Integration of Groundwater Models within an Economical Decision Support System Framework

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EXTENDED ABSTRACT

Groundwater is a vital resource in Australian agriculture. Increased demand for water resulting from rapid economic development accompanied by poor climatic conditions (e.g. low rainfall levels) has induced an increased reliance on groundwater harvesting to sustain intensive irrigation practices. Overdraft of groundwater as a result of reduced surface water availability, increased economic viability of farms and the capping of river catchment allocations have considerably lowered water tables.

This paper describes a decision support system to aid in the sustainable water resource use in the Werribee Irrigation District (WID) in Victoria. This particular district provides an ideal set up for the investigative work described below as it has a fully calibrated groundwater model and more importantly, it is at risk of salinization due to sea water intrusion.

A decision support system linking crop water requirements with the available water for irrigation (surface and groundwater) is developed using a systems dynamic approach (system dynamics offers a new way of modelling the future dynamics of complex systems) by dynamically linking crop distribution patterns with the behaviour of a coastal aquifer using a finite difference three dimensional modelling approach.

This allows the optimisation of agricultural production while respecting sustainable groundwater levels in the aquifer. The Modflow 2000 code is used to simulate groundwater dynamics in the Werribee Irrigation District. VENSIM-DSS software, a system dynamics tool, was used to optimise crop distribution in the Werribee Irrigation District (WID) in Victoria. This was done by linking Crop distribution mix and water demand under set constraints to groundwater drawdown spatial distribution resulting from Modflow simulations scenarios.

The study time frame was set to 12 months. Four case scenarios were tested: a high water use scenario, a medium water use scenario, a no rice water use scenario and a low water use scenario (Vegetables Only). It was found that the "Vegetable Only" scenario was the most sustainable as pumping didn't breach the pre-defined sustainability limit[1].

Economic Surface and Groundwater Model (ESGM) was linked to a calibrated numerical Model developed under Modflow (USGS, 1984). The dynamic link takes care of the constraint checking and makes it easier for non-modellers to test various scenarios. This management tool as proposed presents the advantage of linking system dynamics to physical processes hence giving more realistic outcomes.

[1] Sustainability limit set to 0.5 m AHD for this case study purpose.

1 INTRODUCTION

Recent applications of the System Dynamics (SD) approach in the field of water resources include river-basin planning (Palmer et al., 1999), assessment of water resources, long-term water resource planning and policy analysis (Simonovic and Fahmy, 1999) and reservoir operation (Ahmed and Simonovic, 2000). Irrigation water demand management is a complex issue due to the pressure of uncontrolled variables such as climatic conditions. Difficulties usually arise from the integration of economic and environmental perspectives with the biophysical processes. The dynamic character of the main variables and how they affect water use in the future is not properly captured through traditional approaches (Elmahdi et al, 2004). Although the application of simulation and optimisation techniques have been a major field of research in water resources planning for many years, their adaptation to practical applications has not been successful, due to the fact that they deal with oversimplified systems (Yeh 1985; Simonovic and Fahmy, 1999) and do not dynamically connect to physical processes in these systems.

Therefore, there is a need to explore new tools to represent the complex relationships found in irrigation systems. One of those promising options is SD, a feedback-based, object-oriented approach. Although not a novel approach, system dynamics offers a new way of modelling the future dynamics of complex systems. According to Simonovic and Fahmy (1999), system dynamics is based on the theory of system structure and on a set of tools for representing complex systems and analysing their dynamic behaviour. The most important feature of SD is to elucidate the endogenous structure of the studied system, to see how the system components relate to one another and to experiment with changing relations when different decisions are included.

Moreover, the inherent flexibility and transparency of SD is particularly helpful for the development of simulation models for complex water systems with subjective variables and parameters. This allows the application of hierarchical decomposition in model development and an accrued transparency in its development. It also raises the possibility of practitioners' involvement in the model development, increasing their confidence in its operation and outputs (Simonovic, 2000). Compared with conventional simulations such as hydrological modelling or optimisation models, the system dynamics approach when linked with physical models (e.g. Modflow) gives a better outcome in simulating how different changes in basic elements alters the dynamics of the system.

Another characteristic of SD is the use of feedback loops. The SD tool used in this study to model irrigation demand under environmental constraints has four basic building blocks; stock, flow, connector and converter.

Stocks (levels) are used to represent anything that accumulates (e.g. water storage), flows (rates) represent activities that fill and drain stocks; (e.g. releases or inflows). Connectors (arrows) are used to establish the relationship among variables in the model, the direction of the arrow indicates the dependency relationships. They carry information from one element to another element in the model. Converters transform input into output.

Stocks and flows help describe how a system is connected by feedback loops which create the nonlinearity found so frequently in modern day problems. Figure 1 describes a casual loop diagram with some positive feedback and negative relationships.

Software tools are used to simulate a system dynamics model of the problem being studied. Running "what if" simulations to test certain agricultural decision on such a model can greatly aid in understanding how the system changes over time.

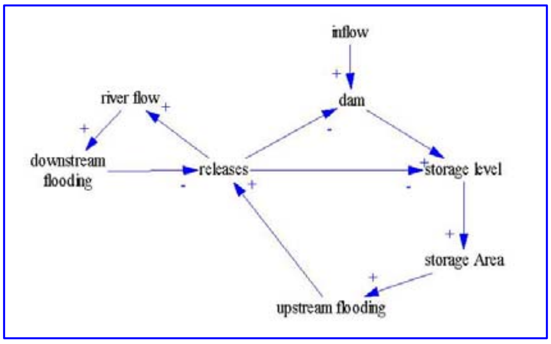


Figure 1: Casual loop Diagram

2 GROUNDWATER FLOW PROCESS

MODFLOW is a computer program that numerically solves the three dimensional groundwater flow equation for a porous medium by using a finite difference method (McDonald and Harbaugh, 1984). It uses the following partial-differential equation of groundwater flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t} \quad (1)$$

where:

- K_{xx}, K_{yy}, and $K_{zz:}$ Hydraulic conductivity along the x, y, and z axes (L/T),
- h: Potentiometric head (L),
- W: Volumetric flux per unit value representing sources and/or sinks of water (

W < 0.0 for outflow of the groundwater system, W > 0.0 for inflow (T-1),

- $S_{S:}$ Specific storage of porous material (L-1)
- T: Time

When combined with boundary and initial conditions, equation (1) describes transient three dimensional groundwater flow in a heterogenous and anisotropic medium. The groundwater flow process solves equation (1) using a finite difference method in which the groundwater flow system is divided into a grid of cells which for each there is a single point called a node. In the current version MODFLOW-2000, the finite-difference grid is assumed to be of rectangular shape horizontally, while the vertical dimension is distorted. Temporal discretization is based on time steps, which are grouped into stress periods. The length of particular time steps is user-defined during the model setup.

The Werribee Irrigation District model was originally set up with MODFLOW-2000, under VISUAL MODFLOW 3.0 (Waterloo Hydrogeologic, 1995) a comprehensive pre and post processor.

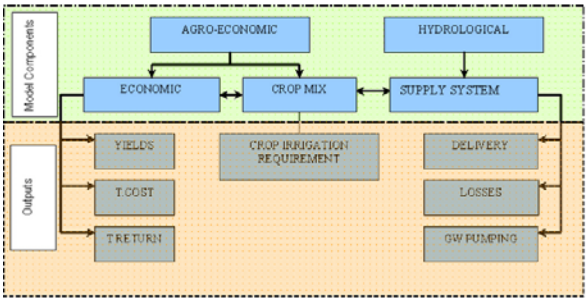
3 VENSIM Decision Support System

The Vensim modelling environment provides a programming environment for model development, thus providing a tool to solve problems that would be very mathematically complex to address

Furthermore, the Vensim environment insulates the user from the underlying mathematics and the details of the language specification. Hence, the created model has its interface to help the decision maker to use it and run "What if" scenarios without any specialised technical experience. The various copping patterns are tested to assess their impact on the biophysical demand, ground water pumping or need and total return.

Using Vensim[2] as a software development tool to configure the water balance network model, an Economic Surface and Groundwater Model (ESGM) has been developed to analyse the historical water allocation for part of the Werribee Irrigation district within constraints of environmental rules based on economic rationale (figure 2). The outputs of ESGM model are total cost, total yields, total return, irrigation demand, gross margin, losses, surface water used and ground water pumping to match the demand within system constraints.

[2] Vensim is a Trade Mark of Ventana 1996



. **Figure 2: ESGM model components**

Figure 3 depicts the DSS interface developed to facilitate user inputs and visualisation of outputs.

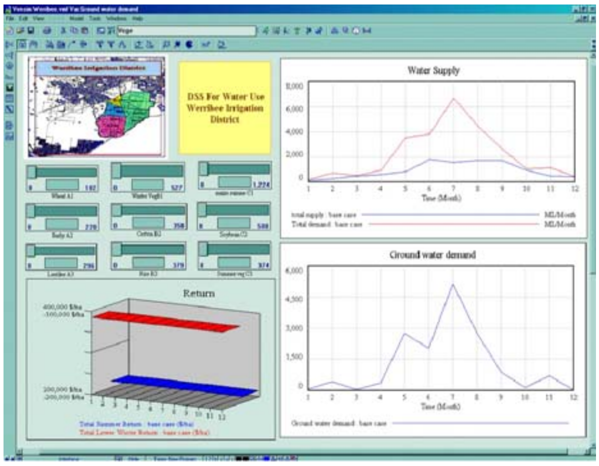


Figure 3: ESGM Interface

4 DYNAMIC LINK BETWEEN VENSIM AND MODFLOW

A major issue in coastal irrigation districts is fresh water contamination by sea water. There is a major drive to try to exploit these areas while insuring a control over these risks within the context of environmental sustainability and farmer economic needs.

The ESGM decision support system (DSS) is used to understand the synergy between surface water and groundwater to match the irrigation demand. Its development involves a semi-dynamic interaction between cropping set ups and groundwater levels constraints in the system.

<u>ESGM model Formulation and Application</u>

The Werribee Irrigation District (WID) was arbitrary divided in three zones A, B and C which were each subdivided in 3 main crop growing areas with their own channel supply and access to groundwater.

The network model consists of a link from a supply node (e.g. weir, ground water), a demand node (e.g. irrigation area or district), and a distribution node or the links connecting the supply and demand nodes.

Using this concept, the model uses a hierarchical decomposition principle by modelling the irrigation water system network of the WID system with all the model components at a monthly time interval. The sustainability criteria is checked using a suite of Fortran programs that test Modflow water table calculation for each time interval against a pre-set head criterion at pre-defined stress areas in the district (e.g. coastal areas, along the Werribee River). Figure 4 illustrates how different element of the DSS and Modflow interact wit each other.

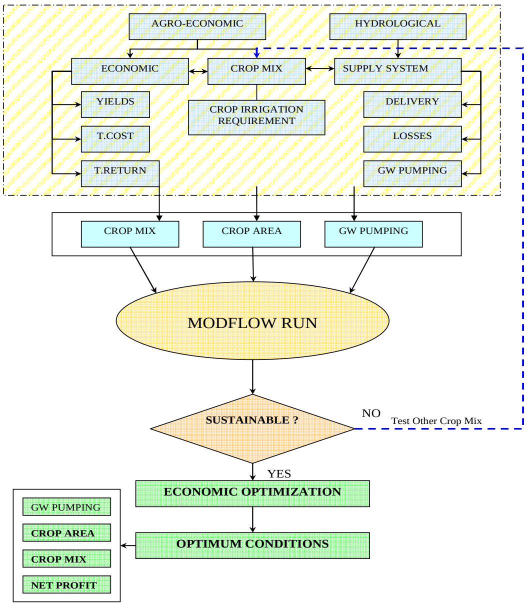


Figure 4: ESGM DSS Flow Chart

Consequently, the proposed model will be capable of exploring a wide variety of water supply and demand scenarios for WID. This interactive computer based tool allows the exploration of how various water supply objectives and demand requirements can be met for future scenarios with environmental and economic constraints. Conceptually, net returns, gross margin and variable costs represent the economist principles while minimizing total pumping requirements and meet the irrigation demand represent the hydrological aspect.

ESGM can simulate the physical water demand from irrigation areas using a hierarchical decomposition approach to calculate water requirement based on the cropping pattern or the cropping plan and the total irrigated area. (Figure 5)

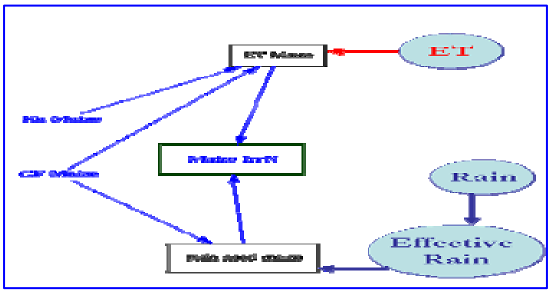


Figure 5: Calculation of crop water requirement for month

In this context, the total irrigation water requirement from the irrigation area per month is calculated as:

$$T.I = \sum_{m=1}^{12} \sum_{c=1}^{n} IN * A$$

Where T.I is the total irrigation water requirement per water year, IN is the crop irrigation requirement for month m and crop c, A is the cropped area of crop C, n is the number of crops and m is the month of the water year various from 1 to 12 for the 12 months of the water year, which start from July to June.

Food and Agricultural Organization of the United Nations (FAO) recommendations for irrigation requirements or biophysical demand were used. The following parameters were considered:

Reference crop evapo-transpiration (ET_o), growth factor (GF), crop factor (K_a), crop water need (ET crop= K_a x $ET_{o,}$), effective rainfall (ER) and irrigation water need (IN):

IN= {(ETcrop) x (B) x (GF)} – {ER x (B) x (GF)}

The fraction of growth period in a given month for a given crop ($GF_{(c,m)}$) will be calculated by:

$$GF_{(c,m)} = \frac{G.duration}{days}$$

Where G.duration $_{(c,m)}$ is the growth duration of a crop C in month m and Days is the total days of month m. Figure 6 shows the rice crop water requirement calculated.

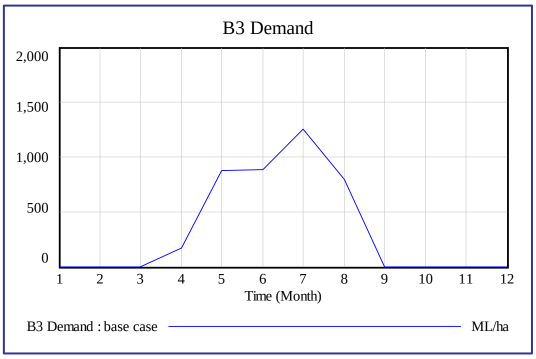


Figure 6: Rice water requirement simulated

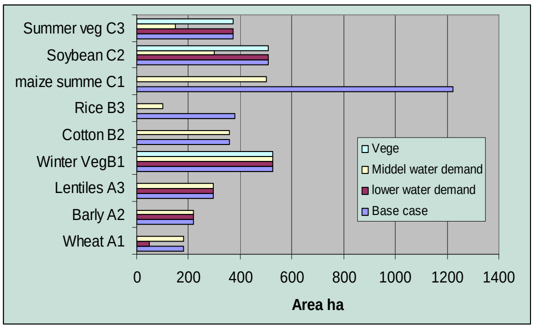


Figure 7: Crop Distribution with different Scenarios

6 WID MODFLOW MODEL

The groundwater model was developed in the MODFLOW 2000 finite difference modelling code using the Visual Modflow graphical user interface. The model grid covers the WID and the Melbourne Water Western Treatment Plant. It extends beyond the coastline in the south east and to the north of the Old Geelong Rd. The grid has a north-south, east-west orientation with 100m spacing over the region of interest, increasing to 200m in areas outside the irrigation district. Figure 8 shows the numerical model grid layout.

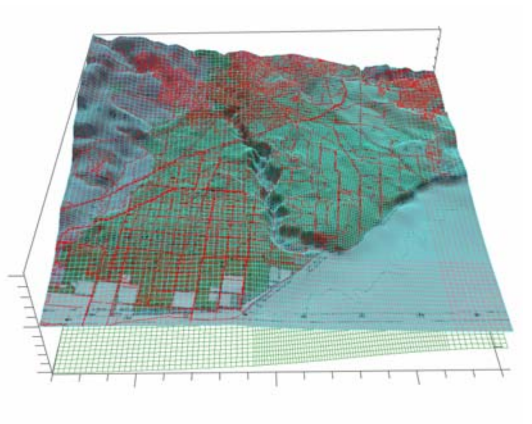


Figure 8: WID Model Grid and Structure

The model consists of four layers that represent the alluvial sediments and volcanics present within the Werribee River delta.

Model layer 2 represents a sandy gravel interval with significant permeability and is considered to be the principal aquifer. Model layer 3 represents a fractured basalt aquifer that covers most of the delta area. All model extremities are defined as no-flow boundaries except for the northern boundary where General Head Boundary (GHB) conditions are specified. This will allow water to enter the model across the northern boundary thereby replicating regional groundwater flow into the delta.

The coast line and sea bed are defined as a Constant Head Boundary set at 0.2 m AHD[3]. Effluent lagoons located at the seaward edge of the Western Treatment Plant are included in the model as a Constant Head Boundary condition set at 0.5 mAHD. The Werribee River is included as a line of River Boundary Cells with the river stage defined by a stream gauge located at the Werribee Weir.

The model was initially calibrated in steady state and in transient modes. The steady state model was modified until a satisfying match between predicted and observed potentiometric surfaces was attained. April 2002 was used as a steady state reference date because groundwater levels at this time are well defined by the available data and are similar to those measured at the start of the transient calibration period. Calculated model water tables were compared with the measured potentiometry and hydraulic parameters and recharge rates were adjusted to optimise the match.

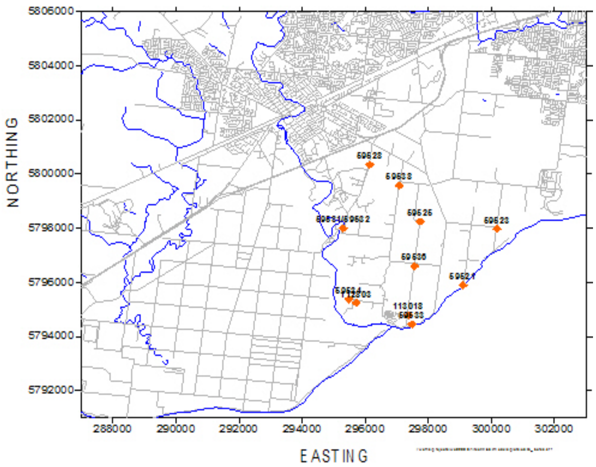


Figure 9: Observation Bores used in the Transient calibration

[3] Australian Height Datum

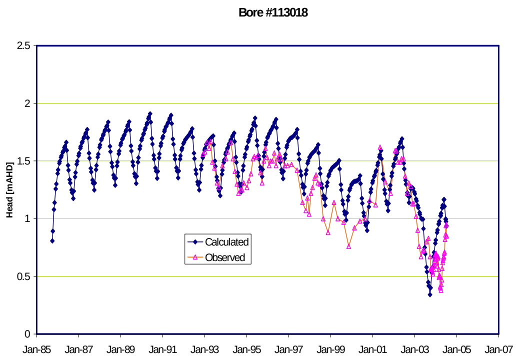


Figure 10: Example of Calibrated vs Observed heads at Observation Bore 113018

The model was calibrated for the period October 1985 until July 2004, and verified for the period May 2004 until February 2005. The verification process showed that the calibrated model follows the general trend of recovery observed in the monitoring bores.

The modelling concluded that when the aquifer is stressed, that is pumped heavily, the potential is created for saline water to flow into the aquifer from both the Werribee River and Port Phillip Bay (SKM, 2004)

7 CASE STUDY

The WID was chosen as a case study due to its constraints. Its location near the coast and the potential for salt water intrusion makes it an ideal site to demonstrate the utility of the ESGM DSS. Figure 11 shows the arbitrary elected areas and sub-areas extents and delineations

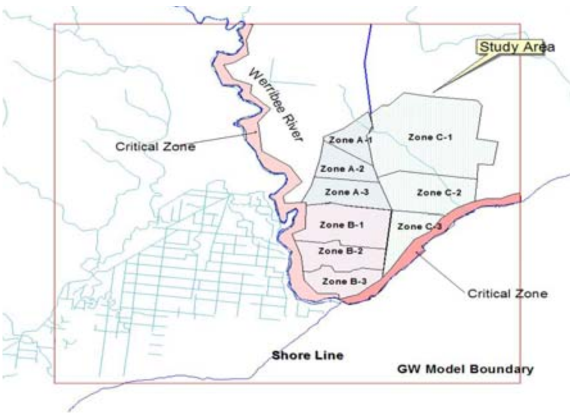


Figure 11: Irrigation District Cropping Areas

Four scenarios were run to represent high and low water demand conditions. The critical groundwater level threshold is set to 0.5 mAHD.

8 RESULTS AND COMMENTS

Four cases have been studied through ESGM DSS by changing the crop distribution. The model also calculates the total return $/ha and variable cost which are changed with different demand and supply options.

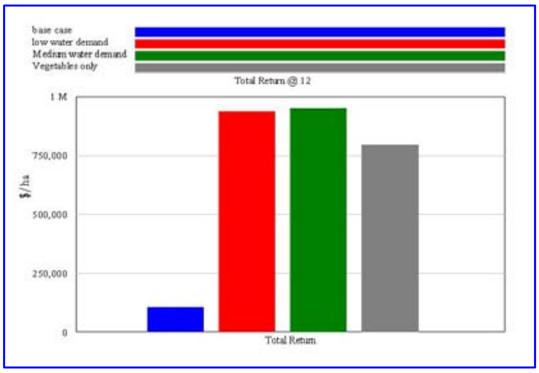


Figure 12: Total return for 4 case scenarios

Figure 12 shows the total return for each case. It is clear that the total return has increased for the middle demand scenario. Moreover, ground water demand has increased over the year. But in the "vegetables only" scenario, the model shows very clearly high return with a low water demand (see figure 13)

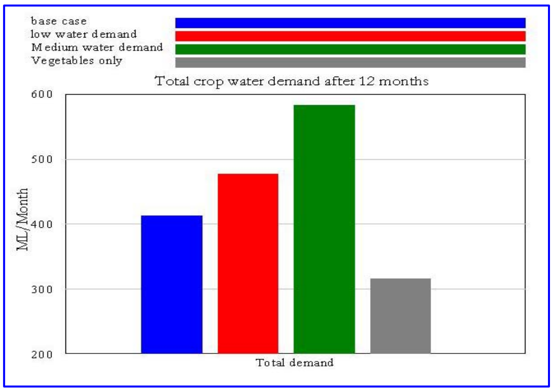


Figure 13: Crops Water demand

The ESGM DSS was run for 3 hypothetical case scenarios developed from the base case by changed the crop pattern and area: low water demand, medium water demand, vegetables only, and a base case scenario (high demand)

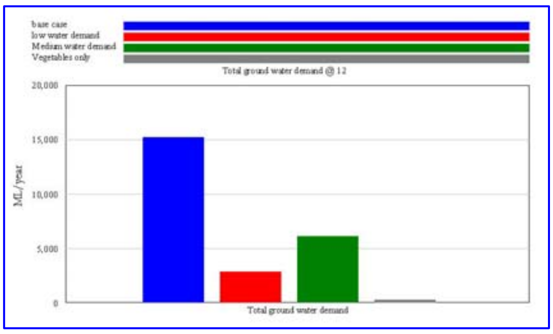


Figure 14: Ground water demand

Figure 15 and 16 shows the groundwater elevation after 335 days of simulation when crop water demand reaches its peak. Contour levels shows zones of water levels higher than the pre-set threshold.

In the Base case (high demand) scenario, ESGM results shows that the set criteria is not respected East of Werribee River on the coast line and in an area along the Werribee River. In the “Vegetables Only” scenario (low demand) the resultant groundwater head distribution as presented in Figure 16 are well above the critical preset threshold.

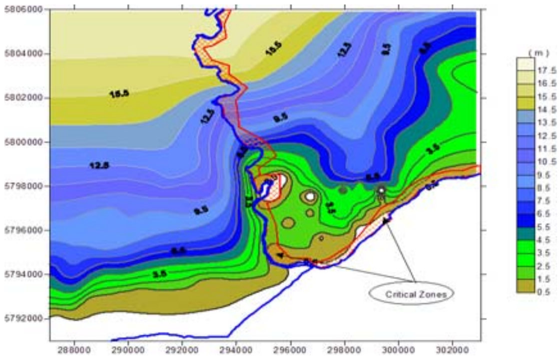


Figure 15: Base case Heads at 335 days

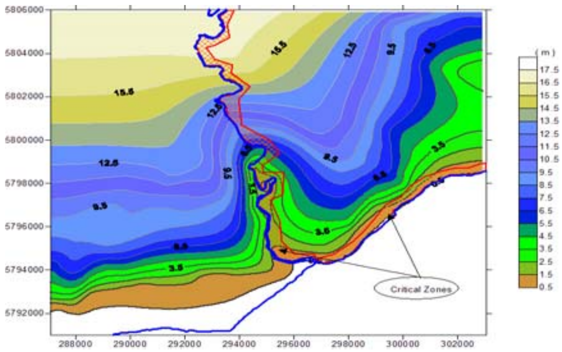


Figure 16: “Vegetables Only” case heads at 335

9 CONCLUSIONS

A Decision Support System has been developed to assist in the management of complex irrigation systems. It aims at assisting decision makers such as Irrigation companies or irrigators in getting a more thorough understanding of the impacts of crop mix choices under a set of environmental constraints. Its objectives are set to provide outlooks at agricultural choices while maximising returns to farmers within a sustainable water resource use. EGSM DSS was applied to the WID which presents typical environmental issues that irrigation districts face. The study time frame was set to 12 months. Four case scenarios were tested: a high water use scenario, a medium water use scenario, a no-rice water use scenario and a “Vegetable only” scenario (low water use). It was found that the “Vegetables Only” scenario was the most sustainable as pumping did not breach the set sustainability constraint. The dynamic link EGSM-Modflow takes care of the constraint checking and makes it easier for non-modeller users to test various scenarios. This management solution as proposed presents the advantage of linking system dynamics to physical processes and gives more realistic outcomes. Although more optimisation capabilities are needed to be added to ESGM DSS, It still is a powerful tool which can be used by water managers to test different crop mix scenarios and their environmental sustainability.

The next phase of development of ESGM-DSS will involve a more interactive user interfacing, Geographic Information System capabilities and pre-post processing enhancements.

10 ACKNOWLEDGMENTS

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11 REFERENCES

Ahmed, S. and Simonovic, S.P. 2000, System dynamics modelling of reservoir operations for flood management, j.Comp.Engrg. ASCE 14 (3), 190-198.

Elmahdi A., Malano H. and Khan S. 2004, A system dynamic approach and irrigation demand management Modelling, Environmental Engineering Research Event 2004 conference 6-9 December 2004. Published by University of Wollongong Press ISBN: 1 74128 080 X. (www.ere.org.au).

Simonovic, S. P. 2000, ‘Tools for water management: one view of the future’, Water International 25(1), 76–88

Simonovic, S. P. and Fahmy, H.: 1999, ‘A new modelling approach for water resources policy analysis’, Water Resource. Res. 35(1), 295–304.

SKM, 2004, Werribee Irrigation District Groundwater Investigations, Consultancy Report - Sinclair Knight Merz Ltd

Harbaugh, A.W., Banta E.R, Hill M.C and McDonald M.G 2000, MODFLOW 2000, the USGS Modular Groundwater Model- User Guide to Modularisation Concepts and the Groundwater Flow Process. USGS Open file Report 00-92, Reston Virginia