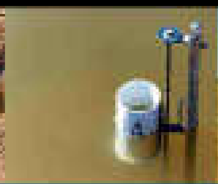


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Publication Details

Published by Australian National Committee on Irrigation and Drainage (ANCID) c/o- Goulburn-Murray Water, PO Box 165, Tatura, Victoria, Australia, 3616.

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

Acknowledgments

This project would not have been possible without the generous investment of the Murray Darling Commission through its Strategic Investigation and Education program and additional significant investment by the following organisations:

DNR State Water Projects, Queensland
Goulburn-Murray Water
Land and Water Resources Research and Development Corporation
Murray Irrigation
Murrumbidgee Irrigation
Southern Rural Water
Sunraysia 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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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, the Land and Water Research and Development Corporation, 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 target the Decision Support Systems needed to assist industry in making decisions on whether or not to undertake what is often very expensive remedial works on seeping channels.

The three stages will run over four years and will involve a total expenditure of close to $2.5 million. Stage 1 in now well under way and Stage 2 is scheduled to commence in October, 2000.

The major outcomes from each of the Stages of the project work will be in the form of reports and Best Practice Guideline Manuals. This report is one of the suite arising out of the project. It summarises the outcomes of a literature review of earthen irrigation channel seepage identification and quantification techniques. Nine major categories are identified in the review. The discussion of techniques represents a summary of the available literature, both in Australia and overseas. Emerging fields such as geophysics and hydrochemistry also include direct contributions from experts in these fields. A significant effort has been involved in its preparation and I commend the contents to you and am sure you will find it interesting and informative.

I would like to also acknowledge the significant support and funding provided to this project by the Murray Darling Basin Commission, the Land and Water Resources Research and Development Corporation, several Water Authorities and Natural Resource Management Agencies. Without their valued support and interest, the project and this report would not have been possible.

Stephen Mills
Chairman
ANCID

Contents

Executive Summary

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

Main factors affecting seepage are soil, hydraulic and channel water characteristics

Seepage Factors

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

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

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

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

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

This literature review is a starting point for ongoing channel seepage assessment

Primary Outcomes

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

- Primary technique (i.e., direct) for the quantification of channel seepage;

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

Table E.1: Channel Seepage Assessment Summary Table

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

Overview of Techniques

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

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

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

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

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

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

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

Geophysical techniques have considerable potential for channel seepage assessment

Of the techniques examined, geophysical assessment appears to have the most potential for future development. The potential of geophysical techniques lie in the fact that they:

- Provide an essentially continuous spatial coverage of the channel;
- Offer a relatively rapid means of assessment; and,
- Represent a field which is continuing to develop.

New developments often bring quicker and cheaper means of conducting surveys. The main challenge in the use of geophysics for quantitative purposes is in the accurate calibration of the survey results.

Selection of a Technique

No single technique accounts for all the factors affecting channel seepage

No single technique is entirely satisfactory for channel seepage measurement. The best technique for a given situation is dependent on a number of factors including the time available, the magnitude of seepage loss being considered and the availability of equipment and skilled technical personnel for making measurements. The following factors need to be considered before selection of a particular channel seepage measurement or identification technique:

- Purpose of investigation;
- Required accuracy;
- Cost;
- Operational constraints; and,
- Personnel / Resource constraints.

Figure E.1 summarises the decisions that need to made when selecting a technique.

Extrapolation of Seepage Measurements

Extrapolation of seepage results is an important tool for minimising seepage assessment costs

The cost of accurately measuring the volume of seepage in a length of channel is relatively high. Therefore the importance of establishing cost effective methods of extrapolating accurate measurements over long sections of channel is important. Extrapolation involves taking the results of a more accurate method of assessment and applying them to other areas, based on results of a more cost effective, but less accurate method.

To improve the accuracy of the extrapolative process it is preferable that:

- The technique upon which the extrapolation is based is calibrated locally, restricting the chance of significant variability in conditions over 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.

Figure E.1: Channel Seepage Measurement Technique Selection

In selecting a channel seepage assessment technique, evaluation of aims, resources and required accuracy is necessary

Define Purpose of Investigation

The purpose of the investigation must be clearly defined from the outset. Key questions to ask are:

- Is the primary objective to identify relatively high seepage points or to measure the volume of seepage?
- What degree of confidence is required?
- Over what length of channel is the information required?

On the basis of these questions several approaches may be available.

↓

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?

↓

Resource Constraints

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

- Are the personnel and resources required to plan, conduct and analyse tests available in-house?
- If not - can these be readily obtained outside of the organisation?

↓

Accuracy / Cost Trade - Off

The ideal investigation often requires tempering, with due consideration given to accuracy requirements and 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., a representative sub-area studied)
- Can an extrapolative technique be employed to lower costs?
- Does the accuracy requirement need review?

(feedback to Define Purpose of Investigation)

↓

Select Technique

1. Introduction

1.1 Background

As the driest inhabited continent in the world, water is a crucial resource in Australia. The availability of water has always been a determining influence within the country, shaping the pattern of human settlement, economic development and options for the future. A critical issue is balancing the needs of environmental and consumptive uses, and increasingly, competition between irrigation users. It is within this context that seepage from earthen channels has become an important issues in Australia for two reasons:

i) The loss of an economically valuable resource; and,
ii) The contribution to groundwater recharge and associated induced land salinisation.

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

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

This literature review represents the start of the channel seepage measurement investigation initiated by ANCID and MDBC

This findings of a channel seepage literature survey, presented in this report, in conjunction with an Australia wide channel seepage survey of more than 40 rural water authorities addresses the first of these major objectives.

This report presents the results of a comprehensive literature review of earthen irrigation channel seepage in Australia and overseas. This included a number of texts which were in themselves channel seepage literature reviews (eg, ICID, 1967; Kraatz, 1977; Christopher, 1983; Hotes et al., 1985; Frevert and Ribbens, 1988). In general direct seepage investigations are less frequently reported, and not often widely published, while mathematical treatments of the seepage problem are extensively discussed.

The main seepage measurement techniques referred to in the literature are listed below. The division between methods of measurement and those of estimation and identification becomes increasingly vague when considering the less frequently utilised methods of seepage measurement:

- Pondage Tests;
- Inflow-Outflow Measurement;
- Seepage Meters;
- Barrel Tests;
- Theoretical Mathematical Models (Requires estimate of hydraulic conductivity - K)

Methods of Measuring K

- Below watertable: Auger hole method, piezometer method, the tube method and the multiple well technique;
- Above watertable: Ring infiltrometer, air entry permeameter, well permeameter, double tube method and disc permeameter;

- Geophysical Techniques
  - DC galvanic systems (resistivity and induced polarisation), electromagnetics, self potential, airborne EM, ground penetrating radar, seismic spectra mapping, sonar reflection and capacitive dipole arrays;
- Remote sensing
  - Infrared (near and thermal) and aerial photographs;
- Soil Classification;
- Piezometric Survey; and,
- Tracers and Isotopes.

The three most common methods discussed in the literature include: inflow-outflow, pondage tests and seepage meters

The three methods most commonly referred to in the literature are the inflow-outflow method, the pondage test method and the seepage meter method. Almost universally pondage tests are regarded as the most accurate method of seepage estimation, although most authors note that every method has certain disadvantages. There was relatively little in the literature on geophysical or remote sensing applications to channel seepage measurement or detection, although the potential of geophysical techniques as a means of more rapidly assessing channel seepage was often mentioned. Visual inspection of channels is an important channel seepage identification technique, however it is not discussed in this report, and it is not widely discussed in the literature.

1.2 Report Structure

Section 2 of the report describes the main factors influencing seepage rates in earthen irrigation channels, including soil characteristics, depth of water in and wetted perimeter of the channel, depth to groundwater and channel water characteristics.

The range of methods listed above are discussed in detail in the body of the report, and have been subdivided into eight categories. **Table 1.1** presents a breakdown of the techniques assessed in the report, and the primary outcomes from the review are summarised. The second column indicates the section in the report where further information on the technique can be found. In the body of the report the various techniques are discussed in terms of theory, methodology, advantages and disadvantages of each technique. Key references for the technique are provided at the end of each section. **Table 1.1** is a useful starting point for ongoing investigations into channel seepage measurement. This table provides a synopsis of the information provided by each technique and its application as either a:

- Primary technique (i.e., direct) for the quantification of channel seepage;
- Primary means of identifying (qualitative) areas where channel seepage occurs;

- Technique which provides a means of estimating channel seepage through a relationship with one other technique; or,
- Technique which provides a means of estimating channel seepage through a relationship with two or more other techniques.

Most of the techniques discussed represent a summary of the available literature, however some parts, including aspects of the geophysical survey, hydrochemical and isotopic sections, also include direct contributions from experts in these fields. Some of the ideas expressed therefore may not have

Table 1.1: Channel Seepage Assessment Summary Table

Technique	Report Section	Direct Measure of Seepage	Indicator of Where Seepage is Occurring	Secondary Measure of Seepage	Tertiary Measure of Seepage
Inflow – Outflow	3.1	Requires very accurate flow measurements. Useful for long channel sections and first cut seepage assessment	NA	NA	NA
Pondage Test	3.2	Provides accurate measurements if conducted properly. Widely considered the standard for channel seepage quantification	Only useful for pinpointing seepage if pondage sections are very short	NA	NA
Point measurement (channel full and empty)	4	NA	Useful for identifying seepage 'hotspots' and relative seepage potential	Numerous tests required for accurate assessment – extrapolation required contains some inaccuracies	Can be used in conjunction with soil surveys and geophysical techniques to extrapolate seepage rates
Mathematical Modelling	5	NA	If full range of parameters collected, model will predict where seepage is likely to occur	Requires input from groundwater surveys and physical parameter testing, eg, hydraulic conductivity	NA
Soil Classification	6	NA	Correlations can be made between soil type and seepage potential – provide rough indication of high seepage zones	Can provide estimate of seepage rate if sufficiently strong relationship developed between soil type and seepage (eg, pondage test, point measurement etc)	NA
Groundwater Techniques	7	Semi-direct method – only detects seepage which migrates to groundwater. Extrapolation required along channel length	Changes in groundwater level can provide indication of significant seepage points	Only detects seepage which migrates to groundwater: requires inputs of aquifer hydraulic properties	NA
Geophysical Techniques	8	NA	Resistivity, Electromagnetics and Self Potential have best demonstrated history of channel seepage detection	Can provide an estimate of seepage rate provided a sufficiently strong relationship can be developed (between geophysical response and pondage tests)	Can provide seepage estimate provided sufficiently strong relationship can be developed between geophysical response and secondarily measured seepage, eg, soil type, point measurement etc
Remote Sensing	9	NA	A primary means of identifying seepage sites – air photos and thermal infrared most applicable	NA	NA
Hydrochemical / Isotopic Mass Balance	10	Combined with pondage tests provides an accurate direct measure of seepage but only useful in low seepage rate environments	NA	NA	NA
Tracing Leaking Plume	10	Semi-direct method - only detects seepage which migrates to groundwater. Many bores required to adequately define seepage plume	Provides an indication of seepage flow paths	Only detects seepage which migrates to groundwater: requires aquifer hydraulic properties and water chemistry input	NA

been specifically trialed for channel seepage applications, but represent techniques with potential for channel seepage measurement.

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

Appendix A contains a summary of the main texts reviewed for the channel seepage literature review. These have been divided into primary and secondary references. Primary references have been categorised as those which deal directly with channel seepage measurement, while secondary references are either those which are indirectly related to channel seepage (eg seepage through dam walls) or texts for which only the abstract was obtained, and therefore a proper summary was not possible. Note that the dominant international terminology for 'channel' is 'canal' (particularly in the US). In this summary, canal has been used where the term has been used in the summarised text. The two terms can be considered interchangeable.

Appendix B contains a glossary of technical terms commonly used throughout the report.

1.3 Units of Seepage Measurement

There are various forms in which seepage rates can be expressed. A common form is the seepage volume per unit length of channel (SI units: $m^3/m/d$). However, losses published in this form without the channel dimensions are difficult to relate to other seepage measurements, i.e., seepage rates reported in this manner will show higher loss rates in larger channels due to the larger dimensions of these channels (McLeod, 1993).

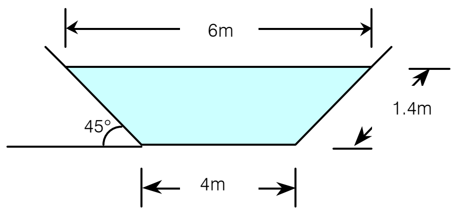
An alternative method of expressing seepage rates is seepage loss as a percentage of water entering an irrigation system (or part thereof). This is especially used in relation to describing the results of inflow-outflow studies. Again, when expressed in this manner these losses become difficult to relate to other channels.

The most widely used and most suitable expression of seepage loss is as the volume lost per representative channel area per unit time (SI units: $m^3/m^2/d$, i.e., m/d). This expression provides the most appropriate information for the interpretation and comparison of seepage rates for channels of all sizes, as the seepage losses are not weighted by channel size. However, there is some difference of opinion regarding the representative area of the channel to use in such calculations. The representative area may either be:

- The water surface area; or,
- The channel wetted area.

The use of water surface area will produce higher seepage rates than the channel wetted area as the following example illustrates:

Example: Consider a 50m length of channel which seeps at 100 m^3/d, with dimensions shown below:



Seepage using water surface area:

$$\frac{100\ m^3}{50m \times 6m} = 0.33\ m^3/m^2/d\ =\ 0.33\ m/d$$

Seepage using wetted perimeter area:

$$\frac{100\ m^3}{50m \times (4m + 1.4m + 1.4m)} = 0.29\ m^3/m^2/d\ =\ 0.29\ m/d$$

It can be seen that in this case using the water surface area gives a difference of about 14 % greater seepage than the wetted perimeter area. Webster (1984) states that for typical channel dimensions in southern Australia, the difference between seepage rates calculated by these different representative areas is around 10%.

The literature shows both areas used by different authors, although the most popular method is the wetted perimeter. Brockway and Worstell (1967), ICID (1967), Kraatz (1977), Byrnes and Webster (1981), Wachyan and Rushton (1987), Frevert and Ribbens (1988) and McLeod (1993) all preferred the wetted perimeter basis for the presentation of their findings.

Based on this assessment, seepage rates per unit length of channel per wetted perimeter per unit time are used as the standard form of presentation in this study and subsequent reports forming part of this ANCID channel seepage measurement project. The units chosen for the expression of seepage are mm/d.

2. Seepage Factors

There are many variables that have an influence on the loss of water by seepage from earthen irrigation channels. These factors act simultaneously and some are interacting so that it is difficult to segregate and separate the effects of individual parameters. Hotes et al (1985) lists the principle variables which influence seepage from irrigation channels:

1) Characteristics of the soil at the soil-water interface and below the channel bed (important soil characteristics are identified as particle size and gradation, porosity, permeability, chemistry, stratigraphy (i.e., layering of different soils / sediments), and biological factors);
2) Chemistry of the water and soil;
3) Amount of sediment carried and deposited by the water;
4) Length of time that water has been in the canal, both seasonally and total life;
5) Channel water depth;
6) Velocity of flow;
7) Temperatures of water;
8) Soil capillary tension;
9) Position and gradient of the watertable;
10) Barometric pressure; and,
11) Channel shape and wetted perimeter.

Main factors affecting channel seepage are soil, hydraulic and channel water characteristics

These eleven factors can be grouped into three broad categories:

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

2.1 Soil Characteristics

Permeability of layers immediately below the channel is the most important characteristic influencing channel seepage

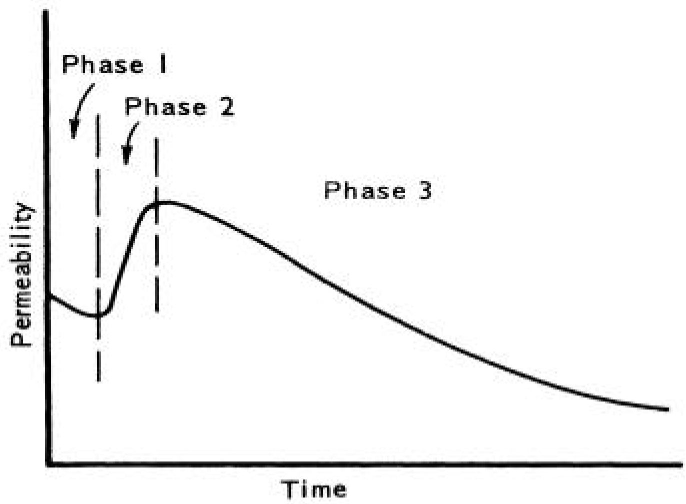
The most important characteristic influencing channel seepage is the permeability of the layers forming, or lying immediately below the wetted perimeter of the channel (Rohwer and Van Pelt Stout, 1948; Robinson and Rohwer, 1959). The variation in permeability with time for soils during prolonged submergence has been studied by several authors [Bodman, (1937), Christiansen (1944), Allison (1947), Brockway (1973), and Cunningham et al (1994)]. Allison (1947) described three main permeability changes with time: an initial decrease in permeability due to dispersion and swelling of soil particles in certain types of clays, followed by a short period of increased permeability due to the entrainment of soil air by the percolating water, and the final stage is described as a gradual decrease in seepage rate due to microbial sealing. These are 3 main changes in permeability with time are presented in **Figure 2.1**.

Byrnes and Webster (1981) counter the concept that the 'principal factor affecting seepage loss from earthen channels is the permeability of the material in which the channel is constructed', claiming that (at least in

Channels naturally partially seal themselves over time

Victoria) this is probably only true for newly constructed, remodelled or de-silted channels. With time they note that channels appear to seal themselves, at least partially, through natural causes. Smith and Turner (1982) also highlight the dominance of the layer of sediment in controlling seepage, which can effectively deposit a liner within the channel.

Figure 2.1: Variation In Permeability With Time For Soils During Prolonged Submergence



Phase 1 - Initial decrease in permeability due to dispersion and swelling of soil particles in certain types of clays.
Phase 2 - Short period of increased permeability due to the entrainment of soil air by the percolating water.
Phase 3 - Gradual decrease in seepage rate due to microbial sealing.

(after Allison, L.E., 1947)

Robinson and Rowher (1959) noted that over periods of 24 hours, seepage rates could vary by as much as 10%-65% depending on the soil type. The expansion and contraction of the air bubbles in the soil were believed to be the primary cause of this phenomena. Rates were also higher at lower temperatures. Dillon (1988) also discusses temporal variability in seepage rates. In addition to the reduction of seepage rates with the progress of time due to the sealing of the channel bed by clay deposition and a rising watertable, the possible effect of algae is discussed. Algae have been observed to have a significant effect on infiltration rates from artificial recharge trenches on the Burdekin Delta (Queensland), where rates dropped by as much as 50% overnight as algae settled on the floor of the trenches during darkness.

2.2 Hydraulic Characteristics

Important hydraulic characteristics influencing channel seepage include: water depth in channel, depth to groundwater and channel wetted perimeter

Bouwer (1969) found the following relationships between seepage and water depth in the channel, depth to groundwater and wetted perimeter of the channel:

1. Seepage losses increase with the increase of water depth in the channel;
2. Seepage losses increase as the difference between water level in the channel and watertable increases – when the difference is approximately five times or more than the surface width of the channel, seepage losses reach an upper limit;
3. The distribution of seepage losses across the channel depends on the position of the watertable or impermeable layer. When the watertable is shallow, the seepage from the sides is greater than that from the bed, and greater from the bed when the watertable is deep. In all cases the maximum seepage loss occurs at the junction of the bed and sides of the channel.
4. The significant depth 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 is minimal. [Later work by Wachyan and Rushton (1987) indicate that some of Bouwer's assumptions regarding site hydrogeological conditions were oversimplified but the principles remain applicable].

2.3 Channel Water Characteristics

2.3.1 Suspended Sediment

Suspended sediment in channel water reduces seepage as soil pore spaces are filled

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 sealing effects over a long period of time. If the velocity is reduced, the sediment carrying capacity of the water decreases, resulting in settlement of part of the suspended material (Kraatz, 1977).

Brockway (1973) attributed long-term reduction in seepage rate to penetration of sediment into the soil matrix while seasonal variation in permeability were due to microbial activity. This theory complements more recent studies by Cunningham et al (1994), who investigated the effects of the suspended sediment variable on channel seepage clogging. Investigations were conducted in the range of 200 - 1,600 ppm solids content. The major conclusions arising from these investigations included:

- For each of the four suspended sediment types examined, reductions in channel bed infiltration rate of 70-95% occurred within 24 hours after the addition of suspended sediment material. Channel bed clogging continued to increase slowly thereafter and, in some cases, became essentially stable.

- Within the range of 200-1,600 ppm solids content in which the experiments were conducted, the suspended sediment concentration did not have any significant effect on the rate of infiltration decrease, i.e., the effect of sediment concentration on the seepage rate was the same for a 200 ppm concentration solids content as for water with 1600 ppm solids content.
- Variation in the magnitude of average channel velocity was observed to have a major effect on the clogging process. For velocities in the range from 0 to about 0.27 m/s, the reduction in channel bed infiltration rate was governed by a 0.46 – 1.27 cm layer of fine material deposited on top of the filter material. For velocities above (approximately) 0.27 m/s, clogging was caused by a very thin layer of fine material impacted into the pore spaces of the topmost layer of channel bed sediments.
- Suspended materials having coarser, more uniform particle size distributions tended to cause less clogging (at low velocities) than the finer, better graded materials. However, as velocity increased, a similar degree of clogging was seen for all four materials.
- A zero horizontal velocity condition slightly reduced the infiltration ratio as compared with similar conditions involving non-zero horizontal velocities. In other words, infiltration is expected to be higher under flowing conditions (at least for relatively low velocities) compared to non-flowing conditions.

<u>Effect of Sediment Layer: Field Trials</u>

McLeod (1993) noted that the general perception of channel bed conductance variation throughout an irrigation season is that it begins at a high level at the start of an irrigation season, attenuates over the course of this season and returns to the previously high level by the start of the next irrigation season. McLeod (1993) defined channel bed conductance as the conductance (conductivity divided by thickness) of the naturally forming channel lining (largely formed by the depositing of suspended sediment) or, in the event of the removal of this lining, the surface layer resistance. McLeod's investigation showed that the channel bed conductance at one of the northern Victorian channels he studied exhibited no such variation during an irrigation season.

The downstream pond of the Tatura East channel was de-silted in August 1991. Thus the 1991-92 irrigation season proceeded without silt in the lower reach of the channel. No identifiable change in the seepage rate of the downstream pond of this channel was observed as a result of this procedure. Through the application of the computer model it was possible to isolate the effect of the de-silting on the channel bed conductance parameter in the model. A noticeable change in channel bed conductance was not observed as a result of the de-silting process. The consistency of the conductance of the natural channel lining despite large changes in the thickness of this lining suggests the net effect of the lining is concentrated in a thin surface layer and this layer appears to be generated over a relatively short period. This concurs with the results of Cunningham's (1994) laboratory investigation which found that the vast majority of the clogging occurred within 24 hours. McLeod (1993) noted that the alternative explanation to the observed results was that the impeding layer may be a sub-surface interface not affected by the silt removal.

2.3.2 Salinity and Sodium Adsorption Ratio

A soil is considered to be sodic when there are a high proportion of sodium ions (Na^+) relative to other cations in the soil (in exchangeable and/or soluble form). Soil sodicity is a condition that degrades soil properties by making the soil more dispersible and erodible, restricting water entry and reducing hydraulic conductivity (ANZECC and ARMCANA, 1999).

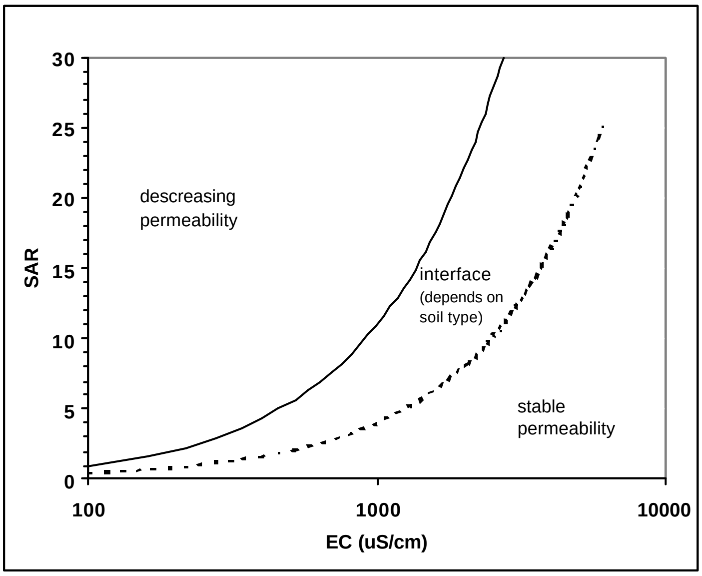
Elevated levels of Na^+ in water can lead to sodicity problems in the soil profile. One of the most common ways of measuring soil sodicity is the sodium adsorption ratio (SAR) which is the relative concentration of sodium to calcium and magnesium in the soil solution. SAR is defined by the following equation:

$$SAR = \frac{Na^+}{\left[\frac{(Ca^{2+} + Mg^{2+})}{2}\right]^{0.5}}$$

The SAR of irrigation water provides an indication of the effect it is likely to have on a soil. Some general relationships can be established for soils which indicate the combination of irrigation water EC and SAR where dispersion (and reduced infiltration) is most likely to occur. **Figure 2.2** shows this general relationship. For irrigation purposes, water composition to the right of the equilibrium lines are considered satisfactory for use. In terms of channel seepage, the composition of water desirable for crops etc, is likely to have a stabilising effect on the soil permeability. While waters with high SARs (and low salinity) are likely to decrease the permeability of the channels, water with high SAR would not be desirable for irrigation. Therefore water within an irrigation supply system is unlikely to have high a SAR.

Byrnes and Webster (1981) conducted seepage trials using the Idaho meter in northern Victoria. The water quality of the supply systems that were tested was in the range of 150 to 850 µS/cm at 25°C, with SARs of 1 to 5. Byrnes and Webster (1981) noted that as these concentrations have persisted for several decades, it is presumed that the exchangeable sodium percentage (ESP) and the salinity of the soil are in equilibrium with the composition of the irrigation water. They concluded that water quality (in terms of EC and SAR) would now have little influence on the permeability of the exposed soil layers in the wetted perimeter of channels.

Figure 2.2: Relationship between SAR and EC of water for prediction of soil structural stability and permeability



After, ANZECC and ARMCANA, 1999

In summary, the SAR and salinity of water will effect infiltration rates, however with respect to channel seepage, the range of SAR and salinity of waters within channels is unlikely to vary significantly. Further, as noted by Byrnes and Webster (1981), particularly for older channels the water quality will have minimal impact on the permeability of the soil layers, due to the equilibrium previously established between the channel water and the soils immediately beneath the channel. Other factors such as the suspended sediment load are likely to have a more significant effect on seepage rates.

3. Direct Measurement

Inflow-outflow and pondage tests are the two methods by which channel seepage can be directly measured

Essentially all seepage measurement methods can be divided into those which are direct and indirect. Direct methods requires measurement of actual seepage loss (not inferred from hydraulic conductivity or soil type etc) while the channel or a section of channel is full. Inflow-outflow measurement and pondage tests are the two methods by which seepage can be directly measured. Due to the direct nature of the measurement these tests are the most common referred to in the literature, and if conducted properly represent the most accurate means of measuring channel seepage.

3.1 Inflow-Outflow Method

Principle

The inflow-outflow method is based on a water balance approach. The method consists of measuring water that flows into and out of the section of channel being studied. The difference between the quantities of water flowing into and out of the channel reach is attributed to seepage, after accounting for deliveries and known losses such as evaporation. If seepage losses are large then the contribution to the water balance of evaporation and precipitation becomes negligible. The accuracy of the technique depends on the accuracy of the inflow and outflow measurements.

Often used as a first cut estimate of seepage, however when conducted properly can be considered reliable as measurement occurs under operating conditions

This method is frequently used to provide a "first cut" estimate of seepage losses in a system. This is achieved by using existing structures to measure inflow and outflow. Provided diversions are known, an estimate of the loss can be obtained. Often used informally in the sense of 'we put this much water down, received this much at the end, so this much has been lost as seepage'. However, when conducted properly (ie, accurately) this method can be considered fundamentally the most direct, and potentially accurate, method available.

Trout and Mackey (1988) examined inflow-outflow measurement accuracy, which yielded the following conclusions:

- The uncertainty in inflow-outflow methods varies with the flow measurement uncertainty and can be large.
- Inflow-outflow infiltration determination uncertainty increases rapidly as the percent of inflow that is infiltrated decreases. Therefore, accurate infiltration measurement requires measuring long channel sections in which much of the flow in infiltrated.
- Using the same type of device to measure inflows and outflows will usually decrease the effects of any systematic errors.
- Measured infiltration can be corrected for measurement process uncertainty.

Methodology

The inflow-outflow method can be conducted at various scales, from an entire irrigation system, to an isolated section of channel. Ideally the level of the channel should be kept constant during test periods in order to eliminate the

Inflow-outflow method best suited to long sections of channel which contain appreciable seepage and no diversions

effect of bank and channel storage. 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). 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. As stated in Trout and Mackey (1988), error is minimised when the test reach is relatively long (desired length depends on the seepage rate, however typical lengths are in the order of tens of kms), and seepage is appreciable.

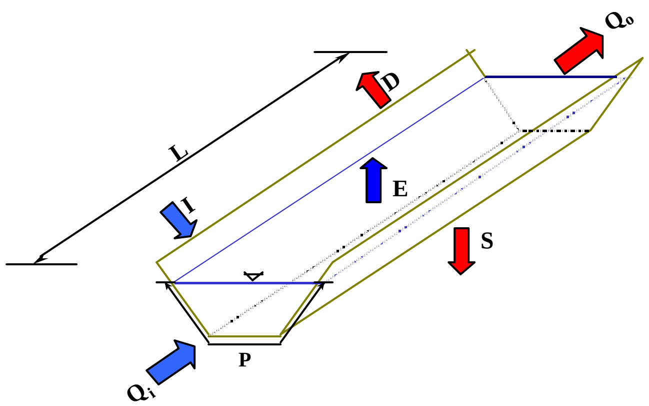
The basic equation for calculating seepage losses using the inflow-outflow method is presented below. **Figure 3.1** graphically displays these components.

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

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]

Units may be m^3/sec or m^3/day or any other discharge units, but they must be consistent for all terms in the equation (preferred units are m^3/day or mm/day)

Figure 3.1: Components of Inflow-Outflow Water Balance



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

1. Use of a current meter to determine the average velocity and application of the discharge equals average velocity multiplied by the cross sectional area relationship. This method is probably the most practical.
2. 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.

Estimates of evaporation can be obtained from the nearest weather station with evaporation data, or for potentially more accurate results 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.

Trout and Mackey (1988) demonstrated how the effect of measurement uncertainty on infiltration measurements can be estimated so that the confidence interval of a mean or the actual infiltration variability level can be determined. Their analysis provides the tools required to provide a statistical basis for the uncertainty in infiltration measurements.

Advantages

- The method has a sound physical basis (mass balance) and requires few theoretical assumptions;
- Measurements reflect seepage losses under actual operating conditions;
- Permits measurements without interruption to the system;
- Applicable to both lined and unlined channels;
- Has potential for long term monitoring; and,
- Long term monitoring can provide an indication of the seasonal variation of seepage losses.

Disadvantages

- Difficulty in obtaining measurements of sufficient accuracy. As volumes flowing into and out of a specified part of a channel network are typically orders of magnitude larger than the volume being lost to seepage, small errors in the larger volume measurements result in large uncertainties in the seepage loss estimates (i.e., accuracy of measurement is proportional to the total flow in the channel);
- Requires use of skilled technicians for accurate flow measurement);
- Determining diversions and other potential inflows and outflows between the gauged sites can be difficult;
- To bring seepage losses within a measurable range the test reaches have to be fairly long (the desirable length depend on the seepage rate, however typical lengths required are in the order of tens of kilometres);

- A substantial period is required to negate the relative influence of channel storage changes and transmission times of water in the channel;
- A constant channel stage should be maintained to eliminate changes in channel or bank storage;
- Temporary weirs may cause considerable loss of head which may make their use impracticable;
- Instrumentation and monitoring of a system is often a large task; and,
- Does not provide an indication of the spatial variation of losses, i.e., localised information of loss rates.

Summary Assessment

Inflow-outflow measurement is best suited to measuring seepage from channel sections which:

- Are relatively long (desired length depends on the seepage rate, however typical lengths are in the order of tens of kms);
- There is appreciable seepage;
- There are no diversions,
- Ideally contain suitable structures to incorporate measuring devices.

The major advantage of the technique is that it is the only method which measures actual seepage under normal operating conditions. When conducted properly, this method can be considered fundamentally the most direct, and potentially correct, method.

Key References

- ICID, 1969
- Kraatz, 1977
- Hotes et al, 1985
- Dillon, 1988
- Frevert and Ribbens, 1988
- McLeod, 1993
- Trout and Mackey (1988)

3.2 Pondage Tests

Principle

Widely regarded as the most accurate channel seepage measurement technique

The pondage test method applies a water balance to an isolated reach of channel to determine the seepage losses. Seepage losses constitute the drop in water level over time in the channel (or volume added to maintain a constant level) after accounting for evaporation and rainfall. Widely considered the most accurate means of measuring channel seepage and generally regarded as the best technique against which other methods can be assessed.

Methodology

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 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 considered the seepage loss (accounting for evaporation and rainfall). This method has the advantage of more accurately representing normal flow conditions.

Figure 3.2 depicts two different stages of a pondage embankment under construction while the channel is full. The upper photo shows the soil beginning to be pushed into the channel to form the embankment, and the lower photo shows the almost completed embankment, with the underlying plastic sheeting exposed in some places.

Figure 3.2: Pondage Test Embankment Undertaken Construction

Figure 3.3 shows the upper part of a hook gauge used for measuring the water level at each end of a pondage section. A short length of PVC surrounds the device which contacts the water, to still the water and prevent the effects of wind during measurement.

Figure 3.3: Hook Gauge Used For Measuring Pondage Water Levels

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 3.1** displays these components.

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

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:

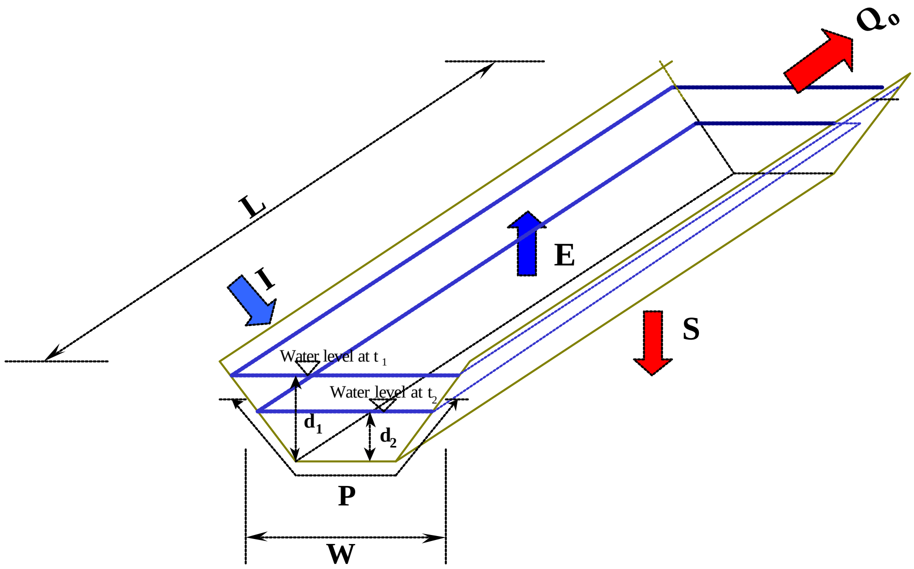
$$S = \frac{W\left[(d_1 - d_2) - E + R\right]}{P(t_2 - t_1)}$$

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]

Units must be consistent for all terms in the equation.

Figure 3.4: Components of Pondage Test Water Balance



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 is usually established adjacent to the pondage test.

The main difficulty with the pondage test is that it must be conducted outside of normal channel operation where non-flow conditions introduce some inaccuracies

Pondage tests are usually conducted outside the irrigation season, and are applied in a non-flow situation in which actual flow conditions are not being simulated. Two problems with the pondage test method are related to this issue of the water being still rather than in its usual state of flow, causing:

- A potential sealing effect of suspended material settling in the water or growth of algae on channel bed; and,
- A surface water level at the upstream end with a lower than normal water level compared to under flowing conditions and a higher than normal level at the downstream end.

The reach should be long enough that the artificial end areas (i.e., embankments) are not very large compared to the total wetted area of the reach. Three percent is considered a maximum desirable ratio of the end area of the embankment to the total wetted area, and smaller values are more desirable (Frevert and Ribbens, 1988). However, as mentioned above pondage tests conducted over very long reaches become unrepresentative of normal operating conditions due to a lower than normal high water level at the upstream end of the reach and a higher level than normal at the downstream end. A balance between these two considerations needs to be achieved.

The danger of a higher than normal water level in the test is that this may raise the water to a region of the bank with properties differing (potentially more permeable) than the majority of the bank. This may cause an over estimate of seepage. To overcome this issue a water level slightly less than full supply level should be applied at the downstream end. The degree to which this needs to be compensated for is dependent on the grade of the channel and length of the pondage test.

Channel and groundwater levels maintained during a pondage test should be representative of typical operating conditions which are encountered during channel operation. To eliminate the effect of wind, the rate of drop should be measured at each end of the pool and averaged. Pondage tests are normally suspended during periods of significant precipitation.

Advantages

- Universally considered the most accurate way of determining channel seepage;
- Kraatz (1977) observes that 'the results from this method are generally used as the standard of comparison for other methods of seepage measurement';
- Test procedures are relatively simple and do not require highly skilled personnel;
- Can be used during construction stage in completed short sections of channel to check the degree of compaction and potential seepage; and,
- Can be used on both lined and unlined channels.

Disadvantages

- Operationally, the pondage method requires that the tested channel reach must remain out of use during the testing period. This generally means tests are conducted outside of the irrigation season (typically at the beginning or end of the season);
- Cost and time of installing impermeable barriers may become limiting, particularly in larger channels;
- Seepage measurements may vary from operational conditions due to the non-flowing conditions, potentially causing: settling of sediments, algal growth and lower water temperatures.
- Seepage measurements may vary from operational conditions due to different sub-surface hydrological conditions. Particularly if conducted at the start of a new irrigation season groundwater levels are likely to be appreciably lower than during the season;
- If conducted at the start of the irrigation season, the initial wetting of the soil may cause higher than normal losses. Either this needs to be allowed for in the analysis, or in the conducting of the test (eg, maintain water at FSL for 1-2 days prior to commencement of test);
- If seepage losses are low compared to evaporation losses, accurate measurement of evaporation becomes very important;
- A ponded channel has a flat water surface causing the upstream end of the pondage to have a lower than normal water level, and the downstream

end a higher than normal water level compared to under flowing conditions. Therefore pondage tests with long sections cannot be conducted on channels with steep gradients.;
- Although the method gives accurate figures for the total pondage section, it does not show spatial variation in rates in different parts of the reach.

Summary Assessment

Pondage tests are widely considered the most accurate method of determining seepage losses

The pondage test method is widely considered the most accurate means of measuring channel seepage and is regarded as the best technique against which other methods can be assessed. The US National Handbook of Recommended Methods For Water Data Acquisition (1997) states that of the methods available for seepage quantification 'pondage tests give the most reliable results'. That this method is the most accurate technique of determining seepage losses is widely held in the literature (eg, ICID, 1967; Smith, 1973; Byrnes and Webster, 1981; and Hotes et al., 1985).

The main difficulty with the test is that it must be conducted outside of normal channel operation, which can be inconvenient and may only provide a limited window of opportunity to conduct the tests. Further, conducting the tests outside of the season may potentially introduce some inaccuracies due to differences in sub-surface hydrological conditions. Non-flowing conditions potentially introduce further inaccuracies, due to settling of sediment and a flat water surface compared to a falling water level. However, due to the relative simplicity of the test it probably represents the best method for accurate seepage measurement.

Key References

- ICID, 1969
- Kraatz, 1977
- Hotes et al, 1985
- Dillon, 1988
- Frevert and Ribbens, 1988
- McLeod, 1993

4. Point Measurement

Point tests are best suited for determining relative seepage rates in different parts of the channel

Point measurement refers to any technique which measures seepage at a given point within a channel, usually involving the application of water to the surface or constructed hole within the channel and measurement of the rate at which it drains away. In general point tests are best suited for determining the distribution of seepage losses (i.e., relative seepage). Due to variable and sometimes erratic values obtained in measurements and often large number of tests required to sufficiently determine the average seepage rate, they are generally not considered reliable for absolute quantitative purposes. Rarely would point measurement techniques be used as a stand alone method, but often a soil survey is required to 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.

This section has been divided into techniques which are applicable while the channel is operating and those used when the channel is empty. In theory, techniques which are applied while the channel is running should be more accurate than when empty, as they are conducted under normal operating conditions. Some techniques, such as seepage meters, provide a direct estimate of seepage, whereas most of the methods discussed provide an estimate of hydraulic conductivity, which can be used as an indicator of seepage, or can be used as an input to a mathematical estimate of seepage.

4.1 Channel Operating Techniques

The major advantage that channel operating techniques have over channel empty techniques is that measurements reflect real operating conditions, particularly the seepage processes and hydrogeological conditions. The three techniques discussed below include seepage meters, barrel tests and the well permeameter. It is presumed that the water used for measurement is similar in chemical make-up to the water that normally runs in the channel. Failure to observe this point could result in quite erroneous results. This should not be difficult for channel full techniques, as the water used for measurement will pres0umably be channel water.

4.1.1 Seepage Meters

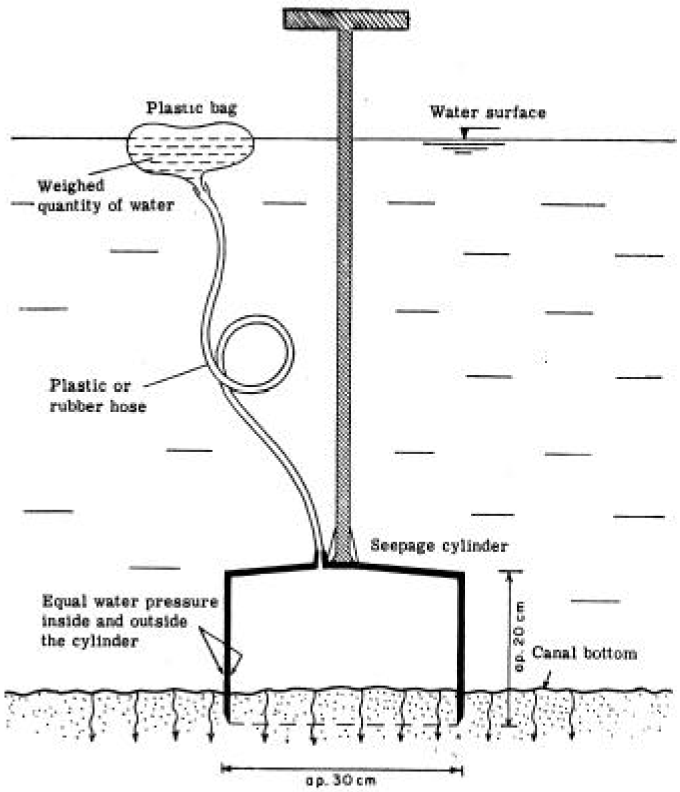
The most common form of point measurement conducted under channel operating conditions is the seepage meter. Seepage meters are essentially cylindrical infiltrometers modified for use under water. Seepage meters are commonly used to make spot measurements of seepage in channels without artificial lining.

Principle

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 4.1** presents a simple version of a constant head seepage meter. It consists of a watertight cup 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 cup are equal. This type of meter is described in more detail later in the section.

For data that are normally distributed, Brockway and Worstell (1968) developed a method to statistically estimate the number of seepage meter tests required in a given reach of channel to obtain a certain percentage measurement error of the true seepage rate for the channel section (dependent of certain preconditions). The number of measurements required to obtain a reasonable degree of accuracy is high. For example, Smith and Turner (1982) found that for a section of channel 366 metres long, 110 measurements (almost one every three metres) were required for a 20% error in the overall seepage rate.

Figure 4.1: Seepage Meter With Submerged Plastic Bag



After Kraatz, 1977.

Methodology

Seepage meters are, in principle, suitable for measuring local seepage rates in channels without artificial lining. Generally they 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 / lower than actual due to potential leakage around the bell and / or changes in the bed structure. The following discussion describes the various types of seepage meters available.

Variable Head Seepage Meter

Bouwer (1962) developed a variable head technique because of the difficulty with a constant head meter, of maintaining equilibrium between the bell and the channel. Bouwer demonstrated that even small variations from equilibrium may seriously effect the accuracy of the results. Seepage is determined in Bouwer's procedure by the deliberate production of head differences between bell and channel and then measurement of the resultant flow into or out of the bell. Bouwer and Rice (1963) extended the variable head technique to cover head-affect seepage and stratified soils. Field measurements consist of taking timed readings of water levels in the manometer. From these data the seepage rate can be calculated graphically or analytically from a falling-head equation. Pontin (1978) and Pontin and Elwan (1978) have further adapted Bouwer's method to allow the direct measurement of seepage in a large canal.

Constant Head Seepage Meter

Idaho Meter

Worstell and Carpenter (1969) designed a constant head seepage meter (Idaho) which included:

- A meter bell with a removable lid to minimise disturbance of the sediments during placement;
- An inverted U-tube manometer to ensure that pressures within and outside the bell are equal;
- A rigid, vertical handle attached to the meter bell enabling operation in low velocity channels up to 1.2m deep; and,
- A Mariotte siphon reservoir which enables the seepage rate to be calculated directly from the rate of fall in the reservoir level.

Worstell and Carpenter investigated the ability of the meter to measure total seepage from a section of channel. They found that the average meter reading in two field tests was 50% lower than that obtained in pondage tests. The difference was attributed to small, undetected areas of high seepage.

The case study below describes the findings of an investigation into the use a modified version of the Idaho seepage meter. A photograph of the modified meter is presented in **Figure 4.2**.

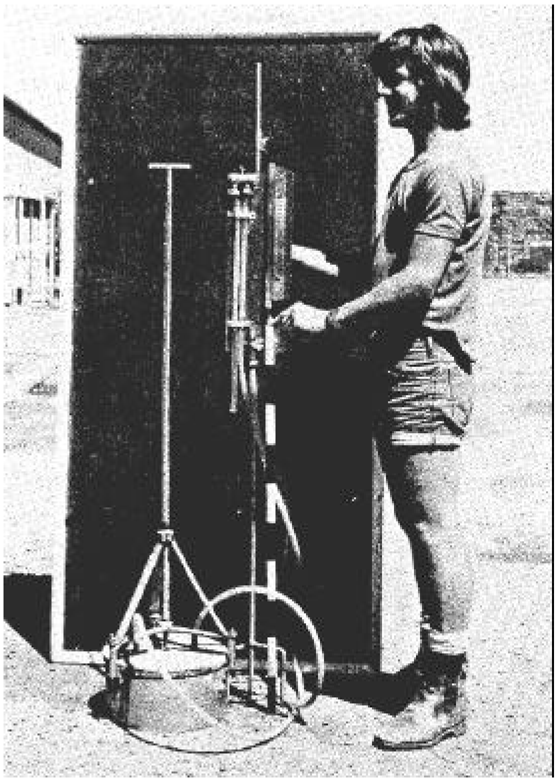
Case Study – Use of Modified Idaho Seepage Meter, Australia. (Byrnes and Webster, 1981).

Byrnes and Webster (1981) conducted a significant study into the Idaho meter comprising laboratory and field investigations, to determine its usefulness, reliability and range of operational effectiveness in Australian conditions. The objectives of the program were to adapt the equipment to overcome the difficulties in tests noted by previous workers, to determine the performance of the meter under controlled and field conditions, and to assess its usefulness in identifying parts of channels where relatively high seepage losses occur. The primary conclusions and recommendations derived from the report were:

1. The accuracy and range of use of the Idaho seepage meter was improved by minor modifications to the meter and operating procedures.
2. In the laboratory, tests of the modified meter on tanks containing different soil cores produced consistent mean metered seepage : tank outflow ratios, of approximately 1.2 : 1.
3. At seepage rates above 400 mm/d the instrument is unreliable.
4. Comprehensive field tests in 14 channels with 382 meter readings produced measurements ranging from 0.1 to 352 mm/d. The distribution of measurements was positively skewed, 82% of the readings being less than 7 mm/d, and the median for all measurements was 1.77 mm/d. Variability in measurements was high; within various section of channels, coefficients of variation ranged from 80 – 360%.
5. Pressurisation of the Idaho meter bell (only occurred in summer months and on the channel bed) was observed in 20% of all channel bed meter locations. Although the problem could be overcome by adapting the equipment, this caused serious operational disadvantages and restricted its large scale use.
6. From statistical treatment of the skewed data it was determined that: there was a significant difference in meter seepage rates in different channels, there was a significant difference in meter seepage rates between beds and batters where a sediment layer is present, there was not a significant difference in seepage rates in light and heavy soil types where a sediment layer was present.
7. In a comparison of total seepage loss from sections of channels by the Idaho meter and ponding methods, mean meter readings significantly underestimated the ponding test results [26% and 34% of the respective ponding losses (5.4 and 12.6 mm/d)].
8. The results confirmed the usefulness of the modified Idaho meter for checking the effectiveness of remedial measures, identification of relatively high seepage losses from a section of channel, and checking whether local groundwater pumping increased the seepage rate from a channel.

It was concluded that the modified Idaho meter is a useful aid in seepage investigations for delineating parts of channels that have relatively high seepage rates, and for checking the effectiveness of remedial measures.

Figure 4.2: Modified Idaho Seepage



After Byrnes and Webster (1981).

Seepage meter with submerged water bag
Described as a simple and cheap device (Kraatz, 1977), this seepage meter consists of a watertight seepage cup connected by a hose to a flexible water bag floating on the water surface. The type of meter is shown in **Figure 4.1**. Water flows from the bag into the cup, where it seeps through the channel area isolated by the cup. By keeping the water bag submerged, it adapts itself to the shrinking volume so that the heads on the areas within and outside the cup are equal. The seepage rate is computed from the weight of water lost in a known period of time and the area covered by the meter. Analyses undertaken to study errors due to pressure differences showed that when seepage losses are low, a small head difference of 1 cm or so could cause errors in the measured seepage approaching the magnitude of the seepage itself. For high seepage rates, however, such pressure differences cause only a small error in the measurement (Kraatz, 1977).

UPIRI Meter
A seepage meter of the constant head type was developed at the Uttar Pradesh Irrigation Research Institute (UPIRI), Roorkee, India, by Chawala, Jain and Chabra (1971). Testing of the instrument in a tank on various media provided meter coefficients (the ratio of meter rate to tank outflow) ranged

from 0.76 (sandy loam) to 1.18 (clay loam). That is, the more permeable sediments underestimated actual seepage rates, while the less permeable sediments overestimated seepage. The authors gave no explanation for the variation in their coefficients.

<u>AAEC Meter</u>
Zuber (1970) measured seepage loss by converting the slow flow through an area enclosed by the meter bell to the fast flow through a narrow bore tube. The velocity through the tube was measured by the transit time of an injected pulse of a radioisotope. The Australian Atomic Energy Commission (AAEC) developed a seepage meter based on the constant head principle and the concept described above. Laboratory testing of the instrument by the State Rivers and Water Supply Commission indicated the equipment had several problems and was generally unsuitable for routine handling by field staff (Byrnes and Webster, 1981).

Advantages

- Useful for qualitative determination of areas of channel seepage relative to each other, and for identifying sections of channel with relatively high seepage loss;
- Relatively rapid installation and ease of measurement;
- Useful for determining relative seepage rates across the channel bed (eg, comparing rates at centre with rates on the inside toe);
- Can be used during channel operation; and,
- Relatively cheap compared to other methods of seepage measurement.

Disadvantages

- Vast majority of the literature concludes that seepage meters are not sufficiently reliability for absolute quantification of channel losses;
- The frequency distribution of seepage rates is positively skewed. That is, a high percentage of the leakage 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 (low) estimates of the total seepage rate and the number of measurements required to accurately estimate the actual seepage is generally prohibitive;
- Seepage rates often vary across the perimeter of the channel (ie, centre of base, junction of base and side and sides). Apart from adding to the number of measurements which may be required, it may not be possible to use the meter on channels with steep banks;
- Disturbance of the soil during insertion of the meter may alter the seepage process (and cause indicated rates to be higher / lower than actual);
- Obtaining a tight seal on the channel bottom or sides can be difficult; and,
- Seepage meters cannot be used in:
  - Deep channels
  - Fast flowing channels (generally considered unsuitable above velocities of 0.6 m/s)

– Channels with hard or gravelly beds, or where there is significant weed growth

Summary Assessment

Seepage meters are probably most helpful in determining approximate locations of relatively high seepage loss. Due to variable and sometimes erratic values obtained in measurements and the large number of tests required to sufficiently determine the average seepage rate, they are not considered reliable for absolute quantitative purposes.

Key References

- ICID, 1969.
- Worstell, 1976.
- Kraatz, 1977.
- Byrnes and Webster, 1981.
- Smith and Turner, 1982.
- Dillon, 1988.
- Frevert and Ribbens, 1988.

4.1.2 Barrel Tests

This testing procedure was developed for the US Bureau of Reclamation in 1982, and is described in Frevert and Ribbens (1988).

Principle and Methodology

The procedure involves the installation of a 55 gallon barrel (with the bottom removed) into the bottom or side of an unlined channel. Water from the barrel is supplied from a head tank via a hose. The water within the barrel is maintained at or near the depth of water in the channel during the irrigation season. The rate at which water disappears from the barrel (and therefore the rate at which it has to be replaced from the head tank) provides an estimate of the seepage rate. In some cases, two barrels may be welded top to bottom to allow modelling of larger heads

Advantages

- Simplicity of installation and ease of measurement;
- Surface area covered by test is larger than a typical seepage meter, allowing greater smoothing out of local variations within the soil;
- Long term test which can be used through the irrigation season; and
- Useful for determining qualitatively which areas of channel are seeping relative to each other, and for identifying sections of channel with high seepage loss.

Disadvantages

- Not widely discussed in the literature (i.e., not a proven and well established technique);
- Does not involve use of standard equipment – needs to be ‘hand-made’;

- Likely to be subject to some of the same variability problems found with seepage meters;
- Installation of the barrel may disturb the channel bottom or side material and therefore the measured values may not be totally representative of actual conditions; and,
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean.

Summary Assessment

Not a widely used technique and little is known about its accuracy or reliability. However it is likely to be subject to many of the same problems found with seepage meters. The simplicity of the method does offer some advantages.

Key Reference

Frevert and Ribbens (1988).

4.1.3 Well Permeameter

The well permeameter method has been used by the US Bureau of Reclamation for many years for determining on-site permeabilities.

Principle

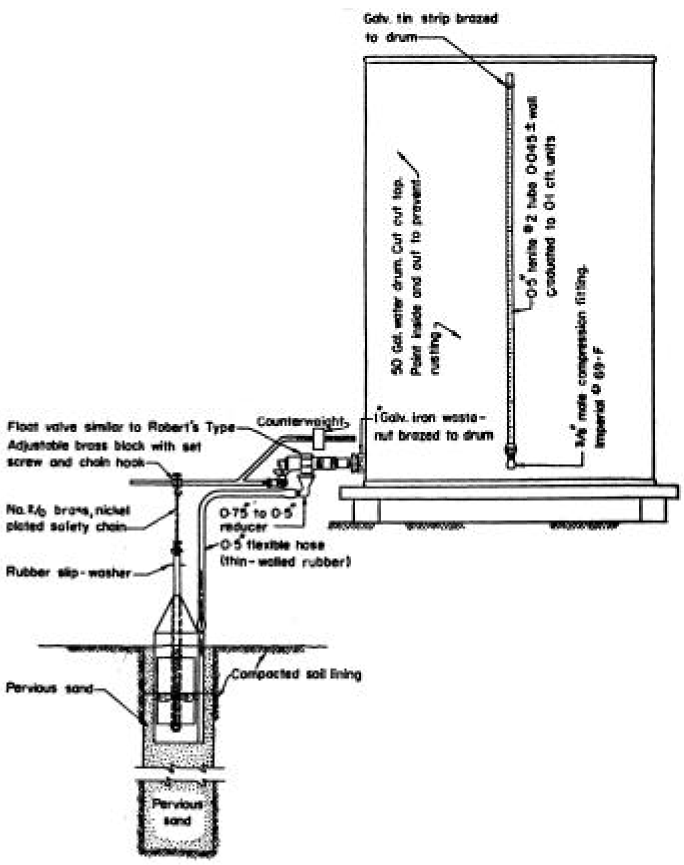
This method consists of erecting a pipe upright in a running channel to segregate a part of it. The lower part of the pipe is embedded to a sufficient depth in the soil of the channel bed. The pipe is then filled with water up to the channel water level and the volume of water over time required to maintain the water level in the pipe is recorded. The use of this method is restricted to unlined or earth-lined channels only.

Methodology

The test consists of determining the steady state flow of water from an uncased well in which the water surface is maintained at a constant elevation. **Figure 4.3** presents the well permeability equipment and set-up. Ideally the test should be conducted along the channel centre line, with the well bottom at channel grade and the water surface at the normal operating level. Some preliminary exploration of the subsurface is required for suitable selection of test sites. The soils where tests are conducted should be representative, and the presence of groundwater or impervious soil layers should be known for use in permeability calculations. The test is better used in unsaturated soils, although with some conditions saturated soils under the influence of high groundwater can be tested. The hydraulic conductivity of the soil can be calculated using formulae developed by the US Bureau of Reclamation.

Kraatz (1977) concludes that 'the well permeameter method is considered of value in studies where a knowledge of the order of magnitude of the hydraulic conductivity is required'.

Figure 4.3: Well Permeameter



After ICID, 1967.

Advantages

- Long term test which can be used through the irrigation season;
- Long record of use in the US; and,
- Useful for determining relative seepage rates in different parts of the channel, and for identifying sections of channel with high seepage loss.

Disadvantages

- Set-up is relatively elaborate, costly and time consuming;
- Available literature indicates technique is not very accurate compared to other methods of hydraulic conductivity estimation; and,
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a

positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean.

Summary Assessment
Not widely discussed in the literature, but available references indicate that it is quite costly and only an order of magnitude accuracy can be expected.

Key Reference
Kraatz 1977.
ICID 1967.

4.2 Channel Empty Techniques

These techniques are essentially used for measuring the hydraulic conductivity of the channel soils, which can then be applied to some mathematical formulae (refer section 5) to determine the seepage rate. There are many different methods for determining hydraulic conductivity above and below the watertable using point measurement techniques. This section focuses on the main techniques available for determining hydraulic conductivity above the watertable.

Many irrigation channels are constructed in areas with a relatively deep watertable, and therefore methods for measuring hydraulic conductivity above the watertable are the most important for seepage investigations. Even in irrigation areas in Australia which are in shallow watertable environments, when the channel is empty it is more likely that the watertable is below the channel bed level, than above. The techniques discussed in this section include the constant head permeameter, the double tube method, disc permeameter, seepage rings and ring infiltrometers. All above the watertable techniques operate on a similar principle. This involves wetting of a portion of the soil (preferably to positive soil-water pressures) and creating in this wetted zone a flow system of known behaviour for the evaluation of hydraulic conductivity.

All of these techniques suffer the same disadvantage over channel running techniques, that they do not characterise conditions representative of actual operating conditions. For this reason in some conditions, channel empty techniques could be virtually useless. For example, it would be pointless to measure the hydraulic properties of a completely dried and cracked channel bed. It should also be noted that water used for measurement should be similar in chemical make-up to the water that normally runs in the channel. Failure to observe this point could result in erroneous results.

A problem common to channel empty techniques is that the judgment of the most appropriate depth to target is somewhat subjective. Generally the most appropriate layer to target is the most restrictive layer, however which layer this is may not be apparently obvious. A further limitation is knowing the depth to which a layer be considered the restricting layer? However these problems can also be seen as a potential advantage of dry channel techniques, in that they can be used to measure the conductivity of different layers within the channel bed. This permits an examination of the effect of different layers on the overall permeability of the channel sub-surface.

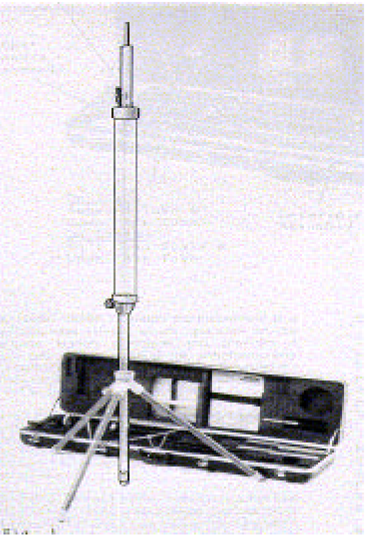
4.2.1 Constant Head Permeameter

Principle

The constant head permeameter is a tool for measuring the saturated hydraulic conductivity of soils. A constant head permeameter maintains a constant head of water in a shallow auger hole. The rate of water leakage from the apparatus to maintain this constant head (once saturated conditions have been reached) is proportional to the saturated hydraulic conductivity (or permeability) of the soils. The method gives a saturated hydraulic conductivity that is a combination of both vertical and horizontal components of hydraulic conductivity.

Figure 4.4 depicts a Guelph Permeameter. The model shown (2800K1 Guelph Permeameter) is a constant-head device which operates on the Mariotte siphon principle and provides a quick and simple method for simultaneously determining field saturated hydraulic conductivity, matric flux potential and soil sorptivity in the field.

Figure 4.4: Guelph Constant Head Permeameter



Methodology

A constant head of water is established in the hole via an air tube and the rate of water decline in the instrument measured and recorded over successive time intervals (usually between 2-5 minutes). Once the rate of water decline reaches a constant minimum value over three successive time periods, the test is stopped. The final constant value of water infiltration into the soil profile around the hole is assumed to be proportional to the saturated hydraulic conductivity of the soil. Intermediate higher readings of infiltration occur when the soil has not reached saturation (ie, the soil profile is still wetting up).

The constant head permeameter can operate between 5-60 cm depth below surface (or deeper if extension tubes are added). Results will be most representative of seepage when the head of water is maintained in the part of the soil profile that acts as the most restricting layer in the channel base. For example, if a highly permeable soil in the base of the channel overlies a less permeable soil, it is the lower permeability soil which is likely to be the limiting factor to channel seepage and should be targeted in constant head permeameter tests. After the hole is augered to the appropriate depth, a bottle brush of slightly larger diameter than the hole should be applied to the hole to ensure that any smearing of the clay on the hole walls caused by the hand augering does not inhibit flow of water out of the hole.

The saturated hydraulic conductivity of the soil profile tested can be calculated from the measured infiltration rate of water into the soil profile at saturation using the technique described in Reynolds et al. (1983).

Advantages

- Useful for determining relative seepage rates in different parts of the channel, and for identifying sections of channel with high seepage loss;
- Reasonably easy and quick to set up;
- Test time is relatively short, typically requiring less than one hour;
- Equipment is light and can be easily transported by one person;
- Relatively small amounts of water required per test (maximum of 10 litres per test);
- Useful for determining the relative seepage across a channel cross section; and,
- Relatively cheap compared to other methods of seepage measurement.

Disadvantages

- If seepage in the channel is controlled by a surface sediment layer, the constant head permeameter which operates below the channel bed level cannot measure this effect;
- The judgment of the most appropriate depth to target is somewhat subjective;
- Difficult to use in channels with hard or gravelly beds;
- Accuracy is poor in low seepage rate environments;
- Very few examples in the literature of application for measuring channel seepage rates;
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean.

Summary Assessment

The use of the constant head permeameter for channel seepage measurement is not widely discussed in the literature. However, as a tool for measurement of hydraulic conductivity of the soils during channel empty conditions, the constant head permeameter is an attractive technique due to its relative speed and simplicity.

Key References

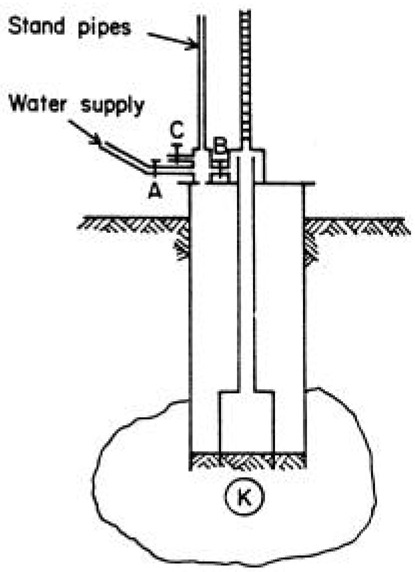
- Reynolds et al., 1983.

4.2.2 Double Tube Method

Principle

This method is described by Bouwer (1969). The apparatus consists of two concentric tubes which are inserted into an auger hole and covered by a lid with a standpipe for each tube. Water levels are maintained at the top of the standpipes to create a zone of positive water pressure in the soil below the auger hole. The hydraulic conductivity of the zone is evaluated from the reduction in the rate of the flow from the inner tube into the soil when the water pressure inside is allowed to become less than that outside the inner tube. **Figure 4.5** shows the basic set-up of the double-tube apparatus.

Figure 4.5: Double-Tube Apparatus



After Bouwer, 1969.

Methodology

Although theoretically not limited by depth, the practical depth range of this method is approximately 0.05 – 0.5m. Depending on the type of soil and the depth of the hole, tests are usually completed one or two hours after the tubes are filled with water. Approximately 200 litres of water are required per test.

Advantages

- Useful for determining qualitatively which areas of channel are seeping relative to each other, and for identifying sections of channel with high seepage loss;
- Reasonably large surface area is subject to infiltration in the test;
- Tests are usually completed within 1-2 hours; and,
- Relatively cheap compared to other methods of seepage measurement.

Disadvantages

- If seepage in the target channel is controlled by a surface sediment layer, the double tube method which operates below the channel bed level cannot measure this effect;
- Few examples in the literature of application for measuring channel seepage rates;
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean;
- Difficult to use in channels with hard or gravelly beds; and,
- Relatively large amounts of water required (generally several hundred litres) per test.

Summary Assessment

This method appears reasonably complicated compared to other methods of hydraulic conductivity measurement. For example, the constant head permeameter appears to be a very similar device, but less complicated to set up, easier to use and requires much less water to operate.

Key References

Bouwer, 1969.
Kraatz, 1977.

4.2.3 Disc Permeameter, Infiltrometer

Principle

The disc permeameter is an instrument commonly used to measure the hydraulic conductivity of soil at (or near to) saturation. Australian scientists contributed to its initial development (Clothier and White, 1981; Perroux and White, 1988) and its continuing development (Smettem et al., 1994). A disc covered with a semipermeable membrane (typically 0.2 m in diameter) is placed on a surface and the subsequent infiltration of water allows calculation of the hydraulic conductivity of that surface. Water is supplied to the disc at a constant head at or near to a surface matric potential of zero. Soil water contents at each test before and after use of the disc permeameter are inputs required for the analysis.

Methodology

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, in some cases a thin layer of contact material may be used to provide a level surface but this does not affect the measurement. 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 this method is used to measure the hydraulic conductivity of soils, soil profiles are often excavated to the required depth (e.g. 30 cm to a B horizon) and a level platform is prepared before the measurement is made. 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.

In practice a small negative head is applied to the disc to avoid the leakage of water. This may result in the measured values of hydraulic conductivity being slightly lower than the saturated value. However this will not affect the application of this method to the estimation of channel seepage. Soil samples extracted before and after use of the disc permeameter need to be analysed for volumetric soil water content.

Advantages

- The method has a good track record of use;
- The channel bed is not disturbed prior to and during the measurement process; and,
- Measurements will allow assessment of variability of channel bed properties along a length of channel and between different parts of the channel.

Disadvantages

- A single measurement may take approximately 90 minutes depending on the hydraulic conductivity of the channel bed;
- The measurements are only made for a circular area of diameter 20 cm;
- Soil samples need to be taken for later analysis; and,
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean.

Summary Assessment

The disc permeameter is widely used within Australia for determining the hydraulic properties of an unsaturated, homogenous and isotropic soil. The technique has a good track record of use, however no literature was found describing use for channel seepage assessment. The method requires an undisturbed channel bed, however soil profiles can be excavated to the required depth and a level platform prepared before the measurement is made. The measurements are only made for a circular area of diameter 20cm, however this is a greater area than covered by some other infiltration devices, such as the constant head permeameter. The analysis assumes homogeneity of soil properties.

Key References

- Clothier and White, 1981.
- Perroux and White, 1988.
- Smettem et al., 1994.

4.2.4 Ring Infiltrometers

Principle

Single and double ring infiltrometers are devices for determining the rate of infiltration into soil from a circular source. Single ring infiltrometers are a simple device used for gaining a rough estimate of infiltration rates. 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 vertically flow through the inner ring into the soil. This generally produces more accurate results compared to rates from single rings.

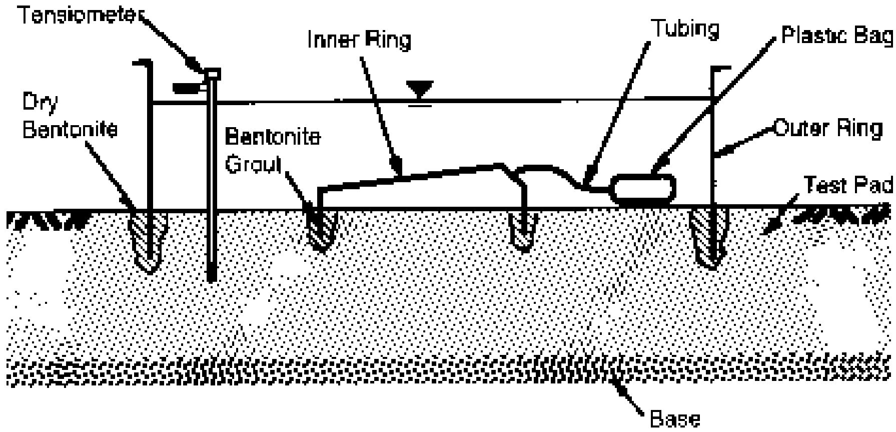
Methodology

Ring infiltrometers are normally metal rings with a diameter of 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 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).

At the most basic level, 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 (former) Victorian Department of Conservation and Natural Resources, in conjunction with the National Soil Conservation Program, released a Salinity Recharge Mapping Kit (no date) which describes this simple type of use of a single ring infiltrometer.

A more complex type of double ring infiltrometer is shown in **Figure 4.6**. This type of double ring infiltrometer consists of an open outer and a sealed inner ring. The rings are embedded and sealed in trenches excavated in the soil. Both rings are filled with water such that the inner ring is submerged. The rate of flow is measured by connecting a flexible bag filled with a known weight of water to a port on the inner ring. As water infiltrates into the ground from the inner ring, an equal amount of water flows into the inner ring from the flexible bag. After a known interval of time, the flexible bag is removed and

Figure 4.6: Double Ring Infiltrometer



After University of Wisconsin Engineering Website, 1998

weighed. The weight loss, converted to volume, is equal to the amount of water that has infiltrated into the ground. An infiltration rate is then determined from this volume of water, the area of the inner ring, and the interval of time. This process is repeated and a plot of infiltration rate versus time is constructed. The test is continued until the infiltration rate becomes steady or until it becomes equal to or less than a specified value. The hydraulic conductivity of the soils as a function of hydraulic pressure near saturation can be determined. From a sequence of applied tensions and the resulting infiltration rates the conductivity is calculated. **Figure 4.7** depicts the installation of this type double-ring infiltrometer.

Evaluation of the data involves the development of a "Horton" equation for the infiltration data collected in the test. This includes plotting cumulative infiltration vs time, determination of the infiltration rate for the time intervals in the test and determination of the Horton Coefficients f_o, f_c, and K.

Case Study – Comparison of Single and Double Ring Infiltrometers

Wu, L., Pan, L., Roberson, M. J. and Shouse, P. J. 1997.

Wu et. al. (1997) undertook a numerical evaluation of ring-infiltrometers under various soil conditions, including a comparison of single and double ring-infiltrometers. They concluded that field evaluation of infiltrometer geometry and of soil conditions on infiltration measurements is difficult because of the spatial and temporal variability of soil properties and the disturbance of soil by infiltrometer installation.

They found that the infiltration rates of a single-ring infiltrometer were f times greater than the 1-D infiltration, where f is a correction factor dependent on soil initial and boundary conditions and ring geometry. When the configuration of a typical double-ring infiltrometer was used in simulation (inner and outer rings were 20 and 30 cm in diameter, respectively), the simulated infiltration rates were about 80% of the single-ring rates. When the outer-ring diameter was increased to 120 cm (inner-ring diameter kept at 20 cm), the double-ring method-measured infiltration rates were 120 to 133% of the 1-D infiltration rates for the three test soils.

Compared with the constant head method, falling head infiltration rates dropped as much as 30% as the ponded head dropped from 5 to 1 cm in the sandy clay loam. Layered soil can significantly affect infiltration rates, depending on the position of the wetting front relative to the textural discontinuity and the time of measurement. The time at which the layering starts playing the role can be estimated from f and the cumulative infiltration.

Figure 4.7: Installation of Double Ring Infiltrometer

After University of Wisconsin Engineering Website, 1998

Advantages

- Compared to other point measurement techniques, the surface area covered by the device (and infiltrating water) is quite large, which should improve the accuracy of the test;
- Inexpensive to construct and relatively simple to run (for single rings);
- A double ring infiltrometer gives a true indication of vertical hydraulic conductivity, compared to other techniques such as the constant head

permeameter which gives an combination of vertical and horizontal hydraulic conductivity; and,

- Useful for determining relative seepage rates in different parts of the channel, and for identifying sections of channel with high seepage loss.

Disadvantages

- Set-up and operation can be difficult and time consuming for large rings;
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean; and,
- Relatively large amounts of water are required.

Summary Assessment

Double ring infiltrometers give more accurate results compared to single ring infiltrometers. Compared to other point measurement techniques this represents a good method due to the relatively large area of soil covered by the test. However the main disadvantage is the size of the equipment and the associated time involved in the set-up. This is compounded if the test is required to be conducted below the channel bed surface.

Key References

- University of Wisconsin Engineering,1998 (www.cae.wisc.edu/wangl/fieldlist.html)
- Wu et al., 1997.

4.2.5 Two-Stage Borehole Permeameter

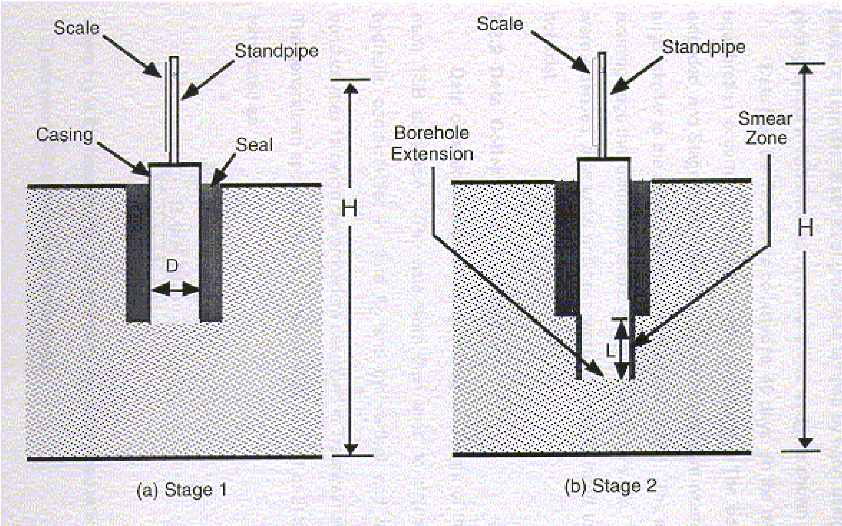
Principle

The two-stage borehole permeameter builds on the concept of the single well permeameter (refer section 4.1.3). The principle is basically the same as for the single well permeameter and consists of measuring essentially steady flow rates from a shallow borehole. The appendage to the method consists of an extension to the borehole with the aim of specifically measuring horizontal hydraulic conductivity.

Methodology

The rate of flow of water into soil through the bottom of a sealed, cased borehole is measured in each of two stages, normally with a standpipe in the falling head procedure. The standpipe can be refilled as necessary. **Figure 4.8** shows the two different stages of the test. In stage one, the bottom of the borehole is flush with the bottom of the casing for maximum effect of vertical hydraulic conductivity (K_v). The test is continued until the flow rate becomes virtually steady. For stage two, the borehole is extended below the bottom of the casing for maximum effect of horizontal hydraulic conductivity (K_h). Stage two of the test is also continued until the flow rate becomes virtually steady. The direct results of the test are apparent hydraulic conductivities K_1 and K_2. The actual hydraulic conductivities K_v and K_h can be calculated from these values (equations not included). **Figure 4.9** depicts the use of a two-stage borehole permeameter in the field.

Figure 4.8: Two-stage Borehole Permeameter



After University of Wisconsin Engineering Website, 1998

Figure 4.9: Two-stage Borehole Permeameter in Field

After University of Wisconsin Engineering Website, 1998

Advantages

- Provides an estimate of both horizontal and vertical hydraulic conductivity; and,
- Is useful for determining relative seepage rates in different parts of the channel, and for identifying sections of channel with high seepage loss.

Disadvantages

- Set-up and operation appears difficult and time consuming; and,
- As per the disadvantages associated with the seepage meter (and all point measurements), the frequency distribution of seepage rates is a positively skewed distribution and therefore many measurements are required to obtain a reliable estimate of the mean.

Summary Assessment

The usefulness of this method is that it provides an estimate of both horizontal and vertical hydraulic conductivity. The relative contribution of vertical and horizontal conductivity to total hydraulic conductivity is essentially dependent on the position of the watertable. The main disadvantage associated with the technique is the time involved in the set-up of the hole.

Key References

- University of Wisconsin Engineering,1998 (www.cae.wisc.edu/wangl/fieldlist.html)

5. Theoretical Mathematical Modelling

Principle

Suited to seepage prediction purposes or as a quick check on the results of other methods

Equations exist where the seepage rate is assumed to be a function of channel capacity and an empirical constant related to the type of soil or channel lining (ICID, 1967; Kraatz, 1977; Christopher, 1983; US Bureau of Reclamation, 1965, 1978 and 1984). These equations are best suited to estimating seepage losses from a proposed channel, but generally tend to ignore sub-surface hydrological conditions which can be a major influence on seepage from a channel. McLeod (1993) observes that seepage rates are not necessarily proportional to flow in the channel as the stage of channel is normally kept approximately constant by the use of regulatory structures.

However, theoretical mathematical models based on the physics of groundwater flow have been found to yield reliable estimates of channel seepage, when the required field data are collected (Frevert and Ribbens, 1988). This data includes watertable elevations, soil and aquifer characteristics, and the hydraulic conditions under which seepage occurs. The US Bureau of Reclamation has found that simple equations are capable of reproducing seepage rates within 15 percent of measured values, as noted in Hotes et al, (1985).

Theoretical mathematical models can yield reliable estimates of channel seepage provided the required field data is available

Hotes et al (1985) state that this approach should only be applied if the soil in, under and adjacent to the test section is thoroughly described, tested for hydraulic conductivity, and the watertable in relation to the channel is monitored. As the most significant data which is required is the hydraulic conductivity of the soil, several authors refer to this mathematical approach to channel seepage measurement as the ‘hydraulic conductivity’ approach.

Bouwer (1969) emphasises that the accuracy of the seepage predicted for a given channel ‘depends largely on how well the pertinent soil, watertable and boundary conditions can be characterised. Although solution techniques may yield exact or accurate answers, the fact that the model for which the solution is obtained is always a simplified version of the field situation renders the solution an estimate at best’.

Methodology

A variety of equations are available for computing channel seepage rates. The most significant and pioneering work was undertaken by Bouwer (1965 and 1969). Subsequent papers by Bouwer (1985 and 1988) have added to his early work, including consideration of a broader range of hydraulic conditions under which seepage occurs. Other workers, most notably Wachyan and Rushton (1987), have further built upon the work of Bouwer to develop equations for use in a wider variety and more commonly occurring environments. The work of Bouwer, Wachyan and Rushton, and the US Bureau of Reclamation are described in this section. These cover the most significant works related to a mathematical approach to channel seepage.

Bouwer (1965, 1969, 1978 and1988)

Bouwer's (1969) "Theory of Seepage From Open Channels" was one of the first papers to demonstrate that seepage losses not only depend on the wetted perimeter of the channel, but on the hydraulic conductivity and the hydraulic conditions within the underlying aquifer. Open channels lose water if the water level in the channel is above the groundwater table adjacent to the channel and gain water if the water level in the channel is below the groundwater water table adjacent to the channel. Bouwer (1969) describes the rate of gain or loss as being determined by:

- The channel geometry (channel shape and water depth);
- The hydraulic conductivity of the soil(s) surrounding the channel;
- The hydraulic conductivity and thickness of sediment or clogging layers on the channel wetted perimeter;
- The depth to other soil layers or lower boundary of the underground flow system; and,
- The position (depth) of the groundwater table at some distance away from the channel.

In this paper Bouwer outlines the three basic conditions to which the many natural profiles of soil hydraulic conductivity can be reduced for theoretical treatment of seepage flow systems:

- Condition A – The soil in which the channel is embedded is uniform and underlain by more permeable (considered as infinitely permeable), material.
- Condition B – The soil in which the channel is embedded is uniform and underlain by less permeable (considered as impermeable) material.
- Condition C – The soil in which the channel is embedded is of much lower hydraulic conductivity than the original soil for a relatively short distance normal to the channel perimeter (clogged soil, semipermeable linings).

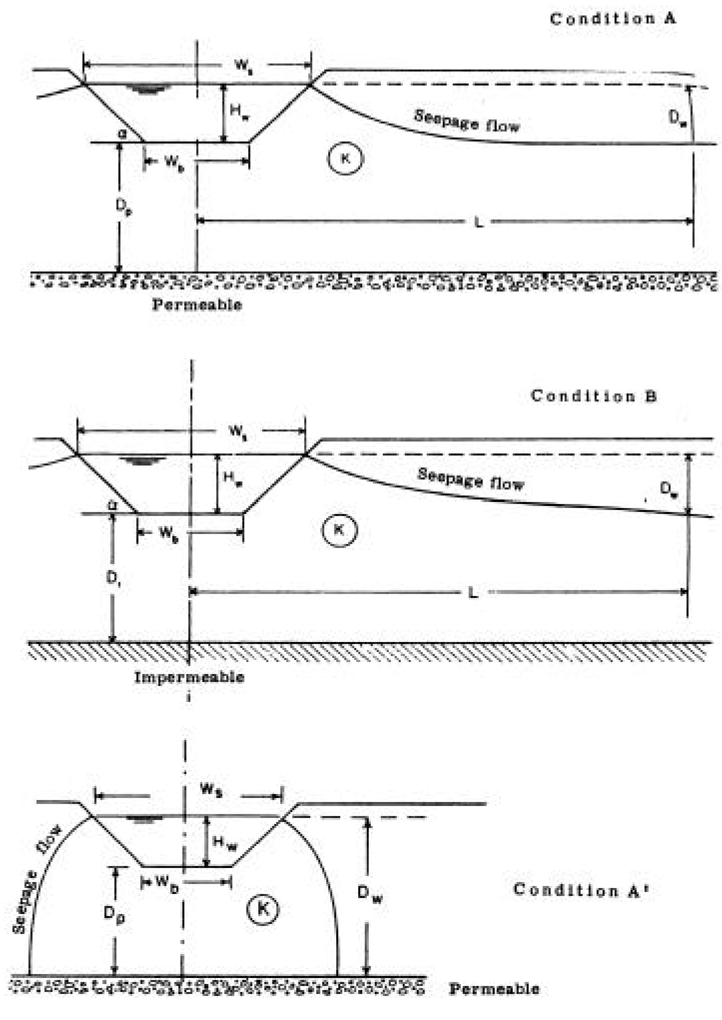
Solutions for seepage under these conditions (for steady state scenarios) are presented. These findings are summarised in 'Surface Water-Groundwater Relations for Open Channels' (Bouwer, 1988):

Losing channels (no clogging)

Figure 5.1 shows the geometry and symbols used by Bouwer for clean channels in uniform soil underlain by infinitely permeable material (condition A) or infinitely impermeable material (condition B). Bouwer determined rates of water loss from open channel without a clogging layer for a) different depths of water in the channel, b) different depths of the watertable at a distance away from the channel, and c) different depths of the lower boundary of the flow system. The soil between the channel and the lower boundary was assumed to be uniform with hydraulic conductivity, K.

W_s is the water level width in the channel, and H_w the height of water in the channel. D_p and D_i represent the depth to a permeable and impermeable layer respectively.

Figure 5.1: Geometry and symbols of clean channels in uniform soil under conditions A, B, and A’



After Bouwer (1969).

The shape of the channel was taken as trapezoidal with 1:1 side slopes. Since channel shape has only a minor effect on seepage (Bouwer, 1965), other channel shapes can be represented by the best fitting cross section with 1:1 side slopes. The depth of the watertable, D_w, was taken as the vertical distance between the water level in the channel and the groundwater table at a horizontal distance of ten times the bottom width, W_b, from the centre of the channel. This distance ($10W_b$) is defined as L in the above figure. At this distance the elevation of the watertable is not directly affected by the seepage flow system of the channel (Bouwer, 1988).

If, for condition A, the watertable is below the top of the permeable layer, the seepage system is one of free drainage into a deeper, very permeable layer.

This condition is called condition A', and is characterised hydrodynamically as a system of seepage to a fixed groundwater table at depth D_p below the bottom of the channel. D_w for condition A' is $D_p + H_w$.

The results of the analysis were expressed in dimensionless diagrams, showing I_s /K as a function of D_w/W_b for different values of D_i/W_b and D_p/W_b. The seepage I_s, is the volume rate of seepage per unit length of channel divided by the water surface width W_s in the channel. Thus I_s is like an infiltration rate and has the dimension length/time. **Figure 5.2** (Bouwer 1965, 1969 and 1978) depicts the solutions for conditions A, A' and B for three different channel water depth to width ratios.

Figure 5.2: Results of Bouwer seepage analysis for trapezoidal channel (after Bouwer 1965, 1969 and 1978)

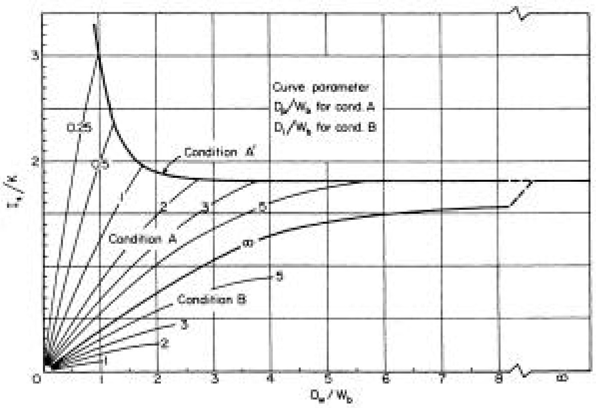


FIG. a. Results of seepage analyses with electric analog for trapezoidal channel with $\alpha = 45°$ and $H_w/W_b = 0.75$.

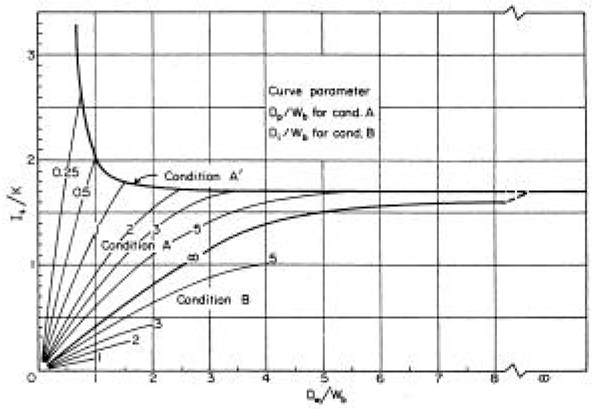


FIG. b. Results of seepage analyses with electric analog for trapezoidal channel with $\alpha = 45°$ and $H_w/W_b = 0.5$.

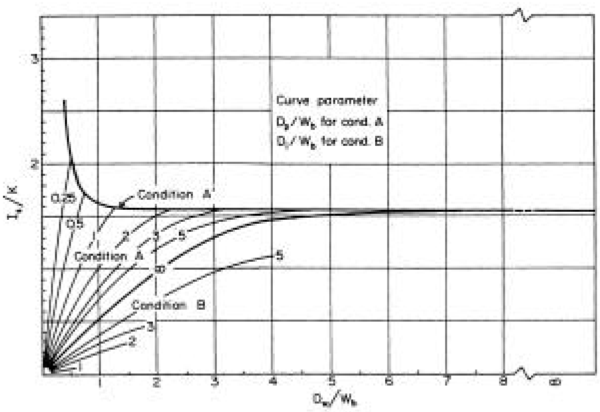


FIG. c. Results of seepage analyses with electric analog for trapezoidal channel with $\alpha = 45°$ and $H_w/W_b = 0.25$.

After Bouwer (1969).

The results of this analysis show that for losing channels with no clogging layers, the seepage rate varies essentially linearly with depth to groundwater if the groundwater is relatively shallow, but is essentially independent of depth to groundwater if the groundwater is relatively deep.

Use of the graphs in **Figure 5.2** – The dimensionless value I_s/K can be obtained from the graphs. From this the seepage rate per metre of channel per day is obtained by the equation:

$$q = \frac{I_s}{K} K W_s$$

where q is the seepage rate per metre of channel per day

$\frac{I_s}{K}$ is a dimensionless value obtained from the graphs

K is the hydraulic conductivity of the aquifer

W_S is the water level width in the channel

To apply the graphs to channels of other shapes, W_b is computed from the actual values of W_s and H_w as if the channel were trapezoidal with a 1:1 side slope, or the x-section can be replaced by the best fitting trapezoidal cross section with a 1:1 side slope.

Losing channels (clogging)

Seepage from losing channels where the wetted perimeter is covered with a clogging layer on their wetted perimeter is controlled by the hydraulic conductivity K_s and the thickness L_s of the clogging layer. **Figure 5.3** depicts this scenario. The wiggly vertical lines indicate unsaturated flow. Seepage is not affected by depth to groundwater as long as the watertable, or, rather, the top of the capillary fringe, is below the clogging layer on the channel bottom.

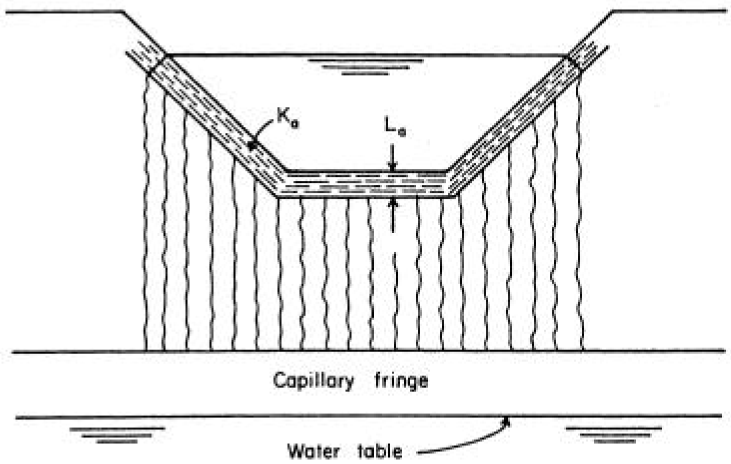
The seepage rate can be calculated by applying Darcy's Law to the clogging layer, using the water depth above the layer as the pressure head at the top of the layer, and a negative pressure head at the bottom of the layer. This negative pressure head is determined by the unsaturated hydraulic characteristics of the underlying, unsaturated soil (discussed in more detail in Bouwer, 1978 and 1982).

Figure 5.3 depicts a situation where the watertable (and capillary fringe) is below the base of the channel. If the watertable is above the bottom of the channel, there is an essentially linear relation between the seepage rate and depth to groundwater (measured from the water surface in the channel).

Gaining channels

For gaining channels, the rate of flow of groundwater into the channel is essentially linear with the height of the watertable (measured from the water surface in the channel), regardless of whether the channel wetted perimeter is clean or covered with sediment or other clogging material.

Figure 5.3: Geometry and Symbols For Channel With Clogging Layer and Watertable Below Channel Base



After Bouwer (1969).

Wachyan and Rushton (1987)

This paper summarises an investigation into seepage losses by performing numerical model solutions for a series of examples with different conditions at the lower boundary of the aquifer, at lateral boundaries and at the watertable within the aquifer. The paper expands upon the analytical solutions to channel seepage developed by Bouwer (1969). The two limiting conditions used by Bouwer are concerned with an aquifer having an underlying layer of very high hydraulic conductivity or an aquifer with an impermeable base having a lateral boundary at which groundwater heads remain at constant value (refer above section for more detail). Wachyan and Rushton (1987) note that closer examination of these two conditions indicates they rarely occur in practice.

Additional conditions are described in this paper which relate more closely to practical situations. These include an underlying layer of lower hydraulic conductivity and a loss of water from the vicinity of the watertable due to evaporation or water taken from storage. For each of these conditions, the channel losses are generally higher than the values based on the existing approaches. Consideration is also given to the influence of the size of the channel and the effectiveness of various forms of lining. A final section presents three alternative situations which can apply at different stages during a typical year.

Partial lining of a channel (i.e., base or walls only) is shown to have little effect on the magnitude of the losses and total lining which contains defects is also ineffective. The paper emphasises the need for detailed field work into the conditions within aquifers in the vicinity of channels.

US Bureau of Reclamation (1984)

Three seepage rate equations are noted in the US Bureau of Reclamation Drainage Manual (1984). One equation is used to estimate seepage under free draining conditions (i.e., the watertable is below the bottom of the channel). If the aquifer is not sufficiently permeable, seepage reaching the watertable will begin to mound beneath the channel. A second equation is used to compute the time required for the mound to rise and intercept the channel bottom. As the mound approaches the base of the channel the seepage rate begins to decrease. When the mound rises to the elevation of the water surface in the channel, the seepage tends to remain constant at a value referred to as the terminal seepage rate. A third equation is used to compute this value. When there is a nearby watertable elevation control, an elevation based on Darcy's Law and horizontal flow is used to compute seepage rates.

Advantages

The advantages of adopting a mathematical approach toward determining channel seepage losses are as follows:

- Reflects actual operating (dynamic) conditions;
- Does not involve interruption of channel operations;
- Suitable for all sizes of channel;
- Except for very small channels this approach may require less resources than direct measurements (personnel and money);
- It is the only approach which can be used for channels not yet constructed;
- Can be used as a "sanity check" on the results of other work;
- 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).

Disadvantages

The disadvantages of adopting a mathematical approach toward determining channel seepage losses include:

- The 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, expense, and require significant expertise.
- It suffers from the same limitation as point measurement - that is that hydraulic conductivity point measurements must be made, and by their

nature these measurements are a positively skewed distribution, and therefore many measurements are required to obtain a reliable estimate of the mean;
- It is difficult to quantify seepage for relatively short sections of channel; and,
- The theory is not applicable to lined channels.

This approach allows estimates of seepage under varied conditions however intensive data requirements are a significant limitation

Summary Assessment

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 may be as a "sanity check" on the results of other work.

Key References

- Bouwer (1965, 1969, 1978 and 1988)
- Wachyan and Rushton (1987)
- US Bureau of Reclamation (1984)

6. Soil Classification

Principle

Seepage rates are determined by many variables. However one of the most influential variables can be the soil type through which the channel is constructed. The basic theory upon which estimation of channel seepage by soil classification is based, is that seepage is primarily a function of hydraulic conductivity, which is in turn a function of the soil texture. If soil categories (based on texture) are assigned seepage rates, knowledge of the distribution of soils within a channel can enable the estimation of total seepage rates along that channel.

Methodology

There are two main approaches by which soil classification can be used to estimate channel seepage:

- At a broad regional scale, using soil maps and published data on seepage and/or hydraulic conductivity rates from similar soil types;
- At a local scale, using point measurement seepage tests to determine seepage rates from a particular soil type, and subsequent extrapolation of seepage rates based on the soil type.

Regional Approach

Regional approach to estimating seepage based on published seepage rates is a useful first cut estimate but accuracy is likely to be relatively low

The first type of application is more commonly referred to in the literature. Smith and Turner (1982) state that despite the difficulty of using soil classification noted by some workers, such systems 'do have a role in reconnaissance for seepage, particularly in the location of prior streams and other high permeable alluvial deposits.' In other words, they view soil mapping as a tool to be used early in the seepage identification process, but more for identification of potential hot spots, rather than actual quantification of seepage rates.

Worstell (1976) determined channel seepage rates for broad soil textural groups by the evaluation and analysis of 765 tests made in the western United States (including pondage and seepage meter tests). Based on these results Worstell developed a soil classification approach to seepage estimation, which allowed for channel capacity (assumed to be a function of width) to arrive at an overall loss rate. Details are provided in the case study below.

There are dangers, however, in blindly applying a system such as that proposed by Worstell (1976). McLeod (1995 and 1996) was involved in a review of channel seepage calculations conducted by operators in the Murray Region of the NSW Department of Land and Water Conservation (Australia). Estimation of seepage was conducted using seepage rates presented in Worstell (1976) and Linsley et al. (1992). In his review of this method McLeod notes that 'the seepage losses used in these investigations were taken from foreign publications and work conducted overseas. The results of comparable studies in south-eastern Australia were ignored'. In addition, the results of Linsley et al. (1992) were based on order of magnitude results from channels situated above the watertable. Investigation of the area where these results were applied showed that local watertables were generally around 2m from the surface, and the use of such figures was therefore inappropriate. Generally the aforementioned foreign investigations reported significantly higher seepage rates than for similar soil groups within south-eastern Australia.

Case Study - Estimating Seepage Losses Based on Broad Scale Soil Classification
(Worstell, 1976)

Worstell (1976) determined channel seepage rates for broad soil textural group by the evaluation and analysis of 765 tests made in the western United States (including pondage and seepage meter tests). Seepage rates varied widely within each broad texture class, but the average rates for all the classes increased as the soil texture graded from fine to coarse. Worstell asserted that because average seepage loss rates fall within a limited range, the average losses from a channel system can be estimated reasonably accurately. The four categories used by Worstell and the corresponding seepage rates are listed below:

General Soil Group	Average Seepage Rate (mm/day)
Clayey	70
Silty	240
Loamy	290
Sandy	480

The procedure described by Worstell for determining seepage losses from a system requires access to a soils map, a map of the channel system, and a table of approximate widths and lengths of the system's channels. For a given reach, the predominant soil texture is to be established (to be assigned to one of the four types listed above) and the associated average seepage rate determined. Then by using a set of curves which related seepage rate and channel width to overall channel loss (volume/time/length of channel), the total loss can be determined for channels with different widths. Worstell concluded that irrigation system designers and resource planners would find these average rates helpful in estimating seepage losses for existing or planned systems, and for evaluating alternative improvements in water management, such as channel-lining programs.

Worstell's soil classification approach to seepage estimation also allows for channel capacity (assumed to be a function of width) to arrive at an overall loss rate. The four soil categories are quite broad, however the system is only presented as a means of estimating seepage at a regional level. It is stated that where 'high losses are suspected, seepage tests should be made on each specific reach of channel involved, rather than using average rates.

A local approach involving an actual soil survey of the channel is likely to significantly improve the accuracy of this technique compared to the regional approach

Local Approach

The second approach (not widely discussed in the literature) involves the use of the soil classification approach at a local level. The primary difference between the regional approach is that this method involves an actual soil survey of the channel under investigation and seepage measurements at certain locations within the channel. A local survey may be able to detect, for example, the presence of duplex soils which could significantly effect seepage rates, which may not be identified by the nominal soil classification assigned in the regional approach.

Based on the seepage results of point measurement techniques (or pondage tests) within different soil types of a given channel, these rates for the different soil types, combined with a soil survey along the channel, can be used to extrapolate the seepage along the channel (provided other variables such as channel dimensions and hydrogeology remain approximately equal). The advantage of this approach over the regional application of a soil survey approach is that:

a) the soil is mapped with a greater degree of accuracy
b) the seepage rate applied to the soil category is directly obtained from that channel, not based on average results from other locations.

Advantages

- Is founded on one of the most influential variables upon which channel seepage is based;
- Relatively quick and cheap;
- Analysis of results not technically demanding; and,
- Seepage losses over a large region can be estimated.

Disadvantages

- Natural lining or clogging of a channel via silting or biological processes can become the dominant seepage control factor, rather than soil type;
- Other significant factors influencing seepage such as groundwater levels are not considered;
- Care must be taken when using seepage rates for given soil types away from the environment where the tests were conducted;
- Seepage rates from one soil type can vary significantly. eg, on the same site with the same soils, with essentially identical waters, with testing performed by highly experience personnel, measured seepage ring rates varied by as much as 50% or more, (Robinson and Rowher, 1959).
- Soil mapping and measurement of soil hydraulic conductivities requires experienced professionals (applicable if local approach adopted);
- Suffers from similar limitation as point measurement - that seepage measurements are a positively skewed distribution, and therefore many measurements are required to obtain a reliable estimate of the mean – this method will probably lead to an underestimation of the seepage, as local high seepage zones will go undetected; and,
- Cannot be used as a post-remediation measurement technique.

Summary Assessment

Regional approach useful for first cut estimate and local approach likely to improve accuracy, however the method ignores some important seepage variables

The regional approach to estimating losses based on published seepage rate data for given soil types is a useful method for providing a first cut estimate of seepage losses from a system. It can also assist in the identification of potential seepage 'hotspots'. The accuracy of a regional approach for quantitative seepage assessment is likely to be relatively low.

A local approach involving an actual soil survey of the channel and an attempt to calibrate soil types based on point or pondage tests is likely to significantly improve the accuracy of this technique. However, the method suffers from the fact that other important seepage variables are ignored. For example, the effect of a surficial clogging layer may exert more control on seepage rates than the underlying soil type, the effect of local hydrogeological conditions can cause significant variation in seepage rates in a given soil type, and the surface soil type may not be the hydraulically limiting layer. However, these conclusions do not down play the importance of soil mapping and testing to the investigation and design phase of new channels.

Key References

- Worstell, 1976.
- Smith and Turner, 1982.
- McLeod, 1995 and 1996.

7. Groundwater Techniques

Monitoring bores provide a permanent tool for measuring effects of channel seepage

While groundwater observation bores are often required as part of a channel seepage investigation (for hydrogeological characterisation, groundwater chemistry analysis etc) this section specifically address the use of groundwater levels and aquifer hydraulic conductivity alone to estimate seepage rates. Groundwater observation bores provide a permanent tool for measuring the effects of channel seepage, which amongst other things can be useful for post remediation seepage analysis.

Principle

The most critical monitoring period is during channel filling and emptying

Close monitoring of the groundwater conditions around a channel, referred to as a piezometric survey, can provide an indication of seepage loss (McLeod, 1993). Observation of groundwater levels in a series of piezometers located at right angles to the centre line of a channel provides data to determine the flow lines and equipotential lines of seepage water. The quantity of seepage can then be calculated when the hydraulic conductivity of the aquifer is determined. The amount of seepage can be estimated by studying the variations in the watertable combined with variations in channel running level. The best period of observation is during the rise in watertable when a channel is put back into operation or during the fall of the watertable at the end of the 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 irrigation season, but at a lower frequency).

Figure 7.1 indicates the basic theory behind the use of a piezometric survey to determine seepage rates. Essentially the principle is one of subtracting groundwater flow before channel influence from groundwater flow after channel influence. This method therefore assumes that a pre-channel groundwater level can be obtained or at least reasonably accurately estimated – therefore this method is best suited to a channel which has a reasonably long closure period which allows groundwater levels to subside significantly. Based on the conditions and groundwater heads as shown in **Figure 7.1** the seepage rate away from (one side of) the channel is given by:

$$q_{channel} = q_2 - q_1$$

q_1 and q_2 can be determined using the Dupuit assumptions [an equation derived by Dupuit (1863) for steady flow in an unconfined aquifer], and the solution for one side of the flow from the channel is given by:

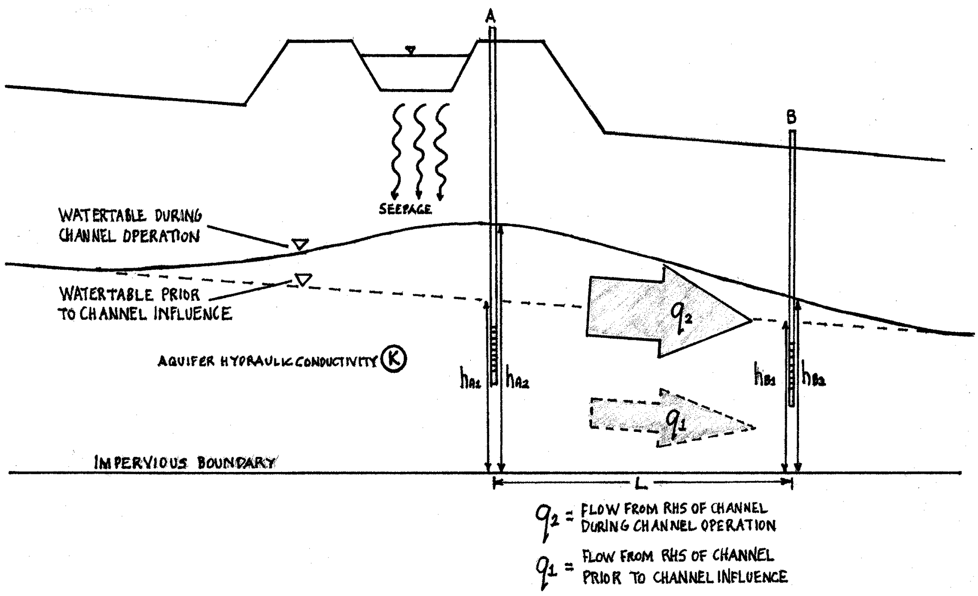
$$q_{channel} = \frac{k}{2L}\left[\left(h_{A2}{}^2 - h_{B2}{}^2\right) - \left(h_{A1}{}^2 - h_{B1}{}^2\right)\right]$$

where $q_{channel}$ is the flow rate away from one side of the channel
k is the hydraulic conductivity of the soil / aquifer
L is the length between the bores

H_{A2} is the head in the near channel bore during channel full conditions
H_{B2} is the head in the away from channel bore during channel full conditions
H_{A1} is the head in the near channel bore during channel empty conditions
H_{B1} is the head in the away from channel bore during channel empty conditions

Note : 1) In semi-confined condition Darcy's equation may be more relevant
2) The above equation only defines seepage flow from one side of the channel. The same approach can be applied to calculate flow from the opposite side of the channel

Figure 7.1: Estimating Channel Seepage From Groundwater Levels



Methodology

This approach requires a minimum of two groundwater observation bores at right angles on either side of the channel. The installation of three bores on either side of a channel (the outermost bores well away from the influence of the channel) may be used to estimate the pre-channel groundwater level by assuming a constant gradient between the bores.

The above approach also requires an estimate of the aquifer hydraulic conductivity. 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.

Advantages

- This method is a direct estimate of channel seepage – it measures all channel water which seeps to the groundwater;

- Groundwater observation bores provide a permanent tool for measuring the effects of channel seepage; and,
- It can be used for post remediation seepage analysis.

Disadvantages

- Installation of groundwater bores is expensive;
- The locating of bores needs to be carefully considered;
- Seepage rate will be sensitive to the hydraulic conductivity (K), which can be difficult to accurately determine;
- Determination of aquifer hydraulic conductivity may require specialist technical input;
- If the results from one transect of bores are to be extrapolated along a section of channel, the assumption is being made that K (and other groundwater conditions) are uniform along the channel, which may not be a reasonable assumption – i.e., the method is essentially a point measurement technique and consequently suffers the same disadvantages as other point measurement techniques; and,
- The method requires an estimate of pre-channel groundwater levels which may be difficult to obtain if the channel does not shut down for a considerable period of time.

The main shortfall of this method is that it is concentrated on a slice across the channel which may not be representative of broader channel conditions

Summary Assessment

Groundwater monitoring across a channel cross section during channel induced groundwater changes can provide information which can be used to assess channel seepage rates. It is important however that the pre-channel groundwater levels can be reasonably accurately calculated. The method also relies on the accurate assessment of aquifer hydraulic conductivity. The main shortfall of this method appears to be that it is concentrated on a slice across the channel, and seepage estimates must be extrapolated along the channel based on these results. The method requires correct placement of bores so that preferred pathways are not missed. However, the reality is that the groundwater heads and the hydraulic conductivity will change along the channel. Installation of numerous cross sections to improve the accuracy of this technique will be expensive.

Key References

- Kraatz, 1977.
- McLeod, 1993.

8. Geophysical Techniques

Geophysics for channel seepage assessment can be fast and relatively inexpensive

Appropriate geophysical methods can provide a relatively fast and inexpensive way to locate seepage without disturbing the natural flow of the channel. Of particular importance is the establishment of methods that can be used to detect seepage while keeping the channel in full service. The use of geophysics for channel seepage assessment is still an emerging area.

Principle

While detection of channel seepage can be achieved with geophysical techniques alone, quantification of seepage requires the integration of geophysical methods with other techniques, in order to calibrate the geophysical results.

The use of geophysical methods to detect channel seepage is essentially based around the detection of differences between:

- Salinity of groundwater and the generally fresher channel water;
- Soil moisture content; and,
- Soil type.

Channel seepage quantification based on geophysics requires integration with other methods

Standard geophysical methods for the mapping of groundwater and reservoir seepage paths have been described by various authors (eg, Ogilvy et al 1969 and Palacky et al 1981). These authors concentrate on variations in electrical resistivity related to groundwater chemical composition or self potential signals (SP) related to groundwater movements. There are several variations of each technique providing variations in sensitivity and operational flexibility. However the data obtained are often contentious and the results for any individual survey may be subject to local interpretation and operator bias.

Methodology

Conventional Methods

Variations in electrical resistivity give the most direct indication of groundwater content. In theory a simple measurement of resistivity can provide an indication of porosity and water content which are related through Archie's law (essentially a power law correlation function). Soil and fluid samples are required for best results and major anomalies may be related simply to variations in geology (especially soil salinity).

Resistivities may be determined conventionally using several methods, including:

- Direct current (DC) galvanic systems [Resistivity / Induced Polarisation (IP)] using Wenner and / or Sclumberger arrays;
- Electromagnetic systems, typically EM34, EM31, EM38. (An example of an EM34 system in use is shown in **Figure 8.1**); and,
- Natural electrical sources [Self Potential (SP)].

All can be used for broad scale mapping but the galvanic systems are relatively slow to deploy and productivity is low compared to the EM units.

However the galvanic systems may be preferred for detailed studies relating to variations in moisture as a function of depth.

Direct current galvanic systems

Direct current techniques involve the introduction of an electrical current directly into the ground by way of an electrode. The resistance of the ground is then determined by the potential measured between two other points around the current electrodes.

An example of a direct current galvanic system is provided in the case study below.

Case Study – Use of Electrical Resistivity to Detect High Seepage Zones in Goulburn Valley, Australia. (Smith and Turner, 1982).

An electrical resistivity survey was conducted as part of a channel seepage investigation on an irrigation channel located in the Goulburn Valley of Victoria, Australia. A four electrode resistance meter in which the energising current is provided by a small hand generator was used, in conjunction with a Wenner array of four electrodes, was used for the survey. Electrode spacings of 3m were used in the traverse. The authors note that the main limitation with using this equipment is that the results are essentially point measurements and not a continuous record of the variation of resistivity along the channel.

The results of the resistivity survey were plotted against corresponding seepage meter measurements (using the Idaho seepage meter). The graph indicated that the regions of highest seepage coincided with high values of resistivity. The authors noted that this was contrary to the findings of previous studies (eg, Wantland and Goodman, 1962), where low values of resistivity were seen as the best indicator of seepage. They therefore concluded that the resistivity traverse did not locate zones of high seepage, but only detected the shallow coarse sand aquifer which was coincident at this point. It is possible the coarse aquifer detected may have been a significant contributor to channel seepage.

Smith and Turner (1982) concluded that soil classification and resistivity measurements are helpful for the purposes of first reconnaissance for seepage and that further testing and data collection are needed to increase the usefulness of these two techniques, combined with visual observation and aerial photography.

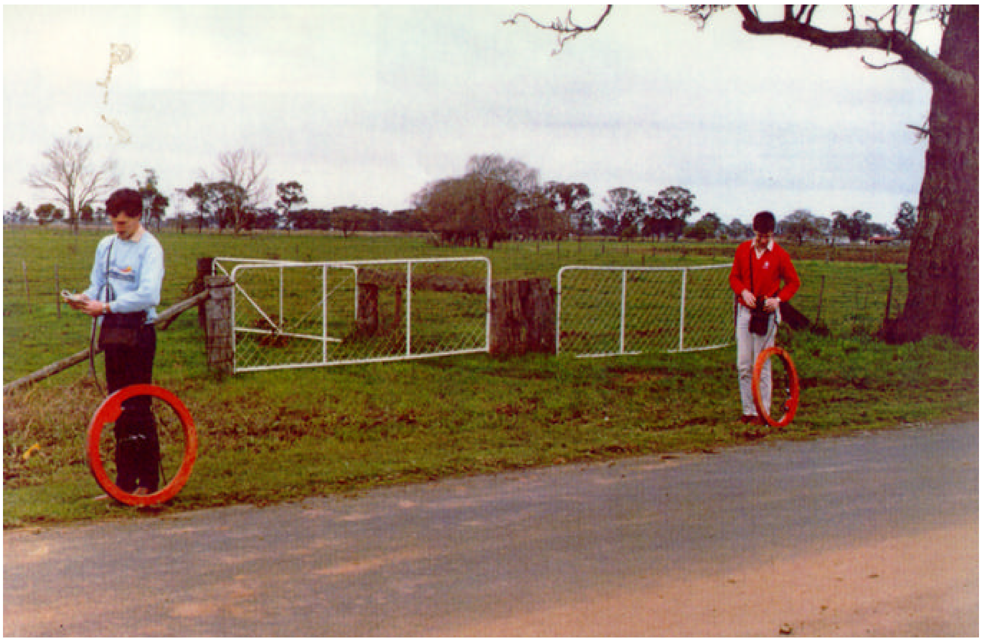
Kraatz (1977) states that resistivity measurements can be used as the basis for estimating seepage or serve as a qualitative indicator of seepage because the electrical resistance of the soil varies with the water and salt content. Kraatz (1977) refers to a resistivity method where measurements are made by an instrumented truck moving along the channel banks, dragging flat electrodes alongside the channel side or bed. These electrodes are connected to a source of alternating current and measurement equipment mounted in the instrument truck. Twenty six kilometres of channel can be logged in eight hours. Investigations were carried out by the US Bureau of Reclamation to check the accuracy of this method by comparing the results with those of other methods (pondage tests, seepage meter etc). It was found that the technique of electrical logging provides a considerable degree of accuracy, however it was noted that some limiting factors would need to be overcome for widespread adoption of the technique.

Electromagnetic systems
Electromagnetic systems can measure the electromagnetic properties of the soil profile up to a depth of 60m, with the penetration depth dependent on the unit type and coil spacing. These properties are dependant on both soil lithology and the salt content of any contained water. In general it can be assumed that the clays will be more conductive due to their chemical structure. These properties are in contrast to the sands, which generally have a lower conductivity.

When both parameters (lithology and groundwater salinity) are varying, the interpretation of EM traces can be difficult. However, in the case of channel seepage, higher permeability soils and low salinity water in areas of high channel seepage will enhance each other to produce a low conductivity and high resistivity response. Therefore, the EM-34 unit can potentially be used to map areas of high permeability soils and low salinity water emanating from the channel. EM units which measure properties higher up in the soil profile (eg EM31 and EM38) may in fact be used in the opposite sense to trace seepage – that is by identifying regions of higher salinity, the effects of elevated watertables (and indirectly channel seepage) may be identified.

A picture of an EM34 in use is presented in **Figure 8.1**. An example of EM use for channel seepage assessment is presented in the case study below.

Figure 8.1: EM34 In Use



Case Study – Use of EM On The Donald Main Channel, Australia (SKM,1998 and1999)

An EM34 survey was conducted along the Donald Main Channel, one of the major channels in the Wimmera Mallee Water supply system (Victoria, Australia). The survey was conducted in 1998 along two channel sections totalling approximately 7km. EM34 readings recorded over the investigation areas were averaged and compared with six pondage test results along the corresponding sections. The EM34 results showed good correlation with the pondage test results, with the best results (correlation coefficient of 0.9) provided by an average of the EM34 values recorded at the toe of the bank and readings offset 75m from the bank. In this case, zones of high resistivity (low conductivity) correlated well with channel lengths known to have high seepage rates (as measured from pondage tests). The study concluded that this was due to high permeability, shallow aquifers containing low salinity, channel dominated water.

In 1999 additional EM34 surveys were conducted along the channel in order to more fully appraise the ability of EM surveys to provide a comparatively in-expensive means of determining relative and absolute channel seepage rates. The best correlation between EM response and channel seepage was obtained using an EM34 along the channel toe (10m coil separation), during channel full conditions. The improved relationship when the channel is full was attributed to the increased presence of fresh water seeping from the channel. Traverses conducted along a line 35m down gradient of the bank provide a similarly high correlation. It was concluded that traverses conducted beyond 50m from the channel toe are unlikely to produce a reasonable correlation with seepage rates. Small improvements in correlation between seepage rates and resistivity were observed with at a 10m coil separation, compared to a 20m coil separation.

Surface land salinisation caused by channel seepage was demonstrated to have an opposite EM response to the channel seepage itself (i.e., low resistivity = high seepage). Changing the coil separation allows the targeting of both processes. EM38 with a very short coil separation is best used for investigating the land salinisation resulting from channel seepage. The study concluded that the optimum coil separation and EM equipment (i.e., EM31, EM34 or EM38) for investigating the process of channel seepage is likely to depend on site conditions, such as depth to watertable. At the Donald Main Channel site, EM34 with a coil separation of 10m provided the best correlation with channel seepage, while EM31 appeared to be measuring a combination of both channel seepage and soil salinity.

Natural electrical sources

Resistivity data can be used only as an indication of porosity and moisture content and any flow paths must be inferred from a surface trace along with other constraints. However Self-Potential (SP) systems can be used to provide a direct indication of fluid mobility. Small direct current signals are associated with the motion of any charged electrolytes percolating in porous media. These self potential signals can be corrupted by other geochemical activity and bio-mass can cause local perturbations to fluid flow. However because of their simplicity SP surveys have been the most wide-spread technique for seepage investigations. Data can be obtained using:

- SP gradient methods involving a 'leap-frog' procedure; or,
- Absolute SP methods with a stationary base electrode.

Both methods are characterised by relatively complex field programs and resultant low survey productivity rates. The case study below describes the use of the gradient Self Potential technique to detect water leakage from a canal. Note however that the investigation was examining seepage from a concrete retaining wall, not an earthen channel.

Seepage Detection Along the Chicago Sanitary and Ship Canal Near Lockport, Illinios (Sjostrom and Hotchkiss, 1996)

Water leakage between the Chicago Sanitary and Ship Canal and an adjacent stream, was detected and monitored along a concrete retaining wall, at Lockport, Illinios. Waterborne total field and gradient Self Potential (SP) methods, dye tracing, and visual inspection were used to determine seepage paths between the canal and creek and detect and locate possible points of seepage inflow along the canal wall.

The SP method measures naturally occurring voltages in the subsurface generated by either fluid flow or electrochemical processes in the subsurface. Electrical voltages generated by the flow of fluids through the soil or rock is called electrokinesis. The magnitude of the SP signatures depend on the electrical and physical properties of the fluid, the coupling coefficient between the fluid and soil/rock matrix, and the pressure gradient along the flow path. Lower total field SP measurements, with respect to background voltage values, reflect areas of subsurface fluid movement through the canal wall. Self-potentials generated by electrochemical processes in the subsurface, may also contribute to the natural surface potentials. This process is more pronounced along the canal wall where voltages generated by the oxidation of the reinforcing bars in the concrete are likely.

Two techniques, the total field and gradient methods, are commonly used to collect SP data. Measuring the total field SP anomalies requires a fixed reference electrode and a single roving electrode, whereas the gradient method maintains a fixed distance between two measuring electrodes, each positioned at some depth below the water surface. The waterborne SP method indicated at least five possible seepage inflow areas along a 900 ft section of the canal retaining wall. These areas were detected with both the total field and gradient methods performed at varying depths below the water surface. Movement of water from the canal to the ponded area and seepage outflow area was confirmed by the results of the dye tracing tests and visual inspection of the area. The water discharging at the outflow area was found to be not due to one leak in the canal wall but rather the cumulative effect of several small seeps; each likely occurring at the concrete monolith joints in the canal wall.

<u>Rapid Transit Methods</u>

New techniques are required for the broad scale mapping of channel leakage paths. Some of the existing techniques can be modified to provide higher rates of productivity and processing standards can be developed to reduce any operator error. However there are now several additional possibilities involving geophysical methods developed for the geotechnical and mineral exploration industries. These include:

- Airborne EM;
- Ground-penetrating radar (GPR);
- Seismic Spectra Mapping;
- Sonar reflection profiles; and,
- Capacitive dipole arrays.

Airborne EM

Very high productivities can be achieved with Frequency-domain Electromagnetics (FEM) systems and there are now several configured for airborne operations. Again the primary aim has been to obtain resistivity data which may indicate groundwater flow paths or salinity problems (eg, Salt Mapper). More sophisticated Transient Electromagnetic (TEM) systems are also available for airborne mapping but current costs may be considered excessive and there may be no significant gain in data quality.

Ground-Penetrating Radar

GPR systems are now relatively common in the geotechnical industry. Several frequencies are used generally in the range 50-200 Mhz giving some control on penetration and resolution. Signal amplitudes are highly sensitive to water content and data can be obtained in rapid scans. However the results are highly site dependent and in some circumstances, such as heavy clays or high soil salinity, penetration is minimal.

Seismic and Sonar Systems

Seismic and sonar systems are to some extent related technologies operating at different frequencies and with different source / receiver configurations. Data can be obtained and processed to provide a conventional profile or the acoustic impedance can be determined using Fast Fourier Transform (FFT) techniques. Both systems can be configured in tow-along format for rapid-transit and the response can be related to physical condition of the channel floor including fluid distribution.

Capacitive Dipole Arrays

The capacitive dipole technique is a relatively new development providing an option to conventional galvanic surveys. Previously dipole-dipole surveys have required physical contact with the ground surface using electrodes manually inserted at the surface. Consequently survey productivity has been very low and labour intensive. The new capacitive systems will enable a tow-along mode for routine operations either within the channel or on the banks for comprehensive mapping. The same system should also provide capacity for SP mapping with subsidiary contacts.

The final case study below presents the results of an integrated remote sensing and geophysical channel seepage investigation, which included electrical geophysical methods such as electrical resistivity, electromagnetics, and GPR.

Case Study – Example of Integrated Remote Sensing And Geophysical Techniques For Locating Canal Seepage In Nebraska (Engelbert et al., 1997)

Combined with colour infrared imagery, electrical geophysical methods such as electrical resistivity, electromagnetics, and ground penetrating radar were used to delineate several potential seepage areas along the Central Nebraska Public Power and Irrigation District channel system. The study developed a procedure for systematically identifying and refining estimates of areas of high potential channel seepage. The method is summarised in the following steps:

1. Identify potential areas of seepage using operational records;
2. Conduct inflow-outflow seepage measurements of suspected reaches;
3. Analyse aerial photography (preferably colour infrared);
4. Determine geoelectric sections for suspected reaches using vertical electrical soundings; and
5. Perform electrical profiling to define suspected high potential seepage reaches.

The reaches suspected of being likely reaches for potential high seepage, based on colour infrared, were selected for investigation with electrical geophysical measurements. Vertical electrical soundings were measured along the reaches and interpreted using the available test hole data to define geological and geoelectrical models for the subsurface along the reaches. These soundings were also interpreted to determine optimal spacings for profiling along the reaches and to allow true resistivities to be estimated from profiling measurements. Profiling measurements were performed to define the variation of resistivities along each reach.

Areas of high potential seepage were identified and the extent and relative seepage potential were estimated. Although the study did not verify these estimates, the point was made that there is a relatively good agreement among the various geophysical techniques used in the investigation. The study also highlighted the benefits of making measurements when the channel is full and when the channel is empty, and suggested that this was an aspect worthy of further investigation. The study identified electrical resistivity soundings and horizontal profiling as an effective and efficient means of identifying potential seepage for reaches less than eight hundred metres in length.

Advantages

- Some geophysical techniques are potentially one of the fastest means of seepage assessment;
- Can provide a continuous assessment along the channel;
- Costs should continue to come down as new ways of conducting surveys are developed; and,
- With adequate local calibration can provide a reasonable estimate for seepage quantification.

Disadvantages

- Interpretation can be difficult and will vary from area to area;
- Interpretation may require subsurface investigation (boreholes etc);
- Can be relatively expensive;
- Technical expertise may be required to carry out and analyse survey results; and,
- Literature indicates that geophysical techniques are not currently widely applied to channel seepage problems.

Summary Assessment

The use of geophysics for channel seepage investigations is still a developing technology. The attraction of geophysical techniques is the potential for rapid

The attraction of geophysical techniques is in their potential for rapid assessment, however care needs to be taken in interpretation of results and local calibration of results is desirable

assessment of long channel sections. However care needs to be taken in the interpretation of results. There are several examples in the literature of geophysical techniques being used for detection of high seepage zones but references to geophysics being used for quantification are very scarce. However, provided the results are locally calibrated, seepage quantification from geophysical techniques appears possible.

Key References

- Ogilvy et al (1969).
- Palacky et al (1981).
- Smith and Turner, 1982.
- Sinclair Knight Merz, 1998.
- Sinclair Knight Merz, 1999.

9. Remote Sensing

Remote sensing has considerable potential for rapid identification (but not quantification) of channel seepage

To an even greater extent than geophysical methods, remote sensing techniques offer a fast way to detect and locate seepage without interfering in 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 (i.e., no direct contact with ground).

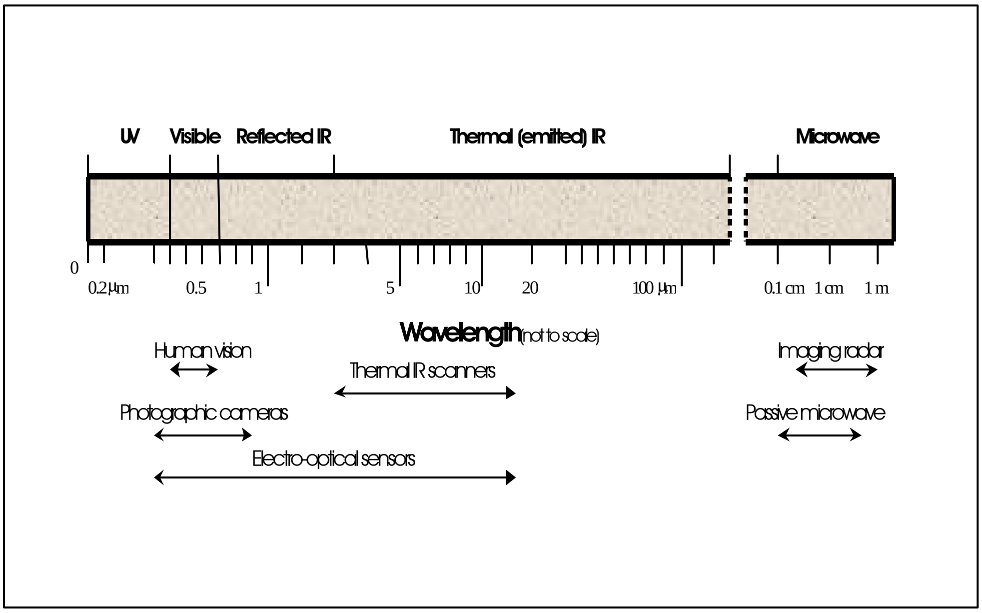
Principle

All remote sensing techniques for channel seepage detection assume that channel seepage has a surface expression adjacent to the channel, and are based around the difference between the properties of moist and dry soils, and differences in vegetation density and health. (Surface expression refers to seepage that migrates laterally and re-surfaces at or near the channel toe, as opposed to seepage that moves vertically to the groundwater and does not re-surface). A key aspect of remotely sensed data is that it must be at a suitable resolution to allow definition of seepage zones. For example, if the ground resolution at which the data is collected is several times the width of the channel, then distinguishing between the signature of the channel and moist soils adjacent the channel will be impossible.

Remote sensing techniques assume seepage has a surface expression adjacent the channel

Figure 9.1 shows the major regions of the electromagnetic spectrum that are used in remote sensing. The regions potentially useful for channel seepage detection include visible, reflected (near) infrared, thermal infrared and microwave.

Figure 9.1: Major regions of the electromagnetic spectrum pertinent to remote sensing



Adapted from Avery and Berlin , 1992.

Traditionally, the most commonly used region of the electromagnetic spectrum in remote sensing, including channel seepage investigations, has been the visible band or the visible spectrum. Its wavelength span is from 0.4 to 0.7 μm, limits established by the sensitivity of the human eye.

The infrared band has wavelengths between red light of the visible band at 0.7μm and microwaves at 1000 μm, or 0.1cm. In remote sensing, the total IR band is usually divided into two components based on basic property differences – the reflected IR band, and the emitted, or thermal IR band. The reflected IR bands represents reflected solar radiation, which behaves like visible light. Its wavelength span is about 0.7 to about 3μm. The dominant type of radiation in the thermal IR band is heat energy, which is continuously emitted by the atmosphere and all objects on the earths surface. Its wavelength span is from about 3 μm to 1000 μm, or 0.1 cm. Because of atmospheric attenuation, thermal IR region beyond about 14 μm is generally not available for remote sensing studies.

The microwave band falls between the infrared and radio bands and has a wavelength extending from approximately 0.1 cm to 1m. It contains the longest wavelengths used in terrestrial remote sensing.

The application of each of these bands to channel seepage detection is discussed below. For channel seepage investigation purposes, typically remote sensors are carried in an aircraft, although with the continually improving resolution of satellite imagery, these sources should also be considered.

Visible

Visible images are usually obtained by photographs taken by cameras carried on platforms operating above the earth's surface. Vertical aerial photographs (90° ± 3°) present relatively undistorted overhead views of the landscape, and is the desirable camera orientation for accurate mapping and interpretation. Oblique aerial photographs are those taken with the camera's optical axis intentionally tilted away from the vertical by an angular amount usually exceeding 20° (Avery and Berlin, 1992). Aerial photographs in the visible spectrum may be used to identify obvious seepage sites (eg, water lying on ground, or green / lush vegetation in summer) but are limited in their potential to detect moist soil compared to infrared images.

Reflected (near) Infrared (NIR)

Many remote sensing techniques for channel seepage detection are based on the fact that water is a strong absorber of near (or reflected) infrared radiation. Therefore moist soils, because of the presence of pore water, absorb NIR radiation and appear in dark tones, whereas dry soil is more reflective and appears in lighter tones. NIR is also a critical band for detecting plant health and density. Maximum reflectance from vegetation occurs in the NIR wavelengths.

Additionally, infrared photographs have excellent haze penetration, because the filters recommended for use with this film remove atmospheric scattering effects that occur in the UV, blue and green spectral regions. The film provides excellent results for high altitude photographs, including high obliques where distant details are rendered clearly.

Thermal Infrared (TIR)

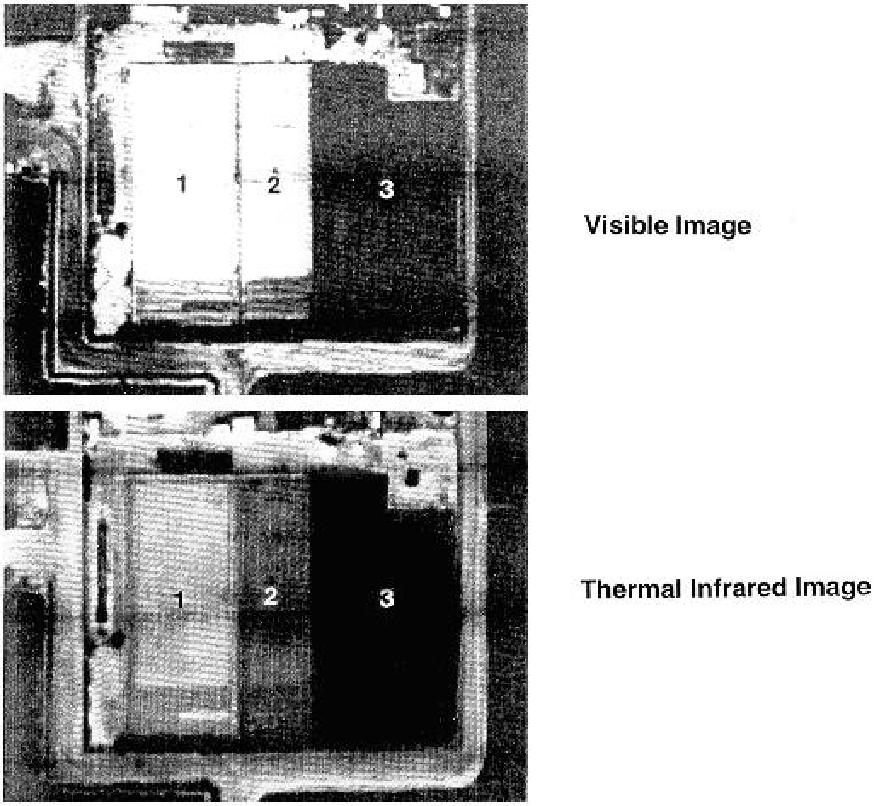
Reflected short-wave radiation concerns the shorter wavelength end of the electromagnetic spectrum including UV, visible and NIR. Thermal infrared refers to emitted long-wave radiation. TIR radiation (heat energy) results from random atomic and molecular motion and is emitted by all substances having a temperature above absolute zero (0°K, -273°C). As the temperature of an object increases, a greater amount of energy is radiated and the spectra of the radiation shifts to shorter wavelengths.

TIR images depict radiant temperature contrasts of a given ground area as tonal variations. Lighter tones represent warm features, and darker tones represent cooler features. Interpretation of TIR in terms of channel seepage detection relies on the difference between the TIR characteristics of water versus soil and rock. Water bodies are generally cooler (darker tones) than soil and rock during the day, but surface temperatures are reversed at night with water being the warmest (lighter tones). This is primarily because convection does not operate to transfer heat energy in soil and rock. It is therefore important that the time of data collection is known.

Figure 9.2 graphically illustrates the advantage of thermal infrared (8 - 14 μm) over visible (0.65 - 0.69 μm) images for depicting moist soils. The figure shows three fields at different stages of drying. The three sections are as follows: 1) dry surface, 2) moist surface and 3) wet surface. Note that sections 1 and 2 both appear light in the visible images, whereas section 3 is dark. However in the TIR image, there is a definite tonal difference between all three sections, with 1 being the lightest, 2 being intermediate and 3 being the darkest.

Critical to the sensing and interpretation of channel seepage sites is the assumption that seepage adjacent or nearly adjacent to the channel system is represented by higher soil moisture (or by significantly more dense or more healthy vegetation) than non-leakage sites . All else being equal, damp ground is cooler (darker tones) than dry ground during both the day and night because of evaporative cooling of contained moisture. Oscillations of temperature in a moist soil are less than in a dry soil area, since sites high in moisture cool slower after sunset and warm more slowly during the day. The net result is that moist sites (channel seepage areas) emit more radiation during the evening hours and less during peak solar radiation hours than the low moisture, or non-leaking sites.

Figure 9.2: Comparison of Visible and Thermal Infrared Images



After Avery and Berlin, 1992.

Microwave
A remote sensing device operating in the microwave band of the electromagnetic spectrum (wavelength 0.1cm – 1m) could also be theoretically used for channel seepage detection. The complex dielectric constant of a material is dependent on the electrical properties of a material and is a measure of a materials ability to conduct or reflect microwave energy. The dielectric constant of most naturally occurring materials, when dry, ranges from about 3 to 8 at radar wavelengths. However, when moist the dielectric constant of a material may approach 80. The dielectric of a terrain material increases in an approximate linear relationship to increasing moisture content. However, no examples were found in the literature of microwave use for channel seepage detection.

Multispectral scanners (MSS) are capable of operating in the near UV, visible, NIR, and TIR regions of the electromagnetic spectrum. This means that both reflected and emitted radiation can be collected by a MSS. The number of spectral channels can range from fewer than 5 to more than 10. TIR scanners function in essentially the same manner as MSS but their operation is confined to the TIR atmospheric windows at 3 to 5 μm and 8 to 14μm. TIR scanners are commercially available that operate within one or both of these atmospheric windows, or within multiple bands of the 8- to 14μm window.

Methodology

All remote sensing techniques for channel seepage detection are based around the difference between the properties of moist and dry soils, and between differences in vegetation health or density. This introduces two potential problems with remote sensing techniques for channel seepage detection:

- Sites which have moist soils or relatively lush vegetation (or emit similar properties to moist soils and lush vegetation) not resultant from channel seepage are likely to be identified as seepage sites (eg, drainage lines, topographic low points etc); and,
- Seepage will only be detected if the affected area has a surface expression.

The following case study addresses the first of these potential problems:

Application of Thermal Infrared Imagery to Canal Leakage Detection (Nellis, 1982)

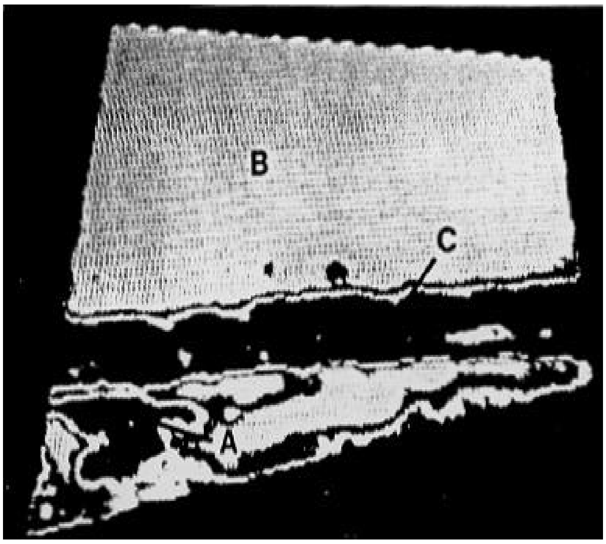
The North Unit Irrigation District of central Oregon conducted an infrared survey in an attempt to determine channel leakage sites using a HRB Singer AN/AAS 14 optical-electronic thermal infrared scanning system, sensing in the 8-14 micron range. The apparatus was flown in an aircraft on May 21, 1979, at 9pm and 900 m altitude over the main North Unit Canal in central Oregon. The sensor had an instantaneous field of view of four mrad, producing a ground resolution of approximately one metre for every 300 m of altitude above the terrain. Therefore the ground resolution was approximately 3m.

It was assumed that seepage sites would contain soils adjacent to the channel system with higher soil moisture content than non-leakage sites. The survey was conducted at 9pm as the moist soils emit more radiation during the evening hours compared to the dry soil (or non seepage sites). Out of 39 sites showing the characteristics of leakage sites, 12 were verified as actual leakage sites by field analyses; approximately a 30% interpretation accuracy. However, inspection of the channel uncovered no leakage sites not appearing on the imagery. Where channel leakage sites were verified by ground observation, characteristics of the leakage site were noted. Verified channel leakage width ranged from 0.6 - 7.3 m (average of 1.7m), and leakage lengths ranged from 12 - 91 m.

Figure 9.3 illustrates one of the seepage sites identified during the study. The canal in this image (C) is 6.7m wide and 1.2m deep. The darker area of high moisture (A) was identified as a seepage site and confirmed to be so through ground truthing. Area B is a low moisture area.

The sites misinterpreted as leakage sites included dense natural vegetation, farm channels, drainage ditches, small holding ponds, or natural depressed drainage areas. This interference could be reduced by taking simultaneous colour photographs. If organised at an appropriate level, eg, irrigation district level, thermal infrared overflights could be cost effective.

Figure 9.3: Enhanced Thermal Infrared Image of Channel Seepage Site in North Unit Irrigation District, Oregon, USA.



A – Area of high moisture identified as seepage site
B – Low moisture area
C – Canal

After Nellis, 1982.

In the above case study, although the interpretation accuracy was low, (of 39 sites identified as potential seepage sites only 12 were confirmed to be so by visual inspection), the irrigation authority considered that the survey was more than worthwhile, as a significant amount of time was saved by checking the limited number of sites, rather than the whole system. Inevitably, interpretation of remote sensing data will not be perfect, however its attraction is in its ability to rapidly asses large areas of channel system.

The second concern raised with remote sensing channel seepage detection, is that seepage will only be detected if is has a surface expression. Generally water will impact soil adjacent the channel if:

a) The watertable adjacent the channel is relatively shallow;
b) Significant leakage through the banks is occurring; or,
c) The part of the channel that is seeping is located above the outside toe of the channel bank (eg, as will occur on a significant cross slope).

The fact that seepage which migrates vertically and does not affect near channel soils will go undetected by remote sensing methods, is a fundamental problem inherent in the technique. Therefore, this technique must not be viewed as a means of defining all seepage zones within a section of channel. Often however, vertical seepage may also be accompanied by some lateral seepage, which may be detected.

Advantages

- Rapid assessment of large areas of channel system;
- Does not interfere with channel operations;
- Costs likely to come down and resolution likely to improve as the technology develops.

Disadvantages

- Relatively expensive;
- Requires specialist technical input at the data gathering, processing and interpretation stages;
- Sites which have moist soils (or emit similar properties to moist soils) not resultant from channel seepage are likely to be identified as seepage sites (eg, drainage lines, topographic low points, irrigated areas etc); and,
- Seepage will only be detected if is has a surface expression.

Summary Assessment

To be cost effective remote sensing assessment of channel seepage needs to conducted at a large scale

Remote sensing techniques offer considerable potential as a tool for rapidly identifying seepage zones. The major drawback associated with this technique is that it assumes seepage will have a surface expression as moist soil adjacent the channel. Despite this disadvantage, remote sensing offers a promising means of providing a first-cut identification tool for targeting potential seepage sites. Assessment needs to be conducted at a suitably large scale if the technique is to be cost effective.

Key References

- Nellis, 1982.
- Engelbert et al., 1997.

10. Hydrochemical and Isotopic Methods

Principle

There are two possible ways that hydrochemistry / isotopes may be used to estimate either, the rate of seepage from a water body (quantitative assessment), or to indicate where in that water body seepage may be higher than average (qualitative assessment). The applicability of these methods to seepage from irrigation channels is discussed below.

Hydrochemical / Isotopic Mass Balance
The first method, a hydrochemical / isotopic mass balance approach, relies on measuring the concentration of a conservative chemical or isotope (tracer) in the water in the irrigation channel and in the other inflow and outflow components. The method combines the use of a water balance and chemical / isotopic mass balance (ie. two equations) allowing estimation of two unknown components (seepage plus either inflow, outflow, evaporation or rainfall). Essentially, therefore, the method involves estimation of the mean residence time of water in the channel. Evaporation is the main process that causes the concentration of a conservative tracer to change and usually results in an increased concentration in the residual water. Hence, this method is applicable to irrigation channels if evaporation and seepage are major components of the water balance for the reach of the irrigation channel being considered (ie. the mean residence time of water in the channel is relatively long).

Tracing the Seepage Plume
The second method, tracing the seepage plume, uses the hydrochemical / isotopic concentration of seepage water to define a volume of water that has escaped from the channel. Hence, for this method, it is important that the hydrochemical / isotopic concentration in the water leaking from the channel (ie. the tracer) is different from that in the surrounding soil / groundwater matrix. It is also important to identify the time period over which seepage (defining the plume) has taken place. Depending on what tracer is used and whether it is at natural abundance or artificially enriched levels, the time period may extend from days to many tens of years.

For conservative chemical tracers (eg, chloride [Cl]), evaporation results in an increase in the concentration of the tracer. For isotopic tracers (eg, the stable isotopes of water, deuterium ^{2}H, and oxygen-18, ^{18}O), the evaporative process usually results in enrichment (an increase in concentration) but, because of exchange with atmospheric water vapour a decrease or no change is also possible.

Methodology

10.1 Hydrochemical / Isotopic Mass Balance Approach

This type of approach to seepage estimation has been used in numerous studies to estimate seepage from lakes and dams but not from irrigation channels. This is primarily because the mean residence time of water in an irrigation channel is usually considerably short (high rates of flow). Leaney and Christen (2000) used a simple spreadsheet model to estimate seepage from disposal basins in which several of the bays were in series, the last bay being terminal. They used a chloride mass balance approach and estimated seepage at 1.0 ± 0.2 mm/d for a disposal basin near Girgarre in the Riverine Plain. The long mean residence time of water in the basin and the ability to monitor the basin for several years resulted in this method being particularly useful in providing an accurate estimate of seepage from the Girgarre basin.

Many studies indicate that seepage rates from irrigation channels (within the Murray Darling Basin) are likely to exceed 10 mm/d which are higher than that seen for disposal basins (<6 mm/d, Christen et al., 2000). Irrigation channels also have a considerable throughflow component (ie. inflow and outflow are high compared to seepage and evaporation).

Traditional hydrochemical / isotopic mass balance approach is unlikely to have significant application to channel seepage measurement due to relatively short residence time of channel water.

An investigation was conducted to determine whether chloride and deuterium mass balance approaches would be useful to estimate seepage in irrigation channels during the routine operation of the channel by using the spreadsheet model developed by Leaney and Christen, 2000 (modified slightly for deuterium use). Unfortunately, the amount of throughflow likely to be seen in most irrigation channels meant that this was a very insensitive way of measuring seepage and hence, this method is not recommended for seepage estimation during periods of routine operation.

There is some potential for hydrochemical / isotopic approaches under pondage test conditions

While this method is unlikely to be useful to estimate during routine operation of the channel, it is possible that, under some circumstances, a chloride (or more likely, ^{2}H or ^{18}O mass balance) may be useful during periods when outflow from the channel is stopped (i.e. during pondage tests). In general, the use of isotopes has the advantage over [Cl] in that they are more sensitive to evaporation, at least during the early stages of evaporation. Because of this, there have been several studies using either a ^{2}H and / or ^{18}O mass balance approach to estimate seepage from lakes or dams (IAEA, 1979). One disadvantage that isotopes have compared to [Cl] is that it is necessary to estimate the isotopic composition of water evaporating from the water body (usually called δE). Measurement of this parameter requires a small scale pan experiment to be run at the same time as the study on the water body (Allison and Leaney, 1982).

In order to evaluate whether or not a ^{2}H and / or ^{18}O mass balance approach under pondage conditions is likely to be useful in seepage estimation, the spreadsheet developed by Leaney and Christen (2000) for single basins was modified to include isotope calculations. **Figure 10.1** presents preliminary results from the modelling exercise. These results suggest that this method is likely to be useful providing the pondage test continues for at least a couple of weeks. The applicability of the method will depend on the climatic conditions at the time of the study, the depth of the irrigation channel and the length of time the water remains ponded. Error of analysis for deuterium is approximately 11‰ (ie. 11 parts per ml) which results in an error of 10-20 % for the seepage estimate. This error is reasonable if seepage rates are low (< 20 mm/d) but for rates of seepage above 50 mm/d there is little gained by using this method compared to a simple water balance approach. For comparison, the results using a [Cl] mass balance are presented in **Figure 10.2**. Given the error of analysis for [Cl], [1 SD (standard deviation) ≈ 5 mg/L] it is unlikely that a [Cl] mass balance approach will be useful to estimate seepage from irrigation channels.

Figure 10.1: Deuterium vs Time For a 1m Deep Channel (mid summer)

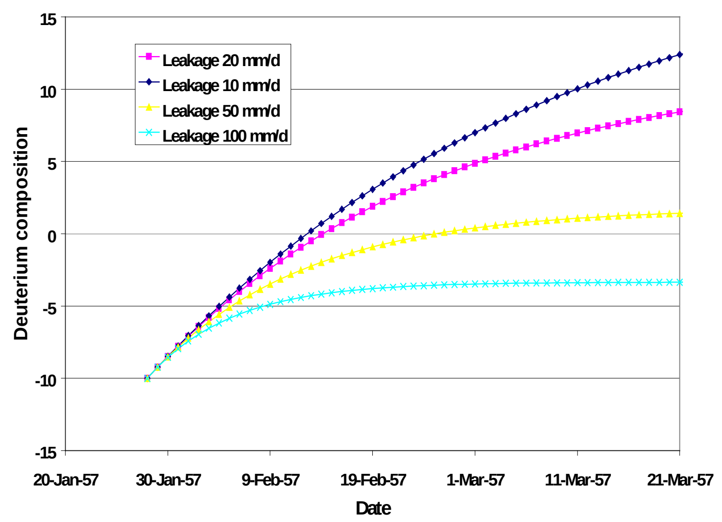
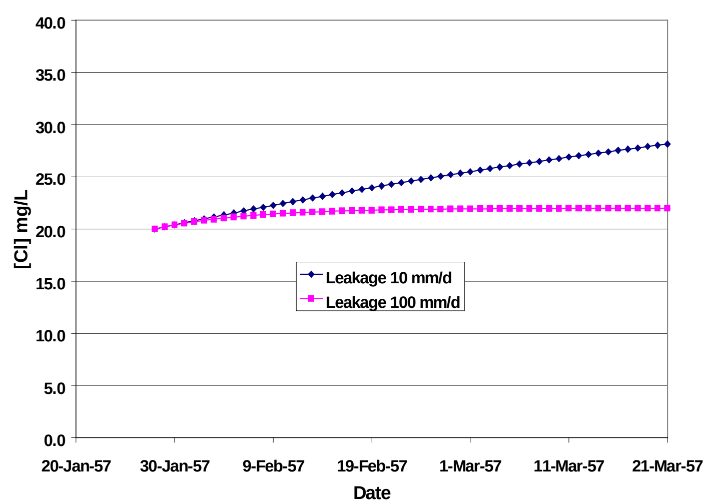


Figure 10.2: Chloride vs Time For a 1m Deep Channel (mid summer)



As referred to previously, the advantage of combining water balance calculations and isotope mass balance calculations is that the seepage rate plus another component can be calculated (as there are two equations and hence two possible variables). Hence, if a component of the water balance is not well known (eg, evaporation or inflow), this can be considered to be a variable during the method. This method could be useful for determining seepage rates where a high degree of accuracy is required.

10.2 Tracing the Seepage Plume

In order to use tracers to estimate the rate of movement of water from a water body, the tracer must:

1. Have a significantly different concentration from the surrounding water in order for it to be readily identified as originating from the water body;
2. Be conservative and preferably not retarded during flow through the matrix. If retarded, the rate of retardation needs to be able to be estimated accurately;
3. Be safe to use, safe to measure and have no residual concentration that may be harmful to water, plant, soil or animals in the environment; and,
4. There must be a method for determining the time frame for the movement of water from the water body.

With the above conditions of use in mind, tracers are usually divided into two categories.

The first category consists of naturally occurring isotopic or hydrochemical tracers that have a concentration that is discernible from the surrounding soil / water matrix and a known temporal history for the input concentration. Tracers of this type include, amongst others, ^{2}H, ^{18}O, [Cl], tritium (^{3}H), chlorofluorocarbons (CFC's), ^{14}C and ^{222}Rn.

The second category includes most, if not all, of the tracers listed above but uses artificially enriched concentrations in the parent water body. It also includes tracers such as [Br], rare earth elements (europium and lanthanum) and several other artificially produced radioactive solutions.

There are advantages and disadvantages with each of the above categories. Naturally occurring tracers do not require seeding of the water body (increasing the concentration of the tracer in the water). Also, because the tracer has usually been present in the water body for some considerable time, the time frame over which movement is measured is considerably longer than that for the situation when the tracer is added to the water. A disadvantage however, is that it is unlikely that the temporal variation in the concentration of naturally occurring tracers in the parent water would be as well defined as that when enriched tracers are used for a specific study.

Using naturally occurring isotopic or hydrochemical tracers

Non-radioactive tracers with constant input concentration (^{2}H,^{18}O, TDS & [Cl])

The tracers Deuterium (^{2}H or D) and Oxygen 18 (^{18}O), and [Cl] are considered ideal tracers of water movement because they are conservative and move at the same rate as water. In fact, in the case of the stable isotopes, ^{2}H and ^{18}O, they are isotopes of hydrogen and oxygen, the two atoms that constitute a water molecule. Measurements of Total Dissolved Solids (TDS) are considered to be less conservative because of the reactions between the soil and water for many ions other than chloride. In the case of seepage from an irrigation channel, the input concentration is that of the water in the channel.

Groundwater Salinity as Indicator of Seepage

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. 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.

Investigation of groundwater salinity at the Donald Main Channel, Victoria, (SKM, 1998) 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 the isotope sampling. The large increase in groundwater salinity observed at the end of each bore line was attributed to the proximity of the bores to a major discharge area. The study concluded that as there are many factors affecting groundwater salinity, it is not possible from the groundwater salinity results alone to determine the extent of channel water migration. This study highlight the aforementioned point, that measurements of EC are less conservative (than Cl) because of the reactions between the soil and water for many ions other than chloride.

Deuterium and Oxygen 18

In the case where ^{2}H and ^{18}O composition of the water is used as a tracer, it is often not obvious whether the isotopic composition of the water in the channel will be depleted (less than), enriched (more than) or not significantly different from that in the groundwater. As previously mentioned, the main way in which the isotopes of water, ^{2}H and ^{18}O, change concentration is from enrichment during evaporation. Hence, if the irrigation channel is close to the off-take point at the river / reservoir, it will usually have a depleted signature compared to water samples further along the channel. In a similar way, the isotopic composition of water samples in the river / reservoir will vary depending on their proximity to the catchment. Simpson and Herczeg (1991) found that the ^{2}H and ^{18}O composition of water in the River Murray was enriched by ~40 and 8 ‰ respectively as it traversed the 2300 km from the townships of Jingelic to Milang (March'89 data). They also measured seasonal changes of up to 25 ‰ (ie. 25 parts / ml) in the ^{2}H composition of the river water at any single site. If the mean isotopic signature of the water in the reach of the irrigation channel being studied is significantly different than that in the groundwater, the seepage plume can be identified in a similar way to that reported using [Cl].

Although water isotopes and [Cl] have been used as tracers in numerous studies on lakes, reservoirs and disposal basins (IAEA, 1979), their use as a tracer from irrigation channels is limited. Studies using EC, ^{2}H and ^{18}O to estimate seepage for two sections of the Donald Main Channel (SKM, 1999) found evidence of a component of seepage reaching at least 200 m from the channel. Groundwater samples from the observation bores were found to have an enriched isotopic signature and were fresher than regional groundwater (SKM, 1999). Samples were only available for shallow groundwater up to 200 m from the channel and hence it was not possible to define the freshwater plume using samples from these bores alone. It was further identified that the process was obviously not via piston flow as both the EC and ^{2}H composition changed gradually with distance from the channel and not in a step-wise manner.

Use of naturally occurring tracers may be valuable if information is obtained on the seepage plume over a sufficiently long time period and an area large enough to account for spatial and temporal changes in seepage

The Donald Main Channel study highlights two potential problems when using these tracers to estimate the movement of seepage from irrigation channels. The first arises because irrigation channels have often been in use for several decades and seepage from the channel may have travelled several hundred metres from the channel. Defining the plume under these conditions requires a large network of bores allowing groundwater to be sampled from several depths beneath the water table. The second arises because of the mixing that occurs between the water leaking from the channel and that already in the groundwater. Hence, it is necessary to identify not the plume per se but to integrate the fraction of water from the channel that reaches the sampling points. This should be done to a distance at which the concentration of the tracers is considered to be that of the "baseline" groundwater. This task could be further complicated in irrigation areas, where the seepage plume is likely to be mixed with recharged water from adjacent irrigation areas. As the irrigation water is sourced from the channels, it is likely to contain isotopes of a very similar age to the channel water, and hence will be difficult to distinguish.

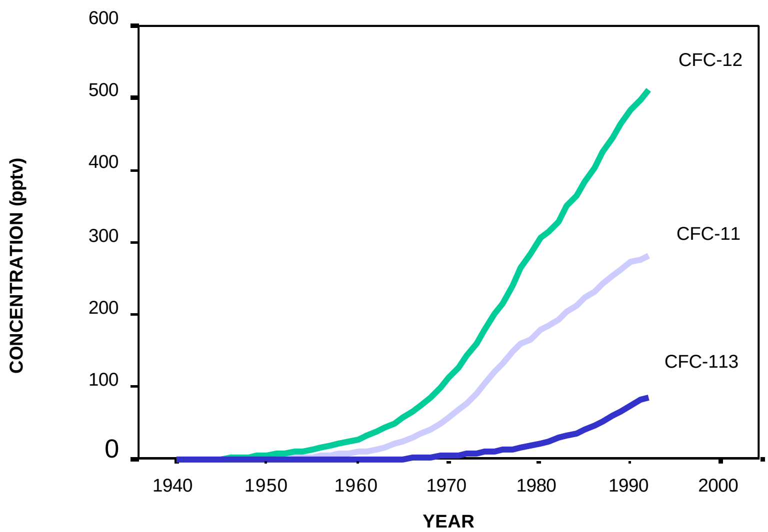
Naturally occurring radioactive tracers or tracers with varying input concentration

One of the most common radioactive tracers used in hydrological studies when investigating processes occurring over the last 40 years has been tritium, ^{3}H. Above ground nuclear testing in the 1950's and 1960's resulted in a large increase in the tritium concentration in the atmosphere. The concentration peaked in 1963 reaching values well in excess of 3000 tritium units (TUs) in the northern hemisphere. The peak concentrations in the southern hemisphere were lower by over an order of magnitude. One main application of tritium involves identifying groundwater that has an enriched signature and assigning an age to it. If several samples are taken, the sample with the highest tritium concentration is usually assigned as 1963 water.

In the case of seepage from an irrigation channel, the principle is simple but unlikely to be useful for channels in the southern hemisphere. This is because the enriched signature, following radioactive decay (half-life for tritium decay is 12.3 years) and mixing with pre-existing groundwater, is likely to have diminished to a level where detection will be difficult.

In the southern hemisphere, the use of chlorofluorocarbons (CFC) analysis as a dating tool is seen as being a possible replacement for tritium. Chloro-fluorocarbons are man-made organic compounds, the concentrations of which in the atmosphere are well documented and have been steadily increasing since the 1950's, as depicted in **Figure 10.3**. Groundwater ages are determined by comparing measured concentrations in groundwater (from piezometer samples) with the known atmospheric history (Busenberg and Plummer, 1992). Chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCL_2F_2) are the most abundant and the most easily measured, and so they have been most widely used.

Figure 10.3: CFC concentrations in the atmosphere



CFC dating of groundwater has the most potential as this detects relatively recent seepage and therefore a less extensive bore network is required

The advantage that CFC dating has over the use of tritium is that CFCs do not decay and hence, are more likely to be found at measurable levels in groundwater. The main disadvantage with CFCs is that the sampling procedure requires some expertise and training. Currently, a new method of sampling is being tested that may make sampling significantly easier. An advantage that CFCs have over stable isotopes or [Cl] is that bores can be sited much closer to the irrigation channel because they do not have to define the seepage plume for a period of several decades.

Tracers with artificially increased input concentration

The major advantage with using tracers at enriched levels to determine seepage from disposal basins is that the concentration of the water in the channel can be increased so that it is easily differentiable from that present in the groundwater prior to the study. The major difference with using these tracers is that field studies are usually over periods of days or, at most, months and hence, seepage from the channel is likely to have moved a maximum of a few metres. At these intervals, sampling is best done over short depth intervals, often by soil sampling soon after the channel is emptied.

The main disadvantage with artificially increased tracers is high cost of doping the water

As mentioned previously, for these types of study, the tracer needs to be environmentally safe at the enriched levels. The overall cost of the study will depend on the cost of doping the channel water, the cost of sampling and the cost of analysis. Often the cost of doping a large volume of water may make this type of investigation prohibitive. The cost for doping a flowing channel would be considerably more expensive than for a ponded channel.

Therefore, a way of overcoming the large outlay in chemical/isotopic costs is to limit the application of the enriched tracer to a small area of the channel. This has the added advantage in ensuring minimal environmental problems compared with doping large quantities of channel water. A method for doing this is to use a seepage meter similar to that suggested by McBride and Pfannkuch (1975) in which doped water is placed into a bladder attached to a tube inserted at the base or side of the channel. The bladder is pegged to the base of the channel and hence is kept at the same hydraulic pressure as the water in the channel. In their experiment, they measured seepage into a lake but the set-up should be equally applicable for seepage from a channel. The rate at which the bladder empties should be equal to the rate at which water leaks from the channel for the cross-sectional area of the tube. This can be confirmed by sampling the soil at the tube site and determining the localised plume of the tracer. One advantage in having duplicate estimates of seepage is to check whether or not the tube has sealed to the channel and water is not flowing around the rim of the tube. When using doped water in bladders, the cost for chemicals/isotopic tracers in this type of set-up is trivial when compared to the overall costs of the investigation.

The least expensive tracer to use is [Cl] with other possibilities being [Br] or ^2H (in increasing level of cost). Bromide would probably give better definition of the plume and could be used at lower concentrations. For each tracer, it is necessary to measure the concentration of the tracer in the soil. This can be done by 1:5 dilution measurements for the chemical tracers (Taras et al. 1975) or by distillation for ^2H (Revesz and Woods, 1990).

One disadvantage of using tracers in this fashion is that the number of seepage estimates is the same as the number of sites sampled. If the intention is to estimate total seepage from a channel, it will be necessary to take enough samples and make enough point estimates to account for the likely spatial variation in seepage rate. An alternative approach is to try to use some method of tracer that is detectable without direct measurement. This basically means the use of radioactive solutions and radiometry.

Only two references were found in the literature concerning this type of work. One was by Mackobck (1970) using a "homogenous cloud of radioactive solution (having a higher density than the surrounding water) at the bottom of a reservoir". Measurement was via portable radiometry with ground truthing using soil sampling at appropriate places on the reservoir bed. Given that the water body being examined is a reservoir, it is likely that the method itself used short lived isotopes and is safe if properly supervised. However, more information should be sought from nuclear physicists if this method is proposed for use in Australia.

The other study was a method utilising a labelled bitumen emulsions (Molinari, et al., 1970). This method consisted of injecting an emulsion labelled with a radioactive tracer into the water. The labelled emulsion becomes entrained into the leakage areas where emulsion particles separate from the water and accumulate. The distribution of these particles, considered as proportional to the specific infiltration flow for structures with interstitial permeability, is then determined by measuring the radioactivity. The plastic properties of bitumen emulsion (labelled with iodine -131) promote agglomeration of the particles and adhesion to the materials of the wall to be studied. The concentration of the tracer in the channel is determined by a surface scanning device.

The ICID (1967) world-wide survey placed tracers in the list of experimental stage techniques. Kraatz (1977) notes that the tracer method 'some ten years ago was considered promising, but little information is available on the actual applicability in the field'. Since that time the trend of virtually no reporting of channel tracer tests continued, and it does not appear that tracers have been widely used in channel seepage investigations. Hotes et al (1985) states radioactive tracer tests have not proved as reliable as the four principal methods (inflow-outflow, ponding, seepage meters and hydraulic conductivity).

Advantages

Hydrochemical/Isotopic Mass Balance

- The advantage of combining water balance calculations and isotope mass balance calculations is that the seepage rate plus another component can be calculated. Therefore if a component of the water balance is not well known (eg, evaporation of inflow) this can be considered a variable during the method. This could be a useful technique where a high degree of accuracy is required.

Tracing the Seepage plume

- The main advantage of using tracer techniques to investigate seepage is in determining where the seepage water flows from the channel. This may be important in determining the area affected by seepage and the potentially detrimental environmental problems.
- Use of CFCs requires a smaller bore sampling network and calculation of a plume representing relatively recent seepage rates.
- Small scale and short time interval trials using enriched isotopes can be used to investigate spatial variation in seepage rates. This method provides a duplicate estimate of seepage (water balance and mass balance) and enable a check on whether or not the measurement device has properly sealed to the channel.
- The advantage of naturally occurring tracers over artificial tracers is that they do require the seeding of the water body.

Disadvantages

Hydrochemical/Isotopic Mass Balance

- The mean residence time of water in a channel is too short for conventional use of this method (pondage tests may be used instead).
- Even when combining this method with pondage tests, there is little to be gained when compared to a simple water balance approach if seepage rates are higher than 50 mm/day, due to the uncertainty of the results. Even when seepage rates are low, a simple water balance approach using a pondage test alone, may provide results of sufficient accuracy.
- It may be difficult to pond the channel for sufficient time for the pondage method to provide useful results (pondage tests combined with an isotopic mass balance require several weeks to conduct).

Tracing the Seepage plume

- The major disadvantage with this method is the large number of piezometers which are required to define the seepage plume, consisting primarily of nested sites.
- An obstacle to deriving an accurate solution is caused by the mixing that occurs between the water leaking from the channel and that already in the groundwater. Hence, it is necessary to identify not the plume per se but to integrate the fraction of water from the channel that reaches the sampling points. This may not be a simple process and will introduce further error to the results.

- The chemical/isotopic sampling costs may be prohibitive for a number of tracers.
- The costs of chemical / isotope dosing of a channel / pondage may be prohibitive.
- A disadvantage of the use of small scale trials using enriched isotopes is that a large number of tests would need to be undertaken to adequately define the overall seepage rate from a section of channel.
- A high degree of specialist technical input required for setting up, sampling and analysis.

Summary Assessment

Hydrochemical and isotopic methods for estimating seepage from channels using either a hydrochemical/isotopic mass balance approach or a method involving the tracing of the seepage plume, have not been widely applied to channel seepage quantification. However with some adaptations to traditional techniques there may be some potential for these methods. A summary of the two techniques is provided below:

This technique is unlikely to have significant application to channel seepage measurement due to the relatively short residence time of channel water - there is some potential for use of this method under pondage test conditions

Hydrochemical/Isotopic Mass Balance

The traditional hydrochemical / isotopic mass balance approach (as used in dam and basin seepage studies) is unlikely to have significant application to channel seepage measurement due to the relatively short time of residence of water in the channel. There is some potential for use of this method under pondage test conditions, provided the pondage tests continue for a least several weeks. The error in this approach is reasonable if leakage rates are low (<20mm/day) but for higher seepage rates (>50mm/day) there is little gained by using this method when compared to a simple water balance approach. It may be also be difficult to pond the channel for sufficient time for this method to provide useful results.

Tracing the Seepage plume

The method of tracing the seepage plume uses the hydrochemical / isotopic concentration of seepage water to define a volume of water that has escaped from the channel. The rate of seepage can then be determined if the time over which that volume has seeped is known. It is important that the hydrochemical / isotopic concentration in the water leaking from the channel (ie, the tracer) is different from that in the surrounding soil / groundwater matrix. It is also important to identify the time period over which seepage (defining the plume) has taken place.

This technique may be valuable if information is available on the seepage plume over a sufficiently long time period and a sufficiently large area

Naturally occurring tracers - The use of naturally occurring tracers may be valuable if information is obtained on the seepage plume over a time period long enough, and an area large enough, to account for spatial and temporal changes in seepage. However, practically this may be difficult, given the number of groundwater bores which may be required to adequately define the seepage plume. The method with the most potential involves the use of CFC dating of groundwater using nested bores located within 10-20m of the channel. Bores can be sited in close proximity to the channel as they do not have to define the seepage plume for a period of several decades, but only several years.

The best use of enriched isotopes is at a small scale and time interval for the investigation of spatial variation in seepage rates

Enriched Tracers - The major disadvantage with using artificially enriched tracers, is that the cost of doping the channel water will generally be prohibitive. Therefore the best use of enriched isotopes is at a small scale and small time interval, to investigate spatial variation in seepage rates. For example, these types of studies may be used to best determine if there are parts of the channel with higher seepage than other parts (eg, sides vs base of the channel). In initial trial studies, it is probably worth using bromide and enriched levels of deuterium as first choice tracers. Bromide is the cheapest to use but may have some problems with absorption on the soil.

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11. Conclusions

11.1 Overview of Techniques

A comprehensive review of the literature has identified nine different techniques which are considered useful for channel seepage quantification or identification. **Table 11.1a-c** summarises the key aspects of each technique, including the basic theory behind the technique, advantages, disadvantages and a summary assessment of the technique.

Table 11.1a: Summary of Techniques Assessed – Direct Measurement and Point Tests

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

Table 11.1b: Summary of Techniques Assessed – Mathematical Modelling, Soil Classification and Groundwater Techniques

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

Table 11.1c: Summary of Techniques Assessed

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

Geophysical techniques appear to hold the most potential for the future development of seepage assessment methods

Of the techniques examined geophysical assessment appears to have the most potential for future development. The potential of geophysics lies in the fact that they provide an essentially continuous coverage of the channel, offer a relatively rapid means of assessment and they represent a field which is continuing to develop technologically. New developments often bring quicker and cheaper means of conducting surveys. The main challenge in the use of geophysics for quantitative purposes is in the accurate calibration of the survey results to local conditions.

11.2 Technique Selection

The best method of channel seepage assessment is dependent on a number of factors

Frevert and Ribbens (1988) concluded from their channel seepage review that no method is entirely satisfactory for channel seepage measurement. The best method for a given situation is dependent on a number of factors including the time available, the magnitude of seepage loss being considered, and the availability of equipment and skilled technical personnel for making measurements.

The following factors need to be considered before selection of a particular channel seepage measurement or identification technique:

- Purpose of investigation;
- Required accuracy;
- Cost;
- Operational constraints; and,
- Personnel / Resource constraints.

Figure 11.1 summarises the decisions that need to made when selecting a technique.

11.3 Extrapolation of Seepage Measurements

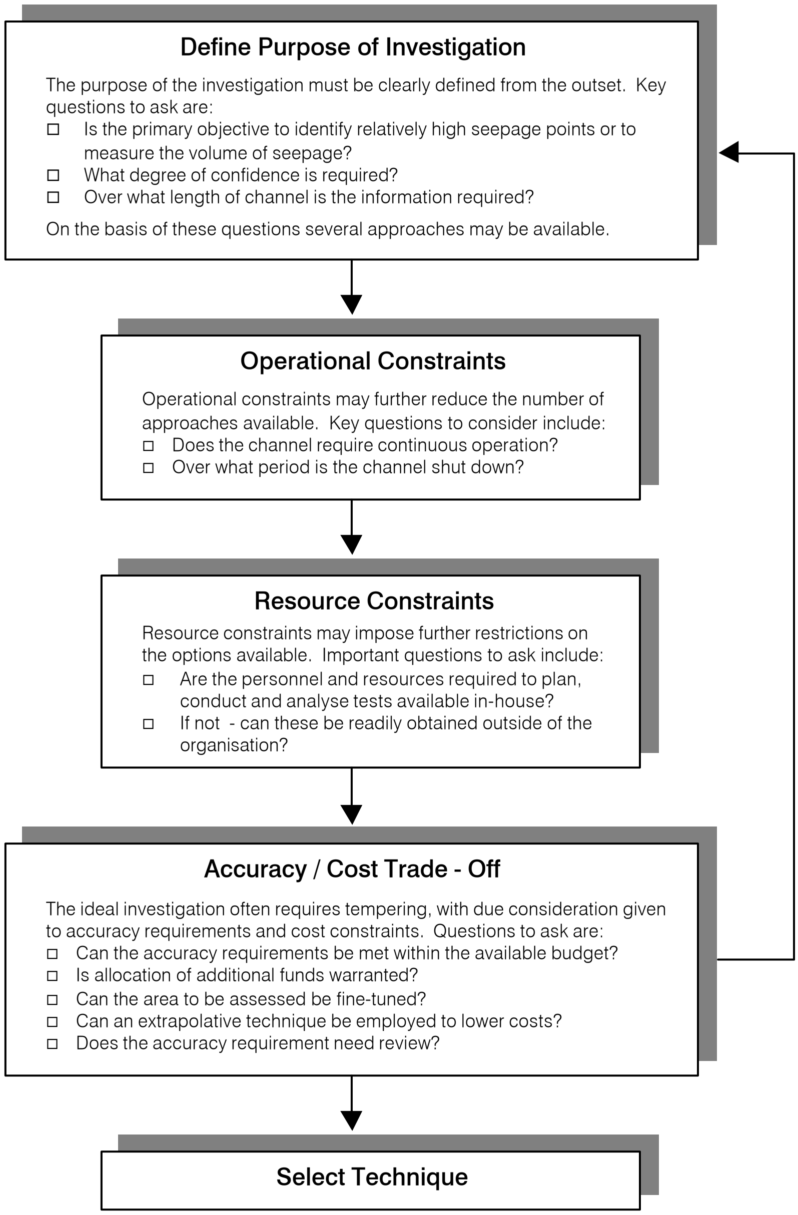
Extrapolation of seepage results is an important tool for minimising seepage assessment costs

The cost of accurately measuring seepage in a length of channel is relatively high. Therefore the importance of establishing cost effective methods of extrapolating accurate measurements over long sections of channel is important.

Extrapolation involves taking the results of a more accurate method of assessment and applying them to other areas based on results of a more cost effective but less accurate method. Soil classification, for example, is basically 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 or pondage test measurements.

The process of extrapolation is discussed in the US National Handbook of Recommended Methods for Water Data Acquisition (1997). This handbook states that in order to extrapolate seepage measurements throughout an evaluation area, the channel system needs to be adequately described.

Figure 11.1: Channel Seepage Measurement Technique Selection



Generally the channel must be described in terms of soil type, hydraulic properties (mean flow, wetted perimeter, and slope), and hydrogeological setting. Often soil type and conveyance properties are known, but the hydrogeological setting analysis is commonly inadequate.

To improve the accuracy of the extrapolative process it is preferable that:

- 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.

Some examples of extrapolative techniques discussed in the literature include:

- Soil types used to extrapolate seepage rates determined from seepage meters and pondage tests (Worstell, 1976);
- Soil types used to extrapolate seepage rates determined from seepage meters (Smith and Turner, 1982);
- Seepage meter readings used to extrapolate seepage rates after calibration against pondage tests (Byrnes and Webster, 1982);
- Resistivity measurements used to extrapolate seepage rates calibrated against infra-red imagery, which was in turn visually verified (Engelbert et al., 1997);
- Relationship between resistivity and hydraulic conductivity (Curtis, 1988, and Curtis and Kelly, 1990); and,
- Average electrical resistivity (from an EM34 survey) used to extrapolate seepage rates calibrated against pondage tests (SKM, 1998 and 1999).

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Appendix A - Reference Summary

A.1 Primary References

Review Of Methods For Measuring And Predicting Seepage

Bouwer, H. and Rice, R.C., 1968.

Methods for measuring and predicting seepage from open channels are reviewed in this paper. They include the inflow-outflow, ponding, seepage meter, salt penetration, and mathematical techniques. Advantages and disadvantages of the various techniques are discussed. Quantitative information of seepage losses from irrigation or natural channels can be obtained by direct measurement on the channel or by calculation.

The second approach, in which seepage is calculated from the hydraulic conductivity of the soil materials and the boundary conditions of the flow system (ie position of the watertable), will be of particular value for canals that are still in the planning stage, for example, in determining desired canal capacities or canal locations for minimum total seepage losses. Solutions can be obtained by mathematical analysis or by analog or model studies. Analyses by resistance network analog and the resulting dimensionless graphs for determining the seepage rate are discussed. In certain cases, knowing seepage in relation to time after water has entered a dry channel will be of interest. This is a problem of 2-dimensional infiltration, showing how simplified solutions can be obtained. The methodology for direct measurement or calculation of seepage from channels or reservoirs has progressed sufficiently to enable acquisition of quantitative seepage data for a wide variety of conditions.

Bouwer, Herman; Rice, Robert C., 1969.
Agricultural Research Service, Phoenix, Ariz. Water Conservation Lab
Second Seepage Symposium, Proceedings, Phoenix, Arizona, Mar 25-27, 1968.
Agricultural Research Service, Washington, Dc, Ars 41-14.

Theory Of Seepage From Open Channels

Bouwer, Herman. 1969.

Prediction of seepage from open channels and the measurement of soil hydraulic properties are discussed in a review of current mathematical and field studies in soil water movement. Solutions are available for seepage rates for a great variety of channel, soil, and water table conditions. Most analyses are for steady-state systems, but some transient systems may be handled. Digital and analog computers permit calculation of many boundary conditions. Recent work in soil physics and soil-property measurement makes possible accurate determination of field parameters and realistic model-making.

Bouwer, Herman, 1969.
Agricultural Research Service, Phoenix, Ariz. Water Conservation Lab, Advance In Hydroscience, Vol 5, Pp 121-172, 1969. 52 P, 32 Fig, 3 Tab, 46, Document Type: Journal Article.

Surface Water-Groundwater Relations for Open Channels
Bouwer H., 1988.

This paper presents a summary of Bouwer's previous work on the theory and mechanism of channel seepage. Relations between flow of water into or out of open channels are important in modelling groundwater and surface water systems, and in litigation where there can be conflicts between the owners of surface water rights and those of groundwater rights.

For losing channels with clean wetted perimeters (no clogging layers), the seepage rate varies essentially linearly with depth to groundwater if the groundwater is relatively shallow, but is essentially independent of depth to groundwater if the groundwater is relatively deep. For losing channels where the wetted perimeter is covered with a clogging layer that controls the seepage rate, seepage is not affected by depth to groundwater as long as the groundwater table, or, rather, the top of the capillary fringe, is below the clogging layer on the channel bottom. If the groundwater is above the bottom of the channel, there is an essentially linear relation between the seepage rate and depth to groundwater (measured from the water surface in the channel).

For gaining channels, the rate of flow of groundwater into the channel is essentially linear with height of groundwater table (measured from the water surface in the channel), regardless of whether the channel wetted perimeter is clean or covered with sediment or other clogging material.

Bouwer, Herman
In: Planning Now for Irrigation and Drainage in the 21st Century. Conference Location: Lincoln, Nebraska, USA . 18-21/7/1988. Sponsor: ASCE, Irrigation and Drainage Div. Edited by DeLynn R. Hay Source: Publ by ASCE, NY, USA p 149-156, 5 refs. Publication Year: 1988.

Field Evaluation of Seepage Measurement Methods
Brockway, C. E. and Worstell, R. V., 1969.

Experiments with ponding tests, seepage meters, and inflow-outflow methods for measuring seepage from canals were conducted in 1965-66 on the Minidoka project in Idaho. The study was performed on a 4.5-mile reach of the main canal near Paul, Idaho. It is 25 to 30 ft wide with a gradient of about 0.5 ft per mile and flows at a depth of 5 to 5.5 ft during the irrigation season. Soils throughout the test reach are very uniform and consist almost entirely of Portneuf silt loam. A compacted, slightly cemented silt layer from 12 to 24 inches thick intersects the canal cross section throughout most of the test reach. The flow system beneath the entire test reach is under tension gradients due to an impeding layer near the soil surface of the canal cross section. Devices for recording water measurement were installed at the inlet and outlet and at all turnouts on the reach. A water budget for the irrigation season was maintained on this reach for 3 years, and the loss rates for 2 week periods were computed.

Of the available methods for evaluating seepage losses, the ponding test is the most accurate but the most expensive. The use of seepage meters for obtaining estimates is fast and economical. However, new types of meters capable of functioning in canals at operating depth should be studied. Almost all the available meters are capable of measuring seepage with reasonable accuracy at a point, but discretion must be used in the amount of confidence placed in average values determined from meters tests. The procedure outlined for estimating the number of meter tests required can be used to judge the confidence to be placed in any group of tests. Inflow-outflow methods are usually too expensive to be used for short duration seepage measurements. However, a good installation does indicate seasonal changes in loss rates. Accuracy of inflow-outflow determinations is limited by the flow-measuring devices, but for canals with large seepage losses, inflow-outflow methods may be the most expedient and sufficiently accurate.

Brockway, CE ; Worstell, RV
Idaho Univ., Moscow. Dept. Of Civil Engineering; and Agricultural Research Service, Kimberly, Idaho. Snake River Research Center
Proc 2nd Seepage Symp, Phoenix, Ariz, Mar 25-27, 1968, Agr Res Serv Rep 41-147, P 121-127, 1969. 7 P, 3 Fig, 2 Tab. 1969
Document Type: Journal article

Direct Measurement Of Seepage From Earthen Channels

Byrnes R.P. and Webster A., 1981.

This investigation comprising laboratory and field investigations of the Idaho meter to determine its usefulness, reliability and range of operational effectiveness in Australia conditions, was initiated by the Australian Water Resources Council, in order to build upon work conducted by Smith (1973). The objectives of the program were to adapt the equipment to overcome the difficulties in tests noted by Smith, to determine the performance of the meter under controlled and field conditions, and to assess its usefulness in identifying parts of channels where relatively high seepage losses occur. This summary presents key aspects of part one of the report which outlines the results of the program of laboratory and field tests with an improved form of the Idaho seepage meter. (Part 2 is a User's Manual for fabrication and operation of the meter).

The first section of the report deals with primary factors determining seepage rates and the theoretical aspects of seepage flow. With regards to the Bouwer solutions for seepage flow, a significant conclusion is drawn that 'the results of the applications of these idealised formulae (in Victoria) often bear little resemblance to measured field losses probably because of the complex and variable soil and silt conditions in the wetted perimeters of channels' (Smith, 1973). The variation in permeability with time for soils during prolonged submergence is covered in some detail, and it is stated that 'the occurrence and thickness of any sediment layer, at least in Victoria, could dominate all other influential factors in determining seepage losses.'

The second section of the report summarises methods of seepage measurement, with a division recognised between direct and indirect measurement. Indirect measurement requires the measurement of the hydraulic conductivity of the subsoils, especially at the soil water interface, and measurement of the watertable profile. The seepage rate can then be calculated from theoretical equations. Byrnes and Webster state that adequate data for these computations are rare, especially since most conditions for soil are complex. Procedures discussed for the direct measurement of seepage are divided into:

i) inflow-outflow and ponding methods for determining the total seepage loss from a section of channel; and,
ii) seepage meter and salt penetration methods that enable measurements to be made at particular points in the channel. The mean of numerous point measurements is, in principle, a measure of total seepage loss from a section of channel.

Inflow-outflow, ponding and salt penetration techniques are briefly discussed in terms of methodology, advantages and disadvantages of each technique. The various types of seepage meters available are discussed in more detail, with the difference between variable and constant head meters explained. The reasoning behind the selection of the Idaho meter as the best technique for direct measurement is set forth.

The remainder of the report describes the laboratory and field tests undertaken, presenting the aims, procedures, results and discussion of each component. The primary conclusions and recommendations derived from the report were:

i) The accuracy and range of use of the Idaho seepage meter was improved by minor modifications to the meter and operating procedures.
ii) In the laboratory, tests of the modified meter on tanks containing different soil cores produced consistent mean metered seepage : tank outflow ratios, of approximately 1.2 : 1.
iii) At seepage rates above 400 mm/d the instrument is unreliable.
iv) Comprehensive field tests in 14 channels with 382 meter readings produced measurements ranging from 0.1 to 352 mm/d. The distribution of measurements was positively skewed, 82% of the readings being less than 7 mm/d, and the median for all measurements was 1.77 mm/d. Variability in measurements was high; within various section of channels, coefficients of variation ranged from 80 – 360%.
v) Pressurisation of the Idaho meter bell (only occurred in summer months and on channel bed) was observed in 20% of all channel bed meter locations, causing serious operation disadvantages.
vi) From statistical treatment of the skewed data it was determined that: there was a significant difference in meter seepage rates in different channels, there was a significant difference in meter seepage rates between beds and batters where a sediment layer is present, and there was not a significant difference in seepage rates in light and heavy soil types where a sediment layer was present.

vii) In a comparison of total seepage loss from sections of channels by the Idaho meter and ponding methods, mean meter readings significantly underestimated the ponding test results [26% and 34% of the respective ponding losses (5.4 and 12.6 mm/d)].

viii) The results of three case studies confirmed the usefulness of the modified Idaho meter for checking the effectiveness of remedial measures, positive identification of relatively high seepage losses from a section of channel, and checking whether local groundwater pumping increased the seepage rate from a channel.

In summary, Byrnes and Webster concluded that the modified Idaho meter is a useful aid in seepage investigations for delineating parts of channels that have relatively high seepage rates, and for checking the effectiveness of remedial measures.

Byrnes RP; Webster A; (Victoria State Rivers and Water Supply Commission)
Source: AGPS, Canberra, 1981, 78p, 10 tables, 11 figs, 2 refs.
Australian Water Resources Council Technical Paper No 64.

Leakage of Clogged Channels that Partially Penetrate Surficial Aquifers
Chin, D.A., 1991

This paper presents a theoretical formulation describing leakage from a clogged channel that partially penetrates a surficial aquifer. This work builds upon the work of Bouwer (1965, 1968, 1978), and a seepage scenario different to the three conditions described by Bouwer is considered. Leakage characteristics are parameterised by a reach transmissivity, which is defined as the volume flow rate out of the channel per unit length of the channel per unit drawdown. An expression is developed to relate the reach transmissivity to the transmissivity of the aquifer, mean channel width, distance of drawdown measurement from the channel centre line, ratio of drawdowns on both sides of the channel, and local reach transmissivity associated with clogging. This theoretical expression was verified using a fine-scaled numerical model. The formulation was field tested at two channels. The measurements of reach transmissivity were found to vary linearly with the drawdown ratio, as predicted by the theory. Furthermore, the aquifer transmissivity obtained by fitting the theoretical formulation to the measurements is in close agreement with independently estimated values.

Chin, David A, 1991
Journal of Hydraulic Engineering, Vol. 117, No 4, April 1991. American Society Civil Engineers, Hydraulics Division. pp 467 – 488, 21 refs.

Effects of Sediment Laden Flow on Channel Bed Clogging
Cunningham A.B., Anderson C.J. and Bouwer H., 1994.

In open channel systems the phenomenon commonly referred to as clogging is caused by settling and straining of suspended sediment as water moves through the channel bed material, as well as by microbial transport, colonisation, and other biological and chemical action. This paper summarises a three year investigation of the clogging process due to accumulation of fine soil particles as it occurs in sediment-laden open channel flow. The major conclusions arising from these investigations are summarised below:

- For each of the four suspended sediment types examined, reductions in channel bed infiltration rate of 70-95% occurred within 24 hours after the addition of suspended sediment material. Channel bed clogging continued to increase slowly thereafter and, in some cases, became quasi-stable.
- Within the range of 200-1,600 ppm solids content, suspended sediment concentration did not have any significant effect on the clogging process and infiltration rates.
- Variation in the magnitude of average channel velocity was observed to have a major effect on the clogging process. For velocities in the range from 0 to about 0.27 m/s, the reduction in channel bed infiltration rate was governed by a 0.46 – 1.27 cm layer of fine material deposited on top of the filter material. For velocities above (approximately) 0.27 m/s, clogging was caused by a very thin layer of fine material impacted into the pore spaces of the topmost layer of channel bed sediments.
- The onset of impaction type clogging corresponded to a flow condition well into the fully turbulent range in channel flow. Also impaction clogging corresponded to a hydraulically rough bed condition. Depositional clogging occurred under both laminar and transitional flow conditions. However the thickness of the depositional layer decreased continuously with increasing Reynolds number.
- Suspended materials having coarser, more uniform particle size distributions tended to cause less clogging (at low velocities) than the finer, better graded materials. However, as velocity increased, a similar degree of clogging was seen for all four materials.
- A zero horizontal velocity condition slightly reduced the infiltration ratio as compared with similar conditions involving non-zero horizontal velocities.

Cunningham AB, Anderson CJ and Bouwer H., 1994.

Journal of Irrigation and Drainage v 113, No. 1, Feb 1987. p 106-117, 14 Refs.
Document Type: JA; (Journal Article)

Estimation of Groundwater Accessions From Irrigation Channel Seepage
Dillon, P.J., 1988.

This paper is written in response to a request to reflect on the subject of quantifying leakage from irrigation channels for use in a groundwater model of the Shepparton region, and specifically on three documents:

- Olshina, A. (1987). The relative importance of channel seepage in the estimation of groundwater recharge in the Goulburn Murray Irrigation District, DITR Discussion Paper, March 1987.
- Bridley, S.F. (1987). Proposal for channel seepage investigation and estimation of accessions from channels. RWC Irrigation Services Branch, October 1987.
- Anonymous (1987) comments on proposal by S.F. Bridley.

The above documents describe problems associated with channel seepage measurement and make constructive suggestions for investigations aimed at identifying local rates of seepage. Dillon states that programs such as those proposed are technically feasible, but that results will continue to be highly variable in sites which fall within the same classifications for channel geometry, soil type and depth to watertable. The focus of this paper is on the variability of spot seepage measurements.

The frequency distribution of hydraulic conductivity values in samples of natural soils commonly takes the form of a log normal distribution. As hydraulic conductivity is a significant determinant of the seepage rate, the frequency distribution of seepage rates may also be log-normal. Dillon illustrates how the data presented in the Olishna (1987) paper appears to fit this form of skewed distribution. It is demonstrated that one third of the total leakage occurs through only 10% of the wetted channel surface, and about half the area contributes around 80% of the leakage. Therefore, many more measurements are required to obtain a reliable estimate of the mean than would be required for an unskewed distribution. Taking too few samples tends to produce biased (low) estimates of the total seepage rate. There is the additional issue of variable seepage rates across the perimeter of the channel (ie, centre of base, junction of base and side and sides). This presents a difficult (and expensive) problem if seepage rates of individual reaches are to be quantified for each channel over a large region.

Also discussed is the issue of temporal variability. A reduction of seepage rates with the progress of time has been attributed to sealing of channel bed by clay deposition and a rising watertable. Even in locations where groundwater levels remain well below the channel, a decline in seepage rate has been observed during intermittent flows due to swelling of clays beneath the channel. Algae have also been observed to have a significant effect on infiltration rates from artificial recharge trenches on the Burdekin Delta (Queensland), where rates dropped by as much as 50% overnight as algae settled on the floor of the trenches during darkness. Any investigation program should identify the possibility of temporal variations in seepage rates.

Dillon proposes a method for quantifying regional accessions to groundwater from channel seepage which involves: i) examining the physical characteristics (geology, channel type, groundwater level) affecting channel seepage, ii) conducting pilot field studies (using ponding tests or inflow-outflow measurements) to establishing relationships between seepage and key physical characteristics, and iii) using relationships from the pilot study to extrapolate to other channels making use of the recorded physical characteristics.

Dillon, P.J. (CSIRO Division of Water Resources).
Centre for Groundwater Studies. Centre for Research in Groundwater Processes Project Report No. 3, February 1988.

Integrated Remote Sensing and Geophysical Techniques for Locating Canal Seepage in Nebraska
Engelbert, P.J.; Hotchkiss, R.H.; Kelly, W.E., 1997.

Rising demands for Platte River water in Nebraska have increased the need for detecting seepage along canals whose diversion source is the Platte River. Of particular importance is to establish methods that can be used to detect seepage while keeping the canal in full service. Appropriate geophysical methods integrated with other techniques can provide a relatively fast and inexpensive way to detect and locate seepage without disturbing the natural flow of the canal. Combined with colour infrared imagery, electrical geophysical methods such as electrical resistivity, electromagnetics, and ground penetrating radar were used to delineate several potential seepage areas along the Central Nebraska Public Power and Irrigation District canal system.

The study developed a procedure for systematically identifying and refining estimates of areas of high potential canal seepage. The method is summarised in the following steps:
1) Identify potential areas of seepage using operational records;
2) Conduct inflow-outflow seepage measurements of suspected reaches;
3) Analyse aerial photography (preferably colour infrared);
4) Determine geoelectric sections for suspected reaches using vertical electrical soundings; and,
5) Perform electrical profiling to define suspected high potential seepage reaches.

The reaches suspected of being likely reaches for potential high seepage, based on colour infrared, were selected for investigation with electrical geophysical measurements. Vertical electrical soundings were measured along the reached and interpreted using the available test hole data to define geological and geoelectrical models for the subsurface along the reaches. These soundings were also interpreted to determine optimal spacings for profiling along the reaches and to allow true resistivities to be estimated from profiling measurements. Profiling measurements were performed to define the variation of resistivities along each reach.

Areas of high potential seepage were identified and the extent and relative seepage potential were estimated. Although the study did not verify these estimates, the point was made that there is a relatively good agreement among the various geophysical techniques used in the investigation. The study also highlighted the benefits of making measurements when the canal is full and when the canal is empty, and suggested that this was an aspect worth further investigation. The study identified electrical resistivity soundings and horizontal profiling as an effective and efficient means of identifying potential seepage for reaches less than eight hundred metres in length.

Engelbert, P.J.; Hotchkiss, R.H.; Kelly, W.E., 1997
Corporate Source: HDR Engineering, Inc, Omaha, NE, USA
Source: Journal of Applied Geophysics v 38 n 2 Dec 1997. p 143-154, 21 Refs.

Methods of Evaluating Canal Transmission Losses

Frevert, D.K. and Ribbens, R.W., 1988.

This paper asserts that evaluation of canal transmission losses has long been an area in which technical capabilities have lagged behind the need for information. It is stated that in many cases the sensitivity and accuracy of the methodology available is insufficient to adequately evaluate the magnitude of the transmission losses, not to mention the differences which could be noted as a result of measures taken to reduce transmission losses.

This paper presents a discussion of various methods presently used to evaluate transmission losses with particular emphasis on those methods used in the Bureau of Reclamation. Because seepage losses are typically the largest portion of transmission losses, the paper focuses primarily on estimation of seepage losses. The methods evaluated include seepage meters, barrel tests, inflow-outflow measurements, ponding tests and theoretical mathematical models. The discussion includes a description of the procedures and assumptions for each method, the advantages and disadvantages of each, and a case study incorporating three methods.

The paper concludes that no method is entirely satisfactory and that estimating canal seepage is both difficult and inexact. The best method for a given situation is dependent on a number of factors including the time available, the magnitude of seepage loss being considered and the availability of equipment and skilled technical personnel for making measurements.

Frevert, D.K. and Ribbens, R.W., 1988. Methods of evaluating canal transmission losses. In: Planning Now for Irrigation and Drainage in the 21st Century, Proceedings of Conference sponsored by the Irrigation and Drainage Division, American Society Civil Engineering., Lincoln, Nebraska, USA, pp. 157-164.

Irrigation Canal Seepage and its Measurement: A State-of-the-Art Review

Hotes, F.L., Kruse, E.G., Christopher, J.N., Niaz, S, and Robinson, A.R., 1985.

Reduction in seepage is one of the primary reasons used to justify investment in canal lining. Such justification depends greatly upon estimates of seepage through surface and subsurface strata along the proposed or actual canal alignment and through various types of canal lining. This review of the literature and the results of field tests concludes that the determination of amounts of seepage is not only difficult, but also inexact, even when executed by experienced, competent professionals. This paper reviews some of the more significant findings on canal seepage and the results of both research tests and seepage measurements on operating canals. The implications of the inherent variability and complexity of canal seepage on canal design and operations are discussed.

The variables which have an influence on the loss of water by seepage from irrigation canals include: 1) characteristics of the soil at the soil-water interface and below the channel bed; 2) chemistry of the water and soil; 3) amount of sediment carried and deposited by the water; 4) length of time that water has been in the canal, both seasonally and total life; 5) water depth; 6) velocity of flow; 7) temperatures of water; 8) soil capillary tension; 9) position and gradient of the watertable; 10) barometric pressure; and 11) canal shape and wetted perimeter.

The paper summarises applicable seepage theory, including the four basic conditions studied by Bouwer (1969). The Robinson and Rohwer studies conducted between 1949 and 1952 are reviewed and are viewed by the author as one of the most complete studies to date. These studies included tests with large concentric seepage rings (outside diameter 3-5m), ponding tests, seepage meter studies, well permeameter tests, and seepage measurements on operating canals. Some of the main results from these studies included: 1) seepage increased with increased depth of water, but not always linearly; 2) seepage increased with increased depth to groundwater, within the 0.76m range of depth tested (except in sand); 3) over periods of 24 hours, seepage rates could vary by as much as 10% - 65%, depending on the soil type (rates were higher at lower temperatures) and, 4) seepage meters of various types generally produced widely differing and conflicting results.

Four principal methods for measuring seepage losses from channels were discussed: Inflow-outflow, ponding tests, seepage meters and hydraulic conductivity. A few other methods were mentioned, including salt penetration or radioactive tracer tests, but in the authors view these have not proved to be as reliable as the four listed above. The methodology behind each of the techniques and the advantages and disadvantages of each are discussed. The overall evaluation is that seepage meters are the least reliable method, although they can be helpful in establishing qualitative comparisons and in identifying section with excess seepage. It is concluded that each of the other three methods has applications in which their use may be the most practicable, however none are considered to give precise results, and the best approach is to obtain reasonable confirmation by use of two or more methods. For estimates of seasonal seepage, the "Hydraulic Conductivity Approach" is considered the most reliable method.

Hotes, Frederick L, Kruse, E. Gordon, Christopher, Jack N., Niaz, Sadiq, and Robinson, A. R.
Conference Title: Development and Management Aspects of Irrigation and Drainage Systems, 1985.
Conference Location: San Antonio, TX, USA Conference Date: 19850717
Sponsor: ASCE, Irrigation and Drainage Div, New York, NY, USA; ASCE, San Antonio Branch, TX, USA; ASAE, St. Joseph, MI, USA; Natl Assoc of Conservation Districts, USA; Soil Conservation Soc of America, Ankeny, IA, USA; et al
Source: Publ by ASCE, New York, NY, USA p 93-105, 18 refs

Controlling Seepage Losses From Irrigation Canals: World-Wide Survey, 1967
International Commission on Irrigation and Drainage, 1967.

This world-wide survey on the methods to reduce seepage from irrigation canals, is primarily focussed on channel lining and other means of seepage control. However, the important issue of prioritising areas for lining is briefly addressed and an appendix is devoted to channel seepage measurement. The following is a summary of those parts of the review related to seepage measurement and the relevant appendix.

Chapter 3 discusses factors affecting seepage losses in earthen canals, including: the type of surface of the canal, surrounding soil type, the wetted area of the canal bed and banks, frequency of canal use, age of canal, weather conditions, amount and grade of sediment contained in the water, depth of water flow, groundwater elevation relative to canal, and other factors. This chapter also discusses methods of seepage estimation. Pre-construction decisions to line or not to line the canal using visual methods is only recommended when the soil is clearly very pervious or impervious. When the permeability of the subgrade is in doubt, in situ field permeability tests provides a basis for estimating potential seepage losses and deciding the necessity for lining.

Techniques recommended for assessing seepage rates in existing canals include ponding, seepage meters, inflow-outflow method, or by well permeability method. "Other special methods, such as use of radioactive and dye tracers and electrical logging of canals to detect seepage are yet in experimental stage. Precise determination of seepage losses are difficult to make and each method has its own limitations…". The chapter concludes with a discussion of estimating seepage from empirical equations where field data or observations from existing canals are not possible. Typical formulae used in various countries are presented.

Appendix B is titled 'Methods of Seepage Measurements'. A brief summary the techniques discussed is presented below:
Ponding method: In addition to the normal ponding test, a modification is presented where water is added to the ponded reach to maintain a constant level. The volume of water added, measured accurately, is the absorption loss (seepage plus evaporation). The ponding method is described as the most accurate and dependable method of determining seepage losses.
Seepage meter method: The seepage meter is a modified version of the constant head permeameter, developed for use under water. The seepage meter is not considered an accurate means of measuring seepage loss. Its main value lies in determining approximate locations of relatively high seepage losses.
Inflow-outflow method: Any inaccuracy in measurements of discharges at various points is reflected in seepage loss measurements. When seepage tests are of long duration, or when the tests are to be repeated in the future, rating curves and tables can be prepared with water level recorders installed at such gauging sites. While this method is considered quite accurate for larger canals, it is not sufficiently accurate for close determination of seepage losses in short reaches of a canal. This method can, however, be employed without interfering with irrigation schedules with canals in operation.

Well-permeability method: This method consists of erecting a pipe upright in a running canal to segregate a part of it. The lower part of the pipe is embedded to a sufficient depth in soil of the canal bed. This pipe is then filled with water up to the canal water level and the drop in the volume of water in this pipe is determined. Some preliminary exploration of the subsurface is required for suitable selection of test sites. The soils where tests are conducted should be representative, and the presence of groundwater or impervious soil layers should be known for use in permeability calculations. The test is better used in unsaturated soils.

International Commission on Irrigation and Drainage (Central Office – 48 Nyaya Marg, Chanakyapuri, New Dehli, India), 1968

Irrigation Canal Lining
Kraatz D.B., 1977.

This summary, reviews Chapter Two ('Determination of seepage losses') of Kraatz, 1977. In this chapter, Kraatz states that seepage rates are obtainable either by estimation or by direct measurement. Estimation is based on knowledge of the relevant hydraulic properties of the soil and of the boundary conditions, such as depth to groundwater, canal cross section and water depth. Because of the many variables involved, no general law for calculating the rate of seepage has been developed. Methods of evaluating seepage from existing canals are listed: a) discharge measurements by the inflow-outflow technique; b) measuring the rate of water loss from a ponded canal; c) measuring the rate of water movement into the bottom or bank of the canal with a seepage meter; and d) special methods essentially limited to qualitative indication of seepage (for example, its distribution along a canal).

The main factors known to have a definite effect on seepage rate are listed and discussed: 1) Characteristics of the soil of the region through which the canal runs; 2) Depth of water in the canal, wetter perimeter of the canal and depth to groundwater; and 3) Amount of sediment in the water, velocity in the canal and length of time the canal has been in operation. The remainder of the chapter is divided into two sections, estimation of seepage from a proposed canal, and measuring seepage from existing canals.

Estimation of seepage from a proposed canal
The simplest method of prediction is to adopt known seepage losses from canals of similar size or shape in similar hydrogeological environments. A qualitative method of prediction consists of estimating or measuring the hydraulic conductivity of the soils in which the canal is to be excavated. A quantitative prediction of losses can be obtained by calculation, including empirically developed formulae, solutions arrived at by analytical methods, and solutions derived by electrical analogy.

The use of empirical formulae can only produce rough estimates, whereas analytical methods give highly accurate results when applied to conditions for which they have been developed. Kraatz observes, however, that analytical methods are generally quite elaborate. The Bouwer graphical solutions for predicting seepage rates from a given canal are presented and discussed. Kraatz states that "these solutions today represent the most accurate and convenient means of determining seepage values from known hydraulic conductivity of the subsoils, geometry of the canal and position of the groundwater table". The main criticism of these methods is the assumption of homogenous natural conditions, which rarely occur.

The application of analytical solutions requires that the soil and boundary conditions of the canal are known. Of particular importance is the proper determination of the hydraulic conductivity of the soils. The accepted methods of hydraulic conductivity measurement above and below the watertable are briefly described and referenced to more detailed sources. Methods discussed for measuring hydraulic conductivity below the watertable include aquifer pumping tests, auger hole method, piezometer method, the tube method and the multiple-well technique. Methods measuring hydraulic conductivity above the watertable were grouped into measurement of simple one-dimensional (ie vertical) flow or for axisymmetric flow. Methods discussed based on vertical flow include the infiltrometer techniques and the air-entry permeameter. Two important methods based on axisymmetric flow systems are the well permeameter method and the double-tube method. Laboratory methods for measuring soil permeability are also discussed.

Measuring seepage from existing canals
"Currently accepted methods of measuring the quantity of water lost by seepage from existing canals are limited to inflow-outflow, ponding, and seepage meter determinations." The methodology, advantages and disadvantages of each technique are discussed. Special methods including the use of tracers, electrical logging or resistivity measurement, piezometric surveys and remote sensing are covered in less detail. Kraatz states that these special methods are essentially limited to a qualitative function, providing an indication of the distribution of seepage along the canal. It is concluded that each method has its own advantages and limitations, and that no single method is adaptable to all conditions encountered in the field. Ponding tests may be the most accurate and reliable method.

Kraatz D.B., 1977
Food and Agricultural Land and Water Development Series No. 1, Food and Agricultural Organisation of the United Nations, Rome, Italy, 200pp, 176 refs

Measurement and Modelling of Irrigation Channel Seepage in Northern Victorian
McLeod A.J., 1993.

This thesis describes the study of irrigation channel seepage carried out by the author from 1989 to 1993. Seepage tests using the pondage method were performed on two irrigation channel reaches in the Rodney Irrigation

Area of the Goulburn Murray Irrigation District of northern Victoria. Seepage rates were calculated for all seepage tests performed (11 at the Tatura East site: 1989-1992; 8 at the Dhurringile site: 1989-1991). The seepage losses from the Dhurringile site were augmented by leakage losses. The cause of this associated, and often confused, transmission loss was investigated. Measurements of leakage losses were made in 5 of the 8 tests at the Dhurringile site and estimates of the relative magnitude of seepage and leakage loss were made.

The data collected from the Tatura East site included channel water elevation and groundwater elevation in several transects perpendicular to the channel. Using these data, an existing computer model employing the boundary integral equation numerical method (BIEM) was modified to similar the seepage processes occurring at this channel site. Through a procedure of calibration and validation of the model results to the field observations, the aquifer parameters were determined and the processes involved in the transmission of seepage away from the channel were identified. The seasonal variation of the channel bed conductance was determined through a process of modified validation and the causes of this variation were examined. Before the third irrigation season, part of the Tatura East site was de-silted so the influence of the naturally forming silt layer on seepage rates and model parameters could be directly measured. For the period of the field experimentation, the component of channel seepage recharging the regional aquifer was quantified. In addition, the prospects of three methods of seepage mitigation were also investigated.

Literature Review

The thesis included a literature review of previous studies of irrigation channel seepage investigations conducted in Australia and overseas. This review was divided into three main sections:

- Previous work (divided into Victoria, Australia and World-Wide;
- Methods of Quantifying Irrigation Channel Seepage; and,
- Influence of Seasonal Variables on Seepage Losses.

Methods of Quantification

McLeod (1993) investigated the three most common methods for channel seepage quantification, which were identified as the inflow-outflow method, the seepage meter method and the pondage method. Also briefly discussed were: remotely sensed thermal surveys, aerial surveying, resistivity traversing, hydraulic conductivity measurements, tracer methods (salt penetration), and piezometric surveys. These were not selected for use in McLeod's investigation as they were not deemed to be sufficiently researched to be adopted as part of this study, or were not considered accurate enough for the requirements of the investigation.

Conclusions

The significant conclusions of the study were separated into those from the field experimentation and those from the computer modelling of the channel seepage processes. These conclusions are:

Field Experimentation (Chapters 3,4 and 5)

- A review of the published studies of irrigation channel seepage revealed that an experimental program comprised of pondage tests conducted at various times over an irrigation season was unique.
- Seepage measurements were made at two channel sites: Tatura East and Dhurringile. Seepage losses in the upstream pond of the Tatura East channel were observed to vary between 20 and 34 mm/d over the duration of the field work. In the downstream pond over this same period the observed variation was 14 to 19 mm/d under normal pondage conditions (due to low channel water level conditions during one seepage test, 8 mm/d was recorded during this test). The upstream pond of the Tatura East channel showed a tendency for higher seepage rates nearer the middle of the irrigation season. At the Dhurringile site, average seepage losses (not including leakage) were calculated for 5 of the 8 tests at this site. These seepage losses varied between 5 and 9 mm/d.
- Analysis of this influence of sub-surface hydrological conditions on the seepage loss rate from the Tatura East channel indicated that the net available head to drive seepage flow from the channel (the difference between channel water level and representative aquifer head) was the most significant factor in determining the seepage loss rate from a channel. Given the channel water level was controlled for the purpose of the experimentation, it was variation in the groundwater level that produced changes in the net available head.
- The related problem of leakage (loss from the channel through holes in the channel bank) from irrigation channel in northern Victoria was highlighted in this study. Further analysis of the data from the Dhurringile channel site was abandoned due to the complicating effect of leakage at this site. The primary cause of the leakage process was attributed to the presence of the yabbie (Cherax destructor) in the irrigation channels. Despite large amounts of anecdotal evidence, the scope of the leakage problem is large unknown.

Computer Modelling (Chapters 6 and 7)

- The calibration and validation of the computer model chosen for this study indicated that the model was able to successfully simulate the interaction between an irrigation channel and the surrounding aquifer.
- The channel bed conductance is defined as the conductance (conductivity divided by thickness) of the naturally forming channel lining or, in the event of the removal of this lining, the surface layer resistance. The general perception of channel bed conductance variation throughout an irrigation season is that it begins at a high level at the start

of an irrigation season, attenuates over the course of this season and returns to the previously high level by the start of the next irrigation season. The work in this thesis has shown that the channel bed conductance at the Tatura East channel site exhibits no such variation during an irrigation season.

- The model simulations of the Tatura East channel indicated approximately two-thirds of the water entering the aquifer as channel seepage progresses to recharge the regional aquifer. The remaining third is lost to evaporation from the water table or goes into storage in the surface aquifer. With rising water tables, the total amount of seepage entering the aquifer is likely to reduce and the influence of evaporation from the water table is likely to increase. The figure of two-thirds can only be considered as approximate and relevant at the Tatura East channel for the 1989-1992 period.
- The downstream pond of the Tatura East channel was de-silted in August 1991. Thus the 1991-92 irrigation season proceeded without silt in the lower reach of the channel. No identifiable change in the seepage rate of the downstream pond of this channel was observed as a result of this procedure. Through the application of the computer model it was possible to isolate the effect of the de-silting on the channel bed conductance parameter in the model. A noticeable change in channel bed conductance was not observed as a result of the de-silting process. The consistency of the conductance of the natural channel lining despite large changes in the thickness of this lining suggests the net effect of the lining is concentrated in a thin surface layer and this layer appears to be generated over a relatively short period. Alternatively the impeding layer may be a sub-surface interface not affected by the silt removal.
- Of the three methods of seepage mitigation assessed in laboratories (other studies) and in the field (this study), two methods were identified as promising. Reduction in seepage loss rate from an irrigation channel of around 30% (Puddling) or 20% (algal inoculation) could be expected if these methods can be successfully applied to an operating irrigation channel.

McLeod A.J., 1993. Measurement and Modelling of Irrigation Channel Seepage in Northern Victoria. Thesis submitted for the degree of Doctor of Philosophy. Department of Civil and Environmental Engineering, University of Melbourne, November 1993.

Measurement Of Irrigation Channel Seepage In Northern Victoria,
McLeod A.J.; Earl G.C.; McMahon T.A.; Moore P.J., 1994.

Seepage has been identified as a significant loss from the irrigation channel system in northern Victoria from both a water quantity and environmental degradation perspective. Measurements of irrigation channel seepage were made between 1989 and 1992 at Tatura East and Dhurringile (Victoria) in the Shepparton region of the Goulburn-Murray Irrigation District. The upstream pond of the Tatura East channel showed a tendency for higher seepage rates nearer the middle of the irrigation season. Indications are that available head to drive seepage flow from the channel was the most significant factor in determining the seepage loss rate from a channel and findings at the Dhurringile site were consistent with these results. The related problem of leakage, which did not occur at the Tatura East site, was a major consideration along with seepage at the Dhurringile site. The primary cause of the leakage process is considered to the yabbie (Cherax destructor) which perforates and undermines the channel banks with burrows.

McLeod A.J. (University of Melbourne Department of Civil and Agricultural Engineering); Earl G.C. (Goulburn Murray Rural Water Authority); McMahon T.A. (University of Melbourne Department of Civil and Agricultural Engineering); Moore P.J. (University of Melbourne Department of Civil and Agricultural Engineering), 1994.
Source: Water Down Under 94, 21-25 Nov 1994, Adelaide SA, Preprints of papers.
Inst .of Eng., Australia, Barton ACT, 1994-10, p711-14, 2 tables, 2 figs, 8 refs.
SE: National conference publication (Inst. of Eng., Australia); 94/10.

Review of Murray Region Seepage Investigations
McLeod, A.J., 1996.

Two reports were released reviewing seepage investigations in the irrigation districts of the Murray Region of the NSW Department of Land and Water Conservation. The investigations under review included the contribution of irrigation channel seepage to regional groundwater accessions in four infrastructure option reports covering the Murray Irrigation Districts, including Berriquin, Denimein, Deniboota and Wakool Districts and the Tullakool Irrigation Area. The findings of the two reports are summarised below.

Report I (May 1995)
In the first report these seepage loss investigations are reviewed, including the choice and application of methodologies adopted. The five methods of seepage estimation used in the investigations included: District Water Balance, Seepage Rates, Darcian Principle, Cause-Effect Study and Idaho Seepage Meter. The methodology for each of these techniques and concerns raised by McLeod regarding each of these methodologies and their application, are summarised below:

District Water Balance – An annual water balance for each district was conducted, with assumptions regarding difficult to quantify components of the water balance. From the water balance, the volume lost to seepage was determined for each year of the study period.
Comment: Estimates of seepage loss should be accompanied with upper and lower bounds based upon realistic estimates of the errors in each of the components of the water balance. Ignoring difficult to quantify terms generally inflates the estimate of seepage.

Seepage Rates – The annual loss to seepage was estimated by assuming an appropriate seepage rate for each site, based on published seepage rates for similar soil types. This assumed seepage rate was combined with the channel geometry to determine the overall loss rate.

Comment: The seepage losses used were taken from foreign publications and work conducted overseas, ignoring the results of comparable studies in south-eastern Australia. In many cases the hydrogeological conditions associated with the applied seepage rates did not match the conditions in which they were being applied.

Darcian Principle – Seepage was determined using the principles provided by Wachyan and Rushton (1987) for seepage loss as a function of saturated hydraulic conductivity, channel and aquifer geometry and groundwater conditions. The saturated hydraulic conductivity was estimated based on published values for similar soil types.
Comment: This method was inappropriately applied, as critical to the calculation is the determination of the distance from the channel centreline to the assumed depth to groundwater. However the choice of this distance was arbitrarily chosen. Furthermore, Wachyan and Rushton (1987) present a number of different channel aquifer configurations. The method used to choose the appropriate configuration was not described. Finally, the method of selection of the appropriate hydraulic conductivity was "inadequate".

Cause-Effect Study - The amount of groundwater accession was estimated from the amount of accession required to produce the average annual rise in the groundwater table in the district.
Comment: "The description of the cause-effect study …. is inadequate and the logic used in sustaining the argument is poor. There appears to be no detailed appreciation of the inaccuracies in such an approach and, as presented, little value can be attached to this cause-effect study."

Idaho Seepage Meter – The Idaho Seepage Meter was used to directly measure seepage losses. A total of 222 observations were performed at 11 sites.
Comment: That the seepage estimates by direct measurement (Idaho) are one fifth of those estimated by indirect methods (seepage rate and Darcian) is ignored in the report. The discrepancy between the direct and indirect estimates of seepage loss should have been investigated.

McLeod concludes that given the level of the investigation, the seepage rate method is the most appropriate for the estimation of seepage losses, if the seepage estimates are based on irrigation channel systems in south-eastern Australia.

The report includes a brief summary of seepage studies within south-eastern Australia, including Webster (1984), Long (1989), McLeod (1993) and Tiwari (1995). Comments are also made regarding the economic analysis, which McLeod recommends is updated with the revised seepage figures, and that the benefit-cost ratio be re-determined for all identified seepage sites.

Report II – 'Further Work' (May 1996)
The second report addresses issues raised in the first review. As part of the review revised seepage estimates are presented for the Berriquin Irrigation District, and upper and lower bounds of the seepage estimates have been

prepared for the total seepage loss. The effect of prior stream formations on channel system seepage losses were estimated. A list of sites was identified to be tested by Murray Irrigation Limited, with pondage tests indicated as the preferred method of measurement.

The usefulness of the Idaho seepage meter is also discussed. McLeod recognises the advantage of determining the calibration between results of an Idaho meter and the results of the more accurate pondage method. "This would enable the former (Idaho meter) to suffice where physical, temporal or financial constraints preclude the latter."

A case study in the Coleambally Irrigation Area based on pre and post-remedial seepage measurements reveals the cost of the works on the channel could not be justified based upon the value of seepage mitigation alone. The report recommends that any organisation providing funds for seepage mitigation should make such funding conditional on the performance of pre-treatment and post-treatment seepage measurements and on a benefit-cost analysis.

McLeod, A.J., 1996.
Review of Murray Region Seepage Investigations.
Department of Land and Water Conservation. Paramatta NSW, Australia.

A New Method Of Detecting Leaks In Reservoirs Or Canals Using Labelled Bitumen Emulsions

Molinari, J ; Guizerix, J ; Chambard, R, 1970.

A method of detecting and localising leaks in natural or artificial lakes, reservoirs, canals, or wells is described. The method consists of injecting an emulsion labelled with a radioactive tracer into the water. The labelled emulsion is entrained into the leakage areas where emulsion particles separate from the water and accumulate. The distribution of these particles, considered as proportional to the specific infiltration flow for structures with interstitial permeability, is then determined by measuring the radioactivity. The plastic properties of bitumen labelled emulsion promote agglomeration of the particles and adhesion to the materials of the revetment or wall to be studied. Preparation and use of a bitumen emulsion labelled with iodine-131 in detecting leaks in a canal are described. This method of leak detection has a wide range of application, and can be used to study relative permeabilities of strata in which wells, pits, or boreholes have been drilled, and to distinguish between areas of varying permeabilities.

Molinari, J ; Guizerix, J ; Chambard, R
Centre D'etude De L'energie Nucleaire, Grenoble (France).
International Atomic Energy Agency, Ser Iaea-Sm-129/47, Isot Hydrol, Vienna, Austria, P 743-760, 1970.
Transl From Fr, 1971. 11 Fi 1971
Document Type: Journal Article

Application of Thermal Infrared Imagery to Canal Leakage Detection
Nellis, M D., 1982

The North Unit Irrigation District of central Oregon is an area of limited water availability. Due to the limited water resources, close monitoring of water conveyance, application, and drainage are required. Consequently canal leakage sites were attempted to be detected using a HRB Singer AN/AAS 14 optical-electronic thermal infrared scanning system, sensing in the 8-14 micron range. The apparatus was flown in an aircraft on May 21, 1979, at 2100 hours and 900 m altitude over the main North Unit Canal in central Oregon. The sensor had an instantaneous field of view of four mrad, producing a ground resolution of approximately one metre for every 300 m of altitude above the terrain. (Therefore the ground resolution was approximately 3m).

Critical to the sensing and interpretation of canal leakage sites was the assumption that leakage adjacent or nearly adjacent to the canal system would result in a higher soil moisture content than non-leakage sites. Soil moisture and soil conductivity are significant factors influencing thermal characteristics of the soil, and thus its appearance on thermal infrared imagery. Additionally, oscillations of temperature in a moist soil are less than in a dry soil area, since sites high in moisture cool slower after sunset and warm more slowly during the day. The net result is that moist sites (canal leakage areas) emit more radiation during the evening hours and less during peak solar radiation hours than the low moisture, or non-leaking sites.

Out of 39 sites showing the characteristics of leakage sites, 12 were verified as actual leakage sites by field analyses; approximately a 30% interpretation accuracy. Inspection of the canal uncovered no leakage sites not appearing on the imagery. Where canal leakage sites were verified by ground observation, characteristics of the leakage site were noted. Verified canal leakage width ranged from 0.6 - 7.3 m (average of 1.7m), and leakage lengths ranged from 12 - 91 m. 75% of seepage sites were oblong in shape, and the remainder were irregular.

The sites misinterpreted as leakage sites featured dense natural vegetation, farm canals, drainage ditches, small holding ponds, or natural depressed drainage areas. This interference could be reduced by taking simultaneous colour photographs. This economical and practical leakage detection method could help save some of the estimated 58,800 acre feet (or 1 acre ft per acre of irrigated land) of water lost to seepage each year in the North Unit Irrigation District. Although the interpretation accuracy was low, a significant amount of time is saved by checking the limited number of sites, rather than the whole system. The tool was positively received by North Unit irrigators and agricultural officials. If organised at an appropriate level, eg irrigation district level, thermal infrared overflights could be cost effective.

Nellis, M D., 1982.
Kansas State Univ. Manhattan. Dept. of Geography
Remote Sensing of Environment Vol 12, No 3, p 229-234, 1982. 4 Fig, 4 Ref.

Donald Main Channel Seepage Investigation - Investigation of Channel Seepage at Ralstons and Sheridans
Sinclair Knight Merz, 1998.

The Donald Main Channel is one of the major channels in the Wimmera Mallee Water supply system and has a long history of seepage problems, investigations and seepage trials. The study, conducted on two sections of the Donald Main Channel was commissioned by Wimmera Mallee Water. The main objectives of the investigation included the quantification of seepage losses from the channel and the evaluation of indirect techniques for the measurement of seepage. Other issues also covered were the delineation of the effects of channel seepage from regional groundwater processes and evaluation of options to reduce the seepage from the channel.

To achieve the project objectives an assessment of background information was conducted, salinised areas were mapped, leakage was quantified through pondage tests, relative seepage was assessed using both EM-34 and constant head permeameter tests, local seepage versus regional groundwater effects were assessed and a literature survey on potential seepage control options was conducted.

A total of six pondage tests were completed with all tests displaying high initial losses in the range of 80 mm/d to 160 mm/d. This was attributed to the initial wetting of the soil profile. After the initial high loss period, the seepage rate was found to be correlated with the wetted perimeter of the channel, with the average seepage rates in the first half of the test varying between 54 mm/d and 82 mm/d.

The constant head permeameter was used to measure the hydraulic conductivity of the soil. This value was used, along with estimates of the hydraulic gradient and seepage path (from adjacent monitoring bores) to calculate the seepage rate based on Darcy's Law. The average permeameter results for each pondage section were used to calculate the seepage rate. A very poor correlation was observed between these results and the pondage test results, with the permeameter values generally significantly underestimating the seepage rates (as determined from pondage tests).

EM34 readings conducted over the length of the channel were averaged and compared with the pondage test results. These results showed a good correlation with the pondage test results, with the best results (correlation coefficient of 0.9) provided by the average of the EM34 values recorded at the toe of the bank and values offset 75m from the toe of the bank. This indirect measurement of seepage using EM34 traverses, correlated with pondage test results, showed significant promise for the identification and quantification of seepage in other parts of the Donald Main Channel, and possibly to other channel systems.

Sinclair Knight Merz, 1998 (Report produced for Wimmera Mallee Water)
Donald Main Channel Seepage Investigation - Investigation of Channel Seepage at Ralstons and Sheridans
September, 1998.

Donald Main Channel Seepage Investigation - Additional Electromagnetic Survey Investigations
Sinclair Knight Merz, 1999.

During 1998 an investigation to estimate seepage from two lengths of the Donald Main Channel was conducted. EM34 results in this initial investigation showed a strong correlation to the pondage test results. The aim of this further work was to more fully appraise the ability of electro-magnetic (EM) surveys to provide a comparatively in-expensive means of determining the relative and absolute channel seepage rates.

The best correlation between EM response and channel seepage was obtained using an EM34 along the channel toe at a10m coil separation, and during channel full conditions. The improved relationship when the channel is full was attributed to the increased presence of fresh water leaking from the channel. Traverses conducted along a line 35 metres downgradient of the bank provide a similarly high correlation. Traverses conducted beyond 50 metres from the channel toe are unlikely to produce a reasonable correlation with seepage rates. Small improvements in correlation between seepage rates and resistivity were observed with the use of the EM34 at a 10m coil separation distance, over a 20m separation distance.

Surface land salinisation caused by channel seepage has an opposite EM response to the channel seepage itself. Changing the coil separation allows the targeting of both processes. EM38 with a very short coil separation is best used for investigating the land salinisation resulting from channel seepage. The study concluded that the optimum coil separation and EM equipment for investigating the process of channel seepage is likely to depend on site conditions such as depth to water table. At the Donald Main Channel site, EM34 with a coil separation of 10 metres provided the best correlation with channel seepage, while the EM31 appeared to be measuring a combination of both channel seepage and land salinisation. It was therefore not particularly useful in providing information on either process.

Sinclair Knight Merz, 1999 (Report produced for Wimmera Mallee Water)
Donald Main Channel Seepage Investigation - Additional Electromagnetic Survey Investigations
April, 1999.

Measurement Of Seepage From Earthen Irrigation Channels
Smith, R.J. and Turner, A.K., 1982.

The tests described in this paper were part of a continuing program by the State Rivers and Water Supply Commission, Victoria, to identify and reduce sources of water loss in distribution. Methods for the detection and measurement of seepage from earthen channels are described. A seepage meter based on the constant head 'Idaho' meter was tested in an irrigation channel located in the Goulburn Valley of Victoria. The soil resistivity technique for the detection of seepage was also tested along the same length of channel. In addition, it was shown that a layer of sediment deposited as a liner within the channel was dominant in minimising seepage.

An introductory section on seepage detection and measurement describes visual inspection as the most basic of seepage detection tools for areas of very high seepage loss. However it is noted that surface effects may not always be evident on land adjacent to channels, even in high loss channels. Aids available for improving the efficiency of the detection of seepage are listed as: i) soil classifications, ii) aerial surveying, and iii) soil resistivity measurements. While difficulty using soil classifications for detailed hydrological investigations is noted by several workers, such systems do have a role in reconnaissance for seepage, particularly in the location of prior streams and other highly permeable alluvial deposits.

The use of aerial infra-red photography for the detection of seepage was outlined by Shaw (1963) and demonstrated in Victoria by Currey (1971). Currey used both colour and infra-red photography to infer zones of high seepage along a channel by detecting areas showing severe waterlogging, surface salting and changes in vegetative health. Smith and Turner note that this technique has the advantage of speed, but suffers the same limitation as visual observation, that seepage must have a visual expression for detection to be possible.

Based on work by Wantland and Goodman (1962), which showed the electrical resistivity of the soils beneath a channel to be an indicator of the likelihood of seepage, electrical resistivity tests were conducted. Wantland and Goodman (1962) proposed that suspected sections of high loss along the length of channel are identified if they are markedly different in resistivity (usually lower) from the adjoining sections. Interpretation of the results must be based on a knowledge of the soils in which the channel is located and the salinity of the groudwater.

Direct and indirect methods of estimating the magnitude of seepage are described. Indirect measurement "involves the measurement of hydraulic conductivities and groundwater levels, and the simulation of the seepage flow using either a mathematical or analogue model". An important note is made that unless the sealing effect of the sediment deposits on the bed of the channel is considered, these techniques are only suitable for new or recently re-modelled channels. The standard methods of direct measurement used by the State Rivers and Water Supply Commission are in the inflow-outflow and ponding methods. Seepage meters are described as a convenient method for defining relative areas of high seepage loss.

The initial field tests for the project were carried out at Shepparton East, and area of irrigated orchards. An Idaho meter was used in the seepage meter tests. Electrical resistivity tests were conducted with a four electrode resistance meter in which the energising current is provided by a small hand generator, in conjunction with a Wenner array of four electrodes. Electrode spacings of 3m were used in the traverse. A major limitation noted was that the results are essentially point measurements and not a continuous record of the variation of resistivity along the channel. An analogue model, described by Mein and Turner (1968) was also used to predict seepage rates.

Results
A total of 164 Idaho seepage measurements were taken, with the results showing a positively skewed data set (a function of the large number of low measurements). From analysis of the data it was concluded that the seepage meter can give a measure of the total seepage loss from a length of channel, provided a sufficient number of measurements can be taken. The number of measurements required is a function of the variability of the measurements and the desired accuracy of the seepage estimate. The seepage rates to the left and right of the channel centre were found to be significantly higher than the seepage rates in the centre of the channel, often by more than an order of magnitude. No consistent relationship could be established between the seepage rates (from Idaho meter) and the soil type.

The electrical resistivity tests indicated the regions of highest seepage coincided with high values of resistivity. "This is contrary to the findings of previous studies, (eg Wantland and Goodman, 1962) where low values of resistivity were seen as the best indicator of seepage." Turner and Smith concluded that the resistivity traverse did not locate the zone of high seepage but only detected the shallow coarse sand aquifer that was coincident at this point.

Seepage rates predicted using the analogue were far in excess of the seepage rates measured by ponding and the seepage meter. This difference was attributed to the presence of a sediment layer, whose presence was not included in the analogue model.

In an attempt to broaden the range of conditions under which the Idaho meter was tested, further testing of the meter in other channels in Northern Victoria was conducted. Of the 277 measurements taken only 89 were reported as successful. The high failure rate of the instrument was attributed to the sediment layer present in these channels, and the methane gas produced in the bed sediments.

Smith RJ; Turner AK, 1982
Source: Transactions of The Institution of Engineers, Australia: Civil Engineering. V CE 24, n 4, 1982. Paper C1357. p 338-345, Pu: Barton: IEAust, Coll.: 8p charts 22 refs

Inflow-Outflow Infiltration Measurement Accuracy
Trout, T.J. and Mackey, B.E., 1988.

Furrow infiltration and channel seepage are often measured with inflow-outflow measurements. Inaccuracy in the flow measurement will cause a larger uncertainty in the calculated infiltration. The infiltration rate determination uncertainty increases rapidly as the percent of the inflow that is infiltrated decreases. The effect of measurement uncertainty on infiltration measurements can be estimated so that the confidence interval of a mean or the actual infiltration variability level can be determined. The analysis provides engineers and soil scientists with the tools required to provide a statistical basis for the uncertainty in infiltration measurements.

The analysis yielded the following conclusions:

1. Inflow-outflow infiltration determination uncertainty varies with the flow measurement uncertainty and can be large.
2. Inflow-outflow infiltration determination uncertainty increases rapidly as the percent of inflow that is infiltrated decreases. Therefore, accurate infiltration measurement requires measuring long furrow sections in which much of the flow in infiltrated.
3. Using the same type of device to measure inflows and outflows will usually decrease the effects of any systematic errors.
4. Due to high spatial variability, measuring several furrows is critical to determining the average infiltration rate with confidence.
5. Measured infiltration can be corrected for measurement process uncertainty.

Trout, T.J. and Mackey, B.E.
Corporate Source: USDA, Kimberly, ID, USA
Source: Journal of Irrigation and Drainage Engineering v 114 n 2 May 1988, p 256-265, 7 refs.
Document Type: JA; (Journal Article) Treatment: X; (Experimental)

Water Losses From Irrigation Canals

Wachyan, E. and Rushton K.R., 1987

This paper investigates the water losses from a canal to an aquifer. From field measurements large losses from canals have been identified, even when the canal is lined. The reasons for these losses are investigated by performing numerical model solutions for a series of examples with different conditions at the lower boundary of the aquifer, at lateral boundaries and at the watertable within the aquifer.

This paper expands upon the analytical solutions to channel seepage developed by Bouwer (1969). The two limiting conditions used by Bouwer are concerned with an aquifer having an underlying layer of a very high hydraulic conductivity or an aquifer with an impermeable base having a lateral boundary at which groundwater heads remain at constant value. A closer examination of these two conditions indicates they rarely occur in practice. Additional conditions are described in this paper which relate more closely to practical situations. These include an underlying layer of lower hydraulic conductivity and a loss of water from the vicinity of the watertable due to evaporation or water taken from storage. For each of these conditions, the canal losses are generally higher than the values based on the existing approaches. Consideration is also given to the influence of the size of the canal and the effectiveness of various forms of lining. A final section presents three alternative situations which can apply at different stages during a typical year.

Partial lining of a canal is shown to have little effect on the magnitude of the losses and total lining which contains defects is also ineffective. The paper emphasises the need for detailed field work into the conditions within aquifers in the vicinity of canals.

Wachyan, E. and Rushton K.R., 1987
Department of Civil Engineering, University of Birmingham, Birmingham, UK.
J. Hydrol., 92: p 275-288. 8 refs

Estimating Seepage Losses From Canal Systems
Worstell, R.V., 1976.

Seepage and operational losses from distribution systems are continuing problems for designers and managers of irrigation districts and for water users. The designer must provide sufficient capacity in the canals to allow for those losses, and the managers must divert extra water into parts of the system to assure ample flow to the lower reaches of all laterals. The water users must provide for ample storage to offset seepage losses. The managers also have to deal with more complex legal and technical problems that arise if seepage losses cause high water tables in fields adjacent to the canal.

As demands increase on all the water supplies of the West (of the USA), regional and state resource management agencies are looking critically at the large volumes of water diverted by agriculture, especially when these volumes are much larger than the amounts used in evapotranspiration. These agencies need guidelines for more accurately determining reasonable water diversions to irrigated agriculture. A simplified method that engineers and resource planners can use to estimate seepage losses from new or existing canal systems is presented in this paper.

Canal seepage rates for broad soil textural groups were evaluated by analysing results of 765 tests made in the western United States. Seepage rates varied widely within each broad texture class, but the average rates for all the classes ranged from 0.06 m/day to 0.6 m/day. Seepage rates were less than 0.3 m/day in most tests. Average rates were similar, whether measured by ponding or by seepage meter. No significant linear regression was found between canal dimensions and seepage rates within any one soil texture group. Average seepage rates for lined canals ranged from 0.03 m to 0.3 m/day. These average rates will be useful for irrigation system designers and resource planners for estimating seepage losses for existing or planned systems. Average rates will also be helpful in evaluating alternative improvements in water management, such as canal-lining programs, modernising measurement and delivery methods, and installing computer-controlled automatic regulation of diversions and deliveries.

Worstell, Robert V., 1976
Corporate Source: Snake River Conserv Cent, Kimberly, Idaho
Source: American Society of Civil Engineers, Journal of the Irrigation and Drainage Division v 102 n 1 Mar 1976 p 137-147, 22 refs.

National Handbook of Recommended Methods for Water Data Acquisition ,1997.

Conveyance loss (evaporation and seepage) can be measured after the return flow of one user and before the withdrawal of the next user. Conveyance loss also can be measured by determining the loss attributable to canal seepage and adding an estimate of evaporation. Several methods commonly are used to measure canal seepage are discussed in this handbook, including ponding tests, inflow-outflow studies, and seepage-meter studies.

Ponding tests give the most reliable results. To conduct a ponding test (Rohwer, 1948), a section of canal is blocked off with dams at each end and filled with water to, or slightly higher than, the level at which it usually flows during the irrigation season. As the water level in the canal section declines, the time is recorded and a seepage rate determined. Necessary corrections for temperature and evaporation are made and the seepage loss-rate computed. Ponding tests are usually conducted during the non-irrigation season, and are applied in a non-flow situation in which actual flow conditions are not being met.

Inflow-outflow studies are conducted using long reaches of the canal and require the least extrapolation of the three methods. However, the inaccuracy of an inflow-outflow measurement is proportionate to the total flow in the canal, and can be a much larger value than the amount of seepage that occurs in a reach that has little seepage. Inflow-outflow studies using discharge measurements are described in detail by Rantz and others (1982). One of the major advantages of using the inflow-outflow method is that it can be applied during the irrigation season.

Seepage meters sometimes are used to determine seepage rates at certain locations on the canal. Obtaining a tight seal on the canal bottom or sides, however, is a problem; therefore, the use of seepage meters is not appropriate in canals with rocky or rubbly perimeters or in canals with flow velocities faster than 2 feet per second. Because seepage rates may vary considerably from point to point, many measurements need to be made throughout the length of the canal to achieve an acceptable average value. Seepage meters probably are most helpful in determining rates at specific locations along the canal, and in determining relative seepage rates at different locations. Seepage meters probably are best used while the canal is in operation. However, because of variable and sometimes erratic values obtained in measurements using the seepage meters, they are seldom used.

In order to extrapolate seepage measurements throughout the evaluation area, the canal system needs to be adequately described. Reaches need to be classified by soil type, conveyance properties (mean flow, wetted perimeter, and slope), and geohydrologic setting. Generally, soil type and conveyance properties are known, but the geohydrologic-setting analysis commonly is inadequate. The hydraulic conditions under which canal seepage occurs needs to be specifically determined for test reaches, and at least qualitatively estimated for the remainder of the canal system.

Basically, two hydraulic conditions may be present in the canal system: (1) If the water table intersects the canal prism, the pore water in the bank material of the canal will be under positive pressure (greater than atmospheric), and the seepage rate will be controlled by the rate of water flowing in the saturated part of the aquifer; and (2) if the pore water in the bank material of the canal is under atmospheric or negative pressure, the seepage rate will be controlled by the hydraulic properties of the bank material and the gradient underlying the canal. Because the transmissivity of the bank material is greater than the transmissivity of the aquifer, seepage will be greater for the bank material than for the water-table condition. The geohydrologic setting can be determined by use of transects of piezometers or wells or both. If the geohydrologic setting is not the same during the seepage test as during normal operation of the canal, use of test results to estimate annual seepage loss is not appropriate.

1997 - (Internet location: http://water.usgs.gov/pubs/chapter11/chapter11H.html)

A.2 Secondary References

Investigation of Channel Seepage Areas at the Existing Kaffrein Dam Site (Jordan) Using Electrical Resistivity Measurements

Abu-Zeid, N., 1994.

A geoelectrical resistivity survey was carried out in the existing Kaffrein dam site, near the Dead Sea, Jordan, in order to investigate channel seepage (underground channel seepage not open channel seepage) and the hydrological conditions of the alluvial deposits in the upstream as well as downstream areas of the dam. The data from the electrical resistivity survey were interpreted by the classical curve matching and computer modelling techniques. Fifteen vertical electrical soundings (VES), utilising the Schlumberger array, Abem Terrameter SAS 300 B and SAS 2000 booster, were conducted in the area. The lengths of these soundings extend up to 800 m.

The study concluded that the vertical electrical resistivity sounding method can easily differentiate between saturated zones and less permeable clayey horizons. Interpretation of resistivity data confirmed the existence of low to moderate resistivities (54-108 Ω.m) at depth (in the alluvial deposits), which may be attributed to the presence of percolating water that also flow beneath the axis of the dam. Shallow boreholes (less than 20 m) drilled in the downstream area to monitor seepage, have confirmed the findings of the resistivity survey. This study demonstrated the usefulness of electrical resistivity measurements in detecting seepage zones under the dams, and concluded that the method is relatively efficient, practical and economical in solving some of the geotechnical problems related to dams.

Abu-Zeid, N., 1994.
Corporate Source: Univ of Ferrara, Ferrara, Italy
Source: Journal of Applied Geophysics v 32 n 2-3 Aug 1994. p 163-175, 12 Refs.

Salt Penetration Technique For Seepage Measurement

Bouwer H. and Rice, R.C., 1968.

Seepage rates in open channels or reservoirs are determined from the rate of salt penetration into the bottom material. A portion of the bottom is covered with crystals of a non-deflocculating salt. After dissolving, part of the salt enters the bottom with the seepage flow. The rate of advance of the peak of the resulting salt concentration 'wave' in the bottom material is measured with an electrical-conductivity probe. Laboratory studies showed that the seepage rate could be calculated by multiplying this salt penetration rate by the porosity of bottom material. A field study in a reservoir showed excellent agreement between the seepage obtained in this manner and the rate of fall of the water surface. The salt-penetration technique is simple and it can be carried out under a wide variety of canal conditions.

Bouwer, Herman; Rice, R C
Agricultural Research Service, Phoenix, Ariz. Water Conservation Lab
Asce Proc, JOURNALIrrig And Drainage Div, Vol 94, No Ir4, Pap 6304, Pp 481-492, Dec 1968. 7 Fig, 2 Tab, 2 Ref. Document Type: Journal Article

Regolith Permeability Maps From Airborne Geophysical Data and Their Use in Dryland Salinity Control

Clarke C.J., Anderson Mayes A.M., Beeston G., Street G.J., George R.J., and Bell R.W., 1998.

Widespread clearing of native vegetation in the wheatbelt of Western Australia has dramatically changed the hydrological balance, resulting in substantial land degradation, altered groundwater flow, increasing saline seepage and stream flow in affected catchments and lessening effectiveness of revegetation. Major faults, minor faults, mafic dykes and Tertiary sediments all influence the development of dryland salinity because of permeability contrasts with the dominantly Archaean granite and gneiss basement of the region. Airborne magnetics, radiometrics and the SALTMAP measurement of regolith electrical conductivity are being used to map these geological features with minimal manual involvement. Borehole slug tests are being used to assign permeability ratios to the four other geological features compared to the Archaean granites and gneisses. The resulting permeability map will be use in computer groundwater models to improve predictions of revegetation strategies.

Clarke CJ, Anderson Mayes A M; Beeston G; Street GJ; George RJ; Bell RW
Source: Groundwater: sustainable solutions: International Groundwater Conference, 8 -13 Feb 1998, Melbourne VIC, Proceedings, Weaver, TR (ed) and Lawrence, CR (ed). International Association of Hydrogeologists, Australian National Chapter Indooroopilly QLD, 1998, ISBN 0646351273, p243-248,

A Note On The Origin Of Wet Seams In Embankment Dams

James P.M., 1993.

Concentrated seepage horizons, or wet seams, occur in the impervious zones of many embankment dams. Their presence has traditionally been taken as a manifestation of hydraulic fracture, even when this mechanism is difficult to justify. An alternative origin is suggested below, briefly focussing on the adverse role of calcitic soils and the manner in which they can produce porous horizons in otherwise well compacted fill.

James P.M., 1993. ,SO: Australian Geomechanics. n23, March 1993. p79-80, PU: Barton: IEAust, 1993

Measurement Of Seepage From Field Channels - A Review

Misra, N. and Satyanarayana, T., 1986.

Methods of measuring seepage are necessary in order to determine the magnitude of the losses and also to isolate reaches of channels where high seepage losses are occurring. Water is becoming increasingly valuable and it is necessary to determine whether the economic value of the water saved and the land reclaimed plus the savings in the cost of operation and maintenance will exceed the cost of lining. It is also desirable to determine whether a new channel should be lined before construction is started. Attempts have been made in this paper to discuss the various methods available to measure the seepage losses in field channels.

Misra, N. and Satyanarayana, T., 1986.
Indian Inst of Technology, Kharagpur, India Source: Journal Inst Eng India Part AG 1 v 67 Aug 1986 p 57-60, 12 refs

Seepage Detection By Remote Sensing

Ory, T.R., 1969.

A number of remote sensing techniques have been shown to have application in the detection and evaluation of seepage. Radar and infra-red sensors are presently available for use in seepage detection research and, to a limited extent, for operational work. When these sensors are used after a careful analysis of the detection problem, and with utilisation of the information available from conventional techniques, the success probability of remote seepage detection should be very good. Future research will undoubtedly yield less expensive and more reliable remote sensors for this application as the payoffs from initial employment begin to stimulate their use.

Ory, Thomas R, 1969.
Hrb Singer, Inc., State College, Pa. Radiometric Lab. Proc 2nd Seepage Symp, Phoenix, Ariz, Mar 25-27, 1968, Agr Res Serv Rep, 41-147, P 128-133, 1969.

Seepage in Small Irrigation Channels

Panigrahi, B, Behera, B P and Nayak, S, 1998.

The study of seepage was conducted in the lined and unlined channels at village Bilamugabadi in the district of Kendrapara of Orissa. The measurement of seepage losses was carried out using pondage tests. Cumulative seepage values and seepage rates were calculated for both unlined and lined channels at different points from the delivery tank and for different time intervals. Relationships between cumulative seepage and seepage rates with time were studied for unlined and lined channels and models developed. The average seepage rate in the unlined channel was calculated to be 46.19 cm^3/cm per day, which was significantly higher than the average seepage rate of 9.09 cm^3/cm per day obtained in the brick masonry lined channel. The seepage rate was found to decrease with time for both unlined and lined cases and the relationship between them was found to be linear for a duration of 1 hour 30 minutes and 4 hours 30 minutes, respectively.

Panigrahi, B ; Behera, B P ; Nayak, S
Water Manage. Project, RRS, OUAT, Chiplima 768025, India
ENVIRONMENT AND ECOLOGY Vol. 16, no. 1, pp. 85-88 1998

Detection Of Subsurface Seepage Between Aquifers By Hydrochemical And Environmental Isotopic Techniques - A Case Study From South Australia

Ramamurthy, L.M. and Holmes J.W., 1983.

The rising salinities and sources of recharge to a confined aquifer by vertical seepage from an overlying unconfined aquifer and by lateral seepage from a freshwater lake (Lake Alexandrina), were investigated using major ions and environmental isotopes. The studies indicate that there is no detectable recharge to the confined aquifer from Lake Alexandrina, and that vertical seepage is from point sources, possibly due to faulty, corroded and leaky borehole casings which form an effective hydraulic connection between the 2 aquifers. A linear correlation between U -concentration and bicarbonate content observed for groundwater proved useful in delineating aquifers and in inferring subsurface seepage between them.

Ramamurthy LM; Holmes JW; (Flinders University of South Australia)
Source: Relation of groundwater quantity and quality: General Assembly of the International Union of Geodesy and Geophysics, 18th, Aug 1983, Hamburg Proceedings, Dunin, F X, Matthess, G and Grass, R A (eds). IAHS Press Wallingford, 1985, ISBN 0947571159, p267-282, 4 tables, 7 figs, 12 refs.
IAHS publication; no 146.

Hydrogeological Investigations for the Wimmera Salinity Management Plan - Mt Zero Channel Leakage Investigation: Laharum Wartook Area
Sinclair Knight Merz, 1999.

This project was undertaken by Sinclair Knight Merz over the period October 1998 to May 1999. The project was administered by Wimmera Mallee Water on behalf of the Wimmera Catchment Management Authority. The investigation was initiated to address the impact of the Mt Zero Channel on land salinisation in the Laharum - Wartook area. Laharum is located on the western margin of the Grampians Ranges in western Victoria.

The main objectives of the project were to identify if the channel leaked, and assuming leakage could be established, identify sections of the channel with high leakage potential, and quantify the recharge volume contributed by the channel compared to recharge from land management changes. In order to achieve project objectives, an EM34 survey traverse was conducted, monitoring bores were constructed adjacent the channel, potential leakage was quantified and the possible increase in recharge resultant from land clearing compared to the change in recharge from channel seepage was quantified. The results of the EM34 survey, verified by the drilling results (Site 1), indicated approximately 25% of the length of channel is leaking within the 5.7 km section surveyed. The bore drilled adjacent the channel in Site 2 contained a predominantly clayey profile and no saturated material was encountered during drilling. Along with the high salinity groundwater, these results indicated that channel seepage is not occurring at this location, which corresponded with the EM survey results. Over the period 1870 to 1998, channel leakage is estimated to have contributed 4% to 7% of the total increase in recharge within the groundwater catchment above Site 1.

Sinclair Knight Merz, 1999 (Internal report produced for Wimmera Mallee Water)
Hydrogeological Investigations for the Wimmera Salinity Management Plan - Mt Zero Channel Leakage Investigation: Laharum Wartook Area, October, 1999.

Seepage Detection Along the Chicago Sanitary and Ship Canal Near Lockport, Illinois
Sjostrom, K.J. and Hotchkiss, G., 1996.

Water leakage between the Chicago Sanitary and Ship Canal and an adjacent stream, was detected and monitored along a concrete retaining wall, at Lockport, Illinois. Waterborne total field and gradient Self Potential (SP) methods, dye tracing, and visual inspection were used to determine seepage paths between the canal and creek and detect and locate possible points of seepage inflow along the canal wall.

The SP method measures naturally occurring voltages in the subsurface generated by either fluid flow or electrochemical processes in the subsurface. Electrical voltages generated by the flow of fluids through the soil or rock is called electrokinesis. The magnitude of the SP signatures depend on the electrical and physical properties of the fluid, the coupling coefficient between the fluid and soil/rock matrix, and the pressure gradient along the flow path. Lower total field SP measurements, with respect to background voltage values, reflect areas of subsurface fluid movement through the canal wall. Self-potentials generated by electrochemical processes in the subsurface, may also contribute to the natural surface potentials. This process is more pronounced along the canal wall where voltages generated by the oxidation of the reinforcing bars in the concrete are likely.

Two techniques, the total field and gradient methods, are commonly used to collect SP data. Measuring the total field SP anomalies requires a fixed reference electrode and a single roving electrode, whereas the gradient method maintains a fixed distance between two measuring electrodes, each positioned at some depth below the water surface.

The waterborne SP method indicated at least five possible seepage inflow areas along a 900 ft section of the canal retaining wall. These areas were detected with both the total field and gradient methods performed at varying depths below the water surface. Movement of water from the canal to the ponded area and seepage outflow area was confirmed by the results of the dye tracing tests and visual inspection of the area. The water discharging at the outflow area is not due to one leak in the canal wall but rather the cumulative effect of several small seeps, each likely occurring at the concrete monolith joints in the canal wall. The locations of the inflow areas will assist any rehabilitation efforts required to reduce water movement through the canal wall.

Sjostrom, K.J. and Hotchkiss, G.
Proceedings on the Application of Geophysics to Engineering and Environmental Problems, Keystone, Colorado, April 28 - May 2, 1996. Sponsored by: Environmental and Engineering Geophysical Society Published by: Environmental and Engineering Geophysical Society, 10200 W. 44th Ave #304 Wheat Ridge, CO USA 80033, April 1996, p377-386, 2 Refs.

Numerical Evaluation of Ring-Infiltrometers Under Various Soil Conditions

Wu, L., Pan, L., Robertson M. J., and Shouse P. J., 1997.

Field evaluation of infiltrometer geometry and of soil conditions on infiltration measurements is difficult because of the spatial and temporal variability of soil properties and the disturbance of soil by infiltrometer installation. Numerical simulation experiments provide a useful tool for evaluating the infiltration rates measured by various configurations of infiltrometers and soil conditions. An axisymmetric 3-dimensional (3-D) numerical model was used to simulate water infiltration in single-and double-ring infiltrometers, as well as one-dimensional (1-D) infiltration for three well studied soil types representing different textures and hydraulic properties.

It was found that the infiltration rates of a single-ring infiltrometer were f times greater than the 1-D infiltration, where f is a correction factor dependent on soil initial and boundary conditions and ring geometry. When the configuration of a typical double-ring infiltrometer was used in simulation (inner and outer rings were 20 and 30 cm in diameter, respectively), the simulated infiltration rates were about 80% of the single-ring rates. When the outer-ring diameter was increased to 120 cm (inner-ring diameter kept at 20 cm), the double-ring method-measured infiltration rates were 120 to 133% of the 1-D infiltration rates for the three test soils. Compared with the constant head method, falling head infiltration rates dropped as much as 30% as the ponded head dropped from 5 to 1 cm in the sandy clay loam. Layered soil can significantly affect infiltration rates, depending on the position of the wetting front relative to the textural discontinuity and the time of measurement. Time at which the layering starts playing the role can be estimated from f and the cumulative infiltration.

Wu, L., Pan, L., Robertson M. J., and Shouse P. J., 1997.
SOIL SCIENCE
An Interdisciplinary Approach to Soils Research
November 1997, Volume 162 Number 11

Appendix B - Glossary of Terms

Apparent conductivity: A method of measuring the induced electrical field in earth to determine the ability of the earth to conduct electricity. The inverse of electrical resistivity. Also known as electrical conductivity and terrain conductivity.

Aquifer: A saturated water bearing rock or sediment formation capable of yielding useful quantities of water.

Aquifer, confined: An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer. When a confined aquifer is intersected by a well the pressure is sufficient to cause the water to rise significantly above the upper level of the aquifer.

Aquifer, semi-confined: An aquifer confined by a low-permeability layer that permits water to slowly flow through it.

Aquifer, unconfined: An aquifer in which there are no confining beds between the saturated zone and the surface.

Bedrock: A general term for the consolidated (solid) rock that underlies soils or other unconsolidated surficial material.

Capillary Fringe: The zone immediately above the watertable, where water is drawn upward by molecular attraction to soil particles.

Capillary tension: The forces acting on soil moisture in the unsaturated zone, attributable to molecular attraction between soil particles and water.

Catchment: The land area from which surface runoff drains into a stream system.

Channel Bed Conductance: The conductance (conductivity divided by thickness) of the naturally forming channel lining (largely due to the depositing of suspended sediment in the water) or, in the event of the removal of this lining, the surface layer resistance.

Electrical Conductivity (EC): Measure of the ability of a fluid (typically water) to conduct electricity (for comparison between water of different temperature, normally reported as equivalent at 25°C). Strongly related to total dissolved solids content.

Full Supply Level (FSL): The maximum level at which a channel is designed to run during the irrigation / operating season.

Geophysics: Techniques which measure the physical properties of soil and rock for the purpose of inferring composition and structure.

Head: The height above a datum plane of a column of water. In a groundwater system it is composed of elevation head and pressure head.

Hydraulic conductivity: The capacity of a rock or sediment to transmit water. A coefficient of proportionality describing the rate at which water can move through a permeable medium.

Hydraulic conductivity (saturated): A variable describing the capability of a soil / rock to allow water to flow through it when it is saturated (i.e. when the soil water content is at a maximum and the soil pore space is completely filled with water [in some cases trapped air may also be present]). Saturated hydraulic conductivity (K_s) varies between soils, typically soils with a high clay content have a lower K_s than do soils with a high sand content.

Hydraulic conductivity (unsaturated): The capability of a soil / rock to allow water to flow through it is a strong function of the soil water content. As the soil water content and soil matric potential decrease, the hydraulic conductivity decreases. The hydraulic conductivity approaches zero when the soil is 'air dry' (i.e. the soil is at or near a residual water content).

Hydrogeology: The science of understanding how fluids move through earth materials such as soil, semi-consolidated and consolidated rock.

Infiltration: The flow of water downward from the land / channel surface into and through the upper soil layers

Isotope: A particular atom of an element that has the same number of electrons and protons as the other atoms of the element, but a different number of neutrons, ie, the atomic numbers are the same but the atomic weights differ. Isotopes have essentially the same chemical properties of other atoms.

Leakage (channel): Loss of water through the banks of the channel via macro-pores in the banks.

Permeability: The measure of the ability of a rock or earth material to transmit fluids. The permeability of a material is dependent largely on the size of the pore spaces and their connectedness.

Piezometer: A non-pumping shallow bore, generally of small diameter, that is used to measure the elevation of the watertable or piezometric surface.

Porosity: The ratio of the volume of pore spaces in a rock or soil to the total volume of rock or soil.

Recharge area (or groundwater recharge): Where surface water (rain, irrigation or streams) infiltrates the soil and adds water to the groundwater system.

Salinity: The total mass of dissolved solids (cations and anions) in a unit of water. It can be measured in parts per hundred (per cent), parts per thousand or milligrams per litre (mg/L), eg 3.5% = 35 ppm= 35,000 mg/L.

Saturated zone: Part of the soil in which all voids, large and small, are filled with water under pressure greater than atmospheric.

Seepage (channel): The loss of water from a channel via infiltration, ie micropores and soil processes. Seepage as measured in pondage tests and inflow-outflow tests includes a leakage component. Generally the term channel seepage refers to both seeped and leaked water, as the two are not separated in practice.

Seepage plume: The horizontal and vertical extent of groundwater which has been mixed with channel seepage water.

Sodium adsorption ratio (SAR): A value used to measure the relative concentration of sodium cations to calcium and magnesium cations in water. The presence of sodium in irrigation water influences the physical properties of the soil, particularly permeability, by affecting the swelling and dispersion of the clay.

Soil matric potential: This variable describes how strongly the water within a soil matrix is bound to the soil by capillary and other forces.

Suspended sediment: Particles upheld in surrounding water by upward component of eddy currents (not dissolved).

Terminal seepage rate: The rate of seepage approached when a seepage mound rises to the elevation of the water surface in the channel.

Unsaturated zone: The zone between the land surface and the watertable. The pores spaces contain water at less than atmospheric pressure, as well as air and other gases.

Watertable: Upper surface of groundwater (ie it is at atmospheric pressure) below which the layers of rock, sand and gravel are saturated with water.

Wetted perimeter: The cross sectional length of a channel covered by water.

“Literature Review of Channel Seepage Measurement and Identification”

Prepared on behalf of ANCID by:

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