ECONOMIC AND ENVIRONMENTALLY SUSTAINABLE USE OF VARIOUS WATER SUPPLY SOURCES FOR IRRIGATION

June 1997

National Program for
Irrigation Research and Development

Economic and Environmentally Sustainable Use of Various Water Supply Sources for Irrigation

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Principal investigators

John Hillier, John Doherty, Jerome Arunakumaren, Kiran Bajracharya, Steven Bengtson, and Sellarthuray Kuhanesan

Other investigators

David Scriven and Andrew Durick

National Program for Irrigation Research and Development

Economic and Environmentally Sustainable Use of Various Water Supply Sources for Irrigation

Project QPI27

Project duration

01 January 1994 - 30 June 1997

Project objectives

1) To develop an extensive set of software utilities to enable experienced modellers to construct, with much less difficulty than at present, a model suitable for the management of a particular conjunctive use irrigation area so that all aspects of the economic and environmental suitability of an irrigation area be considered in its management.

2) To use the modelling system:

- to make better decisions on the optimal mix of water sources to be used at any time (ie. from surface storages, groundwater or other sources) to maximise water availability,
- to consider the use to which water should be put - urban, irrigation, artificial recharge etc. to enable maximum benefit to be obtained from the available resources,
- to ensure that minimum environmental degradation occurs both within and outside the irrigation area.

3) To incorporate a climate prediction model into the linked models to allow decisions on allocations and water storage use to be made considering probable future weather conditions.

4) To calibrate and trial the system in two large integrated source irrigation areas in the Bundaberg area and the Lockyer Valley.

5) To hold a workshop and produce manuals to show managers the benefits in adopting more sophisticated management techniques in irrigation areas.

Milestones and achievement criteria

Milestones and achievement criteria for the 30th June 1997, as set out in the original agreement between LWRRDC and QDPI for project QPI27 are as follows.

Milestones

1) Complete a channel distribution and saltwater intrusion model in the Bundaberg Irrigation Area based on accessible models and unsaturated zone model already developed as part of the project.

2) Document these models, including their methods of construction and general usage, as a case history of model deployment for better water management in a conjunctive use irrigation area.

3) Where possible enhance the models' user interfaces through the development and implementation of utilities which simplify the testing of different water management strategies and enhance the visualisation of model predictions.

4) Provide a mechanism for educating modellers both in Queensland and interstate on the use of software developed as part of the current project.

5) Finalise documentation of all software developed in the course of the project.

Achievement criteria

Submission of Milestone Report to LWRRDC including:

1) a description of the final version of groundwater modules/utilities for use in conjunctive water use modelling and management,

2) an appraisal of the performance of the utilities, including a sound analysis of results trialing in the Bundaberg irrigation areas,

3) an evaluation of the reception by other (including interstate) managers of the utilities based on the education and awareness activities,

4) separate appendices to include utilities manuals, other communication materials and any professional publications.

MILESTONE 1

A description of the final version of groundwater modules/utilities for use in conjunctive water use modelling and management.

GROUNDWATER DATA UTILITIES

In spite of the availability of powerful, user-friendly, model-specific pre- and postprocessing software, groundwater modelling is difficult. One of the main reasons for this is the necessity to transfer large amounts of data into and out of models, and between models, databases and visualisation and display software.

The Groundwater Data Utilities were written to complement existing models, and their graphical pre- and postprocessors, were developed in an attempt to overcome some of the ancillary problems involved in the practice of groundwater modelling. None of the tasks performed by any of the programs developed is particularly difficult; yet to undertake these tasks without software assistance would be time-consuming and error-prone as they generally involve the processing of large amounts of data.

The intention of the Groundwater Data Utilities is to free modellers of some of the more laborious data-handling tasks which accompany all modelling projects, so that they may then be free to turn greater attention to the critically important issues of correct model setup, parameterization and calibration. If this does, indeed, occur then the development of the Groundwater Data Utilities will have been worth the considerable effort required for their development.

Many of the utilities developed have been written specifically for use with MODFLOW (MacDonald and Harbaugh, 1988) and MT3D (Zheng, 1992). With little or no modification these utilities could also be used with other cell-centered finite-difference models such as SHARP (Essaid, 1990). Others of the utilities are model-independent, being used simply for groundwater data manipulation and presentation, whether such processing is required as part of a model-construction exercise or not.

The Groundwater Data Utilities can be used in conjunction with any MODFLOW or MT3D preprocessor. However it is an important part of the philosophical underpinning of the utilities that the preprocessor allow the importing and exporting of MODFLOW/MT3D-compatible, two-dimensional data arrays. “Processing MODFLOW” (ie. PM) written by Wen-Hsing Chiang and Wolfgang Kinzelbach (1993), and its WINDOWS upgrade, PMWIN, also by Wen-Hsing Chiang and Wolfgang Kinzelbach (1996), is such a preprocessor. Where any of the utilities developed read or write real or integer arrays, the PM convention for formatted (ie. ASCII) array storage is adopted; this requires that a header line recording the number of model columns and rows precedes the array itself in its formatted file. If a modeller is using a preprocessor which does not require such a header line (for example the USGS text-based preprocessor MFI by Arlen W. Harbaugh (1994), the header can easily be added or removed with a text editor.

Where required by any of the utilities, grid geographical information is supplied through a “grid specification file”. This file is identical to a file of the same name and function used by the PEST MODFLOW/MT3D Utilities Suite written by John Doherty (1995). Hence the latter suite can be used together with the utilities developed without the necessity for data translation or reformatting. In fact some of the Groundwater Data Utilities were written specifically to enhance the functionality of the model-independent parameter estimator PEST (written by John Doherty, 1994) when used in the context of MODFLOW/MT3D calibration.

Some of the Groundwater Data Utilities allow model-generated data to be interpolated and/or reformatted for importation into graphing and contouring software. Some of these utilities are independent of the user's choice of graphing or contouring software; others, however, relate specifically to Golden Software's SURFER package. SURFER is a grid-based contouring and three dimensional surface plotting graphics program that runs under Microsoft Windows, Windows 95 and Windows NT. Some of the latter utilities provide a mechanism whereby SURFER can be used in a model preprocessing role, while others enhance its ability to display model results with or without diagrammatical representation of the finite difference grid (including any zonation defined within this grid).

Functionality is included within the Groundwater Data Utilities for data exchange between a model and a Geographical Information System (GIS). In particular, model geographical, real and integer array data can be exported to ARCINFO and MAPINFO through "generate" and "mif/mid" files respectively. Model real and integer array data can be read as tables, allowing GIS-exported real and integer array data to be incorporated into a model.

None of the Groundwater Data Utilities are able to read database files. However many of them have been written to extract or process data of the type normally held in databases. To save programming effort and maintain independence from any particular database or platform, the utilities have been written to interface with "flat" ASCII files of the type that can be easily downloaded from a user's groundwater database. Where a user's dataset does not provide all of the information required by certain utilities (for example if measurement date is recorded rather than date and time), a file of the type required by a particular utility can easily be generated from a database-downloaded file by adding appropriate dummy entries (eg. a time of 12:00:00) to each file line. For the databases employed by the Queensland Department of Natural Resources, utilities have been written to provide this translation mechanism. Similar utilities could be easily written for the databases used by other organisations. However in many cases, reformatting can be just as easily carried out using a text editor.

GRAPHICAL GROUNDWATER UTILITIES

Computer simulations of groundwater flow and contaminant transport have been performed during the past 25 years as part of hydrogeological analyses for groundwater resource protection, site characterisation, impact prediction, risk assessments and engineering design. In recent years, there has been a dramatic change in the role of computer simulations in hydrogeological analyses due to the development of graphical user interfaces (GUIs) for various modelling programs and easy access to more powerful computers.

These GUIs have greatly enhanced the process of building and running groundwater modelling simulations by providing the modeller with the ability to graphically design models, and to visualise site characteristics and simulation results on a screen. These GUIs have enabled hydrogeologists to more accurately represent the complex groundwater flow systems that occur in nature.

In spite of the availability of these advanced GUIs, groundwater modelling is still a mystery to many people. Most models now require manual, separate input of parameters such as well locations, observed heads, and so on. Most of these parameters are stored in a number of database formats and it is necessary to transfer large amounts of data into and out of models, and between various models, databases and visualisation programs. The Groundwater Data Utilities were developed as part of this LWRRDC project, to overcome some of the ancillary problems encountered in the practice of groundwater modelling.

The majority of people are able to comprehend a problem more effectively through a Geographical Information System, and so the most logical way of displaying a model configuration, observed model parameters and simulated model results is within a GIS. The Graphical Groundwater Utilities were written to take advantage of the Groundwater Data Utilities to link the modelling environment with a GIS. This removes much of the difficulty of understanding groundwater modelling processes and automates much of time consuming mundane data manipulation work. However, it does not remove the necessity of understanding the systems being modelled. The Graphical Groundwater Utilities allow water resource managers to quickly develop an understanding of the consequences of resource management and allocation decisions, and to act accordingly to husband the groundwater resources.

The Graphical Groundwater Utilities have been written in MAPBASIC and provide MAPINFO, which is a popular and powerful WINDOWS-based GIS package, with an interface between the user and the modelling environment. These utilities are model-independent, being used to display model input/output data through "point-and-click" style inquiries. Amongst the many applications that come with the Groundwater Graphical Utilities are some which provide a link between the model data and MapInfo. The data exchange functionality between MapInfo and cell-centred finite-difference models is included in the Groundwater Data Utilities. If the model structure is not based on a cell-centred finite-difference model, then the user will need to manually create the MapInfo tables to the structure outlined in the Graphical Groundwater Utilities manual.

The Groundwater Graphical Utilities have been developed to perform the following tasks :

- Allow a user to CLICK ON BORES and view a graph of HISTORICAL WATER LEVELS from those bores. Hydrographs for three such bores can be displayed and plotted simultaneously.

- Allow a user to CLICK ON A BORE and view a graph of HISTORICAL WATER LEVELS and MODEL SIMULATED WATER LEVELS from that bore.

- Allow a user to CLICK ON A CELL and view a graph of HISTORICAL WATER USE within that cell.

- Allow a user to CLICK ON A BORE and view a graph of annual CONDUCTIVITY PROFILES from that bore.

- Allow a user to CLICK ON A SERIES OF CELLS and view a graph of an AQUIFER CROSS-SECTION along those cells.

- Allow a user to save the above graphs for further comparison.

- Allow a user to view a soil map, the crop coverage or any other required coverage in the modelling area.

- Allow a user to CLICK ON A CELL and view a graph of LAND USE within that cell and allow the user to modify those land use areas for scenario modelling purposes.

- Allow a user to INTERSECT a model grid with geological data, soils data, and/or land-use data to facilitate model parameterisation.

SOIL PROCESS MODELLING - SPLASH

SPLASH v1.2 (**S**oil, **PLA**nt **S**alinity and rec**H**arge) is a lumped parameter model for simulating the temporal behaviour of moisture in the plant root zone and in the unsaturated zone below the root zone. The model produces simulated time series of consumptive use, irrigation demand, run-off from the soil surface, recharge to the aquifer, salinity concentration of the root zone water and salinity of the recharge water. The model can be run in either “discrete” or “continuous” mode, the former option being used to simulate farm-scale behaviour, while the latter simulates demand patterns on the regional scale where individual usage characteristics are “smoothed out”. SPLASH is not intended to model rainfall-runoff time series.

The development of SPLASH was undertaken as part of LWRRDC Project QPI27. It was developed rather than using an existing model, because no existing model could handle moisture and salt movement in a complex manner on the REGIONAL SCALE required. Existing models [SWIM (Ross, 1990), PERFECT (Littleboy *et. al.*, 1993) etc.] were developed to simulate conditions in a small-scale [“paddock”] situation, using field measured data whereas SPLASH can also simulate on a regional scale.

SPLASH is based partly on an existing in-house lumped parameter soil moisture model (Henry, 1983), which has proved to be a reliable tool for making water allocation decisions across the State.

SPLASH can be calibrated to simulate regional demand and recharge. The regional demand and recharge from the calibrated SPLASH model can be inputs to channel distribution and groundwater flow models. A calibrated SPLASH model will provide a basis for making demand predictions for next year or any future time frame, thus providing assistance in the determination of allocations.

The following land use processes are allowed for in SPLASH:

- the effect of STAGE OF CROP GROWTH, represented by crop coefficient and rooting depth, is to reduce potential evapotranspiration below the maximum determined by climatic conditions.

- the effect of LAND MANAGEMENT PRACTICES, represented by a management factor is to reduce actual consumptive use below potential evapotranspiration.

- the effect of SOIL MOISTURE CONDITIONS within the root zone, represented by the moisture holding characteristics of the soil type, modifies actual consumptive use and water movement.

- the effect of soil moisture conditions in causing simulated IRRIGATION is represented by a MANAGEMENT RULE which provides an “allowable deficit” at different stages of crop development.

- the effect of WATER LOSSES such as channel losses and farm losses, between the point of supply and the point of application is represented by irrigation efficiency parameters.

A Graphical User Interface for SPLASH (VISUAL SPLASH) was also developed to create the input files for SPLASH and to view its output files (time series of consumptive use, irrigation demand and recharge) in a graphical form. VISUAL SPLASH is a 32 bit windows program, which was developed in Visual Basic Version 4.0 and has been tested on Windows 95 but should also run on Windows NT versions 3.51 and 4.0.

SEAWATER INTRUSION MODELLING

SHARP and its preprocessors

The United States Geological Survey freshwater and saltwater flow model SHARP (Essaid, 1990) was modified in order to provide it with an interface which can utilise pre- and post-processing software suitable for MODFLOW. The use of MODFLOW pre- and postprocessors is made possible by the fact that both SHARP and MODFLOW are cell-centered finite difference models. Hence two-dimensional real and integer arrays used for data input and output can be shared by both programs.

A two-stage, text-based, SHARP preprocessor was also developed. Graphical display of SHARP input and output data is available through the use of the Groundwater Data Utilities and the Graphical Groundwater Utilities.

The similarity between MODFLOW and SHARP can be further exploited when undertaking SHARP parameter estimation, in that the "PEST MODFLOW/MT3D Utilities" suite (Doherty, 1994), developed for MODFLOW and MT3D parameter estimation using PEST (Doherty, 1994), can be used with SHARP without modification.

Review of seawater intrusion models

As part of this project, SHARP (USGS cell-centred finite difference seawater intrusion model) was used unsuccessfully to develop a regional scale seawater intrusion model. After it became obvious that SHARP would not suit our needs as a regional-scale seawater intrusion model, the market in seawater intrusion modelling software was surveyed and a number of packages were tested on sample and real problems. The simple, readily available and inexpensive packages have proved to be unsatisfactory for complicated deltaic aquifer systems. The review of seawater intrusion models is documented as part of this project.

SUTRA utilities

The United States Geological Survey saturated and unsaturated transport model SUTRA was used to develop two-dimensional cross-sectional models to study the seawater intrusion processes for instructional purposes. SUTRA is a finite-element model which uses quadrilateral elements to discretise the model domain. These elements are defined by element numbers and their four nodes. SUTRA requires the coordinates of each node and element-nodal connectivity data. Since each node and element have to be defined in SUTRA , the transfer of large amounts of data into and out of SUTRA for an irregular model domain is tedious.

The Groundwater Data Utilities were written specifically for use with cell-centred finite-difference models such as MODFLOW/MT3D, to allow the importing and exporting of two-dimensional data arrays in PMWIN, SURFER and MapInfo to facilitate the pre/post processing of model data. The active part of the cell-centred finite-difference grid created by PMWIN can be considered as quadrilateral elements. As such, three Sutra Utilities (**int2fe, fe2real and fe2vel**) were developed to exploit the use of the Groundwater Data Utilities for graphical display of SUTRA input/output data.

The program **int2fe** converts finite-difference configuration data into the format required by SUTRA. The program **fe2real** interpolates the SUTRA output such as concentration, pressure and saturation at each node to a value at the centroid of each element that can be manipulated by the Groundwater Data Utilities. The program **fe2vel** transforms the SUTRA velocity output into a SURFER file to display velocity vectors.

MILESTONE 2

An appraisal of the performance of the utilities, including a sound analysis of results trialing in the Bundaberg irrigation areas.

BUNDABERG IRRIGATION AREA

INTRODUCTION

The Gooburrum area is situated within the Bundaberg Irrigation Area on the north side of the Burnett River (Figure 1). It covers a coastal area of around 20 by 15 kilometres. Part of the area is served by the Gooburrum surface water irrigation system which was completed in the mid 1980's. This is used along with groundwater to irrigate almost 10 000 ha of land, predominantly for sugarcane. Groundwater contributes to slightly more than half of this irrigated area. Some other crops aside from sugarcane are grown in small quantities, the only one of any significance being macadamias which accounted for about 7% of the crop area in 1992.

A significant topographical feature that occurs in the area is an escarpment that runs north-west splitting the area into two distinct sections. The land on the lower or coastal side of this escarpment is generally below 5 metres AHD while that on the higher side rises to about 30 metres AHD.

The first groundwater management model for the Gooburrum area was developed in the early 1980s, to study the impacts of different land use practices on groundwater levels and to estimate the yield of the aquifer. The “in-house” integrated finite difference model (Henry, 1979) was used in groundwater flow modelling with the “in-house” soil moisture store model (Henry, 1983) used to simulate a time series of irrigation demand and recharge for different land use practices. The groundwater allocations were subsequently made based on this model’s results. As the irrigation scheme matured, it developed problems associated with groundwater such as seawater intrusion occurring near the coast, and high water tables causing water-logging in other areas. These problems are the consequences of non optimal use of ground and surface water, respectively, exacerbated by the unfortunate location of the areas served by surface water vis-a-vis the areas using groundwater.

Groundwater flow modelling

The hydrogeological studies carried out in this area indicated that the Gooburrum aquifer system consists of two geological sequences: the Elliott formation and the deeper Fairymead formation. The current problems and the new interpretation of the aquifer system warranted the development of a multi-layered groundwater management model. The development and calibration of the multi-layered groundwater flow model is outlined in the report by Scriven (1995). New volumes of groundwater allocations were made using this model.

This groundwater flow model was developed using the “in-house” integrated finite difference model which cannot interact readily with available solute transport models.

For this reason and others listed below it was decides to convert the integrated finite difference model to a MODFLOW model. The benefits of this conversion include:

- The Groundwater Data Utilities can be used for data manipulation and to transfer existing model data to the MODFLOW model.

- The visualisation and display mechanisms required to view the model input/output data are already available in other packages such as PMWIN, GMS, Visual MODFLOW, SURFER, MAPINFO. The Groundwater Data Utilities can be used to process the model input/output data into the format required by these packages.

- The Graphical Groundwater Utilities can be used to develop a user-interface linking model environment with a GIS. These utilities were written to display model input/output data through "point and click" style inquiries in the MapInfo environment. This will allows a non-technical person to run the model and comprehend the output without the assistance of a modelling "specialist".

- The PEST MODFLOW/MT3D Utilities (Doherty, 1994) are already available and calibration of the MODFLOW model would be relatively straight forward.

- The LWRRDC Project CTC6 requires the development of a flow and solute transport model to study the relative impacts of various land management strategies on nitrate levels in groundwater. A solute transport model can be developed using MT3D which requires MODFLOW output. The Groundwater Data Utilities can be used to set up the MT3D model.

The Groundwater Data Utilities were found to be extremely useful for setting up MODFLOW and MT3D models. Many of the Groundwater Data Utilities begin execution by reading a grid specification file. The grid specification file contains all the information required to define the finite difference model domain in real-world coordinates. The rectangular model domain is defined with the east and north coordinates of the top left corner of the model domain; the rotation of the model grid row direction with respect to east in an anti-clockwise direction; and the length and width of the model domain. The length and width of the model domain are represented as row and column spacings. The simplicity of the grid specification file helps the modeller to understand the model domain and to check for any errors in defining the model domain.

The Groundwater Data Utilities read the grid specification file to determine the positions of bores with respect to the grid and create a GIS model coverage. The GIS model coverage can be superimposed on other geographical data to allocate geographical data values to each model grid cell. The **grid2pt** program provides the coordinates of the cell centres of the "active" part of the finite-difference grid and the model configuration data such as aquifer top and bottom, initial water level and initial concentration for each cell centre can be interpolated within SURFER. The interpolated data can be transformed into a finite difference real array format using the **tab2real** program.

The Groundwater Data Utilities perform many laborious tasks such as error checking on downloaded data from the groundwater database and rewriting the model input/output data in the format required by comercially available visualisation software such as SURFER, PMWIN, MAPINFO in a matter of minutes.

Soil process modelling

The newly developed lumped parameter soil moisture model SPLASH was adapted to provide inputs to the newly converted MODFLOW model, replacing Henry's soil moisture store model (Henry, 1983). SPLASH provides output as time series of consumptive use, irrigation demand and recharge. The SPLASH outputs, recharge and irrigation demand were the inputs to the MODFLOW model. SPLASH provides a systematic approach to calibrating the regional crop consumptive use and the irrigation demand. The regional recharge is calibrated in conjunction with the MODFLOW model.

Consumptive use

SPLASH considers soil moisture conditions and land use practices in simulating consumptive use. The soil moisture effects are taken into consideration using the Minhas et al. (1974) equation which relates the ratio of actual to potential evapotranspiration as a function of ratio of soil moisture to the capacity of capillary moisture store. The land use practices are taken into consideration by using "management factors" which modifies the calculated "actual" evapotranspiration.

The consumptive use for sugarcane was estimated in each soil type according to the yield of sugarcane using the relationship developed by Kingston (1994). The capacity of the capillary moisture store of each soil, and the management factors were adjusted to best match the SPLASH output and the estimated values from the relationship given by Kingston (1994) below:

Soil Type	Estimated Consumptive Use (Kingston, 1994) (mm)	Simulated Consumptive Use SPLASH (mm)	Adjusted Capacity of Capillary Store (mm/m)	Adjusted Managemen t Factor
1	944	945	190	0.84
2	947	951	160	0.84
3	1081	1076	180	0.98
4	965	965	200	0.87
5	977	969	130	0.87
6	986	975	90	0.86

Consumptive use figures were not available for the other types of ground-cover. For macadamias the management factors were again assumed to be the same as for sugarcane on each soil and for the other types of ground-cover the factors were set at 0.8 which has been found to be appropriate in earlier modelling studies (Scriven, 1995).

Irrigation Demand

Irrigation demand only applies to the two irrigated crops, sugarcane and macadamias. SPLASH considers soil moisture conditions, pattern of irrigation and environmental effects in simulating irrigation demand. The pattern of irrigation is taken into consideration using an "allowable deficit" which defines a warning depth for irrigation. The environmental effects are considered using "channel losses" and "farm losses" to account for any water losses between the point of supply and the application. It is controlled by the channel and farm losses, and the plant available water factor. Calibration of irrigation demand is mainly associated with adjusting the parameters controlling the allowable deficit, channel losses and farm losses to best match the observed irrigation use. The cumulative demand plots for the SPLASH model are compared with the metered use in Figure 2.

Recharge

SPLASH simulates recharge as infiltration through the unsaturated zone to the aquifer using a control function which defines the variation of recharge rate with the depth of soil water in the unsaturated zone. The maximum recharge rate and the capacity of the gravity store which controls percolation through the root

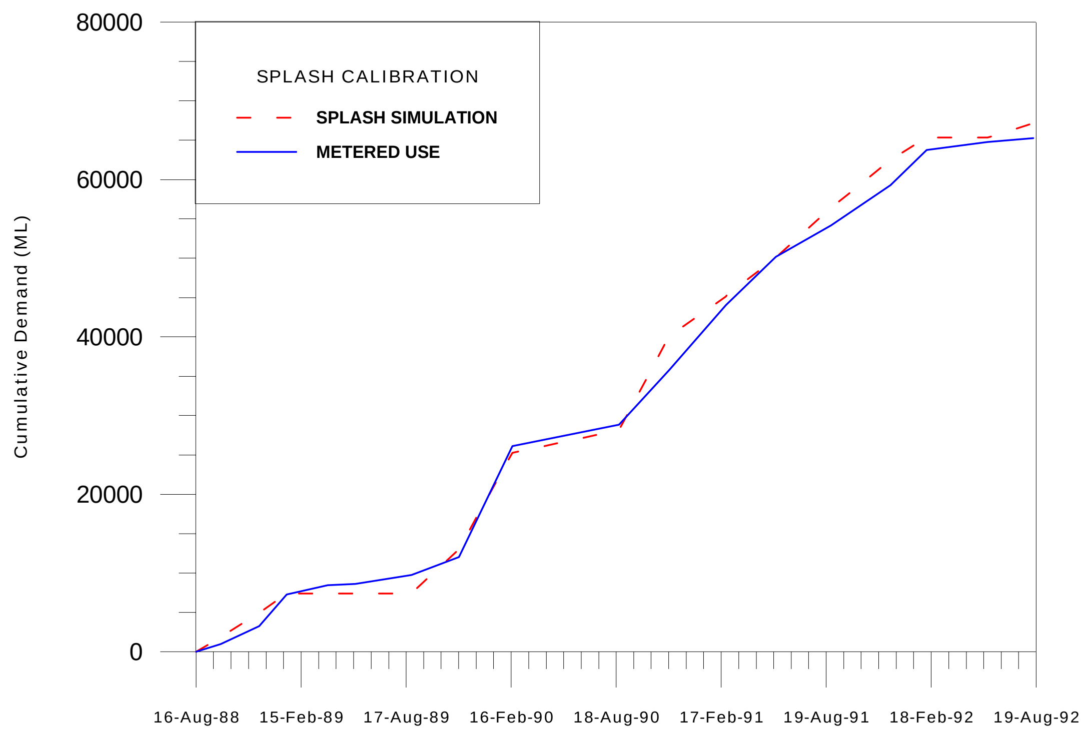

Figure 2 - Irrigation Demand Comparison

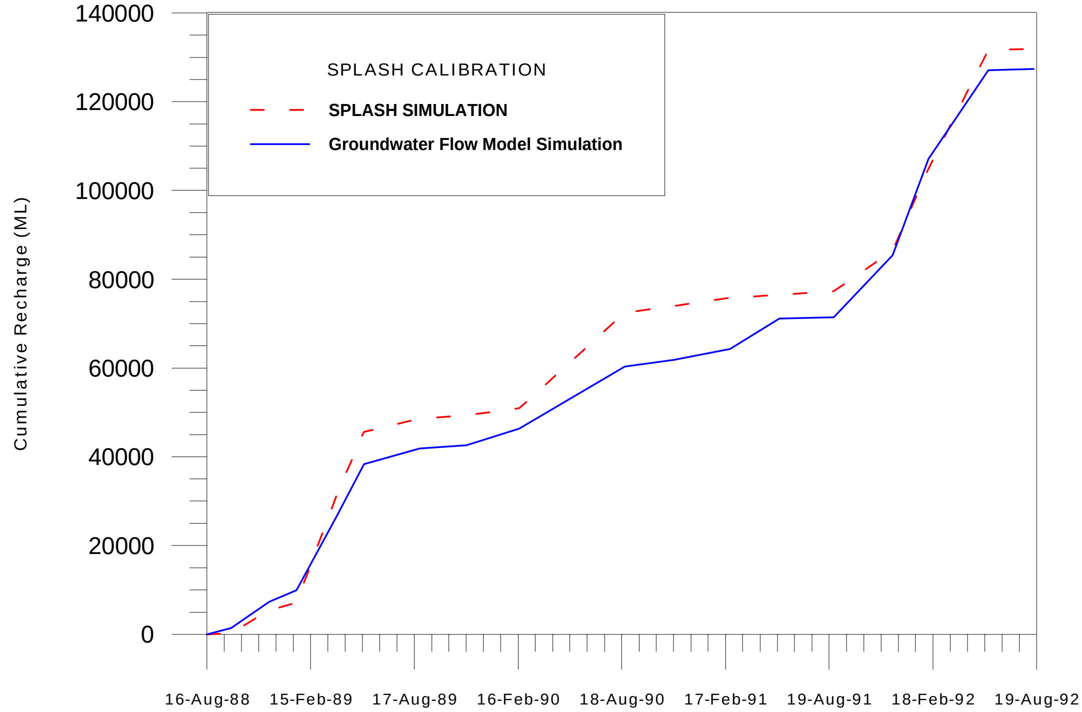

Figure 3 - Recharge Comparison

zone, were adjusted during the MODFLOW model calibration. Plots of the cumulative recharge curves from SPLASH and from the groundwater flow models are shown in Figure 3.

Seawater intrusion modelling

Introduction

Both ground and surface water are used to irrigate the crops in the Bundaberg area, predominantly for sugarcane. As a result of excessive extraction of groundwater its quality has degraded at certain locations. Continued development of groundwater resources for irrigation in the area has raised the concern of how much additional extraction can be allowed from various locations without adversely affecting the water quality as a result of seawater intrusion.

Seawater intrusion modelling is complex as it involves modelling the fluid-density affected processes. Further complexity is added by a heterogeneous aquifer system. The interface separating freshwater and seawater is a transition zone created by the mixing of waters due to the effects of diffusion and mechanical dispersion. Management of groundwater resources in the Bundaberg area requires an understanding of the physical dynamics of the phenomenon of seawater intrusion.

Two types of models exist to study the seawater intrusion processes, viz., immiscible and miscible flow models. The immiscible models employ the concept of a sharp interface separating freshwater and seawater with different densities. The sharp interface approach simplifies the analysis by assuming that freshwater and seawater do not mix. In this case, the freshwater and seawater are separated by an abrupt interface. The miscible models characterise the interface between the seawater and fresh water as a transition zone formed by the mixing of freshwater and seawater due to the effects of hydrodynamic dispersion. The miscible models need to solve groundwater flow and solute transport equations simultaneously and require special techniques to do so.

SHARP

The United States Geological Survey freshwater and saltwater flow model SHARP (Essaid, 1990) was trialed as a groundwater management model for the Gooburrum section of the Bundaberg Irrigation Area. SHARP is a quasi-three dimensional, finite-difference model which simulates freshwater and seawater flow separated by a sharp interface in a layered coastal aquifer. SHARP model was selected for the following reasons:

- SHARP is a block-centred finite-difference model, very similar to MODFLOW. As such, use of MODFLOW compatible pre-and-post processing software and the Groundwater Utilities would be possible.

- SHARP was developed for use in a multi-layered coastal aquifer. Such systems are common in Australia and occur in the Bundaberg Irrigation Area.

- A groundwater management model has already been developed using MODFLOW for the Gooburrum area, so most of the data required by SHARP is already available.

In order to fully utilise the Groudwater Utilities, SHARP was modified to produce MODFLOW look-alike unformatted output files recording model-calculated freshwater heads, seawater heads and interface elevations. A two-stage, text-based, SHARP preprocessor was also developed to create SHARP input files such that model arrays for initial heads, aquifer top and bottom elevations, and so on, could be exported from PMWIN.

The Gooburrum seawater intrusion model was set up by transferring data from the existing model using the Groundwater Utilities and the SHARP pre-processor.

The results obtained from the SHARP model were unsatisfactory. After it became obvious that SHARP would not suit our needs as a regional-scale seawater intrusion model, the market in seawater intrusion modelling software was surveyed and a number of programs were tested on sample and real problem. The simple, readily available and inexpensive packages have proven to be unsatisfactory for complicated deltaic aquifer systems.

SUTRA

The United States Geological Survey saturated and unsaturated transport model, SUTRA, was used to develop two-dimensional cross-sectional models to study the seawater intrusion processes for instructional purposes. SUTRA simulates flow and solute transport in the sub-surface environment. SUTRA is a two-dimensional finite-element model describing density-dependent saturated and unsaturated groundwater flow and solute transport. In reality, studies on seawater intrusion require three-dimensional analysis. However, in some situations, two-dimensional simulations are useful in providing insights for understanding the three-dimensional system.

Two cross-sections as shown in Figure 1, were chosen to develop SUTRA models: Moore Park Section A-A and Burnett River Section B-B. SUTRA uses quadrilateral elements to discretise the model domain. These elements are defined by element numbers and their four node numbers, together with connectivity data.

The active part of cell-centred finite-difference grid created by PMWIN can be considered as quadrilateral elements. Three Sutra Utilities, viz., **int2fe**, **fe2real** and **fe2vel** were developed to exploit the use of the Groundwater Data Utilities for graphical display of SUTRA input/output data. The program **int2fe** translates PMWIN data into elemental and nodal data of SUTRA. The programs **fe2real** and **fe2vel** were written to process the SUTRA output file. The program **fe2real** interpolates the SUTRA output data, such as concentration, pressure and saturation at each of the nodes to a value at the centroid of each element, and writes as a real array. The resulting real array is manipulated by the Groundwater Data Utilities (e.g., **real2srf**) for viewing in SURFER. The program **fe2vel** transforms the SUTRA velocity output into a SURFER file to display velocity vectors in SURFER. Figure 4 shows a steady state flow field plotted in SURFER using **fe2vel**. To summarise, **int2fe** assists in the pre-processing of SUTRA input files whereas **fe2real** and **fe2vel** help in the post-processing of SUTRA output.

Results

For the coastal section AA beginning at Moore Park, it was found that if the average pumping rate based on 1988 - 1992 metered water use continues, no intrusion of salt water is expected in the upper aquifer. However, the average rate pumped from the bottom aquifer based on the 1988-1992 metered water use causes salt water to intrude at the rate of 50 m per annum. For cross section BB at the Burnett River, the current allocated extraction rate also causes salt water to intrude at the rate of 50 m per annum but this time in the upper aquifer.

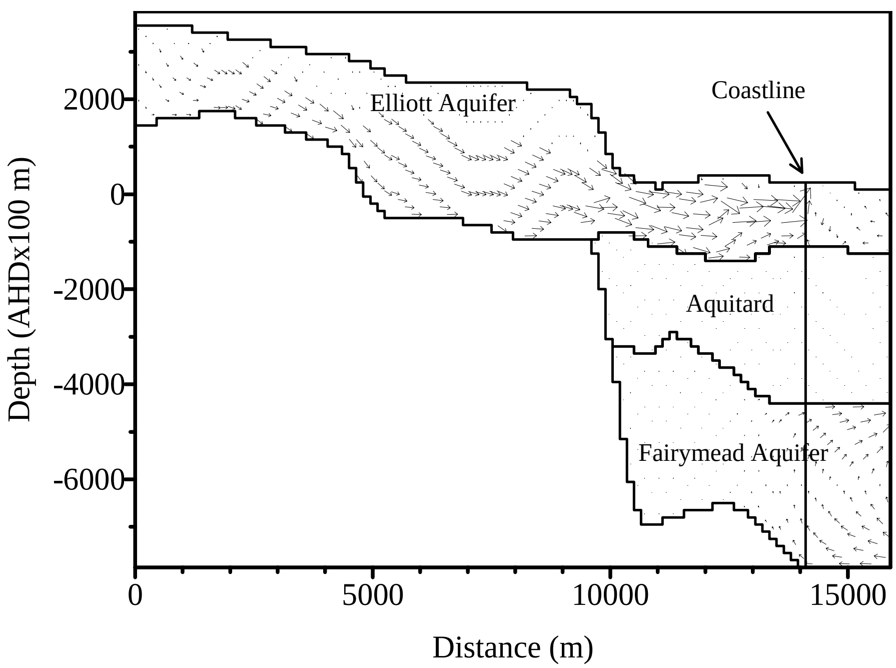

Figure 4 - Flow field at steady state. Vector size reflects the magnitude of velocity

The 2-D salt water intrusion model has provided a great deal of information on the behaviour of flow and salt movement in the project area. The salt levels introduced by both intermittent and continuous pumping were studied. The slice models analysed in this study indicate that the current average rate of extraction causes seawater intrusion in the long run, irrespective of the extraction strategy. Further analysis is, however, required for short term transient conditions. The present study has shown that a simple analysis using constant average rates of recharge and extraction of water are satisfactory for long term transient studies.

The 2-D models have several short comings. The velocity vectors in the aquitard are very small in magnitude (of the order of 10^{-11} m s^{-1}) indicating negligible recharge to the bottom from the top aquifer. However, recharge in the bottom aquifer might be induced from the direction perpendicular to the plane of the section which the two-dimensional model cannot handle. Also, transferring of the data from 3-D to 2-D is difficult (for example water extraction data from wells which are not uniformly distributed). Too many assumptions and averaging in the transfer of data is necessary in 2-D simulation. It is for these reasons that results obtained in this study are not to be taken as predictions of the actual seawater intrusion. This emphasises the need for a 3-D model that will represent the hydraulic behaviour of the system in a more realistic manner. The complex geologic situation can be accounted in the 3-D problem. The water extraction data from a production bore or the recharge over the surface can be directly used in the model without any need for spatial averaging.

It was observed in the course of 2-D simulation that the model is very sensitive to parameters like permeability, porosity and dispersivity. Uncertainties are associated with all of these parameters. Besides, the parameter, field dispersivity, is very poorly understood. As such it is essential that these model parameters be carefully studied.

Conclusion

Instructional 2-D salt water intrusion models have been developed for the Bundaberg area. The models can be used to see the effect of various pumping and recharge scenarios on the movement of salt water. The present study has strongly indicated that 3-D simulation is necessary for realistic modelling of the sea water intrusion problem.

Channel distribution modelling

Introduction

The Bundaberg Irrigation Scheme provides irrigation water to 55,600 hectares of farmland, of which 43,700 hectares is serviced by the surface water system (Figure 5). The Burnett and Kolan River basins are the main catchments contributing water to the surface water system. Fred Haigh dam (586,000 ML) on the Kolan river provides the main surface water storage in the scheme. Bucca weir and the Kolan barrage on the Kolan river, and Bingera weir and the Burnett barrage on the Burnett river provide additional storages to the system.

The surface water system has 14 pumping stations, and four balancing storages across the irrigation area regulate the daily variation of deliveries to the demand centers. Water from Fred Haigh Dam is pumped through the Gin Gin channel which supplies farms in the Gin Gin and Bingera areas and supplements the flow in the Burnett river. The two main rivers are linked through this channel.

The objective of this study is to develop a computer based water allocation model for the Bundaberg surface water system for the following purposes:

- make better decisions on optimal allocation of the water to be used at any time,
- enable maximum benefits to be obtained from available resources at all times, and
- allow decisions on allocations and water storage use to be made considering probable future weather conditions.

REALM

The REsource ALlocation Model (REALM) is a multi-reservoir hydrologic model, developed by the Department of Natural Resources and Environment, Victoria. In REALM, surface water systems are represented by nodes and arcs. Nodes are used to represent reservoirs, junctions, inflow points and demands. Arcs (which are referred to as "carriers" in REALM) are used for rivers, pipes and aqueducts. As well as these physical carriers, conceptual carriers can be used to describe a range of possible system configurations and operating modes. REALM was selected among several water distribution models (WATHNET, IQQM, and WT16) because:

- It is able to operate on a daily, weekly or monthly time-step,
- System management philosophy can be user-defined,
- It automatically optimises the movement of water from storage to demand points,
- It is well documented and has a user-friendly front end,
- It is also able to simulate water quality within the channel distribution system.

REALM uses a linear programming (LP) routine in each time step to perform a water balance and optimise the allocation of water within a network of "capacitated carriers", according to user defined operating rules. REALM allows great flexibility and modelling power through its facilities for describing carrier capacities. As well as capacities, carriers can have a "penalty" assigned. Penalties affect how the LP makes its allocations, and thus allow users to modify carrier usage. Although REALM is an optimising model, the control provided by capacitated carriers with attached penalties enables the model to be used effectively as simulation tool.

Much of the modelling power in REALM derives from the ability to set variable capacities on carriers. This allows complex operating rules and scenarios to be modelled. Variable capacity carriers are defined using a control function which contains 15 variables, such as storage volumes or levels, carrier flows or demand parameters. The control function is evaluated in each time step to set the carrier capacity via a lookup table.

Two other important facilities are provided to control system operation and enable simulation of complex operating rules. First, target curves for reservoirs specify how any total volume in storage should be assigned to individual reservoirs. If a reservoir is above target then water will be preferentially released; if a reservoir is below target then water will be preferentially withheld. A number of target sets are usually defined, and each time-step has a target nominated. Secondly, a table of reductions is specified to define demand restrictions (announced allocation) during water shortages. Reductions can be specified both for demands, and for carriers with minimum capacities specified. In addition, demands can be grouped, and different reductions applied to each group.

REALM comprises 23 separate programs. The individual programs are either run directly from the system prompt, or from the REALM Master Drive. The graphical editor program provides an important and powerful graphical user interface for building the surface water system. Using "point-and-click" procedures, the attributes of a system's components can be defined and edited. The general plotting program provides a flexible tool for viewing any combination of model inputs and outputs. Hard copies of graphs can be generated. The program is designed as an investigative tool, and allows a wide range of graphs and plots for data comparisons. For instance, data series may be added or subtracted from each other and viewed as time series plots or as scatter plots.

System analysis

The reservoir target curves and demand restriction rules are the main operating rules used in REALM to model the Bundaberg surface water system. Reservoir target curves define the desirable level of storage at the end of each time-step. REALM uses these targets to determine the minimum operating cost strategy for increasing system storage by pumping or importation of water.

Simple straight lines between the minimum and maximum storage levels were assigned as target curves for Fred Haigh dam, Bucca weir, Burnett barrage and the Isis balancing storage. The other storages were considered to be full all the time. The actual departmental rules for determining water allocations (announced allocation) at the start of and during the season were used to implement different levels of demand restrictions at various times.

A calibrated SPLASH model was used to generate the irrigation demand at the demand nodes. Two sub-areas (Isis and Gooburrum) were selected to calibrate the SPLASH model. SPLASH simulates a regional irrigation demand whenever soil water depth drops below warning soil water depth, by filling the soil water depth to the warning depth from irrigation. The regional irrigation demand was calibrated by adjusting the monthly allowable deficit, to best match the observed irrigation use. The cumulative regional plots for the SPLASH model are compared with the historical use in the Isis sub-area in Figure 6.

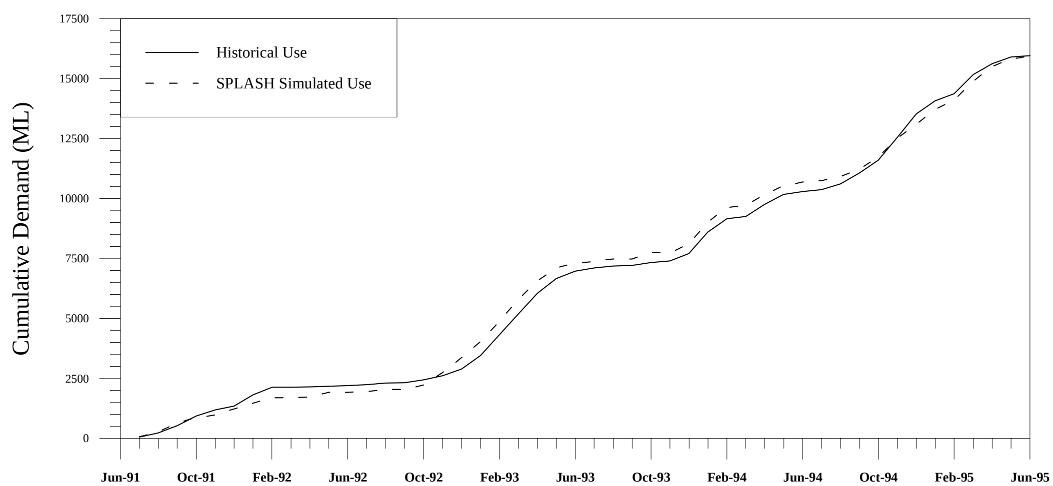

Figure 6 - Irrigation Demand Comparison (Isis sub-area)

During the REALM calibration process, only the channel losses were adjusted. The goal was to match the model generated flows with the historical pumping flows through the pumping stations. Other parameters which define the variable capacity carriers were fixed according to the operating rules. Suitable values for the channel losses were assigned as a percentage of flows in the channels. The model generated flows over the calibration period (July, 1991 - June 1994) were compared with the historical pumped quantities at the 14 pumping stations. A good match between the historical and model generated releases were found through a trial-and-error process. Figure 7 shows one of the observed and calibrated pumping volumes at the Woongarra Pumping Station.

The discrepancies found between the historical and model generated flows may be due to the following factors:

- The water supplies to the irrigation sub-areas during the calibration period were not optimised. The REALM model optimises the channel flows every month.

- There are insufficient data to map the crop areas as they vary from year to year. The SPLASH model uses the crop areas when calibrating the regional irrigation demand.

- There are water losses taking place in earth channels and at the farming level. A better estimate of the quantities involved needs to be derived.

- Riparian farmers along the Kolan and Burnett rivers use "Off Quota" water to supplement their water needs. The value for "Off Quota" was not included in the REALM model owing to insufficient data.

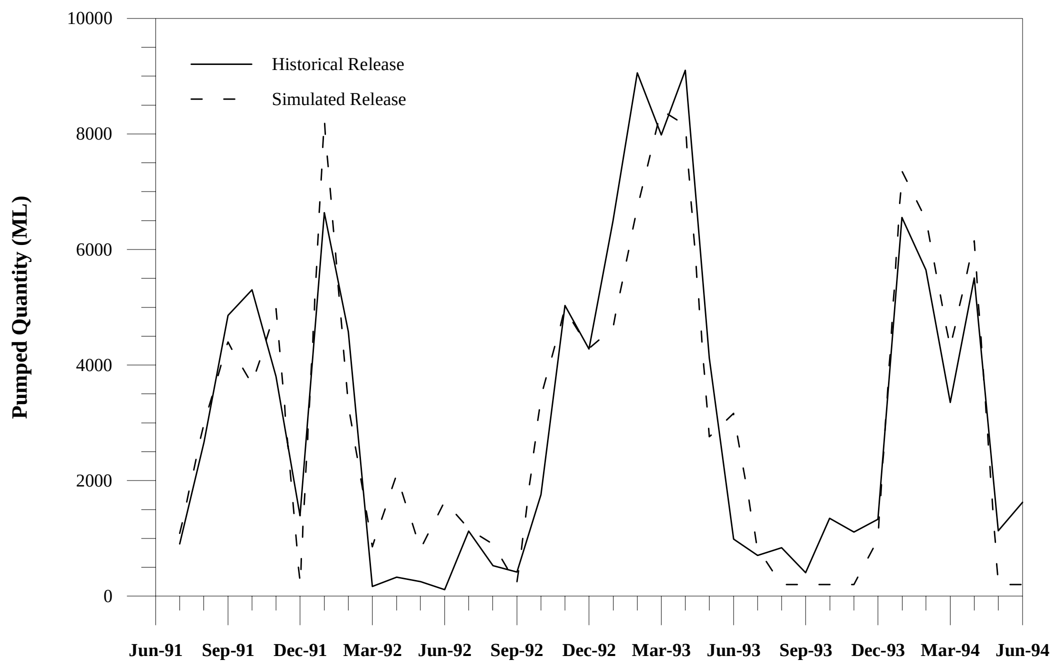

Figure 7 - Comparison of Pumping Releases at the Woongarra Pumping Station

Demand prediction

SPLASH uses daily climatic data such as daily rainfall and daily pan evaporation in its simulation. As such, demand prediction is dependent on the accuracy of climate prediction. Models have been successfully developed to predict global change but catchment scale climate prediction has not, to date, been sufficiently accurate to rely on in modelling. As a "rule of thumb" future rainfall data can be taken from the historical rainfall data, using a period which started in similar circumstances to the present, in terms of recent rainfall behaviour and/or recent variation in the Southern Oscillation Index (SOI) related behaviour. The daily pan evaporation data calculated from the monthly averages may be used as future evaporation data. The calibrated SPLASH model can be used for making future demand predictions with appropriate climatic data, thus providing assistance in the determination of allocations.

Conclusion

The channel distribution model is considered to be reliable enough to be employed as a starting point for evaluating the Bundaberg surface water system performance. The calibrated REALM and SPLASH models provide a means to:

- investigate the extent and sustainability of current resource commitments.
- consider options for re-allocation of water, including environmental uses,
- compare the impacts of any new water resource developments.

APPLICATION OF UTILITIES

LOCKYER VALLEY EXPERIENCE

Introduction

A groundwater flow model was set up using MODFLOW, for the purpose of being a tool for both understanding the Lockyer Valley aquifer, and for the calculation of yields. This work involved validation of existing data followed by the development of a model to study the impacts of irrigation practices on groundwater levels. The outcome of this study is to use the calibrated model in the calculation of aquifer yields for the sub-areas of the proclaimed area.

The software being used to model the Central Lockyer Region (Figure 8) is MODFLOW from the USGS. Other software used in the modelling process include PMWIN, the Groundwater Data Utilities, PEST and its MODFLOW utilities, and the Graphical Groundwater Utilities.

Groundwater data utilities

During the setting up of the model the Groundwater Data Utilities were extremely useful. The model of the Lockyer Valley is large and it contains in excess of 3200 active cells, within a finite difference grid of 15000 cells (100 x 150). Editing of this model array is laborious and typographical errors often occur while editing, requiring immense editing by hand of any of the array based input files .

The metered use data from the GWDB (Groundwater Data Base) was corrupted with inconsistent dates and erroneous volumes during some dates. The erroneous volumes would be due to the actual meter reading being entered instead of the usage between the specified dates. Through the use of **mkpmp1** and **pmpchek** the problem lines were quickly identified. The file contained a large number of records (~ 7000 records), and would have been tedious to check manually.

Not only have the data utilities been useful in the inputs into the model, they have also been useful in the peripheral activities associated with the modelling process. These activities include the generation of ‘blanked’ contour maps and zonation maps.

Figure 8 - Central Lockyer Region

The utilities have also been used during the model run. The Lockyer Valley is being modelled as a confined/unconfined single layer model (MODFLOW type III layer), and as such requires both a specific yield and a specific storage value for each cell. It then uses the appropriate storage type depending on the water level at the time of calculation. If the water level is below the top of the cell, the unconfined conditions exist and specific yield is used in the calculation. If the water level is above the top of the cell then MODFLOW will use the specific storage value associated with that cell for the calculation. The problem is that within PMWIN the specific storage is converted to storage coefficient during the generation of the Block Centred Flow package. As the model was being calibrated on specific storage there needed to be some external access to this data to change it during the calibration process. Through the use of **twoarray** and **arrayrep** (PEST MODFLOW utility) it was possible to change the specific storage. **twoarray** was used to multiply the specific storage value array by the aquifer thickness array to produce a storage coefficient array relating to the specific storage values. Then using **arrayrep** the current storage coefficient array within BCF.DAT was replaced by the new storage coefficient array (from **twoarray**).

Graphical groundwater utilities

Use of the Graphical Utilities mostly centred around the calibration and post-processing of the model. Problems were encountered during the calibration phase of the model where the aquifer thickness had not been properly defined. By using the strata viewing function of the Graphical Utilities on the cells, and neighbouring cells having problems, the lack of aquifer thickness was easily identified.

When it came to calibrating the model and deciding on zonation, it was necessary to evaluate how each bore reacted, and how closely this reaction resembled its neighbours. Through the water level plotting, and in particular multiple bore water level plotting, the neighbouring bore relationships were instantaneously available, avoiding the use of other complicated graphing packages. The multiple bore plotting allows for up to three bores to be simultaneously plotted making bore water level comparisons very easy. Having the plan view available on the screen allowed for the understanding of the spatial relationship between the neighbouring bores.

Plotting the model-generated bore levels with the field measurements simultaneously is another tedious job made easier through the use of the Graphical Utilities. The pre-processor PMWIN can read the binary output from MODFLOW and plot the required actual and calculated water levels for each of the nominated observation bores. While this is easy to achieve, the user is presented with MODFLOW's bore identifiers instead of Registered Numbers (RN). This means that the user has to firstly consult a list of RN's and their corresponding bore identifiers, and then if they wish to get an idea spatially they must consult a map. Within the Graphical Utilities the user needs only to select a bore under the simulated water levels option to be presented with a plot showing the fit of actual and calculated, showing the bore RN, and of course showing the map so the bore location is easily identifiable. This is extremely useful in a spatial sense as there may be a particular area of the model where the calculated water levels are not fitting the observations, and this can be quickly identified by selection and examination of the plots. Within PMWIN this task would require repetitive consultation with the bore identifier list, and with the associated map. The only drawback in this checking procedure is the file preparation of the MapInfo table, however this is made easier through the use of some of the other PEST and Data Utilities (**modbore**, **mod2smp**).

Conclusion

The data utilities themselves are structured and easy to use. The grid specification file is a very good concept. It allows the definition of a model grid by simply supplying the number of rows, the number of columns, a nominated corner of the grid, and finally an angle of rotation from a set axis. The grid specification file is common to all the other utilities requiring spatial information.

The Graphical utilities are relatively easy to use, although it would help if the end user had some background in GIS and in particular MapInfo.

In general the utilities have helped in reducing the time taken to produce a model, and in many cases have reduced the generation of errors during the input phase.

MILESTONE 3

An evaluation of the reception by other (including interstate) managers of the utilities based on the education and awareness activities.

The Groundwater Data Utilities were introduced in two groundwater modelling courses conducted in Brisbane. The first course was conducted jointly by Dr. John Doherty and Dr. Lloyd Townley (CSIRO) as the part of the 14th Australian Groundwater School during 4-8 December, 1995. The second course was conducted by Dr. John Doherty for DNR personnel and the groundwater consultants around Brisbane during 9-12 July, 1996. In both courses had a workshop where a practical groundwater modelling problem was discussed in detail from the project initiation. The participants were allowed to run every Groundwater Utility developed to find out the ease of data manipulation using the Groundwater Data Utilities. The evaluation of participant feedback is attached as part of other supporting material.

Further, Dr. John Doherty spent some time in September, 1995, with Mr. Mathew Bethune who is working on a LWRRDC sponsored conjunctive use project in Tatura, Victoria, in order to assist in the development of the groundwater models required for that project.

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