A computer model to estimate seepage rates from automated irrigation distribution channels during periods of shutdown

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ABSTRACT

Within the last 10 years throughout south-eastern Australia, there has been a rapid expansion of modernisation efforts by irrigation companies that has included installation of automatic control structures, the so-called total channel control (TCC) technology. TCC includes supervisory control and data acquisition technology, which results in production of integrated databases utilising real time measurements of flow and water depth throughout the whole system. Pondage tests are acknowledged as the best direct method for seepage measurement and the recorded water level data from automated systems during periods of gate closure can be treated as pondage test data. This paper presents the development and operation of a new computer model that applies pondage test methodology to automated channel control data during periods of shut down in order to estimate seepage rates in different channel reaches. The Coleambally Irrigation Area (CIA) in southern New South Wales was chosen as the case study, as it is one of the first irrigation districts in the world to be automated. The methodology was tested using the TCC data of the entire CIA during the 2010–11 season and was demonstrated to be successful in identifying all pondage conditions throughout the entire network as well as estimating the seepage rates for each gauge, pondage and pool.

Key words │ Coleambally irrigation, irrigation channels, pondage test, seepage estimation, total channel control

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NOTATION

E_n	Cumulative evaporation at the nth time step
R_n	Cumulative rainfall at the nth time step
W_i	Weight for gauge i during pondage condition
S_n	Seepage rate for the nth gauge during pondage condition
N_n	Number of measured points for the nth gauge during pondage condition
$S_{pondage}$	Seepage rate for pondage condition
R_i^2	R squared value of corrected water elevation readings for gauge i
LOC_i	Level of confidence for pondage i
$NMPP_i$	Number of measured points for pondage i

INTRODUCTION

Earthen channels are a significant element in any irrigation distribution system and are commonly used throughout Australia. They are usually constructed using local materials, sometimes with poor water-retaining characteristics.

In a typical irrigation distribution system, older parts including pipes or unlined channels are generally built to a lower standard or have deteriorated to a point where leakage and seepage losses are significant. Conveyance loss measurements in unlined channels have highlighted that most of the water loss takes place through the upper portions of the channel banks (Kahlown & Kemper 2004).

The most important irrigation districts in Australia were built almost 100 years ago. Significant water losses have been experienced in these districts, partly due to ageing irrigation infrastructure but also the available technology at the time the districts were built. Pumping is rarely used in Australian irrigation channels and water is delivered only under the power of gravity. Therefore, water tends to be kept above supply levels, which has led to large distribution losses due to spillage and outflows. Between 1 and 14% of the total water supplied for rural use via earthen channels is lost due to seepage (Brinkley *et al.* 2000, 2004). Channel seepage involves the relatively uniform passage of water through the wetted perimeter of the channel profile due to poor quality of substrate material (ANCID 2001).

Pondage tests are acknowledged as the best direct method for seepage measurement (Smith 1982; SKM 1997a, b, 2006; Bodla *et al.* 1998; ANCID 2000a, b, 2001, 2003a, b; Brinkley *et al.* 2000, 2004; Alam & Bhutta 2004). Pondage testing may require the construction of earthen banks to create leak-proof sections in the channels where the drop in water level over time can be measured. The location of the barriers depends on project objectives and might be determined by geophysical surveys or perhaps anecdotal information. However, in many cases existing structures can be used, particularly when automated regulating and measurement equipment has been installed, providing they can be sealed effectively. The application of pondage tests as a useful technique for seepage estimation has been shown in several studies conducted in irrigation districts in Australia (Smith 1973, 1982; McLeod *et al.* 1994; SKM 1997a, b, 2006; KTF 1999, 2002; ANCID 2000a, b, 2001, 2003a, b; Brinkley *et al.* 2000, 2004; Akbar 2003).

Channel automation is a way of improving the efficiency of irrigation networks by using new technology to control the flow of water from the storage through the distribution system to the irrigator. It involves replacing manual flow control structures in channels with updated gates that accurately measure flow and provide real time measurement data. Controls include pneumatic and electronic sensors positioned at each gate; timers that open and close irrigation gates at set times; and fully automated centralised control of multiple gates and channels using hydraulic control.

The scarcity of water resources and inefficiency of irrigation infrastructure convinced the Australian government to pursue modernisation and automation of irrigation distribution supply networks in major irrigation districts across the country. The major south-eastern Australian irrigation companies including Coleambally Irrigation Cooperative Limited (CICL), Goulburn–Murray Water and Murray Irrigation have invested in remedial and modernisation works and have employed automatic control structures in order to improve their operational efficiency and minimise water losses. One of the pioneer companies providing channel automation technology in irrigation is Rubicon Water. The commercial name of their technology applied in major irrigation districts in Australia is called total channel control (TCC). TCC is a breakthrough in both irrigation management and flow measurement that has transformed the inefficient manually operated open channel networks into automated, integrated and remotely controlled systems with high efficiencies (Rubicon Water 2013). The system is based on two aspects: (1) the control of large networks of solar-powered canal regulators and gates, which are linked through radio telemetry; and (2) advanced computer software, which enables the automatic and remote operation of the entire channel network.

The main objectives of using TCC technology are to supply water near-on-demand and to control channel water levels (Rubicon Water 2013). TCC includes supervisory control and data acquisition technology which results in the production of integrated databases containing real time measurements of flow and depth over the whole system. These data have the potential to be used to identify sections of channel with high rates of seepage or leakage. The recorded water level data from automated systems during periods of gate closure can be treated as pondage test data.

The application of TCC data for the purpose of seepage and leakage estimation in Northern Victoria has been reported previously (Poulton *et al.* 2007; Lang *et al.* 2009; Schulz 2009). Despite some success, these studies were limited in that they used a small number of selected channels as well as pre-planned pondage conditions. The scope of the current paper is to introduce a unique model consisting of a database containing the TCC data and computer code capable of identifying all pondage conditions throughout the entire irrigation district at the time of gate closure, as

well as estimating the seepage magnitude for each gauge, pondage, and pool. This approach will therefore facilitate real-time identification and control of leaky channels.

THE MODEL

Objective of the model

In order to be able to estimate seepage and leakage losses during periods of gate shut down from the entire TCC data for a whole irrigation scheme during entire irrigation seasons, a model was developed. The model consists of a database containing all required channel information provided from the TCC system and computer code to: (1) define all available pools in the entire irrigation scheme by linking related gates that form a pool; (2) identify all zero flow periods for each pool; (3) classify each zero flow period based on set criteria; and (4) estimate the magnitude of seepage losses for each gauge, pondage, and pool.

TCC data

An important feature of TCC technology is the real time monitoring and control of the entire channel network, which as a by-product produces a database of water level elevation and flow measurement for every channel across the entire season. The data provided from the TCC system and used in this project consist of:

- flow measurements at all automated main gates and farm outlets, recorded irregularly at changes in the flow rate; and
- water level elevations upstream and downstream of all automated main channel gates and upstream of all farm outlets.

These data were provided in Microsoft Excel CSV format. Table 1 illustrates a sample of the flow measurements and water level elevations for a representative gate during a specified period of time. The model currently uses only the water elevations measured upstream of

Table 1 | Sample of flow measurements and water level elevations for a representative gate provided from the TCC system

Gate name	Event time	Flow rate (m³/s)	Event time	Upstream el. (m)
COLY 4-1	27/08/2010 18:23	0.429	27/08/2010 18:27	1.202
COLY 4-1	27/08/2010 18:54	0	28/08/2010 7:04	1.196
COLY 4-1	27/08/2010 19:26	0	28/08/2010 10:01	1.212
COLY 4-1	27/08/2010 19:57	0	28/08/2010 11:02	1.222
COLY 4-1	27/08/2010 20:29	0	28/08/2010 11:50	1.233
COLY 4-1	27/08/2010 21:01	0	28/08/2010 13:47	1.243
COLY 4-1	27/08/2010 21:02	1.045	28/08/2010 15:30	1.254
COLY 4-1	27/08/2010 21:21	0.458	28/08/2010 17:09	1.243
COLY 4-1	27/08/2010 21:53	0	28/08/2010 18:01	1.233
COLY 4-1	27/08/2010 22:25	0	28/08/2010 19:16	1.222
COLY 4-1	27/08/2010 22:57	0	28/08/2010 21:56	1.232
COLY 4-1	27/08/2010 23:28	0	28/08/2010 22:50	1.243
COLY 4-1	28/08/2010 0:00	0	28/08/2010 23:41	1.253
COLY 4-1	28/08/2010 0:32	0	29/08/2010 1:17	1.263
COLY 4-1	28/08/2010 1:03	0	29/08/2010 4:41	1.261
COLY 4-1	28/08/2010 1:35	0	29/08/2010 14:44	1.273
COLY 4-1	28/08/2010 1:37	1.021	29/08/2010 15:53	1.283
COLY 4-1	28/08/2010 1:38	1.609	29/08/2010 17:09	1.293
COLY 4-1	28/08/2010 1:45	2.141	29/08/2010 19:24	1.283

structures as the data from the downstream gauge were considered unreliable by the data provider.

As can be seen in Table 1, two zero flow periods occurred for the nominated gate and if these coincide with the zero flow periods for other gates in the same pool, the shortest zero flow period among all the gates will be identified by the model as a pondage event. Consequently, water elevation measurements for the gauges upstream of each of the gates during the gate shut down period will be extracted from the database.

Evaporation losses

Apart from seepage, the other major component of conveyance loss from an irrigation distribution system that also occurs during no flow periods is the evaporation loss. A considerable amount of water may be lost through evaporation from a network of long channels in arid or semi-arid regions. Total evaporation losses from irrigation channels in northern Victoria may be as much as 70 GL/year (Winter & Albrecht 2011). Factors affecting the evaporation process are: air temperature, sunshine hours, humidity, cloud cover, solar radiation and wind speed (Hameed *et al.* 1995).

The two most common methods used for estimating evaporation rates from channels are: daily evaporation pan measurements multiplied by pan factors, or calculation from weather station data using a combination equation. The application of pan factors in estimating evaporation in channel water loss studies has been cited by many authors (Nelson & Robinson 1966; McLeod & Webster 1996; SKM 1997a, 2006; Iqbal *et al.* 2002; Poulton *et al.* 2007; Lang *et al.* 2009; Schulz 2009; Shirsath & Singh 2010). Given the fact that direct use of data from evaporation pans located some distance away from the water body can result in significant errors, in order to adjust the evaporation from pan with water body evaporation, pan coefficients, which are simply the ratio of the water body evaporation to pan evaporation, have been applied (Winter 1981). However, the most important shortfall of this technique is that coefficients are specific to the pan type, its location and the nature of the water body and so require calibration for individual applications.

Automatic weather stations (AWS) are now located in many parts of Australia. Therefore, weather data, including solar radiation, humidity and wind speed, can be obtained for estimating evaporation. From these data, potential evaporation rates are calculated routinely using the FAO 56 Penman–Monteith equation (Allen *et al.* 1998). Table 2 illustrates a sample of estimated evaporation rates from an AWS during a portion of 1 day.

Mcleod (1993) used the Penman–Monteith method to estimate evaporation in Northern Victoria. The results were then compared with class A pan evaporation and no strong correlation was found between the two methods. Similarly, McJannet *et al.* (2008) used the Penman–Monteith method to develop a model in order to estimate the quantity and temporal variability of water resources across the Murray–Darling Basin (MDB). The model was tested against measured datasets from seven different locations within the MDB and was shown to produce reliable estimates of the net radiation (difference in average daily values less than 5%), water temperature (difference in average daily values less than 6%), and evaporation (difference in average daily values less than 10%) from water bodies ranging in size from irrigation channels to large reservoirs.

The assumption typically made in seepage studies is that the channel evaporation is equal to the potential evaporation. In fact the potential evaporation will most likely underestimate the evaporation loss from a channel

Table 2 │ Sample of estimated instantaneous evaporation rate provided from an AWS

Event time	EVAP (mm/hr)
14/02/2010 3:10	0.0081
14/02/2010 3:40	0.0081
14/02/2010 4:10	0.00779
14/02/2010 4:40	0.00779
14/02/2010 5:10	0.00935
14/02/2010 5:40	0.00935
14/02/2010 6:10	0.01007
14/02/2010 6:40	0.01007
14/02/2010 7:10	0.00956
14/02/2010 7:40	0.00956
14/02/2010 8:10	0.01804
14/02/2010 8:40	0.01804
14/02/2010 9:10	0.03789
14/02/2010 9:40	0.03789
14/02/2010 10:10	0.0995
14/02/2010 10:40	0.0995

significantly by ignoring the much lower surface resistance of free water (compared to growing vegetation) and through neglect of the advected energy (warm dry air) from adjacent drier areas moving laterally over the channel. Finally, due to the limited number of weather stations in any irrigation district, the distance between the nearest station and the water body might lead to further error in the estimated evaporation loss. However, in the absence of more accurate methods, the application of AWS data remains the best available option.

The database

Considering the objectives of the model and the format of TCC data, a database containing the TCC data in the form of individual tables that is capable of linking those tables together was required.

Due to the fact that Microsoft Excel is unable to link tables together and Microsoft Access had size limitations for databases, Microsoft SQL Server was chosen as the preferred software to build the required database. The created database consists of nine tables (Figure 1).

At the same time, the relations between each of the tables were defined. Since the basis of this study is to analyse the TCC data during pondage conditions or periods of shut down, the first primary definition in the table's relation is to identify the pondage conditions. Therefore, based on position of different gates in any irrigation district, the following tables can be defined in the database:

- Main channel
- Gate name
- Pool name
- Pool detail
- Flow data
- Water level elevation
- AWS ID
- Evaporation
- Rainfall

The whole district can be divided into a number of main channels, which are defined in the main channel table. The gate name table consists of all the automated gates and farm outlets in the district. Considering the locations of the different gates and the flow directions, all possible pools are defined in the pool name table, which is linked to the main channel table. Names of all the gates in each pool are provided in the pool detail table, which is linked to the pool table and the gate name table. The flow rate and water elevation data for all of the automated gates are provided in two separate tables,
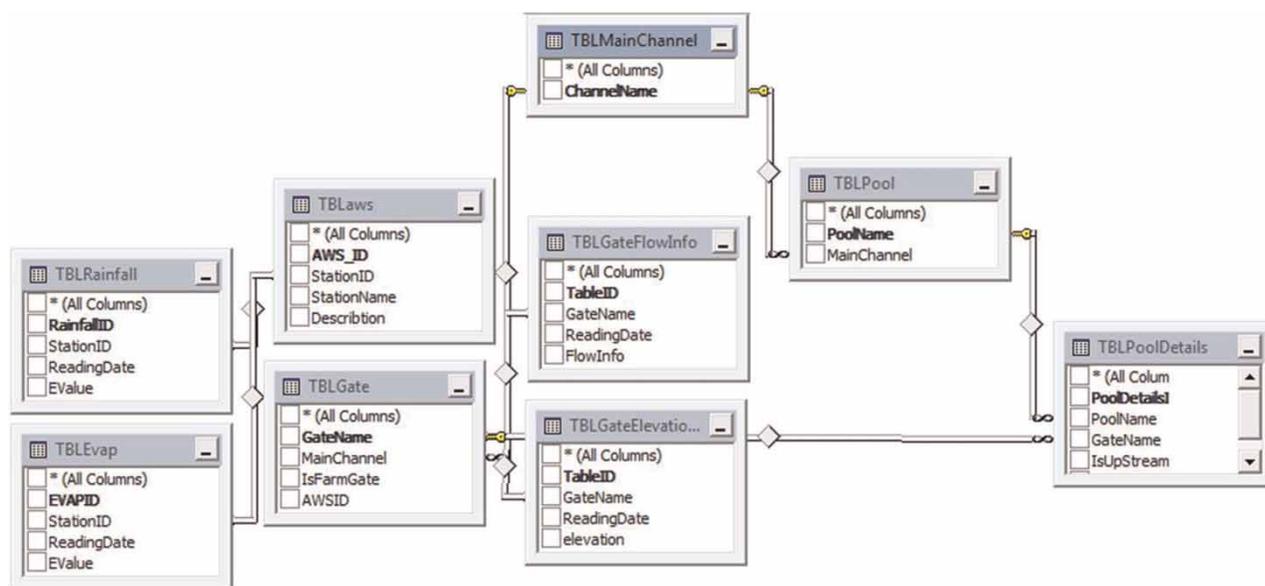

Figure 1 │ Diagram of tables in the database.

which are linked to the gate name table. A list of all available weather stations in the area is provided in the AWS table. Finally, cumulative values of evaporation and rainfall provided from the different weather stations are formed in two separate tables which are linked to the gate name table as well as the AWS table.

Computer code

In order to be able to retrieve and analyse the large quantity of TCC data efficiently, a computer model was built in the C# environment in conjunction with a Microsoft SQL server to produce a stand-alone executable program that can be operated on any personal computer running under Microsoft Windows. Figure 2 provides an overview of the analysis procedure applied in the model.

Zero flow period detection

A zero flow period or pondage condition refers to a condition where all gates constituting a pool are closed and have zero flow. If the flow data for all the gates in each pool are available, the model finds and shows the zero flow duration for each of the gates. Consequently if all the gates in a pool have a common or overlapping zero flow period, the smallest time among all zero flow periods would be distinguished and introduced as the pondage condition.

Water level elevation selection

Having selected the pondage period, the next step is to find water elevation records for each gate during that pondage period. Since the times of the water elevation records do
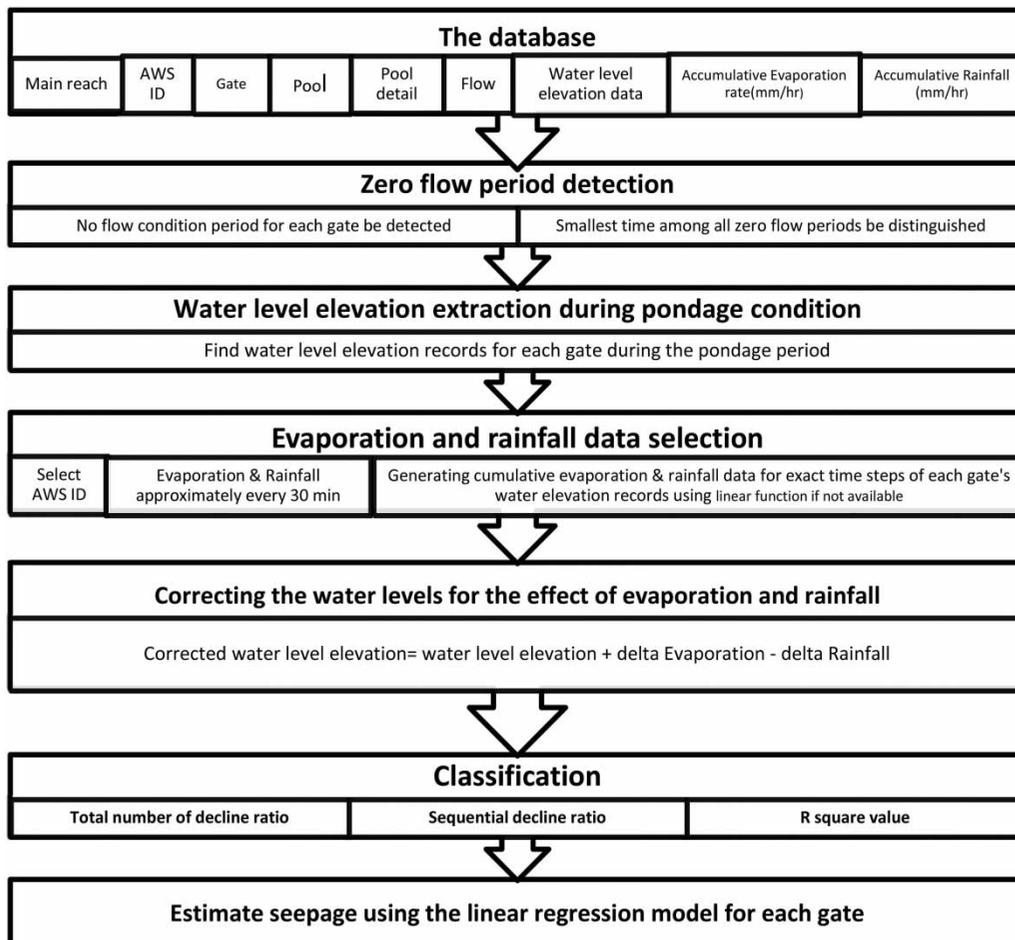

Figure 2 │ Algorithm applied in the model.

not necessarily correspond with those for the flow measurement records, the model will search among all water elevation records to find the water elevation records for each gate that fall within the detected zero flow condition. Consequently the length of the water elevation record used may be shorter than the duration of the zero flow period.

Evaporation and rainfall data

The next step is to select from the nearest AWS the related values of evaporation rates and rainfall during the pondage period. The purpose of this step is to ensure that the water loss is due only to the seepage. Since all the variables should be homogeneous and in the same units, the evaporation rate (mm/h) is converted into a cumulative depth in millimetres. Consequently both rainfall and evaporation were imported into the model in the form of a cumulative value.

Since the water elevation recordings are at different times at each gate, it is necessary to interpolate the evaporation and rainfall data from the AWS database for the exact time steps as for the water elevation recordings at each gate.

Correcting the water levels from the effect of evaporation and rainfall

Having provided the AWS data for each gate, the next step is to eliminate the effect of evaporation and rainfall from the water elevation measurement records at each time step. The 'corrected water elevation' represents the water level that would occur in the absence of all evaporation and rainfall and is calculated using the following equation:

Corrected water elevation$_n$
$$= \text{measured water elevation}_n + (E_n - E_1) - (R_n - R_1) \quad (1)$$

where E is the cumulative evaporation, R is the cumulative rainfall, n represents any of the time steps during the pondage period and 1 represents the initial time in the zero flow period.

Classification

Given that an ideal seepage curve has a gradual decline with time, it is expected that the corrected water elevations will decrease during the pondage period. However, in some cases the data may contain errors or may remain constant during a pondage period due to sensors being above the water level. Therefore, a classification is made to sort out the acceptable (accepted) and unacceptable (rejected) pondage samples. Three criteria were devised in order to classify the corrected water elevation data, which were in turn applied to all possible pondage tests throughout the whole district, namely:

• total decline ratio;
• sequential decline ratio;
• coefficient of determination (R^2).

Total decline ratio

The first criterion applied in the classification of the corrected water elevation data is called the total decline ratio. Using the following equation, the ratio is calculated for each gauge and pondage condition:

Total decline ratio
$$= \frac{\text{Total number of points showing a decline}}{\text{Total number of points} - 1} \quad (2)$$

To define the ratio for the model the difference between each two sequential corrected elevation data values was calculated and if shown to decrease was counted in the dividend. Furthermore if there was no difference between two points, meaning that the elevation remained constant, it also was counted in the dividend. Since the first point cannot be counted in the calculation of the dividend, the divisor is one unit smaller than the total number of points.

Sequential decline ratio

The sequential decline ratio is the result of the total number of points in a row showing a decrease divided by the total number of points. Using the following equation, the ratio for each gauge is calculated:

Sequential decline ratio
$$= \frac{\text{Total number of points in a row showing a decline}}{\text{Total number of points} - 1} \quad (3)$$

As there might be more than one possible ratio for a gauge in any pondage, all are calculated and the maximum value among all ratios is selected as the sequential ratio.

R squared value

The final criteria used for the data classification was the R^2 value, determined by application of linear regression to the plots of corrected water elevation readings versus time for each gauge. The linear regression model also gives a first estimate of the seepage rate for each gauge and pondage.

Accepted samples

Once all pondage conditions are detected by the model, the next step is to make a full assessment of all the samples. The concept of classification is based on the behaviour of corrected water elevation changes of each gauge in the pool during the pondage time, evaluated using the three criteria mentioned earlier. Accepted samples are classified into five different groups as follows.

Group 1: In pools with several gates, if all gauges have a total decline ratio and R^2 of more than 70%, the pool is classified as group 1. Figure 3 shows the corrected water elevation pattern of two gauges in a sample pool as an example of group 1.

Group 2: If a pool has information from only one gate and that gate has a total decline ratio and R^2 greater than 70%, it is classified in group 2.

Group 3: Depending on number of gates in the pool, if some but not all of the gates have a total decline ratio and R^2 greater than 70%, the pool would be classified in group 3.

Group 4: In pools with several gates, if all gates have a total decline ratio and R^2 greater than 50% but less than 70%, the pool is classified as group 4. Figure 4 shows the corrected water elevation pattern of gates in one of pools as an example of group 4.

Group 5: If a pool has only one gate and that gate has a total decline ratio and R^2 greater than 50% but less than 70%, the pool is classified in group 5.
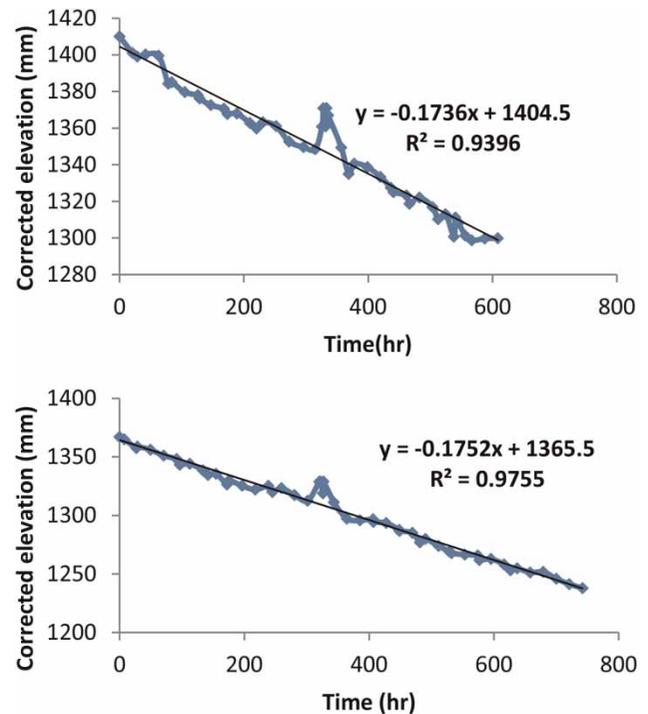

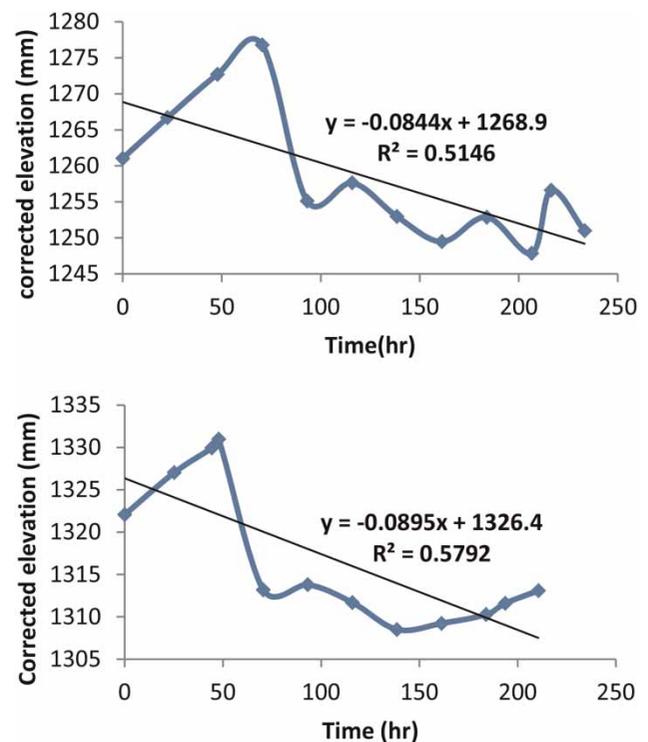**Figure 3** │ Example of a pool classified in group 1.

Figure 4 │ Example of a pool classified in group 4.

Rejected samples

If a pondage sample does not meet the above criteria, it will be classified in the rejected group. Noise associated with the measurement devices was observed in some unusual plots in the rejected pondages and in these cases was the cause of the ponding condition being rejected.

Another common situation observed among the rejected pondage samples was a continuous increase in the measured water elevations during the entire pondage period (Figure 5). There is no obvious explanation for this behaviour. A continuous increase in water level over a long period during a zero flow period implies that an unknown inflow into that channel reach was occurring. Using data retrospectively, as in this study, does not allow a proper diagnosis of such situations. However, irrespective of the cause, data showing this or aberrant behaviour were rejected.

Another common situation observed among the rejected pondage samples was where the measured elevations were constant during the entire pondage period. This suggests that the water level is below the bottom of the sensor.

Seepage magnitude

Three different seepage rates are defined in the model:

1. gauge rate – based on the data from a single depth gauge upstream of either and automated channel gate or a farm outlet;
2. pondage rate – an average of the gauge rates in a single pondage test for a given pool;
3. pool rate – an average of the pondage rates in a given pool in a single season.
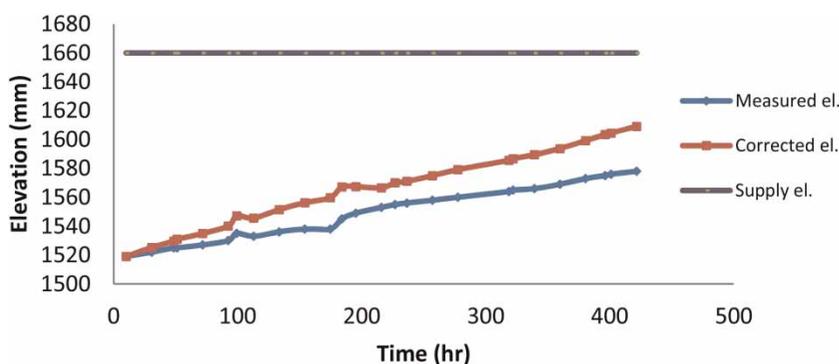
Linear regression was used to give a first estimate of the seepage rate for each gauge during each pondage condition. While evaluating various possible factors affecting the seepage rate for each pondage sample, two variables were defined for any given individual rate in the simulation model and by allocating weights to individual rates, an average seepage rate for each pondage is calculated from the weighted gauge rates.

Similarly, two variables were defined for any given pondage rate and by allocating weights to pondage rates, an average seepage rate for each pool in each season is calculated from the weighted pondage rates.

Seepage rate per pondage

Since the numbers of measured water elevation points at gauges during pondage conditions were not necessarily the same, a weighting for each gauge seepage rate estimate based on this number was considered. The decision to choose the number of measured points as a deciding factor was made considering the fact that there is more confidence in the gauge based seepage rates with a higher number of points compared to those with only two or three points.

In order to estimate the pondage based seepage rate, a weighting was allocated to each gauge rate taking in to account the number of measured points at all gauges in each pool, and the pondage based seepage rate is calculated as a weighted mean of the individual gauge rates.

In a pool with n gauges where a pondage condition occurred, the seepage rate for the first gauge is S_1 and number of measured points for the first gauge is equal to

Figure 5 │ Pondage showing a continuous increase in measured water elevations.

N_n. Similarly S_n and N_n stand for seepage rate and number of measured points for the nth gauge during the pondage condition. The weight for each gauge is calculated as

$$W_i = \frac{N_i}{\sum_{k=1}^{n} N_k} \tag{4}$$

Consequently the seepage rate for the pondage is calculated using the weighted average

$$S_{\text{pondage}} = \sum_{i=1}^{n} S_i W_i \tag{5}$$

In order to indicate the level of confidence (LOC) in each estimated pondage based seepage rate, two variables were defined for each pondage sample:

1. number of measured points per pondage (NMPP);
2. LOC.

The definitions of NMPP and LOC differ depending on the group into which that ponding condition belongs, as shown below in Figure 6.

Obviously the pondage rates in groups 2 and 5 are exactly the same as gauge based rates. However, in groups 1 and 4, the seepage rate for each pondage is calculated using the explained mean average method. Similarly in group 3 averaging is performed between gauges that met group 3 requirements.

$$\text{Group 1 \& 4} \quad \begin{cases} \text{LOC} = \frac{\sum_1^n R^2_i}{n} \\ \\ \text{NMPP} = \frac{\sum_1^n N_i}{n} \end{cases}$$

$$\text{Group 2 \& 5} \quad \begin{cases} \text{LOC} = R^2_1 \\ \\ \text{NMPP} = N_1 \end{cases}$$

$$\text{Group 3} \quad \begin{cases} \text{LOC} = \frac{\sum_1^n R^2_i}{n} \\ \\ \text{NMPP} = \frac{\sum_1^n N_i}{n} \quad \text{Where gate}_i \text{ met criteria} \end{cases}$$

Figure 6 | Determination of LOC and NMPP variables for each pondage sample according to the group.

Seepage rate per pool

In a pool where n accepted pondage conditions have occurred, the seepage rate in the first pondage is S_1 and NMPP of the first pondage is N_1. Similarly S_n and N_n represent the seepage rate and NMPP of nth pondage sample in the pool. Weights for each pondage based rate and the pool based average seepage rate were calculated using Equations (4) and (5).

Moreover, in order to indicate the level of confidence in each estimated pool based seepage rate, using Equations (6) and (7) two new variables were defined from averaging the LOC and NMPP of each pondage sample:

$$\text{LOCP} = \frac{\sum_1^n \text{LOC}_i}{n} \tag{6}$$

$$\text{NMPPP} = \frac{\sum_1^n \text{NMPP}_i}{n} \tag{7}$$

where LOCP is the level of confidence in each estimated pool based seepage rate and NMPPP is the average number of measured points in each pool.

OPERATION OF THE MODEL – THE COLEAMBALLY CASE STUDY

The Coleambally Irrigation Area (CIA) was chosen as the case study for this paper as it was the only scheme able to provide the TCC data (for multiple irrigation seasons). The model was operated to estimate seepage and leakage losses for the entire channel network of the CIA using TCC data during periods of gate closure.

Colleambally Irrigation Area

The CIA is located south of Griffith between Darlington Point and Jerilderie, New South Wales in the southern MDB of Australia (Figure 7). The area consists of 477 irrigation farms containing 79,000 ha of irrigated land supplied through open earthen channels. Water is sourced from Gogelderie Weir on the Murrumbidgee River, one of the major tributaries of the Murray River. Water supplies are

Figure 7 | Location of Coleambally in Australia (Khan *et al.* 2008).

regulated from two major Snowy River Scheme dams, Burrinjuck and Blowering (CICL 2008).

The CIA was developed over the period 1958–1970. It consists of 47 km of main canal from the Murrumbidgee River, 469 km of supply channel, and a further 711 km of drainage channels. In 2002, in response to declining water availability, CICL, made the decision to install TCC automation technologies to improve the efficiency of the channel delivery system. As of September 2007 the entire channel system, 514 km of channels with flow capacities ranging from 15 to 6,000 ML/day, is remotely operated (CICL 2008). The CIA is the first open channel system in the world to automate regulators over its entire channel delivery system. The channel system consists of 322 channel regulating and control structures and 435 farm outlets.

The data used in this case study to illustrate the model are for the 2010–11 irrigation season, which started on 30th June 2010 and ran until 29th June 2011. All data were provided in Microsoft Excel CSV format and include one file for each of the rainfall and evaporation records, 20 files for flow measurement records at all gates and farm outlets and seven files for the upstream water elevation records at all gates and farm outlets.

Based on the schematic map of CIA (Figure 8), the whole district was divided into 22 main channel reaches.

The AWS table was defined and an ID was given to each station. The next table defined for the database was the gate table in which all the gates in the district were defined and linked to the appropriate main reach and AWS ID. This was followed by the definition of the pool table which was linked to the main channel table. All the gates constituting each pool and the upstream gate of the pool were defined in the pool detail table. The total number of gates and farm outlets per main reach is provided in Table 3.

The cumulative value of rainfall and estimated rate of evaporation were provided from the two AWS located in the Northern and Southern sides of the district. Based on their longitudinal location, main channels were divided into two groups (Table 4) to apply weather station data into the seepage calculation. In the case of the main channel, as it was the only main channel running North–South across the district, those pools located on the northern end of the main channel were counted in the AWS1 group and the rest in AWS2, respectively.

Sample results

The pondage events were identified, analysed and classified into the five groups introduced previously. Analysis of the
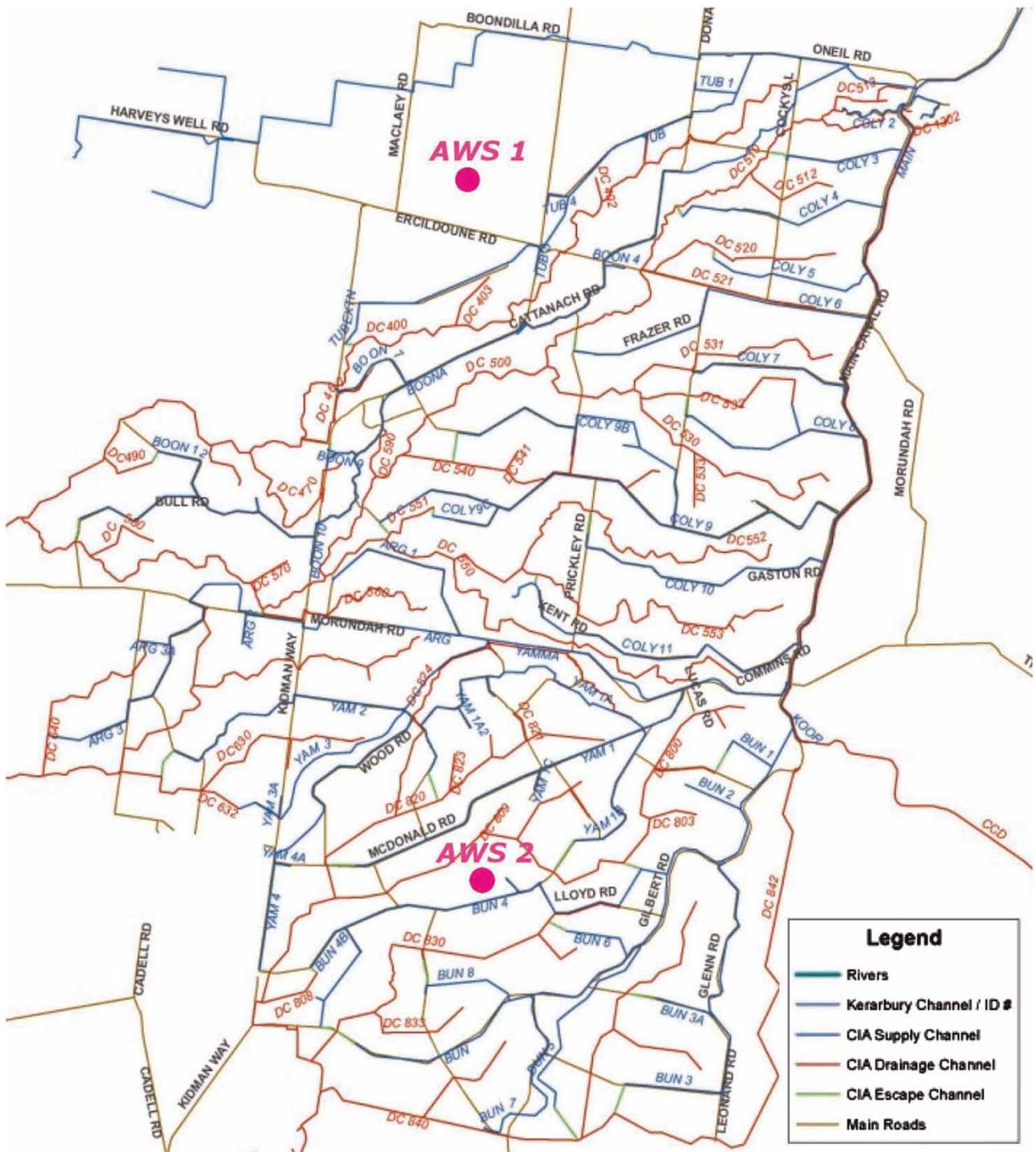
Figure 8 │ Schematic map of supply channels in Coleambally (CICL 2012).

Table 3 │ Number of gates, farm outlets and possible pools in each main reach

Main reach	Gates	Farm outlets	Pools
Argoon	25	35	22
Boona	36	45	28
Bundure	60	79	48
Coly	93	126	79
Main channel	33	44	24
Tubbo	19	26	14
Yamma	56	80	47
Total	322	435	262

results showed that Coly had the highest number of accepted pondage conditions, while the main channel with only 52 had the lowest number of pondage conditions among all main reaches of the district. The analysis also showed that approximately 70% of the accepted samples met the criteria for the first and the second group, with 42% in the first group and 28% in the second group (Table 5).

Using the linear regression model, the seepage rate for each of the gauges in a pool during any possible pondage condition is calculated individually. A histogram of all

individual gauge seepage rates for both accepted and rejected samples during the 2010–11 irrigation season is given in Figure 9. The histogram of accepted samples shows a skewed distribution to the right while the histogram of rejected samples shows a skewed distribution to the left. Moreover, analysis of seepage magnitudes showed that in 2010–11, 20% of the gauges gave seepage rates greater than 0.5 mm/hr, while the median value was 0.2 mm/hr.

DISCUSSION

In order to evaluate the quality and accuracy of seepage rates estimated from the TCC data, a full detailed analysis of all pondage conditions in different channels during the 2010–11 irrigation season was completed and a number of limitations associated with both the model and the TCC data were addressed.

Results of the analysis showed that the occurrence of rainfall during a pondage condition can influence the estimated seepage rate. Detailed examination of the corrected water elevation plots for particular gauges showed that the existence of a rainfall event caused a rise and fall in the

Table 4 │ Distribution of main channels for usage of AWS data

AWS1	TUBBO	BOONA	COLY 2	COLY 3	COLY 4	COLY 5	COLY 6	COLY 7	COLY 8	COLY 9	COLY 10	MAIN 1
AWS2	BUN 1	BUN 3	BUN 4	BUN 5	BUN 6	BUN 7	BUN 8	COLY 11	ARGOON	YAMMA	MAIN 2	

Table 5 │ Summary of analysis of 2010–11 pondage samples

Main channel	No. of pondage condition	Accepted pondage conditions					Total no. of accepted samples	Total no. of rejected samples
		Group 1	Group 2	Group 3	Group 4	Group 5		
Argoon	54	7	19	4	9	1	40	14
Boona	207	46	66	9	9	19	149	58
Bundure	201	74	31	20	8	9	142	59
Coly	366	114	65	40	13	27	259	107
Main channel	52	13	13	5	2	6	39	13
Tubbo	59	22	4	7	6	3	42	17
Yamma	134	51	24	20	8	4	107	27
Total	1,073	327	222	105	55	69	778	295
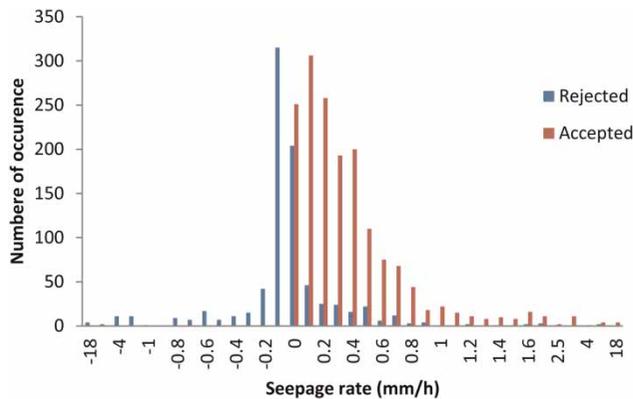
Figure 9 | Frequency of seepage rate for all gauges in 2010–11 using linear regression.

corrected water elevation plot. Due to the fact that rainfall over a 24 h period was measured at 9 am the next day and recorded against that day, the imperfect knowledge about the exact timing and rate of the rainfall may explain the occurrence of this rise and fall in the corrected water elevation plots whenever a considerable rainfall occurred. Therefore, it would be better to work with hourly rainfall readings if available. In addition, having the entire area covered by only two weather stations does not account for any spatial variability in the rainfall rate. Based on further consideration, it was decided to remove any period affected by significant rainfall, that is, any period covered by this rise and fall, from the corrected water elevation plot and re-estimate the seepage rate for the remaining part of the plot. However, due to a shortage of remaining measured points or short duration of the remaining part in some cases, it was necessary to eliminate some of the pondage conditions from the analysis entirely.

The analysis of all pondage conditions revealed that water elevation measurements during shut down periods did not always commence exactly at the start and or finish exactly at the end of the zero flow periods. This resulted in a smaller number of records and a water elevation record covering a shorter duration compared to the real pondage period. This was a common problem in the majority of pondage samples of less than 3 days' duration. However, some of the pondage conditions had a reasonable number of measured points despite the fact that they covered a shorter duration than original pondage period. Therefore, it can be concluded that there is more confidence in estimated seepage rates in pondage conditions with a high number of

recorded points compared to samples with a lower number of recorded points. However, a high number of measurements did not always provide more confidence in a pondage condition as noise in the measurements sometimes produced a large number of repeated elevations. Therefore a weight was allocated to each gate based on its NMP to estimate pondage and pool based seepage rates.

As a number of estimated seepage rates were postulated to be inaccurate, possibly due to the effect of noise in the water elevation data, the analysis required data cleaning. Schulz (2009) also noted that noise was associated with measurement errors in their study and therefore such factors must be eliminated before conducting the analysis. Conversely, Lang *et al.* (2009) assumed that installation of TCC completely eliminates any bias in measurement inaccuracies.

The downstream elevation of each gate was considered to be poor quality and therefore the upstream gate in each pool was omitted from the pondage and pool based seepage calculations. However, while this was the case in the Coleambally TCC data, it might not be the same for other TCC data.

The ideal seepage curve introduced by Schulz (2009) (showing a decline in the loss rate with time or with lower water level) which indicates a leakage component was only observed in some of the samples that had longer pondage durations with a high number of measured points (e.g. Figure 10). A polynomial trend line was applied to the corrected water elevation data of these pondage samples and it was observed that whenever the ideal seepage curve was available, the polynomial trend line was the best
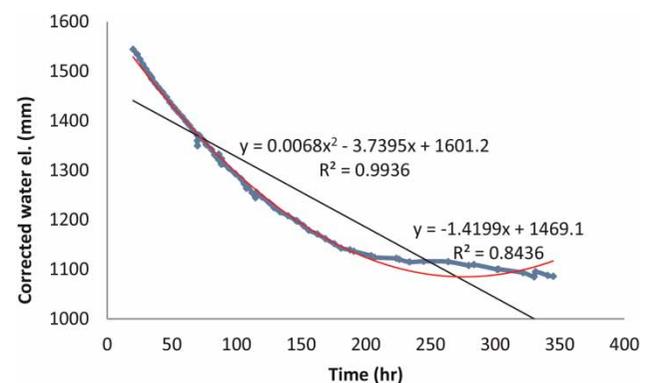
Figure 10 | Application of polynomial and linear regression trend line to ideal seepage curve.

model to estimate the rate of water loss. On the other hand, for all other pondage conditions the linear regression was the simplest and preferred approach.

The potential evaporation rates provided from the AWS are likely to have underestimated the evaporation losses from the channels which would result in the seepage magnitude to be overestimated. However, despite this potential error, the model was able to identify the channel reaches with high seepage rates. The Penman–Monteith equation remains the best available option for evaporation estimation as other common methods including pan factors have higher potential errors.

CONCLUSIONS

A model for the purpose of seepage estimation throughout the entire irrigation scheme using TCC data was developed. The methodology was tested using the TCC data of the entire CIA irrigation scheme during the 2010–11 season and showed to be successful in identifying pondage conditions throughout the network as well as estimating the seepage rate for each gauge, pondage and pool. The criteria defined for the model also appeared to be successful as the rejected pondage samples look quite different from the accepted ones.

Results of the analysis showed that seepage losses from the CIA are significant, with approximately 20% of the estimated seepage rates in the 2010–11 season greater than 0.5 mm/hr (12 mm/d).

The model can be applied to TCC data of other irrigation districts. However, this would require development of a new database based on the characteristics of each irrigation scheme.

ACKNOWLEDGEMENTS

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