The Use of Geophysics to Model Channel Seepage

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EXTENDED ABSTRACT

Effective and efficient water management is important to provide sustainable supplies of food and fibre to the global population. With the ever-increasing global population, the pressures for more crop per drop through water savings are of utmost consequence. A major aspect of all surface water irrigation systems is the conveyance of the water from the river to the farmer. During this process, the volume of water is reduced through leakage, evaporation, and seepage losses in the conveyance of the water. Due to degradation of water quality sometimes the losses are not recoverable through reuse. Predominantly, seepage and evaporation losses occur, while theft, low escape flow and metering errors are also a major consideration for the equitable distribution of water within and downstream of the major irrigation areas. When examining the need to save water, targeted reduction of canal seepage through lining is more cost-effective than piping an entire irrigation system to reduce the evaporation and seepage losses. In order to determine where the lining of irrigation canals should occur, the "hot spots" of seepage should be identified. This can become laborious and costly, therefore a rapid assessment technique is required – which is cost-effective and can be carried out in a minimum period of time.

Geophysics, using the electromagnetic induction or electrical resistivity of land can provide a rapid assessment of relative channel losses. This method can be tied with soil-water modelling using the Hydrus 2D/3D model. The geophysical equipment measures the resistivity of the soil, and must be followed by intensive soil sampling where the soil properties are identified for the samples. This provides the input for the model to carry out the necessary seepage modelling. The previous studies have focussed on the 2-D visualisation of channel seepage. However these studies have failed to predict channel seepage due to rapidly varying hydrogeology along the length of the channels. In this study, an innovative approach of longitudinal modelling was applied. The vertical heterogeneity was incorporated and model simulations were carried out over 30 years. Using this longitudinal analysis approach a typical channel situation in the Coleambally Irrigation Area was modelled with reasonable congruence to groundwater changes experienced in the area. Figure 1 depicts the soil water content changes just below the surface of the canal which shows change in the hydraulic condition over time.

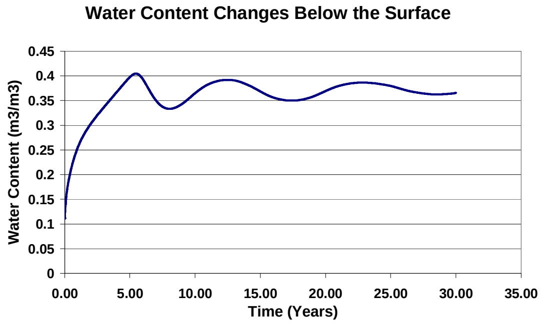

Figure 1. Soil water content below the canal surface.

The analysis of the results indicated a higher hydraulic conductivity will yield a more rapid saturation of the soil profile and therefore the rising of the watertable in the irrigation area. The results showed the water tables under the irrigation areas will remain stable for the initial part of the irrigation, but will at some point show a rapid rate of increase leading to the risk of waterlogging and salinisation. Also, the simulations determined that the soil type affects the water movement only in the initial stages of saturation. Once the profile becomes saturated the soil type does not affect the water movement.

1. INTRODUCTION

Water savings have become very important due to lower availability of water in Australia and around the world. With increasing populations, the pressure to produce more crop per drop is producing many issues for water managers. Saving water is essential for the production of food and for meeting the urban water demand. However, there is increasing pressure for environmental flows to sustain the function of surrounding ecosystems. Another aspect of the water cycle is the loss of productive land to salinisation and waterlogging caused by inefficient conveyance and application of water (Khan *et al*, 2006). Therefore, there are a number of pressures on water managers.

An example of the importance of where water management is necessary is the irrigation industry in the Murray-Darling Basin (MDB). This 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). In order to protect the irrigation industry the land surrounding these areas and others should be prevented from being degraded through salinisation and waterlogging due to inefficient water conveyance and field application of water. Preventing these issues will ensure the survival of the agricultural industry. The conveyance losses in irrigation areas are strongly influenced by the surface and ground water interactions underneath the channel systems. Therefore, the issues facing water managers can be partially solved through the understanding of surface-ground water interactions by identifying seepage "hotspots" in irrigation canals and identifying points of potential salinisation issues.

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. For irrigation managers the conceptualisation of the processes is valid not the geological evolution, therefore the major interactions of note are riverine and glacial/dunal surface-ground water interactions. In Australia, currently few methods are applicable to identifying and quantifying seepage. To improve water management the identification and quantification of seepage points is essential for determining if remediation methods are necessary. The major tool used for the identification of seepage hotspots is geophysical methods, namely EM31 and electrical conductivity. This study was conducted using the geophysical method of resistivity. This is a measurement of the ability of the soil to conduct an electrical current, which is indicative of the soil type, water content and salinity of the soil.

The use of resistivity data gives the user the ability to determine the relative degree of saturation and soil stratification in the landscape. In this paper only the soil texture is considered, and in the future salinity and soil moisture will be considered. Seepage points are identified as the saturated points linked with coarser soils underneath an irrigation canal. The identification of the seepage hotspots along irrigation canals is important for determining the volume of water lost. This assists in determining if remediation methods are necessary; the amount of water to be saved and the type of remediation method applied increase the costs. Currently reasonably accurate point measurements of seepage are available, for example the Idaho Seepage Meter. However, due to their point measurements, it is difficult to accurately determine where and how much seepage is occurring. Also the point measurements of seepage losses are time consuming and costly, and often require more than one type to ensure accuracy and precision (ANCID, 2000). Therefore, the combination of geophysics, point scale measurements and modelling could be beneficial for the irrigation industry. This research applies a rapid assessment technique for seepage identification to be used in conjunction with modelling to predict the relative volume of seepage through the irrigation canals. This paper explains the methodology used and gives the results from a test site in the Coleambally Irrigation Area in NSW, Australia.

2. METHODOLOGY

To rapidly assess seepage points along irrigation canals the use of a geophysical technique was applied. This technique specifically measures the resistivity of the soil. In conjunction, soil sampling was conducted along the geophysical survey. In combination with the geophysical surveys the soils textural analysis was used for deciding the input parameters of the Hydrus 2D/3D model. Once the geophysical survey and the soil analysis was conducted, the data was incorporated into the model for the prediction of seepage from the irrigation canal. The following sections explain in more detail the different aspects of the methodology.

2.1. Geophysics

Geophysics for this research is the measurement of the resistivity of the soil. The method applied uses the Wenner-Schlumberger array. Figure 2 depicts the aspects of this array; where electrodes M and N emit an electrical current and electrodes A and B measure the resistivity of the soil.

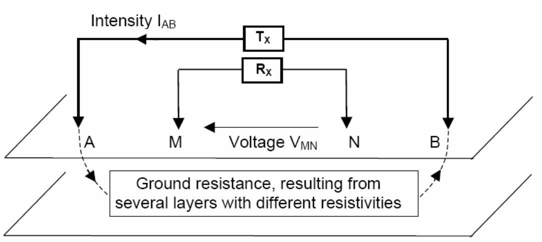

Figure 2. The arrangement for the Wenner-Schlumberger array for geophysics.

The number of electrodes and their spacing determines the depth and accuracy of the survey (Guerin, 2005). Once the resistivity of the soil is obtained the information is inverted using the RES2DINV software package. This package allows the user to interpolate the resistivity measurements to produce an image of the resistivity of the soil below. Once an image is obtained the user is able to determine where the soil sampling should occur.

2.2. Soil Sampling and Analysis to Determine Hydraulic Conductivity

Following the geophysical surveying, the resistivity data was compiled and sorted for the program ESAP-Response Surface Sampling Design (RSSD) from the USDA's Salinity Laboratory (Lesch et al, 2000). This program was used to stochastically determine where the points for the soil sampling regime should be. This program is originally designed to handle data from electrical conductivity surveys, but is adjusted to manage the resistivity data. It was limited to 12 sample sites along the geophysical survey line. The sampling was conducted to two metres with a tractor mounted soil corer.

All the soil samples were analysed for moisture content and particle size. The final 20 centimetres of the soil cores were analysed for bulk density only. The particle size analysis and bulk density are the most important for determining the hydraulic conductivity of the soil samples. Once the particle size was calculated into sand, silt and clay percentages, the results were inputted into the Rosetta model to calculate hydraulic conductivity (Schaap et al, 2001). The Rosetta model implements pedo-transfer functions which are based on an artificial neural network. This model has been trained with soil samples from around the world, but predominantly from the Northern Hemisphere.

2.3. HYDRUS 2D/3D Modelling

Hydrus is a software package for the simulation of water, heat and solute movement in a two- and three-dimensional variably saturated medium (Šimůnek et al, 2006). The package numerically solves Richards equation for variably saturated water flow (equation 1).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_i} + K_{iz}^A\right)\right] - S \qquad (1)$$

θ = volumetric water content
h = pressure head
S = sink
x_i = spatial coordinates (i = 1,2)
t = time
K_{ij}^A = components of the anisotropy tensor
K = unsaturated hydraulic conductivity

Hydrus uses the van Genuchten equation for calculating unsaturated flow in soils (2).

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1+|\alpha h|^n\right]^m} & h < h_s \\ \theta_s & h \geq h_s \end{cases} \qquad (2)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2$$

θ(h) = volumetric water content related to pressure head
θ_r = residual water content
θ_s = saturated water content
α = coefficient in the soil water retention function
m = 1 - 1/n = parameter in the soil water retention function
n = exponent in the soil water retention function
K(h) = hydraulic conductivity related to pressure head
K_s = saturated hydraulic conductivity
S_e = effective water content
l = pore-connectivity parameter

This software package uses the Finite Element Mesh method for the calculation of soil water pressure and fluxes through the soil profile. The mesh can be user defined or generated within the program. This software was used to model the field scenario.

3. THE SCENARIO

The experiment was conducted along an irrigation canal in the Coleambally Irrigation Area in Australia. A static geophysical survey was conducted over 345 metres. A static survey requires 72 pegs to be hammered into the soil surface (about 5 centimetres) and the electrodes to be connected to them. The Wenner-Schlumberger array was applied, which was conducted in approximately 50 minutes – from pushing the start button to the completion of array.

Following the geophysical array the ESAP-RSSD model was used to determine the sampling points along the array. Table 1 gives the list of the 12 sample points from the program for the sampling.

Table 1. The soil sample sites determined from the ESAP-RSSD program.

Sample Site	Distance from start	Resistivity (ohm.m)
W1	12.5	8.59
W2	52.5	7.60
W3	82.5	6.49
W4	152.5	7.05
W5	182.5	4.89
W6	192.5	4.65
W7	202.5	4.73
W8	237.5	8.57
W9	242.5	5.95
W10	292.5	5.24
W11	327.5	7.76
W12	342.5	6.17

The soil samples were taken to two metres, depending on their resistivity (positions calculated using the ESAP-RSSD model), with analyses conducted on every 20 centimetres. The bulk density was performed on the deepest, being 180-200 centimetres. In the laboratory, the soil moisture, particle size, bulk density, electrical conductivity and pH were measured for all soil samples.

To ensure an accurate estimation of water movement through soil, the hydraulic conductivity is required. To obtain this information the Rosetta model was applied for all the samples for which bulk density was measured. The range of hydraulic conductivity estimated from the program was 0.51-0.97 cm/day. Previous studies in the area have measured the hydraulic conductivity to have a broader range of 0.02-1.66cm/day (Hornbuckle and Christen, 1999), therefore the results obtained from Rosetta are within reason.

The channel modelling with the Hydrus model could be carried out in two ways: either a cross-sectional analysis or longitudinal section. A cross-sectional analysis has the area being analysed with the perspective of the irrigation canal in the middle with farms on either side. The longitudinal section is the view of the soil profile directly under the irrigation canal, i.e. the surface layer has a pressure head applied from the irrigation water. Previous studies have conducted the cross-sectional view (reference), therefore a key innovation of this research is the analysis of the longitudinal section by incorporating heterogeneity of underlying soils.

To input the data the geophysical data is used to determine four categories of resistivity, namely 0-5, 5-7, 7-9 and 9-13 ohm metres. These categories were chosen for the ease of division and the capability for input into the Hydrus. The use of geophysics allows the user to input more accurate data on the location and variation of the soil types. According to these resistivity categories soil properties were applied from the soil sampling and analysis which was conducted in the field. This provides the link between the geophysical data and attempting to model the situation beneath an irrigation canal. The resistivity and soils data was used for the top 2metres and assumed to be homogenous to the bottom of the soil profile. Observation nodes were inputted at 1, 12.7 and 30 metres below the canal to obtain point specific output information.

Therefore, the scenario analysed in the Hydrus program was one where four soil materials are modelled. The geophysical data is used to determine the volume and location of each soil type. A variable head boundary was applied to the surface layer, imitating the irrigation water. It was assumed there is no flux along the bottom and two side boundaries. The scenario was modelled over 30 years, with the ground water table starting 20 metres below the soil surface. The results are below.

4. RESULTS

The results from the geophysical survey are given in Figure 3. It is notable that a large area of medium resistivity is apparent (>8ohm-metres). This indicates a seepage area in the canal, which will require further modelling analysis to determine the relative volume of water leaving the canal.

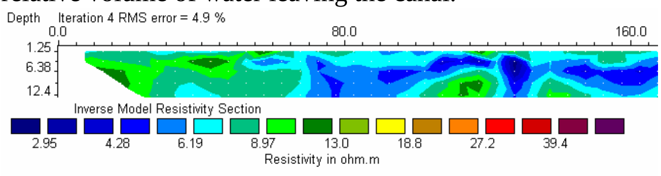

Figure 3. The inverted resistivity diagram.

The soils analysis results are given in Table 2, where the particle size analysis, bulk density and hydraulic conductivities for the lowest soil sample. The hydraulic conductivity was calculated using the Rosetta model.

Soil type 4 did not have specific field properties but was assumed to have a higher hydraulic conductivity and sand content than the other three. The geophysical data was divided into 4 categories and these were incorporated into the Hydrus model using the soils information from Table 2. The model was run using the scenario outlined above.

The initial water content is shown in Figure 4, where there is saturation for upper most layer representing the irrigation canal. The lowest level is also saturated representing the water table.

Table 2. The soils data from 180-200cm section taken from 2m soil cores in the Coleambally Irrigation Area.

Point	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm3)	Hydraulic Conductivity (cm/day)
W1	32	18	51	1.54	0.87
W2	36	16	49	1.57	0.76
W3	30	18	53	1.61	0.83
W4	29	18	53	1.57	0.79
W5	27	19	54	1.58	0.97
W6	25	22	53	1.47	0.83
W7	26	26	49	1.53	0.77
W8	31	25	44	1.55	0.87
W9	31	27	42	1.49	0.66
W10	27	25	48	1.61	0.74
W11	27	25	48	1.57	0.51
W12	34	33	33	1.62	0.87

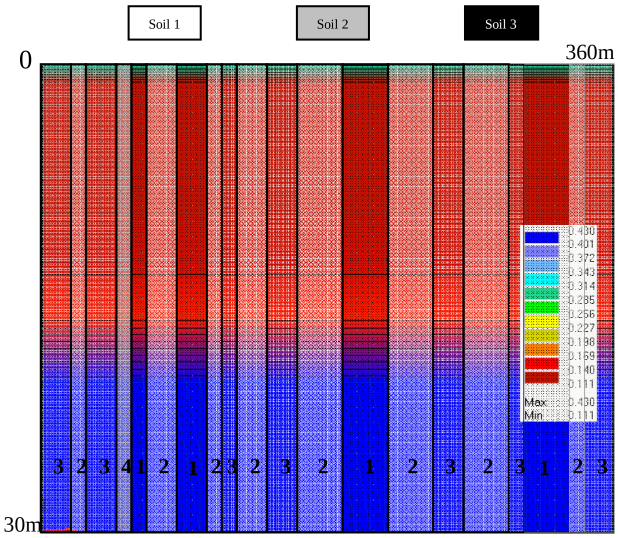

Figure 4. The initial water content conditions for the simulation in Hydrus, with the soil types indicated by shading and numbering. The hydraulic conductivity used the soils are 0.006, 0.0059, 0.0062 and 0.01 respectively.

Figure 5 shows the graphical output of the simulation. It indicates that a wetting front is moving faster down the soil region that has the higher resistivity and hydraulic conductivity (circled).

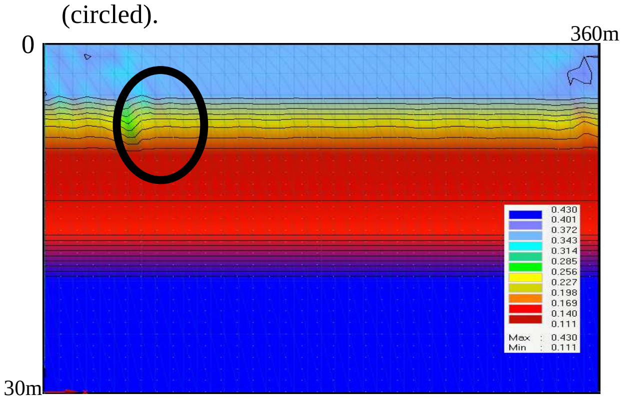

Figure 5. The water content after 3504 days.

Observation nodes were used to obtain numerical values of the simulation. The data obtained from these nodes is the pressure head and volumetric water content. Figure 6 and 7 depict the pressure head and volumetric water content changes down the soil profile for the different soil types.

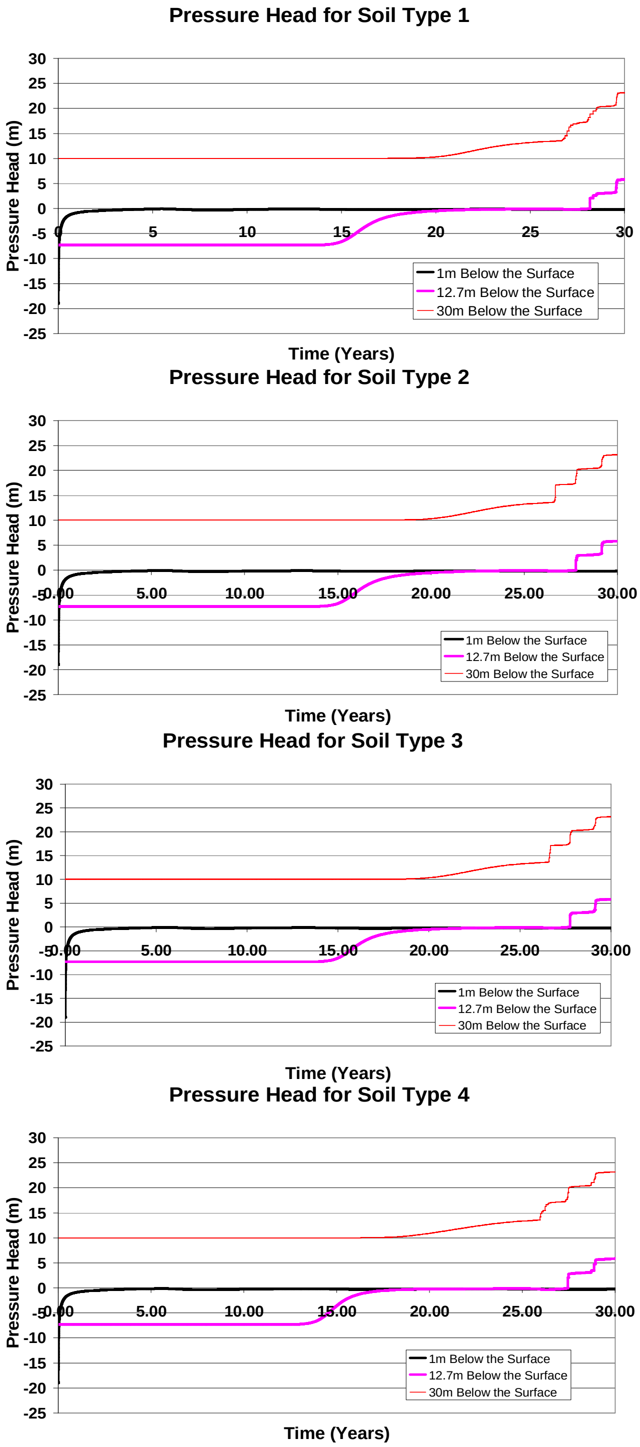

Figure 6. The pressure head values along the soil profile and for the different soil types.

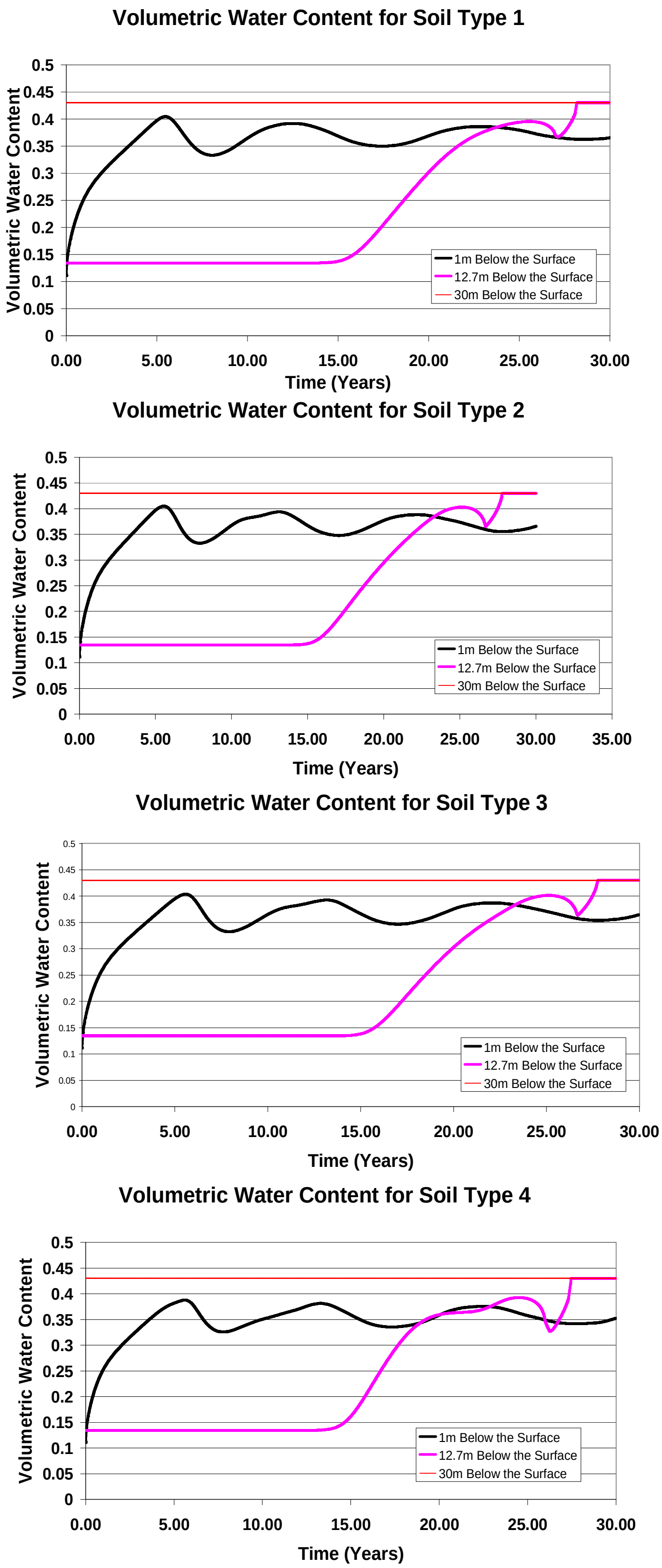

Figure 7. The volumetric water content along the soil profile and for the different soil types.

5. DISCUSSION

The model simulation was performed to conceptualise the possible water movement below a channel after many years of use. Using the Coleambally irrigation canal as an example the initial depth of the water table was set at 20 metres below the surface. The depth in the canal was seasonal according to the irrigation pattern of the area and precipitation experienced on average.

The output figures depict the fluctuating water content, which is experienced throughout the simulation. Figure 5 specifically depicts the water content movement in the soil, with the highest hydraulic conductivity highlighted. This indicates during the initial stages of the use of the irrigation canals will experience a higher degree of saturation if the hydraulic conductivity is higher. However, Figure 5 indicates the wetting profile for all the soil types is similar, suggesting soil type does not affect the saturation at a mature level of channel use.

Figure 6 shows the modelled soil water pressure at 1 metre below the surface becoming saturated rapidly. Once this section of the soil is saturated it remains close to saturation for the remainder of the simulations. The graphs for all the soil types indicate that at 12.7 and 30 metres below the surface there is a fluctuation of the pressure head value according to the seasonal variation of the water in the canal.

The graphs in Figure 6 indicate the soil at 12.7 metres below the soil surface begins with a higher pressure head than the surface soil and has a slow increase. Once the pressure head reaches saturation it remains stable for approximately 10 years. After which the graph has a step-like resemblance as the pressure head increases slowly over the remaining years. Figure 6, also, indicates the pressure head value for the lowest point (30 metres below the surface) remains constant for about 20 years as this is always below the watertable. This shows the 20 years of the same cycle will not change the pressure head at 30 metres below the soil surface, indicating changes occur slower the further below the surface. The same pattern for all three depths is depicted for all the different soil types.

In Figure 7, the volumetric water content at 30 metres below the surface is shown as remaining constant throughout the simulation. This is expected as this part of the soil remains under a constant pressure head, thus indicating the water table to be above this position. The volumetric water content 12.7 metres below the surface, again, shows a long equilibrium from the start for about 15 years. Following the 15 years, a rapid increase in volumetric water content is experienced, until it finally reaches saturation about 28 years after initiation. The lines representing 1 metre below the surface indicate a rapid increase to just below saturation. The lines become wavy indicating that volumetric water content is fluctuating according to the seasonally variable pressure head in the canal.

Soil type 4 had the highest hydraulic conductivity of 0.1m/day. From Figure 6, this soil type had a slightly earlier increase (about 2 years) in pressure head at 30 metres below the surface. Figure 7, also depicts with the line for 12.7 metres below the surface, where after about 13 years the volumetric water content begins to change. This is comparable to the other soil types which begin changing at about 15 years. This information provides further proof that the soils with a higher hydraulic conductivity will have more seepage and will cause the soil profile to become saturated quicker.

This analysis can be potentially of great importance to the irrigation industry as it helps water managers to better understand what is happening below their irrigation canals. These results indicate that during the first 15 years of irrigation the water tables under the irrigation area will remain reasonably stable. However, after 15 years the watertable response will change to rapid rise. The results indicate that as the soil hydraulic conductivity reaches the saturated hydraulic conductivity the rate of rise of the watertable will become more rapid. This is supported in the Coleambally Irrigation Area where the water tables were about 20 metres below the surface in the 1960s when irrigation began. In about the 1980s signs of waterlogging and salinity became evident predominantly in the lower reaches of the area. Thus indicating this methodology using the geophysical, soil sampling and Hydrus framework, provides a reasonable representation of the actual field conditions. A key advantage of this framework is that it allows for the soil profile heterogeneity to be more precisely determined prior to the modelling scenarios. Also, it uses all the available information in a user friendly manner. The model used, also, allows the user to obtain the water balance data for each node modelled, thus producing the opportunity to determine the volume of seepage loss. In this paper the volume of seepage water is not analysed.

6. CONCLUSIONS

In conclusion, the proposed geophysical survey and longitudinal channel seepage analysis for determining channel seepage hotspots (during the early stages of development of an irrigation area) can help target irrigation water saving investments through a better understanding of temporal and spatial variation in channel seepage. The model used allows the user to obtain the water balance data for each node modelled, thus determining the volume of seepage loss. The dynamic analysis shows that initially the irrigation areas are not under threat of waterlogging and salinity during the start-up period due to predominantly unsaturated soil conditions. However, as time elapses and the system attempts to reach a new equilibrium (in this case about 15 years after the start) the system will have a higher threat of waterlogging and salinity due to the rapid rise of water tables following the saturation of the soil profile. Also, the soil type plays an important role in water movement during the initial stages. However, once the water table has risen to the level of the channel bed the soil type becomes irrelevant due to the overall soil profile saturation and is limited by the regional groundwater outflow capacity. Therefore, understanding the changing dynamics of surface-ground water interactions is essential to secure the sustainability of irrigation areas through efficient conveyance and application of irrigation water.

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