Do Surface and Ground Water Interactions Matter in Irrigation Sustainability?

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Abstract

Irrigation is one of the major inputs of primary producers and has an economic effect in Australia, therefore the sustainability of irrigation areas is essential. Currently, in Australia, surface and ground water are licensed and allocated as separate entities, which produces numerous problems. Surface-ground water interactions are understood to a certain extent. The major interactions that occur in a surface-ground water system are seepage from/to channels, leakage from farm dams and lakes and interactions with irrigation systems if they occur. Surface-ground water interactions are time varying and ground water dynamics change over time. Considering the importance of integrated water resource management, a comprehensive knowledge of surface-ground water interactions is essential. Therefore, a rapid assessment technique needs to be developed to enable managers to understand where these interactions occur and what volumes of water are being exchanged between the surface and ground water resources. Conjointly a new water policy framework should be implemented to account for the interactions that occur between surface waters and the aquifers below the soil surface.

Introduction

Irrigation sustainability is essential for primary food production as well as the economy of Australia. The loss of land through salinisation and waterlogging is immense and growing at a steady pace, therefore there is a desperate need to improve our water management skills. One of the options for doing so is through the understanding of surface-ground water interactions within and surrounding irrigation management areas. An improved understanding of this relationship will enhance the available knowledge and possibly alter the water policy frameworks in place around Australia.

Irrigation in the Murray-Darling Basin (MDB) produced a gross revenue of $13.6 billion in 2000/01, with irrigated agriculture accounting for 1.4% of the land and producing 36% of the total profit for the MDB (Bryan and Marvenek, 2004). Therefore, the protection and enhancement of irrigation areas is essential for the economy and for the environmental systems contained and surrounded by them. If the land is degraded through salinisation and waterlogging the ability to produce crops and run livestock reduces, which will in turn have a negative affect on both the economy as well as the remaining land. If more land is lost, the remaining land will be under pressure to produce as much or more than previously, which will lead to further degradation and loss of arable land. This requires a better understanding of water quantity and quality especially in terms of conjunctive management of surface and ground water.

To assist the sustainability of current irrigated land, all knowledge gaps need to be filled, specifically (in this case) the understanding of surface-ground water interactions. Winter *et al* (1998) determined the main types of surface-ground water interactions, which has enabled water managers to better understand the major processes relating to surface-ground water movement. However, since this publication, the expansion of knowledge about the measurement and understanding of these interactions has been limited. Notably in Australia, David Allen conducted his Ph.D research into the identification of seepage using geophysics (2005). As with most other methods of identifying surface-ground water interaction sites, this research was predominantly qualitative. Quantitative methods have been successful in identifying seepage spots, however lack the ability to quantify losses from hundreds of metres of canals.

It is very important to combine the qualitative and quantitative methods to assist water managers. This may be through the development of a rapid assessment technique to quantify channel losses and to detect saline inflow into drains and low lying areas. This research will use a similar geophysics technique as used by Allen (2005) in addition to a ground-truthing approach. These will be merged into a computer model to simulate an irrigation system, namely Coleambally Irrigation Area in New South Wales, to produce an identification and quantification technique for seepage from irrigation canals. The results of this research will enhance the sustainability of irrigation systems as it will enable water managers to determine the cost-benefit ratio of clay lining irrigation supply channels. This paper specifically examines the types of surface-ground water interactions present in irrigation landscapes with Australian examples, the types of techniques currently used to investigate them with the focus on geophysics and how this knowledge may be used to change the water policy framework.

The Types of Surface-Ground Water Interactions

Surface-ground water interactions possibilities are numerous and diverse, with different types occurring at various spatial and temporal scales within the landscape. Winter *et al* (1998) determined that there are five main types of surface-ground water interactions: mountainous, glacial/dunal, riverine (large and small), karstic and coastal (Figure 1).

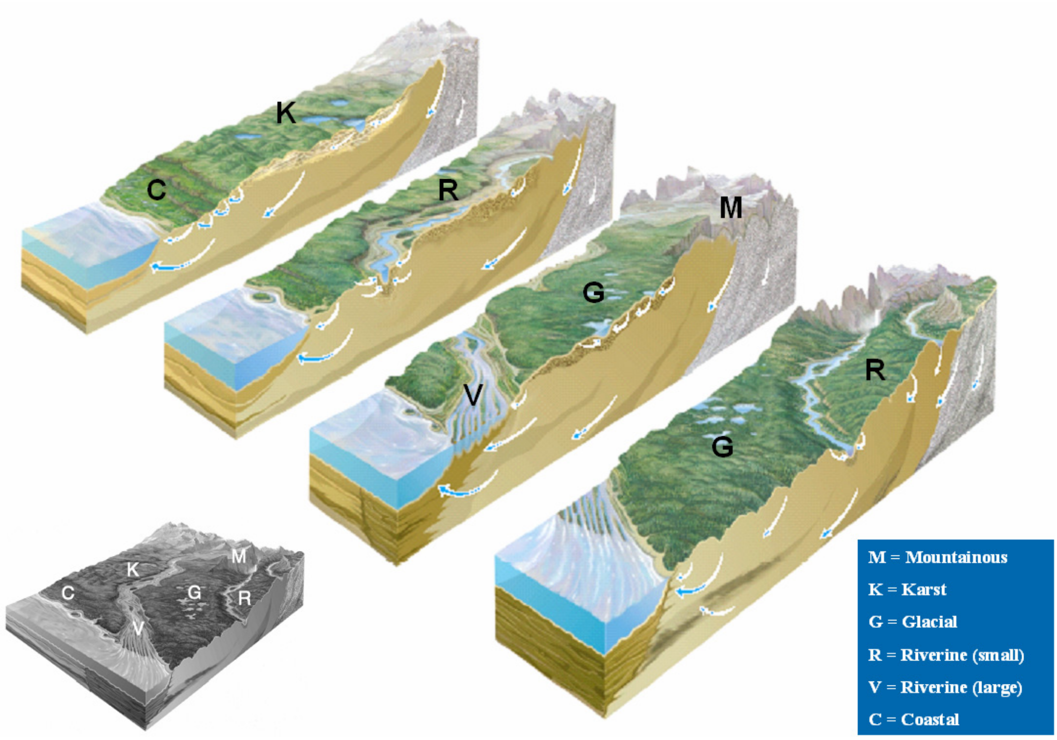

Figure 1. Schematic representation of the 5 main surface-ground water interactions (Winter *et al*, 1998).

Within irrigation systems there are three key surface-ground water interactions occurring, namely seepage to/from irrigation canals/drains, leakage from on-farm dams and interactions with irrigation systems (application methods).

1. *Seepage from/to channels/drains*

Under the scope of the riverine surface-ground water interaction falls the interaction between irrigation canals and the ground water. The effect of these interactions is determined from the height of the ground water level with respect to the water level within the channel, to establish if the surface water seeps down to the ground water. The seepage of surface water to ground water occurs as saturated or unsaturated flow depending on the period of time elapsed and the position of the ground water "mound" below the channel (Figure 2).

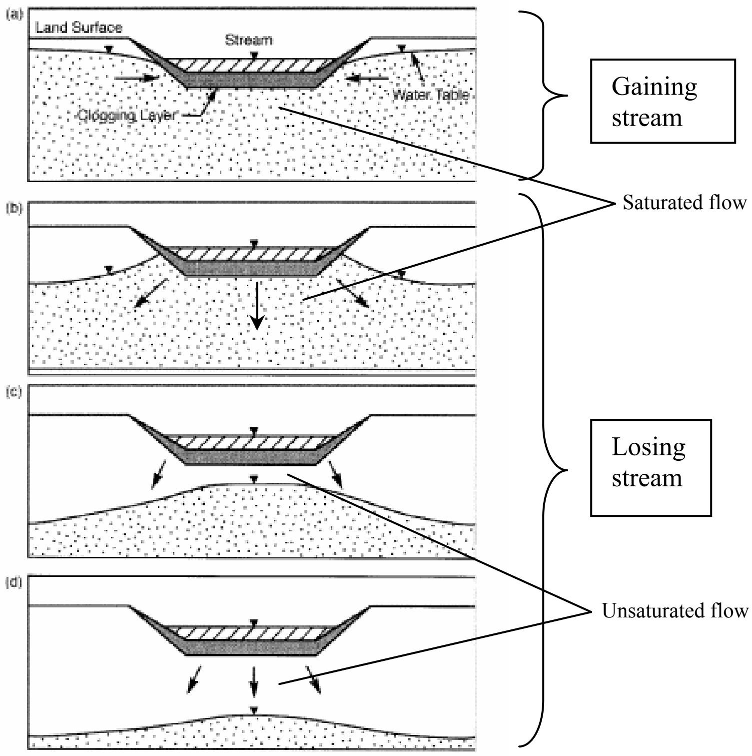

Figure 2. Schematic representation of influent and effluents streams (Peterson and Wilson, 1988). (a) represents a connected gaining stream, (b) represents a connected losing stream, (c) represents a disconnected stream with a shallow aquifer and (d) represents a disconnected stream with a deep aquifer.

2. *Leakage from on-farm dams*

The leakage from on-farm dams falls under the glacial/dune category. Dams can have all inflow from ground water, all outflow to ground water or can have some inflow and some outflow to the ground water. The type of interaction is largely dependent on the position with respect to the local and regional ground water flow systems and the position within the whole farm/field. On-farm dams are also indirectly affected by irrigation; as ground water levels rise the volume of water available from the dam may be altered. Figure 3 depicts the surface-ground water interactions of an on-farm dam.

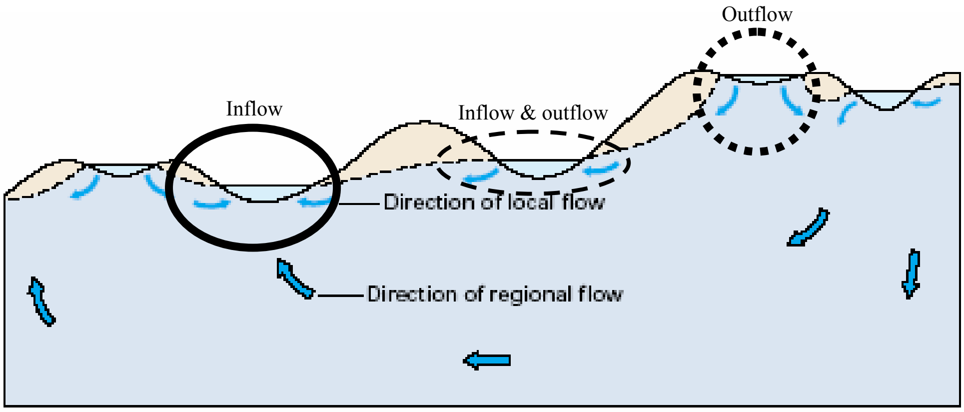

Figure 3. Schematic of on-farm dam surface-ground water interactions (Winter *et al*, 1998).

3. *Interactions with irrigation systems (application method)*

The type of irrigation used on a farm affects the surface-ground water interactions. For example, if a ponding method is used the amount of water infiltrating increases, which causes the seepage rate to the ground water to increase. This can cause a rapid and steady increase in the water table height, leading to secondary salinisation and/or waterlogging of agricultural fields. In comparison, if drip irrigation is used, the wetted perimeter of the soil is significantly reduced and relies on soil suction pressure to disperse the water. This decreases the amount of seepage to the water table, which decreases the possibility of waterlogging and soil salinisation. However, this could have a detrimental effect if most seepage is stopped the water table height may drop, causing lower baseflows in local rivers and producing a higher occurrence of salinisation in the wetted area. Figure 4 provides a schematic representation of a rice field under flood irrigation and an orchard under drip irrigation.

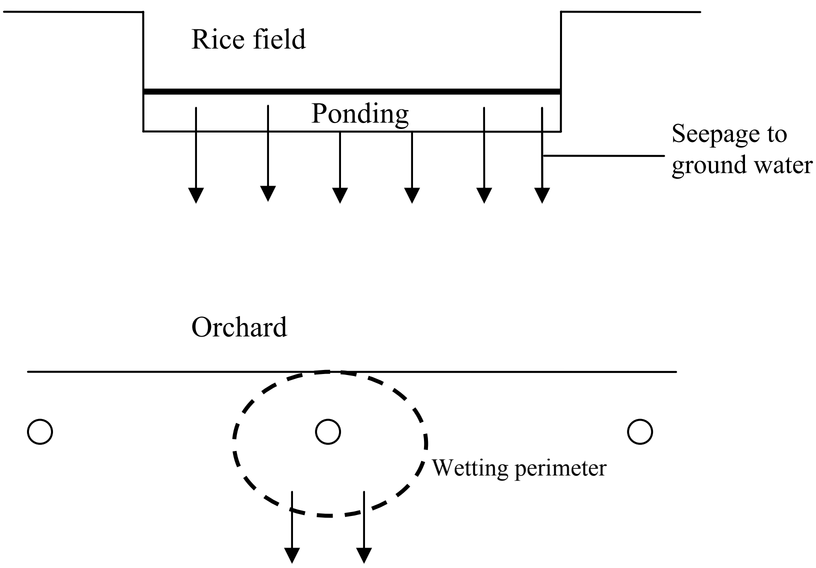

Figure 4. Schematic representation of the seepage from different types of irrigation methods.

Australian Examples of Surface-Ground Water Interactions

Understanding surface-ground water interactions is essential for water management; however an understanding of how these interactions alter on spatial and temporal scales is also fundamental. An example of how surface-ground water interactions alter is a comparison of watertable depths prior to irrigation in the Coleambally Irrigation Area (NSW) to 40 years later. Prior to the setup and implementation of irrigation in the region the watertable depths were well below the soil surface (approximately 25 metres below the soil surface). In this situation all the channels in the area were losing channels. Compared to the mature irrigation system (40 years later) where the watertable has risen to within 1-2 metres of the soil surface creating salinity and waterlogging issues. In this situation hydraulic gradients under some of the losing channels and low lying areas have reversed and therefore they are now gaining saline groundwater from the surrounding areas. Further detailed examples of how surface-ground water interactions alter in irrigation systems, specifically looking at the Murray-Darling Basin (MDB) are given below.

The Condamine Aquifer System in the Northern MDB

The use of the Condamine alluvial aquifer system has been increasing due the increased cropping development in cotton and maize. The alluvial aquifer system consists of varying bands of sands and gravels interbedded with clay aquitards (Huxley, 1982). Figure 5 shows the shape of the bedrock which indicates a relatively thick alluvium exists in the vicinity of the river. Responding to increased water abstractions the aquifer's water levels are showing an overall declining trend (about a 10 metre decline in 10 years), suggesting there has been greater use of groundwater compared to the amount of recharge.

The estimated average groundwater use in this area is around 30,000 ML/year to 50,000 ML/year with average recharge of around 20,000 ML/year. An extensive groundwater depression (greater than 25 metres in depth) has developed in the area. Figure 6 shows groundwater pressure decline at some of the piezometers due to the increased abstractions in the area. However, these piezometers also show a rapid annual recovery of around 10 meters.

This recovery pattern suggests a strong connection between the aquifer system and the Condamine River and its tributaries. Further suggesting reduced groundwater levels in the aquifer have been responsible for attracting extra recharge from the river. The overall sustainable development potential of both the surface and groundwater needs to be considered together.

Groundwater modelling studies by the Department of Natural Resources (1997) also concluded that river leakage is the main source of groundwater recharge (over 60 percent of total annual recharge). However, in their study the river-aquifer interactions may have been underestimated due to very low specific yield parameters (e.g. 0.01?) used for modelling shallow aquifers. Lower specific yields show greater rise in water levels per unit recharge. In an effort to match the history of groundwater levels close to the river the use of lower specific yields means river parameters need to provide less recharge. There is a need to re-evaluate sustainable groundwater development levels in this aquifer system by critically evaluating model assumptions.

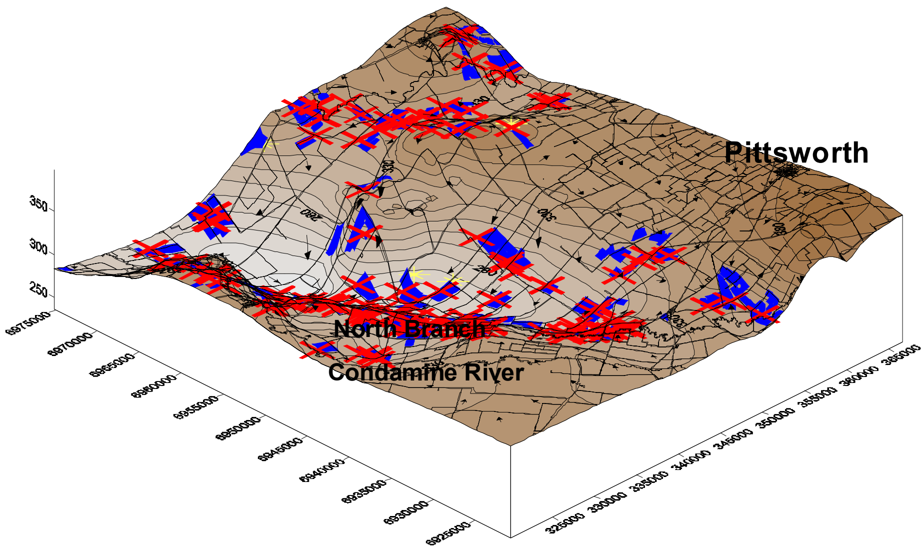

Figure 5. Shape of bedrock of the Condamine aquifer.

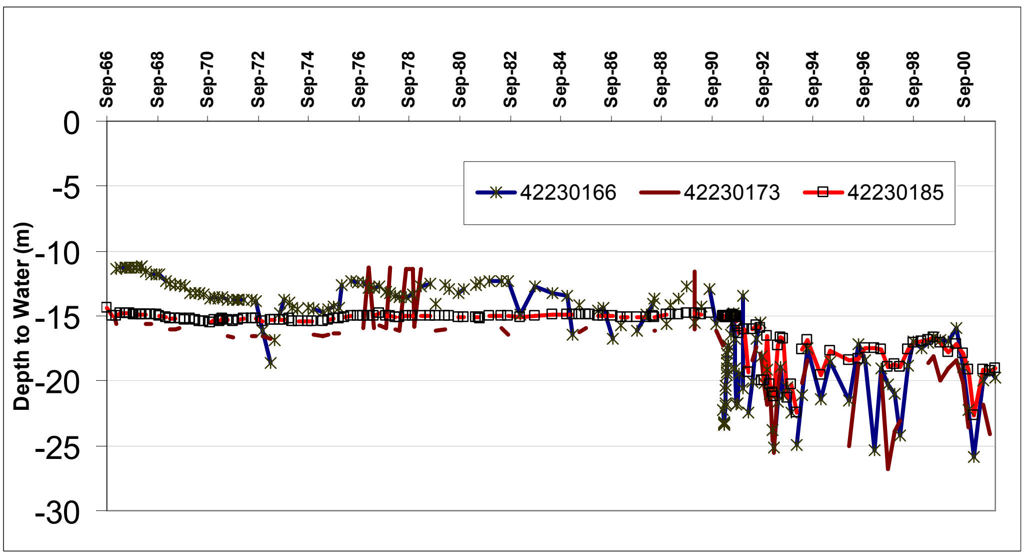

Figure 6. Groundwater levels – Condamine aquifer.

The Mid-Murrumbidgee Aquifer System in the Southern MDB

The mid-Murrumbidgee alluvial aquifers are broadly classified as an upper unconfined Cowra Formation and a lower confined Lachlan Formation (Wooley, 1991; Lawson and Webb, 1998). The Cowra formation consists of low yielding (<15 L/s) sands which vary in thickness from around 15 m near Gundagai to 35 m near Narrandera. The groundwater salinity of the Cowra formation between Gundagai and Wagga Wagga is less than 1.6 dS/m and increases between Wagga Wagga and Narrandera. The Lachlan Formation consists of well-sorted sands and gravels varying in thickness from around 10 m near Gundagai to 125 m near Narrandera. The pumping rates of current bores in the Lachlan formation vary from 5 L/s at Gundagai to over 150 L/s near Narrandera. Town water supplies from the borefields of Gumly Gumly and Wagga Wagga for 1998/99 were 21,190 ML (Gumly Gumly 3,650 ML, Wagga Wagga 12,932 ML). Aquifer salinity is low (less than 0.85 dS/m) near the river, indicating frequent recharge and discharge from the river. Aquifer salinity increases away from the river to levels greater than 5 dS/m.

The estimated annual recharge to the Middle Murrumbidgee aquifer is around 127,000 ML (Webb, 2000). The current entitlements are around 55,000 ML. The direct impact of pumping on enhanced recharge from river flows for bore 30332 is shown in Figure 7. After an initial drawdown of around 5 metres, subsequent good recovery of summer drawdowns (over 10 metres) every year confirms that the Gumly Gumly scheme is drawing a significant amount of water directly from the river. These surface-groundwater interactions have been confirmed for the mid and the lower Murrumbidgee aquifers by Khan *et al* (2003) and Baarten and Gates (2003) using a monthly water balance approach.

This situation also illustrates the changed groundwater dynamics following changes in pumping and therefore the necessity to consider surface and groundwater as a linked resource and be able to measure and identify these interactions.

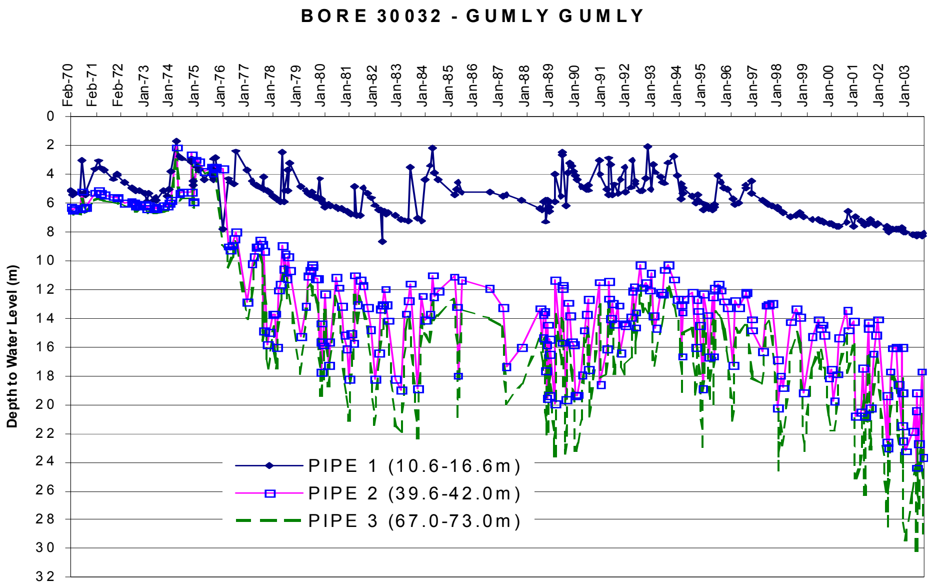

Figure 7. Groundwater Response Close to Gumly Gumly Borefield.

Techniques for Quantifying Surface-Ground Water Interactions

As indicated in the previous section it is essential to know and understand surface-ground water interactions for the management of water systems. However, to be able to know what types of interactions are occurring some type of methodology is required to measure/indicate where surface-ground water interactions may be occurring. In Australia, the Australian National Committee on Irrigation and Drainage (ANCID) conducted a review of how seepage is identified and measured, in 2000. The paper determined eight methods for the measurement of seepage which were analysed in detail, namely:

- Direct measurement

- Point measurement
- Mathematical modelling
- Soil classification
- Groundwater techniques
- Geophysical techniques
- Remote sensing
- Hydrochemical and isotopic methods

Methods described in the *direct measurement* of seepage are the inflow-outflow and pondage methods. The inflow-outflow method is a water balance approach whereby the volume of water flowing into and out of channel reaches is measured, and known losses (such as evapotranspiration) are accounted for. This method does not allow for spatial variation to be considered. Pondage tests apply the water balance approach on isolated reaches, where sections of the channel are segregated and the loss of water is measured over time. This method is costly on large channels and does not provide a spatial variation aspect.

The *point measurement method* is any one of the techniques that measures the infiltration or hydraulic conductivity at a given point, examples include Idaho Seepage Meter or Disc Permeameter. ANCID (2000) determined these techniques were not reliable for quantifying seepage and provide an infiltration rate for a relatively tiny percentage of the channel compared to the size of the entire channel.

Mathematical modelling uses equations that have been previously determined to describe the physics of unsaturated and saturated flow of water within the soil matrix. Quality of results depends on the quality of input data, which can be impractical due to the number of variables involved. The *soil classification method* categorises soil textures as a function of hydraulic conductivity, where seepage rates can then be assigned to calculate seepage for a channel section. This method can use existing soil data, however other factors are not accounted for and a large number of soil measurements are required to reliably estimate seepage.

Groundwater techniques involve the use of piezometers at right angles to the channels. The seepage rate is calculated using equations; if the hydraulic conductivity is known with reasonable accuracy. This method assumes hydraulic conductivity is uniform across the piezometer transect, however this method is a permanent method for measuring seepage. *Geophysical techniques* involve sending an electrical current into the water/soil medium and the reflected current is measured. This is a costly technique, however does provide a rapid assessment technique without interrupting channel operations. This technique requires other methods described in this section to calibrate the results for interpretation.

Remote sensing for the identification of seepage is predominantly used in the near infrared or thermal infrared wavelengths and is based on the difference between wet and dry soils. This method does not interfere with channel operations, however it assumes seepage has a surface expression, hence sites where moist soil occurs that is not affected by seepage will be classed as seepage sites.

Hydrochemical and isotopic methods include mass balance and tracing the seepage plume techniques. The mass balance approach relies on the measurement of a chemical or isotope in the channel and ground water; it combines with a water balance to determine two unknown components. This method is unsuitable for channel seepage measurements due to the short residence time of the water in the channel. Tracing of the seepage plume techniques uses the hydrochemical or isotopic concentration of the seepage water to determine the volume that escapes over a period of time. This method requires a large number of bores and the mixing of channel and ground water makes it difficult to estimate the volume.

ANCID (2000) determined that the optimal technique for measuring seepage from channels is the geophysical technique. The predominant advantage of this technique is its ability to rapidly assess the location of seepage spots. The paper also indicates the need for other techniques to be used in conjunction with the geophysical technique, for the calibration of the results. Once calibration is completed, mathematical modelling can be applied to quantify the volume of seepage, rather than only having a qualitative identification of the seepage.

The Geophysical Technique

Within the geophysical technique numerous types of methods are used, these are encompassed within two categories: active and passive. An active geophysical survey requires a signal (in this case an electrical current) to be injected into the soil medium and the soil's response is measured. A passive geophysical survey uses the naturally occurring fields/properties, such as gravity or magnetic surveys. This paper is focuses on the active geophysical surveys. Some advantages and disadvantages of active geophysical surveys are listed below in Table 1.

Table 1. List of the advantages and disadvantages of active geophysical surveys.

Advantage	Disadvantage
Better control of noise sources through control of injected signal.	Field equipment tends to be more complex.
Provide better depth control over source of anomalous signal.	Field operations and logistics are generally more complex and time consuming.
Great flexibility in customizing surveys for particular problems.	Many different source/receiver configurations can be used allowing for a wide variety of survey designs – causing numerous setup and analysis problems.
Produces a vast quantity of data to interpret subtle details of the earth's subsurface.	The large quantity of data becomes difficult to interpret and analyse.

Active geophysical surveying methods include seismic refraction, induced polarisation, radiometrics, resistivity, electrical conductivity and remote sensing. In this paper the resistivity method is examined. Resistivity is the measure of the soil/rock's ability to conduct or insulate an electrical current, which is related to its physical and chemical properties. For this scenario, two electrodes, namely M and N, inject or emit an electrical current into the soil. The potential (or measuring electrodes), A and B, measure the voltage difference that is caused by the soil medium (Figure 8).

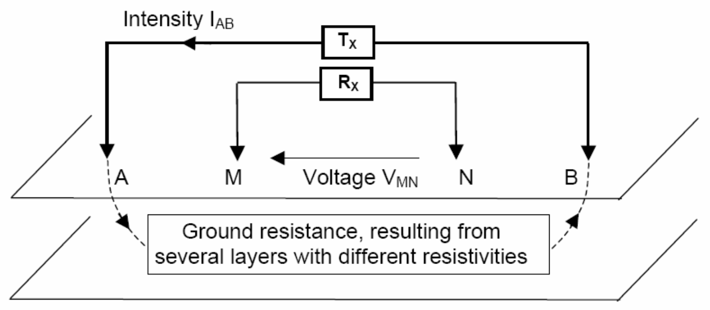

Figure 8. A schematic representation of the geophysical equipment.

Within the resistivity method numerous setup configurations of the electrodes are possible, with the only limitation being that a minimum of four electrodes are to be used. The configurations predominantly used are the Dipole-Dipole and the Wenner (or Reciprocal) Schlumberger. In the Dipole-Dipole configuration the first two electrodes are the injecting/emitting electrodes, while the other electrodes are the potential electrodes. The Wenner-Schlumberger array has the injecting electrodes in the centre with the potential electrodes on either side. A diagram of the different setups and the measurement points are given in Figure 9.

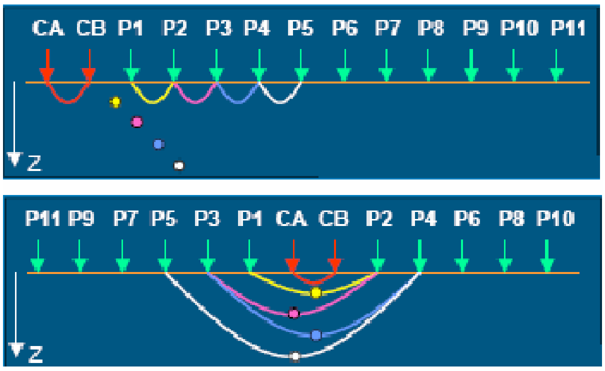

Figure 9. Diagram of the Dipole-Dipole and Wenner-Schlumberger arrays.

Once the measurement of apparent resistivity is completed, the data is inverted using a software program called Res2DInv. This program calculates and interpolates the resistivity data to produce a “map” of the soil profile below where the survey was taken. A resistivity survey can be performed in three main ways: dynamic land, dynamic marine and static land. The dynamic land and marine have a cable attached to a car or boat, with the electrodes, dragged behind as it moves; the land has the electrode running along the soil surface and in marine the electrodes are floating on the water surface. The dynamic method cuts out setup time and maximises the amount of land covered in a period of time. The static land survey requires the electrodes to be hammered into the ground; increasing setup time and reducing the amount of land covered. As a comparison a 500 metre length of canal was covered in one hour using a dynamic land survey, while a different 240 metres of canal was covered in 4.5 hours using a static land survey.

Geophysics can be used to determine surface-ground water interactions through the images of apparent resistivity that are produced from the surveys. Allen (2005) determined that geophysics can be used to determine seepage spots within irrigation canals. Seepage spots are points where most water is lost from the surface water to the ground water. Allen’s research showed a correlation between a low resistivity with seepage points, and limited ground-truthing was performed using yabbie pumps. This method is qualitative and did not determine the volume of seepage loss from an irrigation canal, which is essential in determining the cost-benefit ratio for lining a canal. The work conducted for this Ph.D research attempts to link geophysics, with intensive ground truthing and inverse modelling in order to quantify the seepage losses from irrigation canals. The results from this work will improve current quantitative knowledge of surface-ground water interactions, and in turn push for a change in the water policy framework in place within Australia.

The Need for a Water Policy Framework

There have been significant reforms in the management of surface water resources in the MDB e.g. the Council of Australian Governments (COAG – comprising all the states, territories and the Commonwealth) articulated a water reform agenda (COAG 1995) aimed at a better process for:

- sharing water between users and the environment
- trading water between users
- better defining a water right for users
- recovering the real cost of storing and supplying water to users according to the Council of the Australian Governments (COAG)

Another important step forward for managing surface water resources was, following a water audit of the Murray-Darling Basin in 1993, the Murray-Darling Basin Ministerial Council (MDBMC) introduced an overall *Cap* on water diversions at the 1993-94 levels of development.
The overall impact of surface water reforms coupled with the drought has lead to increased use of groundwater. Groundwater potential has not been accurately assessed from a sustainable development viewpoint, in some situations this has increased risk of groundwater pollution and ecological damage. If the groundwater levels are declining the potential to utilise groundwater for sustaining the Australian economy during times of limited surface water supplies has not been fully explored.
If we consider the overall aim of COAG reforms and the MDBC surface water Cap there is a need to establish sustainable development potential of groundwater resources and define and develop a similar groundwater development "Cap" realising surface and ground water are two components of an integrated hydrologic cycle.

Conclusions

Irrigation sustainability is possible, however the development of our knowledge and understanding is essential for this to occur. Managing surface and ground water as separate entities should become a practice of the past as our knowledge of surface-ground water interactions improves. Specifically in irrigation systems there are three main types of surface-ground water interactions and the understanding of how each affects the groundwater as well as the surface water will go a long way to reducing the environmental footprint of irrigation with smarter knowledge. The ability to identify and quantify surface-ground water interactions is being addressed with this research through the use of geophysics, ground-truthing and inverse modelling. It will be beneficial if the knowledge acquired through this research is used to enhance our water policy framework. Hopefully, the resulting sustainability of arable land and the reduction of environmental destruction will insure the longevity of irrigation systems.

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