STREAM BASEFLOW PRESERVATION WITH OPTIMAL AQUIFER MANAGEMENT

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ABSTRACT: The public water supply in the Gosford-Wyong area of New South Wales, Australia, is reliant on streams that originate in elevated sandstone country. About half of the stream flow is believed to be baseflow from the sandstone aquifer system in the Kulnura-Mangrove area. At the same time as the population is growing steadily on the coast, there is increased demand for groundwater for horticultural, agricultural and industrial purposes along the sandstone ridges. Hence, good groundwater management is critical, to ensure that stream baseflow is not jeopardised.

The study area consists of nine catchments and is located north of Sydney and inland from Gosford with an area of about 1,400 km^2. Baseflow has been estimated for seven flow gauges located at the creeks by applying a digital filtering algorithm to separate the baseflow from the total stream flow. The groundwater hydrographs for 20 monitoring bores show strong correlation with residual rainfall mass, which suggests that rainfall recharge provides the major control on aquifer behaviour. Hydrographs at the same location show that, under natural conditions, there is a huge vertical head difference between layers of alternating sandstone (as much as 30 metres).

A management model that couples a simulation model (MODFLOW-SURFACT) with an optimisation model (OPTIMAQ) has been developed to preserve stream baseflow. MODFLOW-SURFACT was selected to simulate the complex multi-layer Kulnura-Mangrove aquifer system. The model has an area of 40 km x 59 km with approximately 400 m difference in elevation. The model was divided into 30 flat layers that reflect the alternation between sheet and massive facies in the Hawkesbury Sandstone Formation. A uniform cell size 500 m x 500 m results in a grid mesh of 118 rows and 80 columns. The model was calibrated for both steady state and transient conditions.

The results of steady-state calibration revealed that the model performs very well in representing the values and the patterns of the composite groundwater level contours map. Also, the results showed a good agreement between the observed and computed target values across all the model layers with a coefficient of determination of 0.994. The transient model started in January 1985 and ended in October 2003 with a monthly stress period. The results of the transient calibration illustrated that the model matched very well with all observed hydrographs, even in the areas that have high vertical head difference. Also, the results showed a good agreement between the estimated baseflow and that simulated by MODFLOW-SURFACT for all the flow gauges.

OPTIMAQ software, based on generic optimisation software (GAMS), solves the management problem with linear or nonlinear objectives by using the response matrix approach. OPTIMAQ was linked successfully with MODFLOW-SURFACT to compose the management model for the multi-layer aquifer system in the Kulnura-Mangrove area. The main target for the management model is to preserve baseflow in the creeks by determining the optimal limits on groundwater extraction from the existing or planned bores. The objective function of the management model is to maximise the pumping rates of the bores, subject to groundwater level constraints imposed along the creeks. In effect, this approach determines a sustainable yield for the aquifer system that is compliant with surface water constraints.

KEYWORDS

Stream – Aquifer interaction; Baseflow; Management Model; Sustainable Yield; Modflow Surfact.

INTRODUCTION

Only recently have researchers started to focus their attention on groundwater management models. Among them is Merrick (2000) who determined the optimal pumping rate for a highly exploited aquifer in Australia (lower Naomi Valley) by developing a management model that couples a groundwater simulation model in MODFLOW with an optimisation model called OPTIMAQ. Very few researchers have coupled optimization methods with stream-aquifer interaction.

Barlow *et al.* (2003) developed conjunctive-management models that couple numerical simulation with linear optimization to evaluate trade-offs between groundwater withdrawals and streamflow depletions. They used the stream routing package for the MODFLOW code to simulate groundwater - surface water interactions and the response-matrix technique was used to couple the simulation and optimization models (Ahlfeld and Mulligan 2000; Merrick 2000).

Ahlfeld (2004) examined the nature of the response between the streamflow and groundwater extraction by using MODFLOW with the stream package. The results showed that the streamflow function might be convex or concave depending on the location of the observation point relative to the pumping bore and the ratio of streambed conductance to hydraulic conductivity.

Hantush (2005) introduced analytical solutions for stream-aquifer interactions during storm events and baseflow periods. The solutions are based on a linearised one-dimensional representation of the Boussinesq equation and linear representation of channel flow and storage. The solutions are obtained by using Laplace transforms in terms of integral convolutions of impulse response and unit step response functions derived for channel and stream-aquifer interactions.

This paper will present first a developing three-dimensional numerical model for the multi-layers Kulnura-Mangrove aquifer system; and the calibration of the model by using MODFLOW-SURFACT. A management model that couples a simulation model (MODFLOW-SURFACT) with an optimisation model (OPTIMAQ) is presented and two scenarios are carried out to preserve the stream baseflow within tolerable limits with maximising the pumping rates from the aquifer system. The sustainable yield of the Kulnura-Mangrove aquifer system is calculated for each scenario of the hydraulic gradient reduction tolerance fraction.

STUDY AREA

The study area is located north of Sydney, and inland from Gosford, between 319000 to 359000 east and from 6283500 to 6342500 north according to AMG coordinate system, Figure 1. It covers an area of about 1,380 km^2 and consists of nine catchments.

The topography in the study area has an elevation difference of about 450 m between its highest and lowest points, Figure 2. The highest altitude of 463 m AHD can be found at the northern edge of the Wyong catchment and drops to a few metres adjacent to the creeks that cross the catchments. The topography around the creeks is quite steep and rises sharply.

The mean annual rainfall ranges from less than 900 mm in the southwestern parts at the lower Mangrove catchment to 1300 mm at the northern highest elevation in the Wyong catchment. Generally, the mean annual rainfall decreases from East to West.

According to the drainage and topographic characteristics of the main creeks, the study area can be divided into six zones, three of them on the eastern side of the Hunter Range comprising the catchments of the Wyong River, Ourimbah Creek and Brisbane Water. The catchments of Mangrove Creek, Mooney Mooney Creek and Popran Creek on the western side of the Hunter Range drain much of the central and southern areas towards the Hawkesbury River. Wyong River and Ourimbah Creek drain toward Tuggerah Lake.

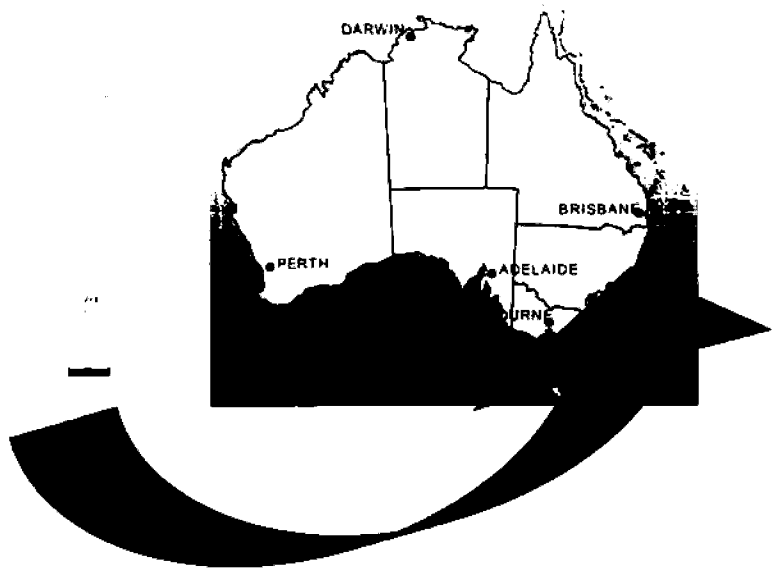

Figure 1. Location map of the study area

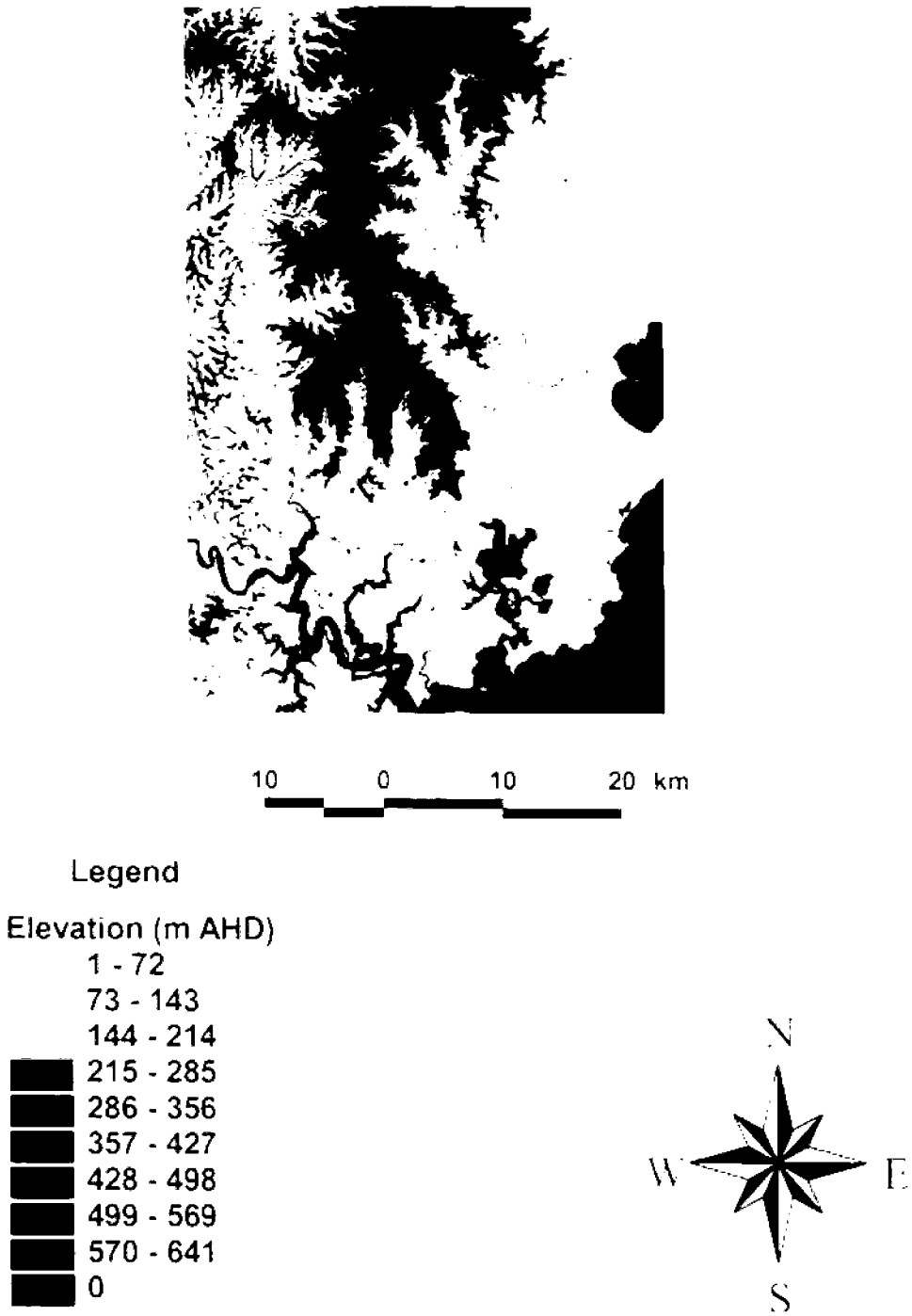

Figure 2. Topographical map of the study area

BASEFLOW ESTIMATION

The Department of Natural Resources (DNR) derived estimates of the baseflow for the number of flow gauges located in the study area. The estimate of baseflow was based on applying a digital filtering algorithm (Lyne and Hollick 1979) to separate the baseflow from the total stream flow. The baseflow estimates were provided for seven flow gauges.

Some of these gauges have a long record period starting from January 1977 to March 2004 while others have ceased. These data are considered the baseline to calibrate the baseflow for the Kulnura model. For the modelling process, the drainage lines are divided into reaches (segments). The software provides a water budget summary for each reach. Figure 3 depicts the location map of the flow gauges and their reach numbers.

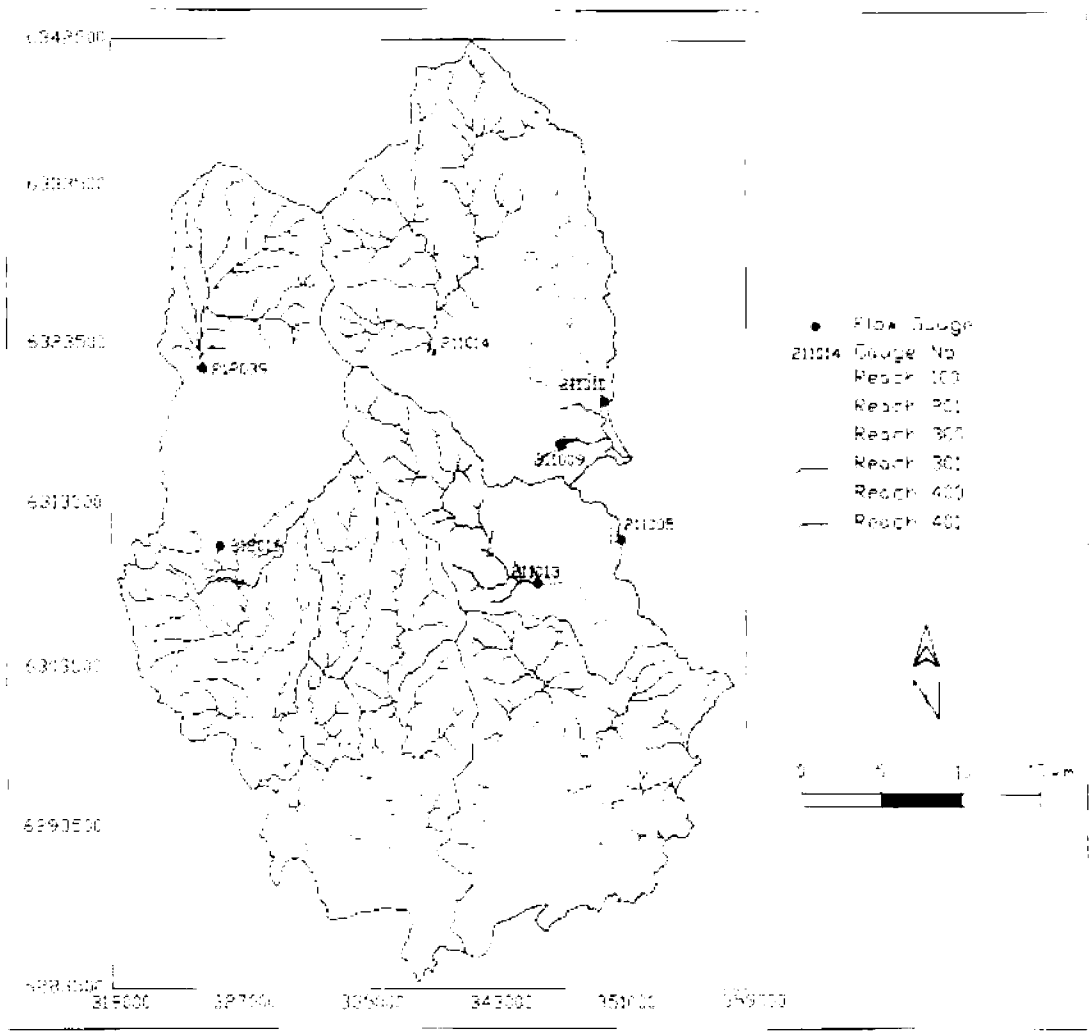

Figure 3. Flow gauge and reach location map

MONITORING BORES NETWORK

There are 20 monitoring bores distributed over the study area. Groundwater hydrographs and residual rainfall mass curve for Peats Ridge rainfall station are plotted together to see the relation between the rainfall and the groundwater level.

Figure 4 demonstrates that groundwater hydrographs appear similar to residual rainfall mass curves where groundwater levels reflect normal variation with seasonal condition. As the residual rainfall curve goes down (dry times), the groundwater level falls due to less rain and possibly higher use of pumping bores, while rainfall recharge and recovery take place in wetter times when there is conversely less use of pumped groundwater.

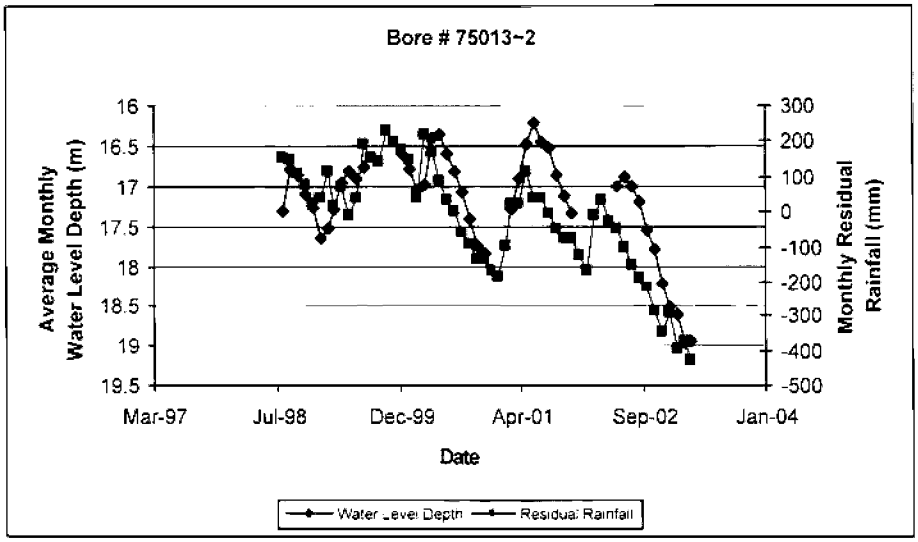

Figure 4. Groundwater hydrograph versus residual rainfall mass curve

HYDROGEOLOGY

Aquifer Systems

The Aquifer Systems in the study area are controlled by the Hawkesbury Sandstone Formation. It has been subdivided by Conghan and Jones (1975) into two contrasting Sandstone Facies, the Sheet Sandstone Facies and the Massive Sandstone Facies. The silica cemented Sheet Facies Sandstone forms the major Aquifer Zones. The combination of clay and silica cemented together with little sedimentary structure makes the massive sandstones not conductive to yielding groundwater at a rate sufficient for a successful bore.

The Sheet Facies Sandstone is defined as an aquifer with 5 m thicknesses and it is modelled as a Semi-Confined Aquifer except for the first layer, which is modelled as an Unconfined Aquifer. The Massive Facies Sandstone has thickness ranges between 10 - 30 m and is defined as an Aquitard.

The Narrabeen Group, Tertiary Volcanic and Alluvium Deposits were taken into consideration when defining the hydrogeological characteristics for each layer.

GROUNDWATER FLOW MODELLING

Groundwater Vistas Software version 3.0 (Jim and Doug Rumbaugh 2001) with MODFLOW-SURFACT version 2.2 (Hydrogeologic Inc, 1996) was selected to simulate the behaviour of groundwater flow systems in the Kulnura Mangrove area. This model simulates three dimensional groundwater flow by using finite difference techniques.

Governing Equations

MODFLOW-SURFACT is based on the governing equation (Huyakorn et al. 1986) which describes the three dimensional movement of groundwater flow in a variably saturated system:

$$\frac{\partial}{\partial x}\left(K_{xx}K_{rw}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}K_{rw}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}K_{rw}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial Sw}{\partial t}+S_w S_s\frac{\partial h}{\partial t} \qquad (1)$$

where:

K_x, K_y, K_z are values of hydraulic conductivity along the x, y and z coordinate axes (L t);
K_{rw} is the relative permeability, which is a function of water saturation;
h: is the hydraulic head (L);
W: is the volumetric flux per unit volume and represents sources and/or sinks of water per unit of time (t^{-1});
S_w: is the degree of saturation of water, which is a function of the pressure head;
Ss: is the specific storage of the porous material (L^{-1});
S_y: is the specific yield; and
t is time (t).

For a fully saturated medium (i.e., S_w = 1.0), the relative permeability is unity and equation (1) reduces to:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t} \quad (2)$$

The first part of this problem was run to get a steady state solution, which takes the form:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=0 \quad (3)$$

Conceptualization

The geology of the study area is dominated by the Hawkesbury Sandstone Formation which has a maximum thickness of 250 m. Consequently, the Aquifer Zones are flat-lying contrasting between Sheet Sandstone and Massive Sandstone Facies.

Figure 5 represents the conceptual model. It consists of thirty flat hydrogeological layers. The first model layer represents the Upper Aquifer which consists of Unsaturated Sandstone and Sheet Sandstone. It is modelled as an Unconfined Aquifer. The Massive Sandstone Aquitard represents the second layer in the conceptual model. The third model layer represents the Middle Aquifer (Sheet Sandstone) and it is modelled as a Semi-Confined Aquifer. The lowermost model layer represents the Basal Narrabeen Group and it is modelled as Semi-Confined. The dominant recharge processes as shown in Figure 5 are the infiltration from rainfall and irrigation while the abstraction, evapotranspiration, seepage face, springs outflow and baseflow are the dominant discharge process in the aquifer system.

Model Domain and Grid Size

The model domain of the Kulnura Mangrove Mountain area is located between 319000, 6283500 (Left lower corner) and 359000, 6342500 (Upper right corner) according to AMG coordinate system (40 km * 59 km). The model grid of the study area has been designed having a uniform cell size of 500 m by 500 m; consequently the grid mesh is divided into 118 rows and 80 columns, which makes the total of 9.440 cells per layer and covers 2360 km^2 of the model area. As there are thirty layers in the model, the total number of cells is 283.200 cells. The inactive area of the model (outside the boundary of the study area) is about 42 %.

Model Layers

Due to high grade in topography and the thin aquifer zone (5 m thickness), few model layers don't cover the whole elevation range. Therefore more layers had to be added into the model to cover the whole thickness and to extend the stratigraphy to the sea level. Model layers are defined from two geological cross-sections and the lithological bores description. The model currently has 30 layers. The layer thickness in the Hawkesbury Sandstone Formation varies from 6.5 m in layer 2, 4 m in layer 5 to 2.5 m in layer 7 and to 10 m in layer 12. The layers are horizontal as stated by Conaghan and Jones (1975).

Steady-State Calibration

Both heads and fluxes were used as calibration targets. Model calibration was carried out by matching between the observed composite heads of the groundwater level contour map and the calculated heads by the MODFLOW simulation.

Sequential model runs were carried out manually to adjust the horizontal and vertical hydraulic conductivities and recharge values until the best fit between the observed and simulated water levels was obtained.

A good matching between the observed and simulated heads was obtained as well as good agreement between predicted discharges to water bodies and baseflow estimates. A comparison between the measured and simulated water level contour maps of the model area is shown in Figure 6. The patterns match very well in all areas. The average error in water level is about 3 m, in a background range of water levels from 0 to 330 m AHD. Figure 7 shows the good agreement between the observed and computed target values across all the model layers with a coefficient of determination of 0.994. The targets are the maximum measured heads at 20 DNR monitoring bores and all available private bores.

Table 1 illustrates the comparison between simulated and measured baseflow. The simulated values are generally within 0 - 35 % of baseflow estimates, which are recognised as having considerable uncertainty. The groundwater balance for the steady state condition of the whole model domain is summarized in Table 2. The recharge from rainfall is about 206 GL/year. The groundwater discharge is apportioned as 34 % to cliff seepage faces, 33 % as

evapotranspiration, 22 % as baseflow to creeks and 11 % outflow to Hawkesbury River, Tuggerah Lake and Tasman Sea.

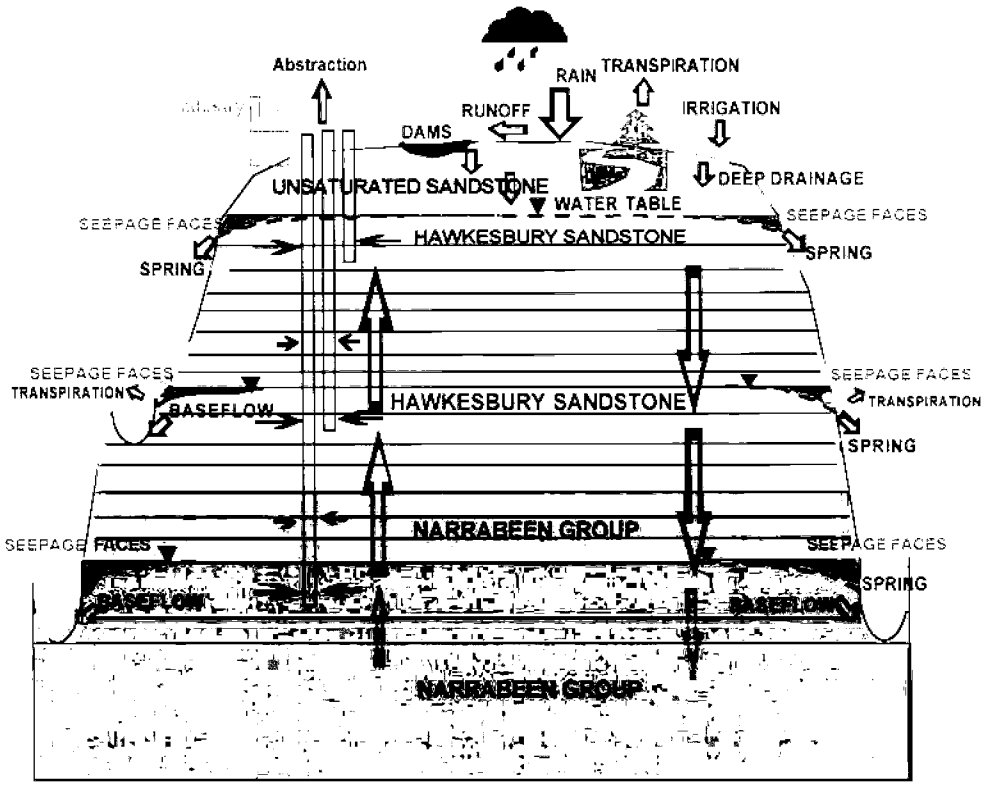

Figure 5. Conceptual model

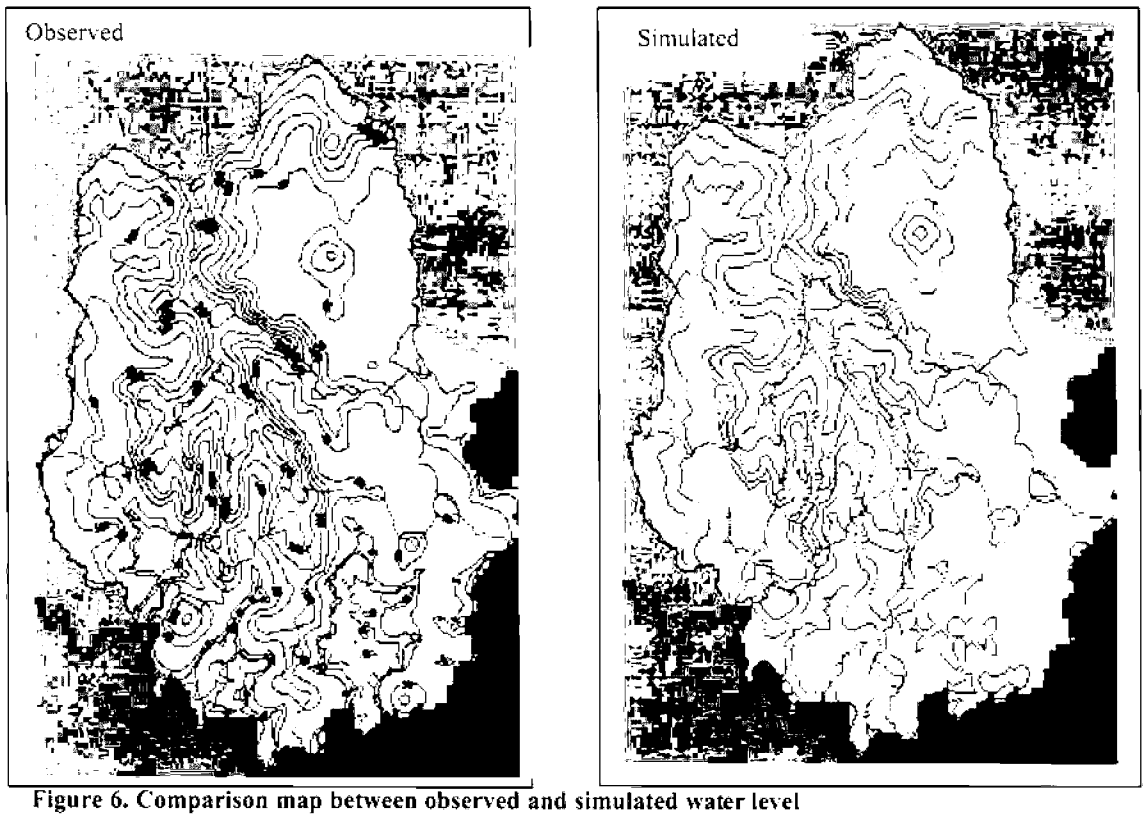

Figure 6. Comparison map between observed and simulated water level

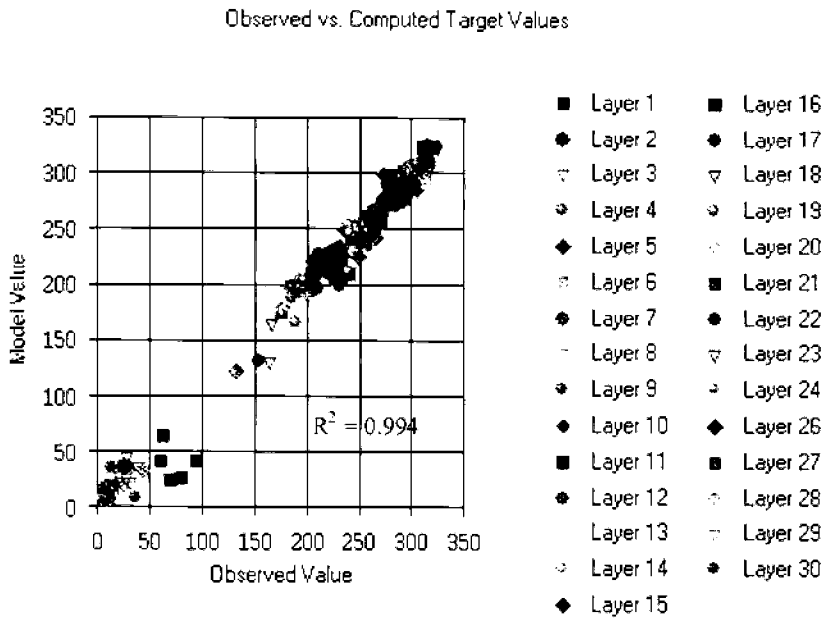

Figure 7. Observed versus computed target values through the model layers

Table 1: Comparison between estimated and simulated baseflow under steady state condition

Reach No.	Estimated Baseflow by Hybase (ML/d)	Simulated Baseflow by SURFACT (ML/d)
100 (Mangrove Creek)	10.5	12.2
201 (Jilliby Creek)	4.3	4.3
300 (Ourimbah Creek)	5.4	7.1
301 (Ourimbah Creek)	12.6	13.4
400 (Wyong River)	8.9	5.8
401 (Wyong River)	14.7	15.2

Table 2: Groundwater budget of the model during the steady state calibration

Boundary	Inflow (ML/d)	Outflow (ML/d)
Constant Head	0.2	59.9
Drain (baseflow)		125.7
Recharge	563.9	
Evapotranspiration		187.1
Seepage Face		191.4
Total	**564.1**	**564.1**

Time Scale Selection

The year of 1985 was considered as the year for the steady state condition in which rainfall was steady based on the residual rainfall mass curve. The model time is on a monthly basis for transient modelling to simulate the water level fluctuation regarding to the recharge variation over the year. The model start date is January 1985 and the end is at October 2003 based on the data availability of rainfall. The model has 18 years and ten months of simulation; it has been defined in Vistas as 227 stress periods to cover all of the months during this period. The period length for each stress period varies from 28 to 31 days depending on the number of days for the specified month. The first stress period represents the steady state condition, which produces initial heads for the following transient simulation.

Transient Model Calibration

Transient simulation describes the present situation and predicts the long-term dynamic behaviour of the hydraulic system (change of storage and drawdown levels) in response to seasonal variations in recharge and groundwater withdrawal (Anderson and Woessner 1992).

The available head data of 20 monitoring bores are used in the calibration process. The calibration was done by changing the specific yield and storage coefficient values for unconfined and confined aquifers, respectively until reasonable matches are obtained between the observed and simulated water level. Table 3 lists the range of hydraulic parameters resulting from the steady and transient model calibration.

Table 3: Ranges of the calibrated hydraulic parameters

Unit	Kx (m/d)	Kz (m/d)	Sy	S
Hawkesbury Sandstone	0.01 – 0.5	0.0004 – 0.05	0.02 – 0.05	$2.0*10^{-4} - 5.0*10^{-4}$
Narrabeen Group	0.001 – 0.07	0.0003 – 0.007	0.009 – 0.01	$9.0*10^{-5} - 1.0*10^{-4}$
Quaternary Alluvium	1 – 10	0.1 – 1.0	0.2	

The dynamic stress on the system is varying rainfall recharge and groundwater extraction. Generally, good agreement in seasonal pattern, and good replication of absolute water levels were obtained. Figure 8 shows the simulated and observed hydrographs for the monitoring bores GW075013~1, GW075013~2 and GW075013~3. These bores are located in the same cell (59,28) but in different layers: GW075013~1 is in layer 11, GW075013~2 in layer 14 and GW075013~3 in layer 19. It can be seen clearly that the vertical head difference between these bores is around 20 m and the model simulates this difference correctly.

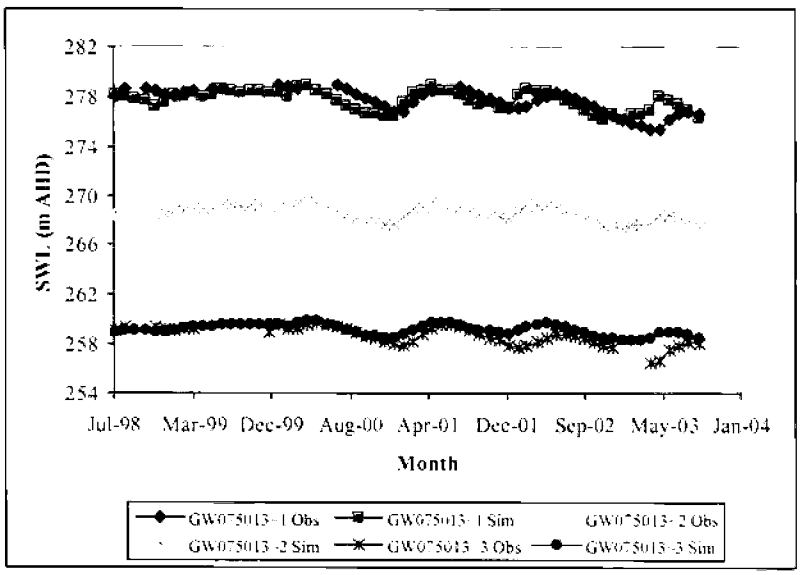

Figure 8. Observed versus simulated hydrographs

OPTIMISATION MODEL

Model Formulation

The main target of this study is to preserve baseflow in the creeks by determining the optimal limits on groundwater extraction from the existing or planned bores. This objective can be achieved by forcing the groundwater levels close to the creeks to be maintained.

Therefore the objective function of the management model is to maximize the pumping rate of bores from the multi-layers aquifer systems in Kulnura – Mangrove area:

$$Maximize \sum_{k=1}^{n} \sum_{t=1}^{p} Q_{k,t} \qquad (4)$$

subject to:

Drawdown constraint adjacent to the both sides of the creeks

$$DD(i,j) \leq \left[H_{OS}(i,j) - H_{DB}(i,j)\right] * T \qquad (5)$$

where:

w: total number of bores

p: total number of planning periods $p \geq 1$ (e.g. p = 12 months)

$Q_{k,t}$: total amount of groundwater withdrawal at bore k and planning period t (ML/d)

Hos(i,j): Head at the observation site i,j (m AHD)

Hdb(j,j): Head at the drain boundary i,j (m AHD)

T: hydraulic gradient reduction tolerance fraction

The hydraulic gradient reduction tolerance fraction is defined as a percentage range from 0.1 to 10 %.

OPTIMAQ Software

OPTIMAQ Software developed by Merrick (2000) is used to formulate the groundwater management model in the multi-layers aquifer systems in Kulnura – Mangrove area.

OPTIMAQ software couples MODFLOW simulation software (McDonald and Harbaugh 1988) with generic optimisation software (GAMS) (Brooke et al. 1988) to solve problems with linear or nonlinear objectives by using the response matrix approach.

In summary, this software can be divided into three main steps:

1. Pre-processing procedures for generating the required MODFLOW input files for the output control (OC), well (WEL) and hydrograph (HYD) packages:
2. A recursive batch procedure for repeated MODFLOW simulations for each pulsed cell; and
3. Post-processing procedures to convert MODFLOW-computed drawdown into a form acceptable to GAMS.

Steady-State Optimisation

Although OPTIMAQ can optimise over multiple planning periods, only steady-state optimisation is reported here. The steady-state optimisation model has been built by defining one planning period and 2826 constraints close to 1349 drain cells. The decision variables represent the withdrawal rate from 464 pumping bores located inside the model domain.

Two optimisation scenarios were carried out. The first scenario was run by assuming the maximum withdrawal rate for each individual model cell to be 60 m^3/d: this is based on a maximum extraction from a single bore 30 m^3/d with two bores in a cell being common. The second scenario is based on a known case that has total withdrawal rates (120 m^3/d) from three bores located in one grid cell. Therefore the maximum withdrawal rate for each individual cell in this scenario was equal to 120 m^3/d. The minimum withdrawal rate for each cell was set equal to zero in both scenarios.

OPTIMAQ software was run gradually and Modflow Surfact was run 464 times to calculate the drawdown for the all observation points from each pulse. The output of OPTIMAQ (PMP.GMS), (OBS.GMS) and (RMAT-4D.GMS) are imported directly to the GAMS optimisation routine. Then GAMS OPTIMISER was run under two scenarios (maximum pumping use 60 and 120 m^3/d respectively) to find the optimal solution of pumping rates with hydraulic gradient reduction tolerance ranges from 0.1 to 10 % and by taking into consideration the drawdown constraint in equation 5.

The results for each scenario are summarised in Tables 4 and 5. Figure 9 illustrates the variation of sustainable yield with hydraulic gradient reduction tolerance for the two maximum pumping use scenarios.

Table 4: Maximum sustainable yield and the observation site location at the maximum drawdown for each fraction of gradient reduction tolerance under scenario No. 1

Hydraulic Gradient Reduction Tolerance Fraction (%)	Maximum Pumping Use (60 m^3/d)				
	Sustainable Yield	Maximum Drawdown			
	(ML/yr)	(m)	Row	Column	Layer
0.1	2300	0.98	66	43	9
1	4025	1.34	66	18	17
5	6015	3.89	53	30	2
10	7100	6.86	53	30	2

Table 5: Maximum sustainable yield and the observation site location at the maximum drawdown for each fraction of gradient reduction tolerance under scenario No. 2

Hydraulic Gradient Reduction Tolerance Fraction (%)	Maximum Pumping Use (120 m^3/d)				
	Sustainable Yield	Maximum Drawdown			
	(ML/yr)	(m)	Row	Col	Layer
0.1	3900	1.00	66	43	9
1	6765	2.34	66	43	9
5	10120	4.90	66	18	17
10	11985	7.77	53	30	2

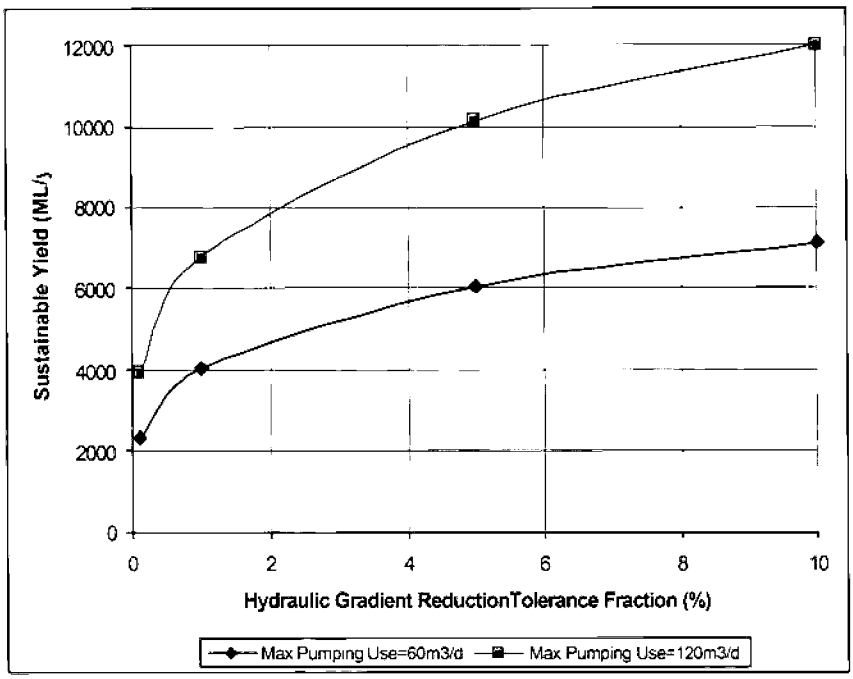

Figure 9. Sustainable yield versus hydraulic gradient reduction tolerance fraction for two optimisation scenarios

MODFLOW-SURFACT was run again, after importing the optimal pumping bores for each run, to determine the actual percent reduction of the baseflow for each scenario. Tables 6 and 7 summarise the results of MODFLOW-SURFACT runs.

Table 6: Actual percent reduction of baseflow of scenario No. 1 for each creek reach

Hydraulic Gradient Reduction Tolerance Fraction (%)	Maximum Pumping Use (60 m^3/d)					
	Percent of Baseflow Reduction (%)					
	Mangrove CK Reach 100	Jilliby CK Reach 201	Ourimbah CK Reach 300	Ourimbah CK Reach 301	Wyong River Reach 400	Wyong River Reach 401
1	0.08 %	1.18 %	1.72 %	0.45 %	0.17 %	0.00 %
5	0.65 %	1.18 %	3.01 %	0.83 %	0.87 %	0.00 %
10	1.14 %	1.41 %	3.44 %	1.05 %	1.39 %	0.07 %

Table 7: Actual percent reduction of baseflow of scenario No. 2 for each creek reach

Hydraulic Gradient Reduction Tolerance Fraction (%)	Maximum Pumping Use (120 m^3/d)					
	Percent of Baseflow Reduction (%)					
	Mangrove CK Reach 100	Jilliby CK Reach 201	Ourimbah CK Reach 300	Ourimbah CK Reach 301	Wyong River Reach 400	Wyong River Reach 401
1	0.16 %	1.88 %	2.60 %	0.83 %	0.52 %	0.07 %
5	0.74 %	2.41 %	5.80 %	1.38 %	1.41 %	0.07 %
10	1.31 %	2.35 %	6.64 %	1.81 %	2.26 %	0.13 %

CONCLUSION

A management model that couples a simulation model (MODFLOW-SURFACT) with an optimisation model (OPTIMAQ) has been developed for the Kulnura-Mangrove aquifer system to evaluate the trade-offs between the increased aquifer yields and baseflow reduction.

The calibration results of the simulation model show that the model performs very well in representing the values and the patterns of the groundwater level for both steady state and transient conditions.

The optimisation model was defined to preserve stream baseflow within tolerable limits while maximising the pumping rates from the aquifer system. Two optimisation scenarios were carried out (maximum pumping use 60 and 120 m^3/d respectively) with hydraulic gradient reduction tolerance ranges from 0.1 to 10 %. The initial optimisation results revealed that the impacts of the baseflow reduction from the change of hydraulic gradient by 0.1 to 10 % were not significant in most of the creeks except Ourimbah creek reach 300. This suggests that baseflow reduction is very conservative when inferred from the change (0.1 – 10 %) in the hydraulic gradient over 500 metres.

The sustainable yield was calculated for each scenario and for each hydraulic gradient reduction tolerance fraction. It ranges from 2300 to 7100 ML/yr for scenario 1 and from 3900 to about 12000 ML/yr in scenario 2.

ACKNOWLEDGMENTS

Gosford-Wyong Council's Water Authority are acknowledged for funding this research and also the Department of Natural Resources (DNR) for their supporting and providing all the required data to achieve the objectives of this research.

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