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Great Artesian Basin groundwater modelling

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ABSTRACT: This paper describes the history of groundwater modelling in the Great Artesian Basin and the challenges the data pose to groundwater modellers. Whole of basin modelling commenced in the 1970s and was taken up again in the 1990s. Improvements in computing hardware and software, data quality and hydrodynamic understanding of the Basin enabled iterative improvements in the models. Some issues persist, such as data quality and a limited understanding of the hydrogeology of the Eulo-Nebine Ridge area in southern Queensland. A method of more accurately interpolating the hydraulic head where water level measurements are decades apart is presented.

INTRODUCTION

The hydrogeological Great Artesian Basin (GAB) comprises the geological Eromanga, Surat and Carpentaria Basins and parts of the Bowen and Galilee Basins (Habermehl 1980). It covers about 20% of Australia and is the most important source of water in western Queensland and parts of regional NSW, SA and NT and supports rural and mining industries worth over $3billion (Figure 1). The groundwater contained in the aquifers is potable for stock, and in most areas is under sufficient pressure to provide a naturally flowing water source when tapped by bores. However, many bores have been allowed to flow uncontrolled into open bore drains, wasting water and reducing groundwater pressures.

Natural groundwater discharge zones, the GAB springs, have also declined due to over-extraction of groundwater. In 2001 the native ecosystems dependent on GAB springs were listed as *endangered* under the Commonwealth Environment Protection and Biodiversity Conservation Act (1999).

The Commonwealth and State governments have responded by extending the GAB Sustainability Initiative: $85.4million will be used over 5 years to reduce groundwater wastage and allow groundwater pressures to increase by capping free-flowing bores and replacing earth drains with pipes.

A transient groundwater flow model is being developed to determine priority areas for bore rehabilitation. A history of GAB groundwater modelling is presented in this paper.

HYDROGEOLOGIC FRAMEWORK

The sedimentary Mesozoic Great Artesian groundwater Basin comprises a multi-layered system of confined sandstone aquifers separated by mudstone and siltstone aquitards, and extends down to about 3000 m below ground surface in the central depocentres. The first artesian water encountered by drillers is typically found in aquifers of the Cadna-owie Formation, Hooray, Pilliga, Algebuckina and Longsight Sandstones and their equivalents. These stratigraphic units together form a basin-wide, sheet-like aquifer that extends relatively unchanged for hundreds of kilometres.

The Basin margin is elevated most dominantly along the Great Dividing Range in the east, and by the Selwyn, Macdonnell, Musgrave, Flinders and Barrier Ranges in the west and south

(Figure 1). The Basin extends into the Gulf of Carpentaria in the north.

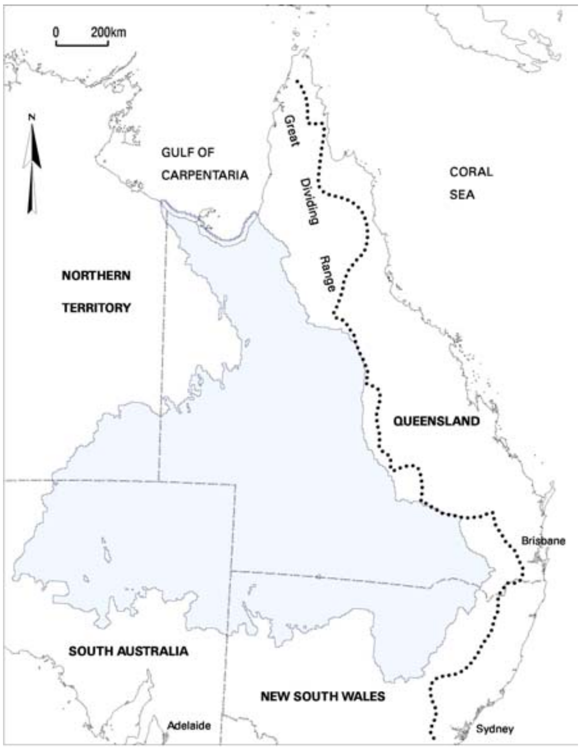

Figure 1 Extent and location of the post-1990 whole-of-Basin models.

CONCEPTUAL MODEL

Water entering the exposed parts of the elevated boundary aquifers drives the hydraulic gradient that is responsible for the artesian pressures in the topographically lower parts of the Basin.

Recharge via rainfall and river leakage into unconfined outcropping and subcropping sandstones is most significant along the Great Dividing Range. This water flows across the Basin generally to the south and southwest. In the west of the Basin rainfall and recharge rates are lower and flows are generally toward Lake Eyre. Radke et al. (2000), in their hydrochemical study of the Cadna-owie-Hooray Aquifer, suggest that recharge also occurs as infiltration through overlying aquitards in limited areas.

Hydraulic heads generally increase with aquifer depth, as the deeper aquifers, which occur along the north-east of the Basin, tend to outcrop at higher altitudes in the Great Dividing Range. Vertical inter-aquifer leakage is driven by hydraulic head differences and impeded by the aquitards. Vertical leakage to the water table and subsequent evaporation is significant (Woods 1990).

Natural springs occur in both recharge and discharge settings. They are generally associated with faulting and/or a thinning of the overlying aquitard. Decreasing groundwater pressures have lead to significant reductions in spring flows. Experience suggests that restoring pressure at ceased-to-flow spring sites may not revive spring flows, as inactive vents may become blocked (Lloyd Sampson, SA Department of Water, Land and Biodiversity Conservation, pers comm. 2002).

The GAB is underlain by older sedimentary, metamorphic and igneous rocks. The high geothermal gradient, where artesian water temperatures generally increase with depth and vary from 22°C in some recharge areas to 99°C along the northern part of the Birdsville Track, is attributed to this underlying crystalline basement. These temperature gradients may provide an additional driving force for upward leakage, but convective flow is unlikely (Radke et al. 2000).

Water bores for stock and domestic uses date back to the late 1800s. Early bores were free-flowing, but increasing levels of government regulation over the decades have required flows to be regulated and the water used more efficiently.

The Basin hosts petroleum reserves in South Australia and Queensland, and commercial mineral deposits occur on the Basin margin. Groundwater extraction to support these activities dates from the 1960s.

MODELLING APPROACHES

The history of quantitative modelling of the GAB reflects an iterative approach commensurate with improvements in computing power, software developments, data quality and hydrodynamic understanding of the Basin. The purpose of each model was to provide an assessment of the groundwater resources and to predict the effects of water extraction for management purposes. Additionally the early models sought to predict free-flow bore discharge rates.

1970s Models

The first basin-wide groundwater simulation model of the GAB, named GABSIM, commenced development in 1971. It combined the entire Triassic to Cretaceous sedimentary sequence into two alternating confining beds and aquifers (Ungemach 1975). The Basin south of 20°S was discretised into 58 x 67 cells, each 25 km x 25 km, and the model ran from 1880 to 1970. Constant head cells were imposed along the southern, eastern and northern boundaries of the two deeper layers and a no-flow boundary was set along the western edge. Constant heads were imposed along all boundary cells of the upper confining bed. The finite-difference software was written in-house. Calibration by the trial and error method was attempted only in the deeper aquifer and was not successful.

The GABHYD model (Seidel 1978) built on the experiences gained from the GABSIM model. It used the same hydrogeologic framework and discretisation with 5-year stress periods. It was a quasi-3D model, incorporating the confining layers as leakage terms in the aquifer layers. The water table was fixed. Bores, still mostly free-flowing at that time, were simulated as artesian pressures acting on flow coefficients. Discharge springs were treated as localised high vertical leakages. The in-house finite-difference software was extended to include iterative inversion techniques that obtained progressively better estimates of transmissivity from aquifer potentials. Calibration was only attempted for the Jurassic aquifer from 1960 to 1970 and was successful.

Problems with data quality and unevenness of data distribution were noted. There were also problems in the Eulo Ridge area, which recorded the largest balance errors during calibration, yet was the most heavily developed area with abundant data. Seidel (1978) recommended further work on the study of the aquifer geometry and hydraulics in the Eulo Ridge area where 'physically impossible' potentials were observed.

Part-Basin Models

Most of the part-Basin models have been developed to support water abstraction for commercial mining operations on the Basin margin.

WMC Resources Ltd produced its first groundwater investigation report for the Olympic Dam operation in 1982 and drilled its first production bore in the same year. WMC's 1995 model of the Basin southeast of Lake Eyre simulates transient conditions from pre-WMC development, in 1983, to 1994 (Berry & Armstrong 1995). The Basin is represented by four layers: the top two are aquitards and the bottom two are aquifers. The deepest layer includes the Cooper Basin and Proterozoic metasediments. Layers 1, 2 and 4 each have uniform parameters; layer 3, which includes the Algebuckina Sandstone, has hydraulic conductivity variations implemented as constant-value zones. The MODFLOW (McDonald & Harbaugh 1988) grid is rotated 20° anticlockwise with a telescopic mesh of 68 x 85 cells varying between 1.25 km and 20 km.

Modelling for the Cannington and Osborne prospects (RUST PPK 1994) located southeast of Mount Isa uses AQUIFEM-N code (Townley) with triangular finite-element discretisation. The aquifer is modelled as a steady state, single confined layer with permeability variations implemented as constant-value zones. The model covers more than 100,000 km^2 and comprises 2,032 elements defined by 1,042 nodes. The steady state calibration is used as initial conditions for transient prediction scenarios.

A regional, steady state pre-mining model was developed to investigate the effects of dewatering the Ernest Henry mine east of Mount Isa (Woodward-Clyde 1995). The aquifer is modelled as a single confined/unconfined layer in MODFLOW. The cells in the 45 x 56 grid vary between 3 km and 25 km. The steady state calibration is used as initial conditions for transient prediction scenarios.

The impacts of irrigation pumping near Northstar in New South Wales were modelled by Hopkins (1996). Covering 5400 km^2 with 24 x 36 cells each 2.5 km, the single confined/unconfined layer MODFLOW model includes river recharge/discharge. The steady state calibration using hydraulic conductivity variations implemented as constant-value zones is used as initial conditions for transient prediction scenarios with seasonally varying pumping rates.

Whole of Basin MODFLOW Models

GAB whole of basin groundwater modelling recommenced in the early 1990s. GABHYD data were supplemented with the most recent state and territory data (Brodie et al. 1991). The new model, named GABFLOW (Welsh 2000), simulates conditions as steady state for 1960 and only models the most exploited, basin-wide Cadna-owie-Hooray and equivalents aquifer. This avoids the earliest and arguably most unreliable data as well as the deeper artesian and shallower sub-artesian aquifers that are relatively data-poor. It also precedes large-scale commercial groundwater extractions. Figure 1 shows the extent of the post-1990 whole-of-Basin models.

The Basin is modelled as a quasi-3D single layer with vertical leakage implemented as General Head Boundary cells in the finite-difference MODFLOW code. The aquifer south of about 17°S is discretised into 359 x 369 cells each 5 km x 5 km. The model covers the geological extent of the aquifer (Habermehl & Lau 1997), with a line of constant head cells in the Gulf of Carpentaria and no-flow boundaries elsewhere. Bores, springs and recharge are implemented as specified flows in the MODFLOW well and recharge packages. The use of geographic information system (GIS) software was integral to the model development and calibration.

The calibration process used PEST parameter estimation software (Doherty 1998) with hydraulic conductivity variations implemented as constant-value zones that were subsequently modified by trial and error techniques. The final parameters all vary smoothly over the model domain. The calibration was successful, although there were difficulties calibrating the Eulo-Nebine Ridge area. Transmissivity and recharge parameters in this area are unreasonably high. The model has been successfully used with Phase I of the GAB Sustainability Initiative, which expired in June 2004.

GABFLOW is currently being upgraded to extend from 1960 to 2000 with 5-year stress periods. Additional data on bores, springs and petroleum and mining extractions have been compiled and combined with existing data. This vast amount of data is being processed using GIS, linear programming and statistical software.

The model extent, hydrogeologic framework and discretisation are unchanged. The model is being run under MODFLOW-2000 (Harbaugh et al. 2000) and calibrated using PEST parameter estimation software (Doherty 2004, Doherty 2003). Parameter heterogeneity is represented by pilot points, which allow continuous aquifer property variation.

DATA ISSUES

The large amount of data from disparate sources is no longer an issue of computer capacity, but is an issue of data management. Also, the different databases do not always hold the same measurement values for what appear to be the same measurements.

Data errors can arise during measurement, transcription, entry to the database or during conversion, for example when pressure is converted to standing water level. Additionally, an error in any one of pressure/water level, elevation or temperature will lead to an error in the density-corrected hydraulic head. Data quality can be determined by assessing trends, but the large number of bores with very few flow and/or water level measurements inhibits this.

Berry & Armstrong (1995, p. 8) describe the problems with the 1970-1994 pressure measurement data for the South Australian Olympic Dam model:

> No clear and general temporal trends can be identified in the pressure history data. This is consistent with the difficulties of obtaining reliable and repeatable pressure measurements from pastoral bores of dubious mechanical integrity and with variable discharge rate and shut-in period.

Also, the pressure and flow data were not collected specifically for groundwater modelling. For example, modelling requires actual bore flow rates but the maximum flow rates with flow control devices removed are the only data available for some bores.

Interpolating water level measurements

Bores with many water level measurements spanning decades show a trend of water level decline consistent with a decay function. Consequently, linear interpolations are inappropriate for the water levels of bores with large data gaps. To find a curve of best fit all bores with at least 50 water level measurements over at least 40 years were used. The solution to the general decay equation:

$$y = A + B\left(1 - e^{-\alpha x}\right) \tag{1}$$

is

$$A = \frac{y_2 R - y_1 S}{R - S} \tag{2}$$

and

$$B = \frac{y_1 - y_2}{R - S} \tag{3}$$

where

$$R = 1 - e^{-\alpha x_1} \tag{4}$$

and

$$S = 1 - e^{-\alpha x_2} \quad (5)$$

for $x_2 > x_1$ (time) and $y_2 < y_1$ (water level) in this case. After trialling different values of α, a value of 0.00014 was found to give the best average match. Only the end-point measurements, i.e. one set of x_1, y_1, and x_2, y_2. measurements per bore, were used. The measured values generally lie within α between 0.0001 and 0.00025 in equation (1). Figure 2 compares interpolations with measured water levels for some bores with good measurement histories.

Eulo-Nebine Ridge hydrogeology

The hydrogeology of the Eulo-Nebine Ridge area continues to be problematic. Figure 3 shows the geologic structures, locations of discharge springs and the Cadna-owie-Hooray aquifer hydraulic heads density-corrected and interpolated to 1960. The lower heads probably represent the regional groundwater flow, while the higher heads may result from lensing or faulting that prevents the groundwater from draining and enhances the gravity-driven groundwater pressures.

Radke et al. (2000) provide some hydrogeochemical insight. Their data show that the area of the Cadna-owie-Hooray aquifer in southern Queensland bounded by the Nebine and Eulo Ridges is hydrochemically slightly different - the water is fresher: locally lower in chloride, sodium, sulphate and total dissolved solids. They state that the groundwater flow rates are faster than in the adjacent deeper parts of the aquifer, groundwater temperatures are lower than on the Euroka Arch where local hot spots occur, and significant inter-aquifer leakage is more pronounced here, where the intervening Rolling Downs Group Aquitard is thin.

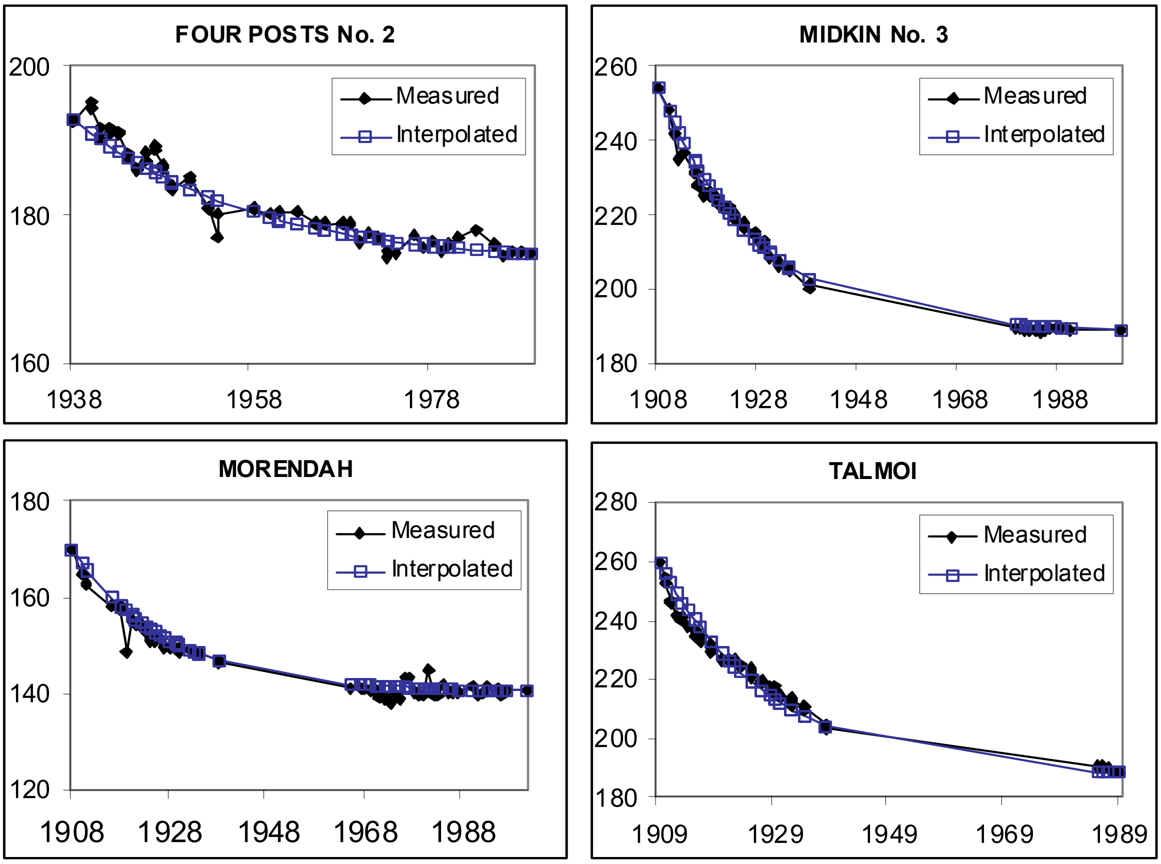

Figure 2 Measured and interpolated water levels for some bores with long datasets. Interpolated values use equation (1) with α=0.00014 and are based only on the first and last measurements of each bore.

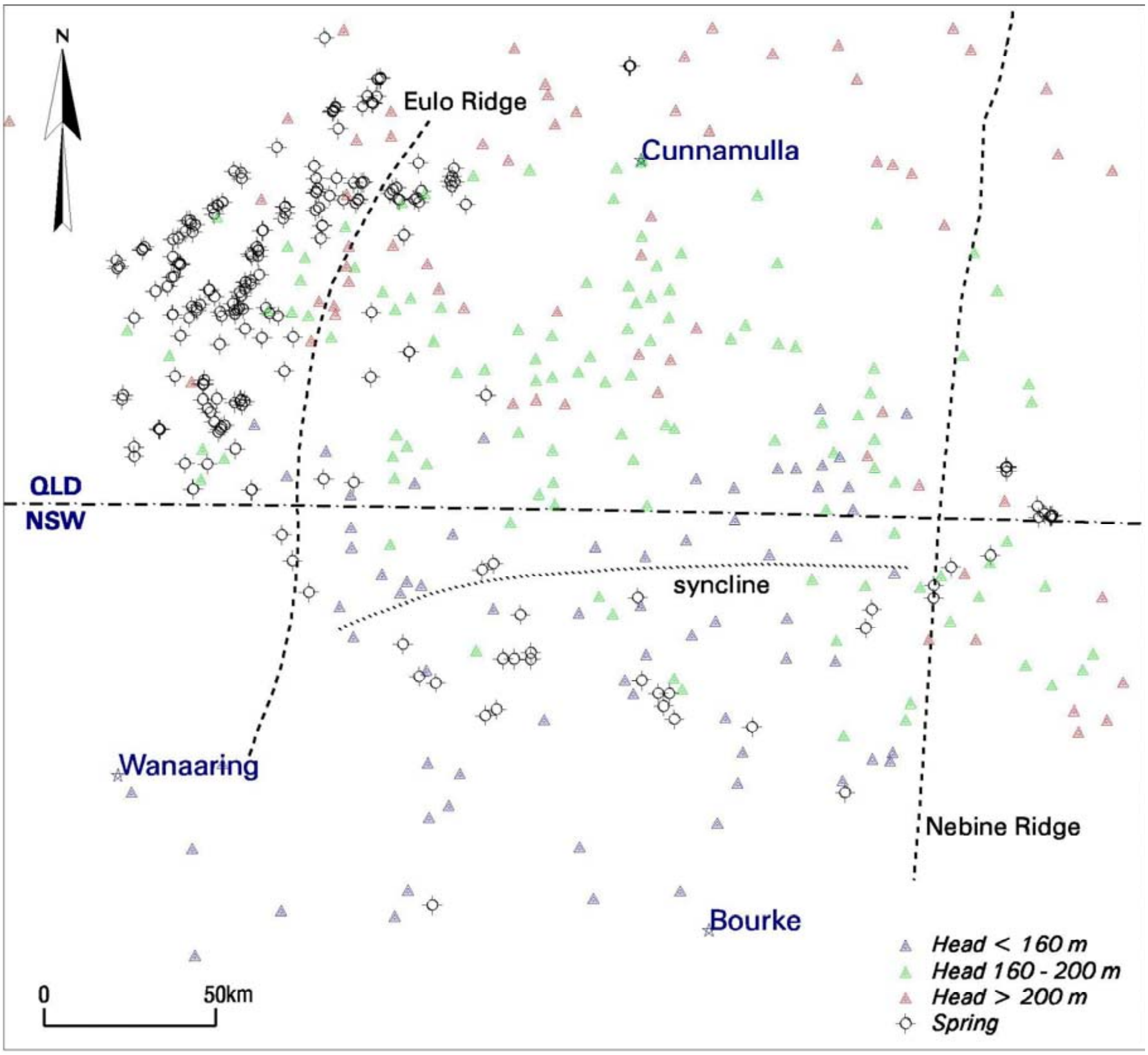

Figure 3 Temperature-corrected hydraulic heads in the Eulo-Nebine Ridge area (geologic structures from Radke et al. 2000).

Radke et al. (2000, p. 3) suggest a recharge mechanism to explain the observed hydrogeochemical signature:

> …in the eastern region of the Eulo-Nebine Ridge area a repeated subarcuate pattern of discontinuous hydrochemical anomalies is attributed to unique recharge phenomena following extended periods of aridity during the Pleistocene. … Hydrochemical signatures … most probably indicate recharge through the overlying relatively permeable Doncaster Member. These anomalies apparently formed immediately following periods of sustained aridity when the lowered potentiometric surface … was ineffective in countering this recharge through the overlying aquitard.

DISCUSSION

GAB groundwater modelling began with Fortran-based in-house computer code and discretisation limited by the computing power of the time. Since GABHYD, geological mapping and hydrodynamic understanding of the Basin have improved. Subsequent models have been developed using commercial software packages. GABFLOW's discretisation, at over 132,000 cells, was determined by the capability of personal computers at the time.

Improvements in computer hardware and software have eased the burden of dealing with the huge volume of GAB data. However, significant data issues and data gaps persist:

- Data quality is a time-consuming issue as it is difficult to define a comprehensive filter and many bores have insufficient measurements to provide certainty about which data are correct.

- Unrestricted flow rates were an accurate measure of actual flows when the bores were free-flowing. Using these maximum yields as flow rates for bores that are now controlled may make transient calibration difficult because the water level changes that are to be modelled will be driven by changes in bore discharge rates. Vertical leakage and recharge change slowly and spring discharge is a small proportion of bore discharge, so none of these is the main driver of artesian pressure change. Similarly, the sparsity of measurements is a problem. If flow rate and water level measurements were taken at intervals greater than their rate of change it will be difficult to model a relationship between the two.

- The hydrogeology of the Cadna-owie-Hooray aquifer in southern Queensland bounded by the Nebine and Eulo Ridges is unresolved. Although the extensive groundwater use in this area would be expected to cause an uneven potentiometric surface, the juxtaposition of bores with density-corrected heads differing by more than 60 metres suggests that the basin-wide, sheet-like aquifer concept does not fully explain the hydrogeology of this area.

In the development of the latest whole of basin GAB models the synthesis of the available data has further quantified our understanding of the Basin structure. The steady state model is being used to estimate water level increases due to bore water savings. State and federal authorities use the model output in the prioritisation process for government-subsidised capping and piping projects.

Because the transient GAB model is being calibrated using time series of water levels and flow rates, the final parameter sets for variables such as transmissivity, recharge and vertical leakage should be superior to the steady state model. The model will be distributed to the four State groundwater agencies, and used to estimate the effects on water levels of changing bore flow rates, both by pastoralists and industry.

The 25 km^2 cells are probably too large for the model to be used to assess the effect of changing water levels on spring flow rates. It would also be of limited use in testing recharge strategies, such as injection, because it is a confined-type model and recharge occurs in the narrow unconfined rim of the basin. Both of these studies would require finer-scale local models that could be derived from the regional model.

CONCLUSION

This paper presents a work in progress − the basin-wide transient model is currently being completed. The challenges to groundwater modelling in the GAB include gaps (both spatial and temporal) in bore datasets, the large area being modelled and the incompletely understood hydrogeology around Cunnamulla, which is important because of its high groundwater use. As a means of overcoming some of the obstacles, a method for estimating the hydraulic head based on water level measurements with sparse temporal coverage has been presented.

ACKNOWLEDGMENTS

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