Optimisation of Spatio-Temporal Aspects of Drainage

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Keywords: *Subsurface Drainage, Design, Optimization, MODFLOW and Genetic Algorithm*

EXTENDED ABSTRACT

Drainage schemes for agro-ecological salinity management have been set to lower the shallow groundwater to help increase production and reduce the ecological risk. Once the groundwater levels are lowered to desired agro-ecological thresholds then drainage scheme's operation needs to be optimised according to the groundwater dynamics both in terms of space and time to achieve hydro-economic efficiency. Every system, even the most complicated ones, can be modelled if its behaviour is fully known and understood but a key difficulty in optimization is dealing with non-linear spatio-temporal problems. Such problems can be optimised using genetic algorithm aimed at finding near optimal solutions to highly non-linear optimization problems. GAs are nature inspired stochastic computational techniques. The major advantages of these algorithms are their broad applicability, flexibility and their ability to find optimal or near optimal solutions with relatively modest computational requirements.

This paper presents the development of a surface-groundwater interaction model for the spatio-temporal optimization of pumping operation of Subsurface Drainage Schemes to achieve the similar or better level of service both in space and time domains. A drainage scheme, Wakool Tullakool Subsurface Drainage Scheme (WTSSDS), from New South Wales is included as a case study to illustrate the need for the optimisation of drainage operation to achieve the hydro-economic efficiency. The model results are being used to plan an optimal operation of the tubewells to control water logging and salinisation.

Once a groundwater pumping system is put in place to service the waterlogging and salinity problems in an irrigation area, changing temporal conditions (rainfall, flooding and irrigation practices) necessitate a dynamic management response. Such an approach needs to be based on a comprehensive understanding of the groundwater dynamics for achieving economic efficiency of drainage since some of the tubewells may become ineffective while others start drawing more water than required to keep the watertable at the desired levels.

The optimal management strategy, as determined by the simulation-optimization analyses, suggests the same or even better pumping performance of the scheme could be achieved using 42 wells (rather than 53) and a maximum pumping rate of 1000 m^3 d^{-1} for an individual pump. The groundwater pumping can be reduced by around 1 MCM yr^{-1} which is approximately 20 % lesser than the existing rate. This will lead to substantial cost savings by reducing the number of wells needed and less pumping. Preliminary cost estimates indicated that \$ 4000 MCM yr^{-1} pumping cost could be saved.

This study has also shown that a MODFLOW based surface-groundwater interaction model, using hydrogeology, soils, groundwater levels, groundwater pumping, channel network and net recharge information can be a useful tool to develop understanding of the groundwater dynamics. The simulation-optimization analyses can effectively be used to plan an optimal operation of the subsurface drainage scheme to control water logging and salinisation in a hydro-economically viable way.

1. INTRODUCTION

The productivity of major irrigation areas in the semi arid and arid regions of the world is being challenged by the waterlogging and secondary salinisation of landscapes (Ghassemi et al., 1995). It is estimated that more than 60 million ha or 24% of the all irrigated land in the world is salinised (World Bank, 1992). A small fraction of deep percolation (leaching fraction) under crops is necessary to leach out excess salts from the root zone to maintain productivity (Hoffman, 1990; Rhoades and Loveday, 1990).

Excessive irrigation of crops and seepage losses from channels and storages results in groundwater recharge to unconfined aquifers (Rushton, 1990). If the groundwater recharge is greater than the combined groundwater leakage to the deeper aquifers and lateral regional groundwater flow the watertables will start rising. When the watertable is less than 2m from the surface, the root zone of the plants becomes restricted and capillary upflows from the watertable start accumulating salts in the root zone and at the surface, causing reduction in crop yields (Kijne et al., 1998).

The waterlogging and salinisation situation is very complex if low quality water exits in the superficial aquifers consisting of slowly permeable materials such as medium and heavy clays. In such aquifers shallow groundwater pumping is possible only in limited locations and re-use or disposal of saline groundwater poses a major problem (Beltran, 1999).

Once a shallow groundwater pumping regime is put in place to service a waterlogged area, changing temporal conditions (rainfall, flooding and irrigation practices) necessitate a dynamic management approach based on a comprehensive understanding of the underlying groundwater dynamics. Over a period of time some tubewells may prove to be ineffective while others may be drawing more water than their design discharges (Khan, 2005).

Water resource design problems are often analysed by using coupled optimization and numerical models to identify effective designs (Mayer et al. 2002). However there use of GA linked with MODFLOW to optimise waterlogging and salinity problems has not been cited in the recent literature.

This paper presents the development of a surface-groundwater interaction model linked with an optimisation model based on the GA approach to optimise the pumping operation of the Wakool Tullakool Subsurface Drainage Scheme (WTSSDS) commissioned in the Wakool and Tullakool Irrigation Districts in the New South Wales, Australia to achieve the hydro-economic viability.

2. MODELLING AND OPTIMISATION

2.1 Background and the Study area

The Wakool Tullakool Subsurface Drainage Scheme (WTSSDS) is located in the Wakool and Tullakool Irrigation Districts of New South Wales, Australia (Figure 1). The total area of these irrigation districts is 208,000 ha which includes 357 holdings. Rice, winter pasture, summer pasture, dairying and winter crops are the major irrigated enterprises. Extensive clearing of land combined with inefficient irrigation practices resulted in recharge greater than aquifer storage capacity and regional groundwater flow leading to gradual rise of the watertables. In 1944, eight years after irrigation commenced in the area, the average depth to the watertable was eight metres. From 1945 to 1981 the watertable rose 8 cm per year, bringing the average watertable depth to around 5m. In 1981, 32,300 ha had watertables within 1.5 m of the ground surface in the Wakool District. Waterlogging combined with secondary salinisation caused over 2000 ha of land to go out of production and crop yields declined by around 50% in the remaining areas.

Drainage efforts started in 1960 when some landholders started shallow groundwater pumping. However, these efforts were of limited success due to recharge from non-groundwater pumping farms and limited drainage disposal capacity due to restrictions on direct discharge through surface drains into the rivers. This disposal method was perhaps only acceptable in periods of high river flow enabling dilution of saline drainage waters. Realising these constraints the Wakool Tullakool Subsurface Drainage Scheme (WTSSDS) consistin of drainage wells and evaporation basins was built between 1978 and 1988 to alleviate waterlogging and salinity problems caused by clearing of land, introduction of irrigation, extremely wet periods and natural floods. The Scheme was progressively constructed as Stage I and Stage II, with 35 and 24 well sites respectively (WLWMPWG 1995). The current WTSSDS consists of 59 tubewells spread over an area of 25,000 ha. These tubewells discharge into two evaporation basins covering an area of 2,100 ha.

According to current estimates, the existing scheme protects around 50,000 ha of farmland in the Wakool area by pumping around 36,000 $m^3\ d^{-1}$ (or 13 MCM yr^{-1}) of groundwater, with an average salinity greater than 25,000 µS cm^{-1}. The net interception of salts through the current operations is around 200,000 tonnes yr^{-1}. The current pumping operation criterion is to keep watertables deeper than 2.5m to protect land from salinisation. The estimated drainage rate for the existing scheme ranges between 230 to 600 m^3 ha^{-1} (AWE 2001).

Figure 1. Location map of the Wakool and Tullakool Irrigation Districts of New South Wales, Australia

Despite relative dry climate and very low water allocations for the year 2001-02, the groundwater levels in WTSSDS recorded during March 2002 suggested that the shallow watertables (less than 2 m) persist over more than 9% of the area. Around 20% of the area had watertables within 2.5 m from the surface while more than 50% of the area had watertables within 3.0 m from the surface. Figure 2 shows that area with depth to groundwater shallower than 3 m was continually increasing from 1991-2002 since the inception of this scheme. Recent data from this area show decline in watertables due to dry climate, reduced water allocation and improved irrigation practices.

Achieving salinity control depends on minimising the capillary upflow rates from the watertable. For clayey soils types in the WTSSDS area the capillary upflow rates need to be minimised by keeping watertables deeper than 2 m below the surface. However this watertable depth criteria needs to be combined with the potential for leaching root zone salts due to the winter recharge in the area when watertables can be shallower than 2 m following a major rainfall event. Therefore to achieve effective watertable and salinity control in an irrigated area the drainage scheme should serve to keep the waterlevels between 2-3 m below the natural surface. However in many locations in the WTSSDS the watertable have been much deeper than 3 m while at other locations the watertables have been closer to the surface. Therefore the current operation is not hydro-economically efficient therefore Wakool drainage scheme's operation needs to be optimised according to the changing groundwater dynamics both in terms of space and time to achieve the hydro-economic efficiency. For the optimal operation of the WTSSDS scheme a 3-D dynamic surface-groundwater interaction modelling approach coupled with an optimisation model based on Generic Algorithms was developed by the Murray Irrigation Limited and CSIRO Land and Water.

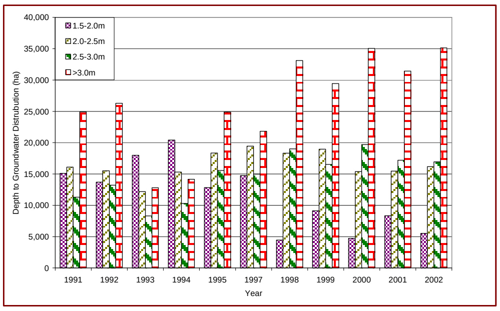

Figure 2. Depth to Groundwater Spatial Distribution (ha) for WTSSDS (1991 – 2002)

2.2 Development of the 3- D Surface-ground Water Flow Model

This section of the paper describes the development of a surface-ground water interaction model for the optimization of pumping operations in the Wakool Tullakool Subsurface Drainage Scheme (WTSSDS).

2.2.1 Conceptual Model

Figure 3 shows a schematic diagram of the conceptual model of the WTSSDS that includes lithology of the Upper Shepparton, Lower Shepparton, Calivil and Renmark formations- including top and bottom elevations and hydraulic characteristics of each formation. Conceptual model also illustrates vertical interactions (leakage) between the aquifers, groundwater recharge due to irrigation and rainfall, groundwater abstractions from different aquifer layers, leakage to and from the supply/drainage channels and rivers, and regional groundwater flow interactions for different aquifers at the boundaries of the model domain.

2.2.2 Modeling Framework and Description

The US geological survey model MODFLOW (modular finite-difference groundwater flow model) under the PMWIN (Processing MODFLOW for Windows) environment was used to evaluate the groundwater processes of the hydrogeological system in WTSSDS area. MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) is a modelling code for simulating confined or unconfined, saturated flow in one, two, or three dimensions. It allows both steady-state and transient simulation of groundwater systems. MODFLOW is one of the most popular ground-water modeling programs in existence by the number of publications available that have described use of the MODFLOW models to analyse groundwater flow such as the special volume of the GROUND WATER journal (Vol. 41, No. 2). The advantage of MODFLOW is that it provides different modules to undertake 3-D groundwater flow simulations in confined and unconfined aquifers as well as in aquifers with variable confinement therefore allowing use of constant and variable transmissivity values. The modules provided by MODFLOW can be used to simulate the effect on an aquifer resulting from the presence of extraction and/or injection wells, the areal distribution of recharge and/or evapotranspiration and different hydrological features such as rivers, drains (e.g. springs) and lakes.

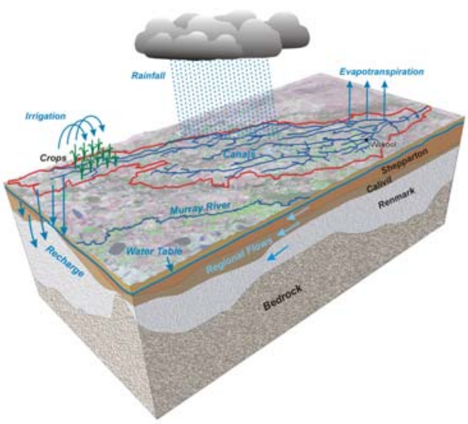

Figure 3. Schematic of the conceptual model of WTTSSDS, illustrating the hydrogeological features, flows in, through and out of the model

The WTSSDS model area is between 235400 m east and 269000 m east, and between 6,065,700 m north and 6,093,700 m north relative to Zone 55 of the Australian Map Grid. The spatial domain represented in the model consists of two layers, 280 rows and 337 columns (total of 94360 cells in each layer with each cell being 100m x 100m). Extensive datasets on the aquifer lithology (structural contours, borelogs, and aquifer properties), piezometric levels, groundwater salinity, and groundwater pumping were collected and collated in model input file format. Several customised computer programs were written for the manipulation of the difficult data sets to incorporate them into the desired MODFLOW format. General Head Boundary (GHB) was incorporated to simulate head-dependent lateral flows into or out of model domain from an external source. Stress periods of 30 days were used with five computational time steps in each stress period.

2.3 Surface-groundwater Flow Model Calibration

The WTSSDS model was calibrated for a 3 years period (1999-2002) using a monthly stress period. The initial conditions used for model simulation are specified as September 1999. Hydraulic conductivity, vertical leakance, specific storage, recharge and general head boundary were adjusted to calibrated the model against the historic piezometeric data of 370 piezometers in the WTSSDS area. To measure the performance of the model, calibrated water levels were compared with the observed water levels for 370 observation bores. The historic data for these wells (September-1999 to August-2002 period) was used for the calibration purposes. The results of the calibrated model show that the simulated water levels match well with the observed water levels at 370 bores. Two example hydrographs are given in Figure 4.

To further assess the performance of the model, spatial assessment of the “goodness” of fit between modelled and measured groundwater level contours was performed by comparing the modeled contours with the interpolated measured groundwater levels. Water level contours for different stress periods which show that the model replicates groundwater contours in the whole WTSSDS very well (Figure 5)

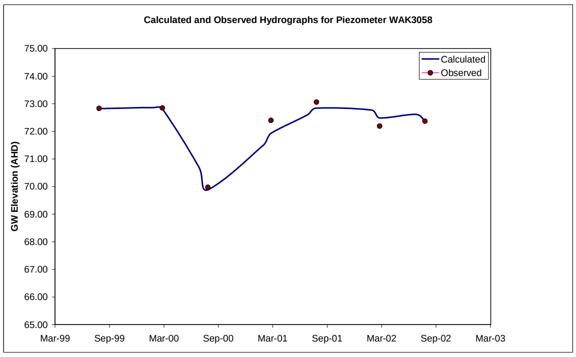

Figure 4. Sample hydrograph to measure the Model performance - calibrated groundwater levels compared with the observed groundwater levels

Using the Australian Groundwater Modelling Guidelines (Middlemis, 2000) quantitative calibration performance was also assessed using the statistics of piezometric head residuals (the difference between measured and modelled heads).

A scattergram plot is produced with measured heads on the horizontal axis, and modelled heads on the vertical axis, with one point plotted for each pair of data at selected monitoring sites (Figure 6).

All the points occurred with a small degree of scatter about the 1:1 line. The coefficient of determination (R^2) was calculated as 0.95, which indicated a very high degree of correspondence between the modelled and interpolated observations.

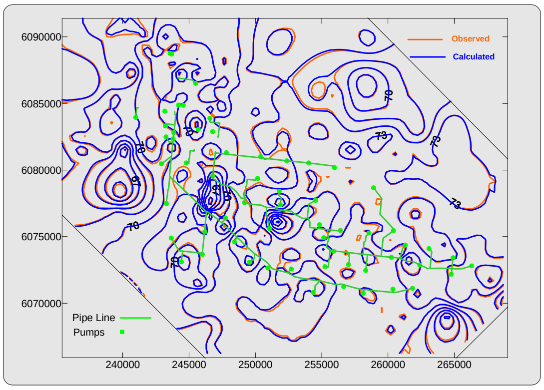

Figure 5. Comparison of Computed and observed Groundwater level contours for Upper Shepparton (September-2001)

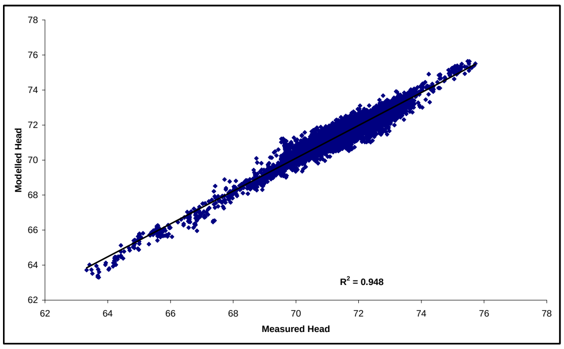

Figure 6. Scattergram between modelled and measured hydraulic heads

2.4 Optimisation using Genetic Algorithm

The calibrated surface-groundwater interaction model of WTSSDS was used to optimise the pumping operation of current tubewells using Modular Groundwater Optimizer (MGO). MGO is a general simulation optimization code incorporating MODFLOW and MT3D for groundwater resource and quality management (Zheng and Wang, 2001). This program was used by the authors to determine the optimal well pumping rates at pumping wells in order to achieve a specific objective as minimizing the pumping rate at one or more pumping wells. This was also desired to maintain the same or better watertable control performance of the scheme i.e. maintaining a minimum of 2 m groundwater depth below the natural surface in the shallower aquifer.

The objective function for the optimisation routine is

Minimize $$J = \sum_{i=1}^{N} |Q_i| \Delta t_i + \sum_{n=1}^{N} p_n \qquad (1)$$

Subject to

$$Q_{\min} \le |Q_i| \le Q_{\max} \qquad (2)$$

$$h_{\min} \le h_m \le h_{\max} \qquad (3)$$

$$p = p_h (h_m - h_{\max}) \qquad (4)$$

$$p = p_h (h_{\min} - h_m) \qquad (5)$$

J represents the management objective in terms of the absolute sum of all pumping rates multiplied by Δt, the length of the stress period used in the flow model. Q_i is the pumping rate of well represented by parameter i (negative for pumping) and N is the total number of parameters to be optimized. Δt_i presents the duration of pumping associated with parameter i. The term parameter is used to represent the pumping rate associated with a particular well location at a specific management period. For this optimization problem with multiple management periods, the flow rate of any well varies from one management period to another. Thus, multiple parameters were needed to represent the flow rates of the well at different management periods. p is a penalty for error, proportional to the amount of violation and ph is a penalty coefficient used to control the magnitude

Equation 2 is a constraint stating that the flow rate of a well at any specific management period must be within the specified minimum and maximum values (Qmin and Qmax). Equation 3 is a constraint stating that the hydraulic head at any monitoring location, hm, must be within the specified lower and upper bounds (hmin and hmax).

Equation 4 is a constraint stating that if the calculated head exceeds the upper bound at any location, a penalty, p, proportional to the amount of violation will be the penalty added to the objective function. Equation 5 is a constraint stating that if the calculated head is less than the lower bound at any location, a penalty, p, proportional to the amount of violation will be the penalty added to the objective function.

Genetic algorithms (GA) are a family of combinatorial methods that search for solutions of complex problems using an analogy between optimization and natural selection (Goldberg, 1989; Holland, 1992). GA mimics the biological evolution based on the Darwinist theory (survival of the fittest), where the strongest (or any selected) offspring in a generation are more likely to survive and reproduce. The method starts with a number of possible solutions, referred to as the initial population, which are randomly selected within the predetermined lower and upper bounds of each model parameter to be optimized. Each of the possible solutions in the initial population is referred to as an individual, typically encoded as a binary string (called chromosome). For each individual, the objective function (also referred to as the fitness function in GA) is evaluated. During the course of the search, new generations of individuals are reproduced from the old generations through random selection, crossover, and mutation based on certain probabilistic rules. The selection is in favour of those interim solutions with lower objective function values (in a minimization problem). Gradually, the population will evolve toward the optimal solution.

3. RESULTS AND DISCUSSION

The results of the detailed analysis of optimization demonstrate that it is possible to achieve the same level of watertable control with 20% less groundwater pumping (around 1 MCM yr^{-1} less than 1999-2002 pumping levels). This can lead to substantial cost savings by reducing the number of wells needed and lower pumping rates at some wells. Preliminary cost estimates indicated that pumping cost of \$4000 MCM^{-1} yr^{-1} could be saved. The optimal pumping strategy, as determined by the simulation-optimization analyses, suggests similar or even better drainage performance of the scheme could be achieved using 42 wells (rather than 53 wells) and a maximum pumping rate of 1000 m^3 d^{-1} for an individual pump.

Spatial groundwater analysis shows that with the existing pumping rates (20.5 MCM for the period of September 1999-August 2002) the average groundwater levels are 2.96 m below the natural surface at the end of the calibration period (August 2002). Twenty five percent of the area has depth to watertable (DTW) within 2.33 m from the surface and another 25% area has DTW as 3.53m. The remaining 50% of the WTSSDS area is lying within 2.92 m DTW below the natural surface. Under the optimised pumping scenario (16.9 MCM for the period of September 1999-August 2002) the average groundwater levels are predicted at 2.94 m from the surface. The twenty five percent of the area is predicted to be within 2.31 m depth to watertable (DTW) and another 25% area with 3.49m DTW. The remaining 50% of the WTSSDS area is predicted to be lying within 2.89 m DTW below the natural surface (Table 1).

Optimisation strategy suggests that 11 out of 53 pumps are redundant (Figure 7). The redundant pumps have got the uniform spatial spread which shows that less number of pumps could serve the same purpose now as compare to the initial design. Optimisation also suggests the need for increased pumping at 8 sites and four of the tubewells to be located at the eastern boundary of the scheme which may be due to the lateral groundwater flux. Genetic algorithms based optimisation shows no change in pumping at 33 pump stations, therefore these well positions can remain active.

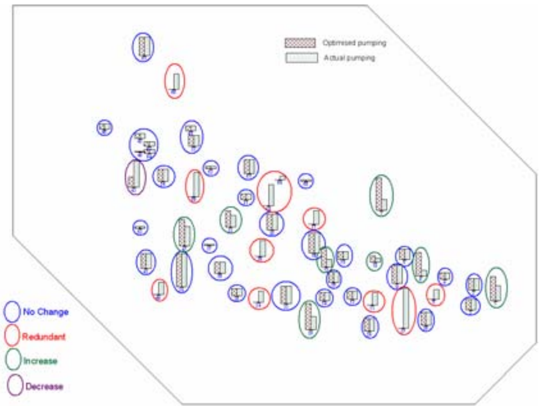

Figure 7. Spatial pumping change under optimization pumping scenario

4. CONCLUSION

Once a groundwater pumping system is put in place to service the waterlogging and salinity problems in an irrigation area, changing temporal conditions (rainfall, flooding and irrigation practices) necessitate a dynamic management response. Such an approach needs to be based on a comprehensive understanding of the groundwater dynamics for achieving economic efficiency of drainage.

The optimal management strategy, as determined by the simulation-optimization analyses, suggests the same or even better pumping performance of the scheme could be achieved using 42 wells (rather than 53) and a maximum pumping rate of 1000 m^3 d^{-1} for an individual pump. The groundwater pumping can be reduced by 20 % of the existing rate and preliminary cost estimates indicated that \$ 4000 MCM yr^{-1} pumping cost could be saved.

Table 1. Comparison of the existing and optimized pumping scenarios

Scenario	Total Pumping (MCM) Sept1999-Aug.2002	Depth to Water table(m)						
		Min	Max	Mean	Median	First quartile	Third quartile	Std. deviation
Existing Pumping	20.491	0.01	11.83	2.96	2.92	2.33	3.53	0.93
Optimised Pumping	16.925	0.41	11.43	2.94	2.89	2.31	3.49	0.92

5. REFERENCES

Australian Water Environments (AWM). 2001. Wakool Subsurface Drainage Scheme Stage III Investigation and Concept Design, Final Report to Murray Irrigation Limited, Deniliquin, NSW: Australia.

Beltran, J.M. 1999. Irrigation with saline water: benefits and environmental impact

Ghassemi, F., A.J. Jakeman, H. A. Nix. 1995. Salinisation of Land and Water Resources. Centre for Resources and Environmental Studies, Canberra, Australia.

Harbaugh, A.W. and M.G. McDonald. 1996. User's documentation for MODFLOW-96: an update to the US Geological Survey modular finite-difference groundwater flow model. US Geological Survey Open-File Report 96-485, 56 pp.

Hoffman G.J. 1990. Leaching fraction and root zone salinity control. In Tanji, K.K (Ed.) Agricultural Salinity Assessment and Management. American Society of Civil Engineers, New York.

Khan, S. 2005. Rethinking Rational Solutions for Irrigation Salinity. Australian Journal of Water Resources, Special Issue on Salinity Engineering, no. 9(2): 129 -140

Kijne J. W., S.A. Prathapar, M.C.S. Wopereis and K.L. Sahrawat 1998. How to manage salinity in irrigated lands: a selective review with particular reference to irrigation in developing countries. SWIM Paper 2. IIMI, Colombo, Sri Lanka.

Mayer, A. S., C. T. Kelley and C. T. Miller. 2002. Optimal design for problems involving flow and transport phenomena in saturated subsurface systems. Adv. Water Resources, no. 25(8–12): 1233–1256.

McDonald, M.G. and A.W., Harbaugh. 1988. A modular three-dimensional finite-difference groundwater flow model. US Geological Survey Techniques of Water-Resources Investigations, book 6, Chap. A1, 586 pp.

Middlemis, H. (2000). Murray-Darling BasinCommission. Groundwater flow modelling guidelines. South Perth. Western Australia, Aquaterra Consulting Pty Ltd

Rhoades, J.D. and J. Loveday. 1990. Soil salinity in irrigated agriculture. In: Stewart, B.A., Nielsen, D.R. (Eds.) Irrigation of Agricultural Crops. American Society of Agronomy, Madison, Wisconsin.

Rushton, K.R., 1990. Groundwater aspects: losses are inevitable but re-use is possible? Agricultural Water Management no. 40:111-116

Wakool Land and Water Management Plan Working Group. 1995. Wakool: Wakool Community’s Land and Water Management Plan., Deniliquin, NSW: Australia.

World Bank 1992. Development and Environment. World Development Report 1992. World Bank Washington, DC. 57.

Zheng, C., and P.P. Wang. 2001. MGO – Modular Groundwater Optimizer, Documentation and User’s Guide, University of Alabama and Groundwater Systems Research Ltd., Tuscaloosa, AL.