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Water balance modelling in Bowen, Queensland, and the ten iterative steps in model development and evaluation

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Abstract

Jakeman et al. (Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602–614) outline ten steps in the pursuit of good practice in model development and application to increase the credibility and impact of results from environmental models. This paper shows how the ten steps of model development are relevant to numerical groundwater modelling, using a model of a data-rich coastal groundwater system near Bowen in Queensland, Australia as an example. The model is Geographic Information System-based and estimates the dynamical water balance using Darcy's Law. The method, which is generally applicable to data-rich aquifers, proved cost and time effective and provided important insights to the groundwater dynamics of the area.

Keywords: Groundwater; Geographic Information System (GIS); Queensland; Model development; Groundwater management; Ten steps

1. Introduction

There are many different approaches to modelling groundwater systems. Each depends on the purpose of the modelling. Some examples from the recent literature include Ataie-Ashtiani (2006), who describes regional-scale, finite-difference, quasi three-dimensional flow and contaminant transport software called MODsharp, designed to model layered coastal aquifers. Li and Liu (2006) have taken advantage of recent advances in computer technology to provide real-time modelling, visualisation and analysis with their two- and three-dimensional flow and transport software called IGW (Interactive Groundwater). Cartwright et al. (2006) describe the validation of a coupled MikeSHE-Mike11 ground-surface water model against experimental observations of water table fluctuations induced by periodic fluctuations in an adjacent clear water reservoir. Masciopinto (2006) describes an approach for evaluating the position of the seawater–freshwater interface in a coastal fractured rock aquifer. Finsterle (2006) illustrates the optimisation of contaminant plume remediation strategies to minimise cleanup costs using iTOUGH2 inverse modelling software.

The data used in model development are also important. Reed et al. (2007) and Theodossiou and Latinopoulos (2006) present alternative methods for optimising bore monitoring strategies to minimise cost and data redundancy.

The approach of Masciopinto (2006), who uses the Dupuit and Ghyben-Herzberg approximations in the assessment of the extent of seawater intrusion, is the most similar to the method described here. Both methods use simplified mathematical formulations, rather than solving partial differential equations. Ataie-Ashtiani (2006), Li and Liu (2006), Finsterle (2006) and Reed et al. (2007) discuss the use of flow and contaminant transport models. Cartwright et al. (2006) use a coupled

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ground-surface water model to predict water table fluctuations. This is more complex than using a groundwater only model like MODFLOW (McDonald and Harbaugh, 1988). The study by Theodossiou and Latinopoulos (2006) is concerned with improving modelling outcomes by improving the quality of observation networks.

Jakeman et al. (2006) outline ten steps for good, disciplined development of environmental models, aimed at increasing the credibility and impact of modelling results. This paper shows how these ten steps are relevant to numerical groundwater modelling, using a model of a groundwater system near Bowen in Queensland, Australia as an example.

Bowen is a coastal town in the dry tropics. There are on average nearly 300 dry days per year, and the summer-dominant rainfall is extremely variable, ranging from 255 to 2358 mm/year and averaging 944 mm/year (Welsh, 2002). The adjacent Don River Delta irrigation area is one of the largest horticultural areas in the dry tropics of Queensland (Baskaran et al., 2001) and is groundwater dependent. With horticulture increasingly replacing grazing on the floodplain, the groundwater resource is under increasing demand, particularly during prolonged dry periods. A model was sought to assist with management of the groundwater resource.

2. Model development and evaluation

The following discussion describes the model development and evaluation in terms of the Jakeman et al. (2006) ten steps. Although the ten step generic treatment of the modelling process was not available during development of this model, a similar approach, as described by Murray-Darling Basin Commission (2000), was standard for groundwater modelling.

2.1. Model purpose

A numerical groundwater model of the Bowen irrigation aquifer was requested by the Queensland Department of Natural Resources, Mines and Water (QDNRM&W) to assist with management of the resource. At issue was overpumping of the groundwater and the possibility of this inducing seawater intrusion, which would contaminate the aquifer and further reduce the availability of the resource.

The purpose of the modelling was not to assess the risk of seawater intrusion, but to provide a sound basis for managing the water resources sustainably through an improved understanding of the groundwater dynamics and a quantification of the groundwater components over space and time.

2.2. Modelling context: scope and resources

QDNRM&W were the clients for the model and the point of first contact for data and information. The irrigators and the Bowen Shire Council may also have been interested, but had no direct input to the modelling.

The model was required to quantify the groundwater distribution and the important recharge and discharge mechanisms. The outcome would be a better understanding of the physical framework of the system (i.e. the aquifer geometry and properties) and the behaviour of the water within this framework as it interacts with water outside the framework.

The purpose of the model dictated that it extend over a few years to highlight observed trends. Time was discretised into 28-day intervals, commencing 18 June 1989 and terminating between 7 June 1997 and 8 April 2000 depending on the available data. A longer time interval would have blurred seasonal variations and a shorter time interval would have given less reliable water table surfaces as these measurements were generally bi-monthly.

Spatially, the model needed to extend over both the extensively cropped river delta and inland over the increasingly cultivated floodplain. To reduce potential errors in the calculations the study area boundary was chosen to minimise the amount of groundwater flowing across it. Where possible the boundary coincides with the edge of the saturated aquifer or is parallel to the direction of groundwater flow. Areas of outcropping basement are not included.

The study area was discretised into polygons whose sizes were influenced by the density of the data and chosen to show an estimate of the spatial variation of the water balance components. Polygon sizes vary from 0.04 km^2 to approximately 5 km^2, as discussed in Sections 2.5.3–2.5.5.

2.3. System conceptualisation, data specification, prior knowledge

The Don River irrigation area (Fig. 1) covers about 220 km^2 and occupies a valley open-ended to the ocean in the north. Euri Creek lies along the western edge and the Don River lies along the east. Both contribute to groundwater recharge and are ephemeral. Each has one stream gauge whose average water levels were used in calculations of the groundwater–surface water interactions in the rivers.

The aquifer consists of unconsolidated fluvio-deltaic deposits and weathered granite, which has the appearance of medium to coarse sand (Welsh, 2002). Production bores extract water from both lithologies. Groundwater preferentially flows through the infilled channels in the unweathered granite that is assumed to be the hydraulic basement. The aquifer is unconfined and groundwater flow is from the south toward the coast.

The alluvial sediments are thickest at the coast and the weathered granite is thickest in the south. Because the water table deepens toward the south, the saturated part of the aquifer is mostly alluvial sediments in the north grading to mostly weathered granite in the south.

Conceptually, water enters the aquifer as deep drainage of rainfall and excess irrigation through the soil, laterally from up-gradient parts of the aquifer outside the study area and through the riverbed sediments when the river water elevation is greater than the water table elevation. Water exits the aquifer as freshwater discharge to the sea, through water bores, as river baseflow and via evapotranspiration. Groundwater storage changes by the difference between the inflows and outflows.

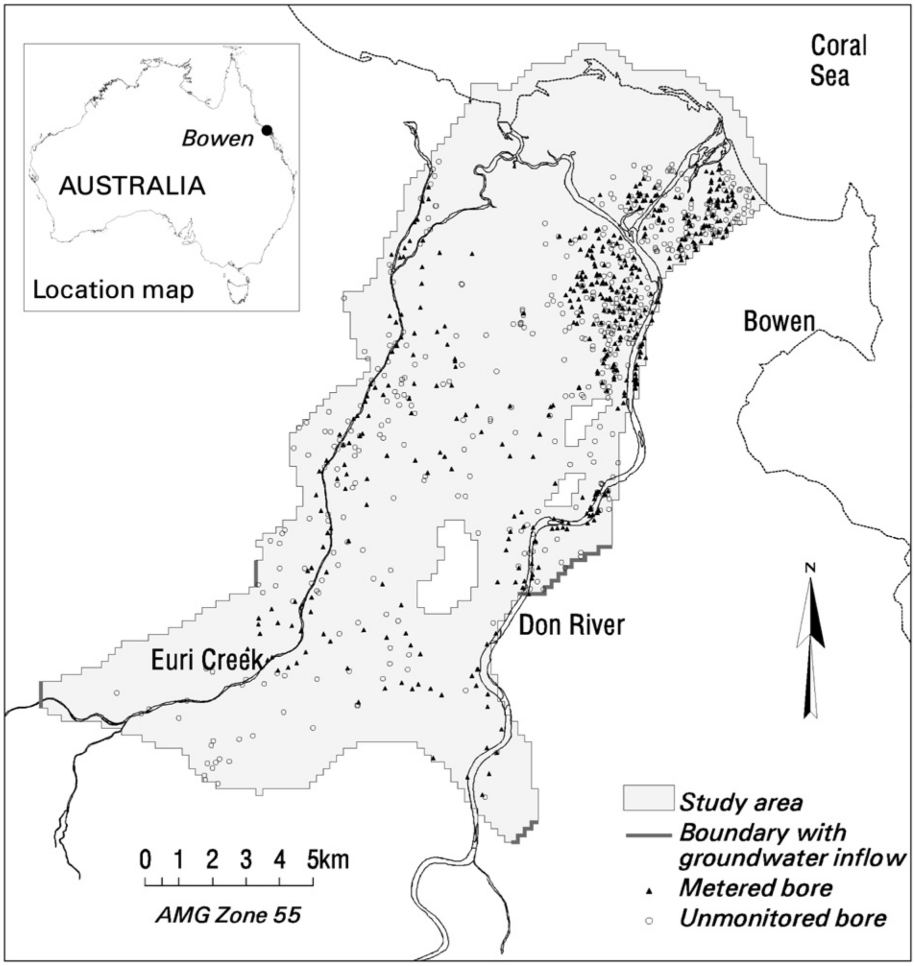

Fig. 1. Location of production bores within the study area.

In recognition of the aquifer's stressed nature and economic importance to the region, data collection and monitoring has been a high priority. There are 726 bore hole lithological logs, water levels from 260 dedicated monitoring bores, including 10 multi-piped bores near the coast, 6 bores with pump-test transmissivities, metered water use read 4–5 times annually from 454 production bores, the locations of 469 unmetered stock and domestic bores, air photos and mean daily river heights at two locations. In addition, topography from 1:100,000 scale mapping, surface geology and bottom elevation of the alluvial sediments from the Water Resources Commission (1988), rainfall and pan evaporation rates from the Bureau of Meteorology, soil type and texture from the National Land and Water Resources Audit (2001), and land use mapped at a scale of 1:25,000 in 2000 were available. The model assumes that the meteorological components were spatially uniform.

2.4. Selection of model features and family

The model is data-driven. It consists of simple representations of physical fluxes using variations of Darcy's Law, which describes laminar water flow through soils. The equations calculate water balance components over space and time. All model parameters are distributed except the storage coefficient and deep drainage recharge from rainfall and excess irrigation, which are lumped parameters determined during calibration. All other water balance components are calculated independently of each other. Calibration (Section 2.6) was achieved by adjusting parameters so that the difference between the sum of inflows and the sum of outflows matched the change in groundwater storage.

The spatially and temporally varying water table elevation is pivotal in determining all components of the water balance except the bore discharges. The simulation model does not move water laterally between polygons. It calculates recharge or discharge from each polygon independently based on water level differences, such as the difference between the river and aquifer water levels, within the polygon. Evapotranspiration calculations use water table depth to regulate discharge. The lateral hydraulic connectivity between polygons is reflected in the differences in observed water table elevations.

The model is not predictive. By interpolating past measurements to a set of points in time it exposes the trends and relationships of the water balance elements.

2.5. Selection of model structure and parameter values

As a numerical model was the suggested product of the study, and MODFLOW is the industry standard (Camp Dresser & McKee, 2001) for groundwater flow models, this influenced the choice of model structure. Like MODFLOW, this model is based on Darcy's Law, and its application involves discretising and simplifying the groundwater system components so that the important processes are captured. The model structure is spatially-based with simple physics applied within and between polygons.

2.5.1. Preliminary data processing

Water level measurements in the multi-piped bores were used to ascertain whether the permeable lithologies at different depths could be modelled as a single aquifer. The water levels in each set of pipes were compared after correcting for density variations due to salinity.

Water table measurements from monitoring bores, both inside and outside the study area, were interpolated to the model timesteps after adjustment to a common datum using topographic data and corrections for density variations.

The lithological logs were used to calculate point estimates of saturated-zone horizontal hydraulic conductivity (K_h) of the alluvial sediments using standard conductivities for the lithologies (Freeze and Cherry, 1979). These were then calibrated against the transmissivity measurements. Estimated alluvial K_h in the saturated zone varies between 0.1 and 100 m/day. Based on the appearance of the weathered granite and the standard conductivities, the weathered granite was assigned a constant K_h of 20 m/day.

2.5.2. Water bore discharges

Discharge volumes from metered irrigation bores were summed for the model timesteps and an estimate of use from stock and domestic bores, based on published household use from nearby regions (Australian Water Association, 2002), was added to give the bore discharge rates, Q_{bore}.

2.5.3. Coastal outflows

Estimates of freshwater discharge to the sea were calculated for 14 coastal polygons (Fig. 2) oriented parallel to the direction of groundwater flow and extending from the 2 m hydraulic head contour to sea level. The Ghyben–Herzberg Concept for hydrostatic equilibrium of freshwater/saltwater pressures is invoked to estimate the depth of freshwater because there are no measurements of this at the coast. The Ghyben–Herzberg Concept estimates that in a coastal aquifer the depth of the freshwater–seawater interface is approximately 40 times the head of freshwater above mean sea level at that location (Freeze and Cherry, 1979) due to the density difference between the two media.

The flow rate is estimated using Darcy's Law, in which the volumetric rate of flow through a tube Q is the negative product of the hydraulic conductivity K, the hydraulic gradient $\mathrm{d}H/\mathrm{d}L$ and the cross-section area A of the saturated media (Freeze and Cherry, 1979):

$$Q = -K\frac{\mathrm{d}H}{\mathrm{d}L}A \tag{1}$$

Each coastal polygon is treated as a tube with a hydraulic gradient given by the drop in hydraulic head ($H_{max} - 0 = 2$ m, in this case) divided by the average polygon length L_{av} and a cross-section area as the average polygon width W_{av} by the depth of freshwater, which is 41 times the average height of freshwater above mean sea level H_{av}. A multiplier of 41 represents 40 m below sea level for every 1 m above sea level. The coastal groundwater discharge is calculated as:

$$Q_{coast} = K_h\frac{H_{max} - 0}{L_{av}}41H_{av}W_{av} \tag{2}$$

(after Queensland Department of Natural Resources and Mines, 2000). The discharge was calculated for each polygon in each 28-day period.

2.5.4. River interactions

Water flow between the Don River/Euri Creek and the aquifer was calculated for 16 and 9 river polygons respectively for each 28-day period.

Darcy's Law is applied to vertical tubes whose cross-section areas A are the polygon areas. Hydraulic conductivity is the vertical hydraulic conductivity of the riverbed sediments K_z, tube length is the thickness of the riverbed sediments L_{riv} and the change in hydraulic head is the difference between the river stage H_{riv} and the water table elevation H:

$$Q_{river} = K_z\frac{H_{riv} - H}{L_{riv}}A \tag{3}$$

A negative Q_{river} represents groundwater discharging into the river; a positive Q_{river} represents river water recharging the aquifer.

Groundwater discharges when the river stage is below the elevation of the water table. Conversely the river loses to the aquifer when the river stage is above the water table elevation. Horizontal flow between the aquifer and the river is assumed to be negligible.

Riverbed outlines were digitised from air photos; streambed thickness was estimated from published information (Water Resources Commission, 1988); water depths were assumed to be constant along the lengths of the rivers and to correspond to the relevant gauging stations; and a constant value of 0.01 m/day was assumed for K_z based on the hydraulic conductivity for a silty sand (Freeze and Cherry, 1979) and assuming a K_h/K_z anisotropy ratio of about 10 (Bouwer, 1978).

2.5.5. Evapotranspiration

Evapotranspiration is a combination of evaporation from open bodies of water, evaporation from soil surfaces and transpiration from the soil by plants. This study considers only evapotranspiration losses extracted from groundwater storage by vegetation.

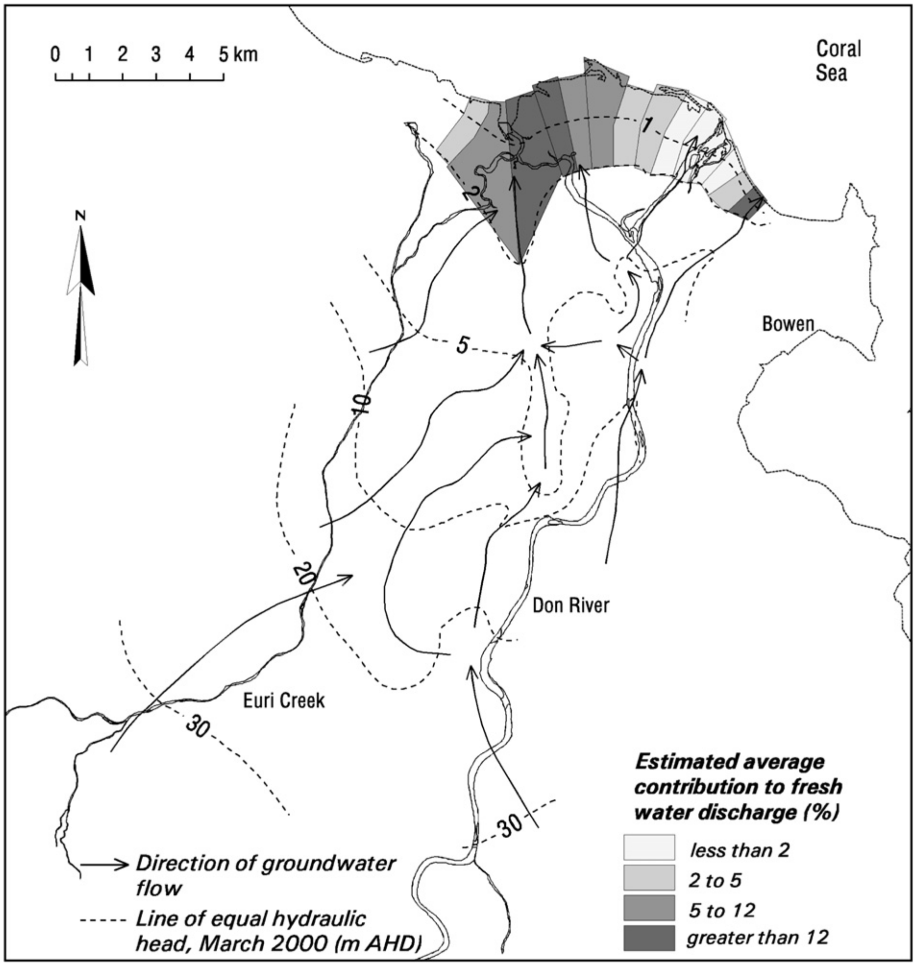

Fig. 2. Coastal discharge polygons and groundwater flow directions.

The rate of evapotranspiration is a portion of measured pan evaporation and is a function of soil type, land use and root extinction depth, D_{ext}. Evapotranspiration is assumed to be zero when the root zone is entirely above the water table.

The maximum evaporation rate E_{max} was assumed to be 85% of the measured pan evaporation rate. This value was chosen empirically, noting that actual evapotranspiration rates are less than pan evaporation rates, the difference decreasing with increasing rainfall (Hobbins et al., 2004). The mapped land uses were reduced to 8 classes for the purpose of assigning root extinction depths, which are listed in Table 1. Estimates of maximum root depth were based on plant height, with grasses having relatively longer roots than trees. Root depths for loamy sediments are reduced to 90% of the listed values because root development is slightly greater in sandy soils (see, for example, Silver et al., 2000).

Table 1
Estimated maximum root extinction depths

Vegetation type	Root extinction depth (m)
Mangroves	2
Irrigated horticulture	2[a]
Cleared pasture	1
Improved pasture	1.5
Near-shore native vegetation	2
Other native trees	5
Rivers	–[b]
Other water bodies	–[c]

[a] Maximum root depths for irrigated agriculture vary from 0.01% to 100% of 2 m from January/February to December each year.
[b] Evapotranspiration over the rivers is included in the river–aquifer interactions.
[c] Other water bodies were assigned the maximum evapotranspiration.

Evapotranspiration Q_{evap} is estimated as the product of E_{max} and the proportion of the root zone that is below the water table, which is calculated using the ground surface elevation G, the water table elevation H and D_{ext}:

$$Q_{evap} = E_{max}\frac{D_{ext} - (G - H)}{D_{ext}} \tag{4}$$

(after McDonald and Harbaugh, 1988). Evapotranspiration was calculated for each 28-day period with the study area discretised into approximately 5000 cells, each 200 m × 200 m.

2.5.6. Lateral inflows

Groundwater flows into the study area across four sections of the boundary (Fig. 1). The flow rate was calculated across 200 m edge length square boundary cells using Darcy's Law.

The hydraulic gradient is the change in hydraulic head ΔH along the length of the cell L_{cell}; the cross-section area is the product of cell width W_{cell} and the saturated aquifer thickness D_{aquifer}:

$$Q_{\text{lateral}} = K_{\text{h}} \frac{\Delta H}{L_{\text{cell}}} W_{\text{cell}} D_{\text{aquifer}} \tag{5}$$

2.5.7. Storage

Aquifer storage is the volume of saturated media between the water table and hydraulic basement multiplied by the specific yield, which can be thought of as drainable porosity.

Saturated aquifer volumes were calculated at 28-day intervals using time-varying hydraulic head surfaces and the hydraulic basement surface in the GIS. The specific yield was estimated during model calibration.

2.5.8. Rainfall and irrigation deep drainage

Rainfall recharges the aquifer predominantly in the wet summer months. As most crops are planted at the end of the wet season, irrigation deep drainage contributes to recharge in the dry months. As detailed crop information was not available this component of recharge is calculated as a lumped parameter during calibration.

2.6. Choice of estimation performance criteria and technique

Model calibration was achieved by manually adjusting selected parameters. Although plant root extinction depths were modified slightly, specific yield and deep drainage recharge were the only model inputs entirely determined during parameter estimation.

Invoking the mass balance equation for change in storage:

$$\Delta S = \text{Inflows} - \text{Outflows} \tag{6}$$

allows an estimate of rainfall and irrigation deep drainage when the equations are re-arranged as:

$$Q_{\text{recharge}} = \Delta S + Q_{\text{bore}} + Q_{\text{coast}} + Q_{\text{evap}} - Q_{\text{river}} - Q_{\text{lateral}} \tag{7}$$

This equation describes the water balance for each time period. Since recharge is by definition into the ground, and therefore positive, specific yield was modified to ensure that deep drainage recharge rates were not negative in any 28-day period. Specific yield was assumed to be uniform because it has a small range of possible values, usually 0.01–0.3 (Freeze and Cherry, 1979), compared to, for example, hydraulic conductivity, which can vary over 13 orders of magnitude (Anderson and Woessner, 2002). The value for specific yield determined during calibration is 0.06.

2.7. Identification of model structure and parameters

The model structure and parameters were largely determined by circumstances. A preliminary MODFLOW steady state model was run with a range of recharge estimates, but was not calibrated. This model facilitated understanding of the hydrogeology of the area and was a test of the conceptual model. Subsequently, a change in corporate priorities required the modelling to be deferred. When the project resumed the time remaining for completion was only a few months.

To continue with MODFLOW would have required the development of a transient model because of the seasonality of the irrigation and the groundwater recharge. A steady state model would not add much to the understanding of the hydrogeology. The data were suitable, but it was thought that the combined data processing and calibration might not be completed in the timeframe.

The area is data-rich compared to most Australian groundwater basins. A method of extracting information from the data was sought that was spatial and temporal and would not involve a protracted calibration. Coastal outflows were first calculated using a modified version of an equation in Queensland Department of Natural Resources and Mines (2000). This led to the realisation that other components of the water balance could be calculated by using applications of Darcy's Law and borrowing equations from MODFLOW. Using Eq.(6) enabled the missing component, recharge, to be estimated, creating the complete analytical water balance. This is the first time this approach has been applied to generate a complete dynamical groundwater balance.

2.8. Conditional verification and diagnostic testing

As the model is not predictive, there are no measured minus modelled residuals with which to make an assessment of the calibration.

The specific yield of 0.06 lies within the ranges for silt (0.03–0.19) and sandy clay (0.03–0.12) compiled by Johnson (1967), and is consistent with the clay loam soils that dominate the study area (Welsh, 2002) and with the lithologies from the bore logs.

The recharge rates estimated are about 20% of the average annual rainfall. This compares with 35% for the Lower Burdekin aquifer in the Burdekin River Delta (Queensland Department of Natural Resources and Mines, 2001), of which about one quarter is artificial recharge through purpose-built recharge pits. The Burdekin River Delta lies 100 km to the north-west of Bowen and its climate is very similar, with highly-seasonal rainfall varying from 250 to 2500 mm/year and averaging about 1000 mm/year (Queensland Department of Natural Resources and Mines, 2000). The dominant soils are loams and sandy loams (Northcote et al., 1960–1968), which would be expected to support a slightly higher recharge rate.

Rainfall is not a model input, but it drives the groundwater flow. Consequently, the model outputs were plotted against rainfall to check the temporal relationship between rainfall and the changes in magnitude of the water balance components (Figs. 3–8).

The effect of changes in parameter values on the water balance was determined for weathered granite K_{h}, unmetered bore flow rates, riverbed thickness and K_z, specific yield and

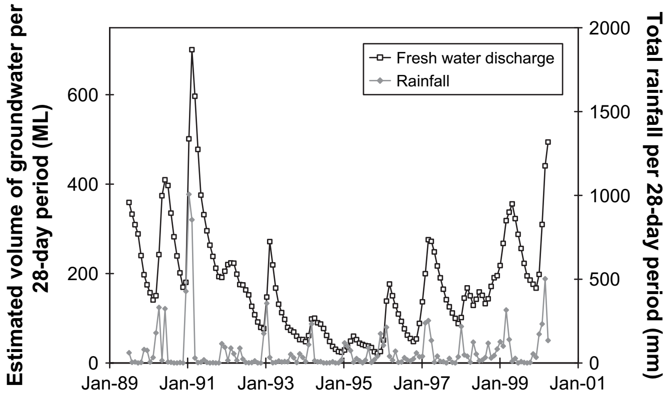

Fig. 3. Estimated volume of groundwater flowing to the coast per 28-day period.

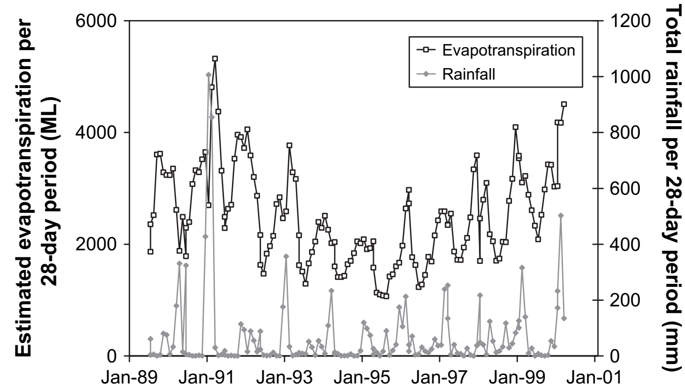

Fig. 5. Estimated evapotranspiration losses from the study area groundwater for each 28-day period from July 1989 to March 2000.

evapotranspiration parameters. With each sensitivity analysis the remaining components of the model were recalculated, providing calibrated sensitivity results.

A water balance with the line items listed in Table 2 was compiled after each model run. Although individual components changed significantly from their baseline values, the total inflows and outflows changed little in most sensitivity runs. Fig. 9 shows the effect of the parameter value changes on the total water balance inflows and outflows compared to the baseline calibrated model. For example, halving all root extinction depths reduces both total inflows and total outflows by 28%.

Rather than testing the effect of changes to one water balance component on other individual components, the sensitivity analyses test the implications of using different parameter values. For example, reducing root extinction depths reduces the evapotranspiration estimates (Eq. (4)). This in turn decreases the estimates of recharge (Eq. (7)). Because the model data are historical the water table elevations are fixed, and so are the temporal volumes of groundwater in storage. In the sensitivity analyses total inflows and total outflows will increase together or decrease together because of Eq. (6).

Hydraulic conductivity was changed by a large amount because it has a power relation with grainsize (Freeze and Cherry, 1979), meaning that a small change in aquifer grainsize will have a large effect on both K_h and K_z.

Changes to weathered granite K_h and riverbed thickness caused significant differences in the lateral flows and river leakages respectively, but only small differences from the baseline model in the water balance totals. Changing unmetered bore flow rates also had little impact because stock and domestic bore water use is very much less than irrigation use.

Although deep drainage recharge and the water balance for individual stress periods are sensitive to changes in specific yield, the average flows over all 28-day periods did not change significantly because the increases and decreases balance out. The calculated deep drainage recharge in some 28-day periods became negative with the higher specific yield.

The water balance is sensitive to decreases in riverbed K_z.

Evapotranspiration occurs over a large area and is the largest component of the water balance outflows. Varying the maximum rate from 85% of the pan evaporation rate to 60% and 100% had a significant impact on the total flows. The root extinction depth matrix (Table 1) is the most sensitive parameter. Altering these depths for loamy soils from 90% to 70% and 100% had a small impact on the water balance. However, halving all root extinction depths decreased total average inflows and outflows by nearly 30% and reduced the calculated deep

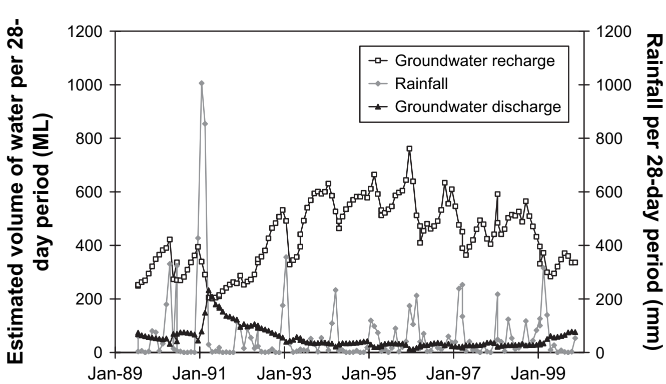

Fig. 4. Estimated groundwater discharge into the rivers and recharge from the rivers for each 28-day period.

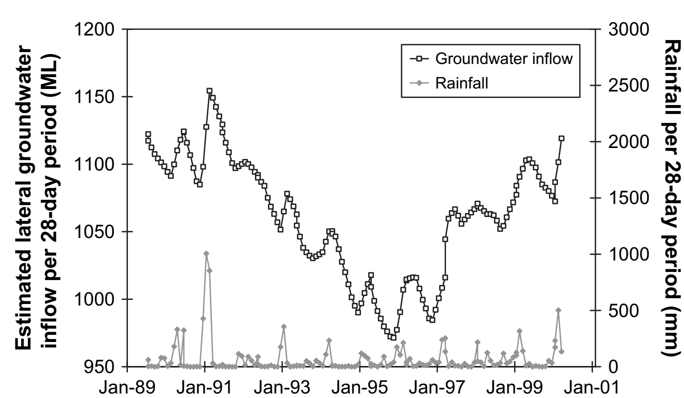

Fig. 6. Estimated lateral inflows to the study area groundwater for each 28-day period from July 1989 to March 2000.

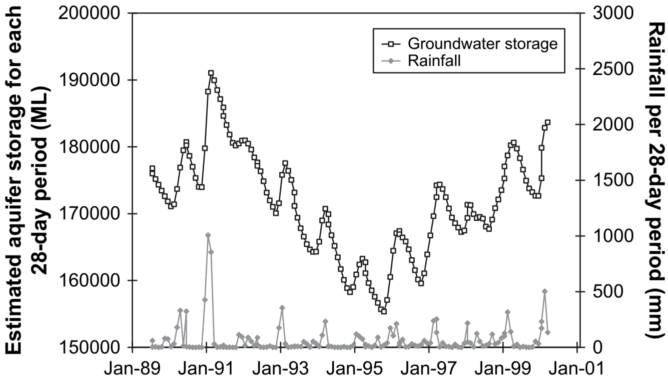

Fig. 7. Estimated groundwater storage in the study area for each 28-day period from July 1989 to March 2000.

drainage recharge to 15% of rainfall. Doubling root extinction depths increased total average inflows and outflows by nearly 50% and increased the calculated deep drainage recharge to 34% of rainfall.

2.9. Quantification of uncertainty

The uncertainty associated with the selected modelling method and with the adopted discretisation has not been quantified.

The measured water levels drive the model. The monitoring bores are sufficiently spaced to allow a good interpolation of the water table surface except in part of the central east of the study area where the hydraulic gradient is very steep. More measurements in this area would give greater confidence to the interpolations. The sensitivity of the results to time step size was not tested. The 28-day time steps, discussed in Section 2.2, were considered to be the minimum that the data could sustain. There will be some error associated with this, but the likely effect is that temporally local maxima and minima were not captured by the data.

Comparisons between irrigation bore discharge rates and the other water balance components are of particular interest to water managers. Unfortunately these discharge records were incomplete. Plotting water use against rainfall highlighted some

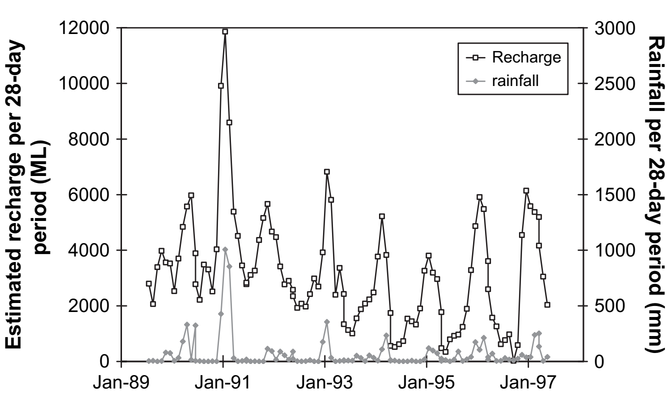

Fig. 8. Deep drainage recharge calculated from changes in storage and the other water balance components.

Table 2
Estimated water balance for a selection of 28-day periods for the study area (volumes are ML per 28 days)

Component	12 Jan 1991	1 May 1993	11 Nov 1995	Average Jul 1989 to May 1997
Inflows				
Deep drainage	11861	2427	3287	3138
Rivers	339	395	644	435
Lateral flows	32	30	27	30
Total	12232	2852	3958	3603
Outflows				
Rivers	78	54	28	59
Lateral flows	501	131	21	163
Water bores	478	2391	564	1004
Evapotranspiration	2698	2158	1604	2407
Total	3755	4734	2217	3633
In–out	8477	−1882	1741	−30

zero-values when pumping would be expected to be high in the last full year of data. The pumping data also had the shortest time-series; no data were available beyond May 1997.

Although the modelling outputs are quantitative, the water budgets are most reliably viewed as qualitative, showing where and when the individual components increase or decrease. The relative amount of river water that replenishes the aquifer as compared to the amount of groundwater that is lost to the river, is likely to be quite reasonable because the inputs in Eq. (3) that are not time-dependant are the same for these two water balance components. River leakages are proportional to the time-varying observed water level differences between the water table and the river stage.

2.10. Model evaluation or testing

The initial request for a numerical groundwater model was met in part: the model produced by the study succeeds in quantifying the important components of the groundwater system but does not include a future predictive capacity. The model makes good use of the available data and provides an incremental improvement in the understanding of the Don River groundwater system.

The model was developed with input from QDNRM&W staff and documented in a 70-page report (Welsh, 2002) listing the assumptions, detailing the methodology and illustrating the parameter sets and results.

The input parameters are considered to be plausible, being based on field measurements and knowledge of similar systems. It is not possible to validate the model against data not used in its construction because additional data were not available.

3. Results

Figs. 2 and 10 illustrate the spatial distributions determined for discharge to the sea and evapotranspiration. Submarine discharge is greatest from the western part of the coast. The highest rates of evapotranspiration occur near the coast and adjacent to the rivers where the watertable is shallowest. Areas where the

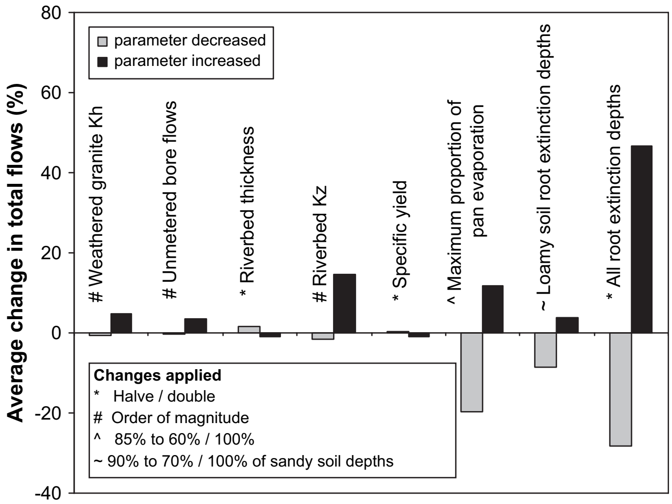

Fig. 9. Mean changes in total flows for the sensitivity analyses.

root zone is entirely above the water table are shown as having no evapotranspiration losses from groundwater storage.

River leakage from the Don River to the aquifer occurs along both its upstream and downstream reaches, while baseflow enters the river near the centre of the study area. Euri Creek is a dominantly losing stream.

Figs. 3–8 compare the calculated time series of discharge to the sea, river leakage, evapotranspiration, lateral inflows, groundwater storage and recharge respectively with rainfall. All parameters show strong seasonal variations. Recharge from rivers and deep drainage increases with rainfall, with the response to early summer rains being proportionately greatest. Groundwater storage, discharge to rivers, coastal outflows and lateral inflows increase with rainfall and gradually decrease during the year. This study suggests that the time delay between rainfall and changes in groundwater storage (Fig. 7) is 4 weeks. However, this is also the finest temporal resolution of the model.

Fig. 4 shows that the volume of water discharged into the rivers increases with the summer rains then tapers off as water drains from the aquifer. River recharge increases during the first month after the start of the summer rains, as the rivers fill. As the water table rises the height difference between it and the river decreases, so the rate of recharge decreases. River recharge then increases again as the water table drops.

The estimated recharge rates, as illustrated in Fig. 8, suggest that the December 1990/January 1991 flood doubled the maximum recharge rate for that wet season and enhanced the recharge for years afterward. They also suggest that relatively small rainfall events do contribute to groundwater recharge.

The calibrated values of both the specific yield and deep drainage recharge, as discussed in Section 2.8, are plausible when compared with published values.

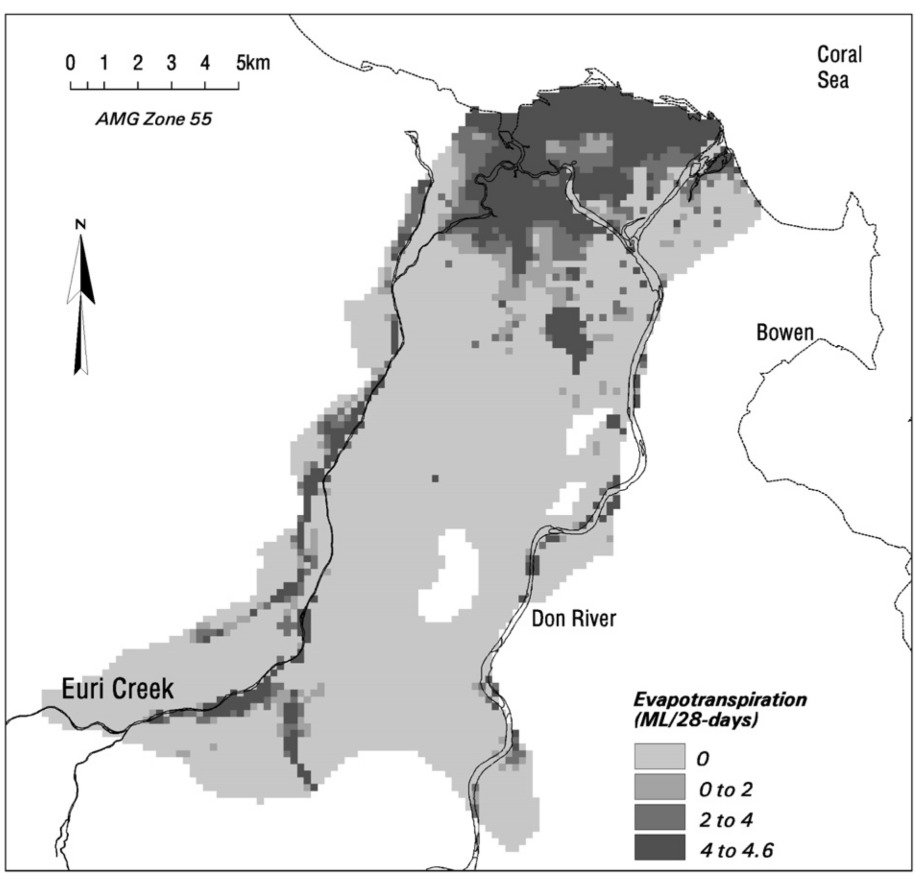

Fig. 10. Estimated evapotranspiration losses from the groundwater for March 2000 calculated from 200 m × 200 m polygons.

The estimated water balance for the study area for selected periods is shown in Table 2. The 12 January 1991 period has the highest rainfall, 1 May 1993 is in the dry season prior to the mandated move from flood to trickle irrigation and has the greatest groundwater pumping, and 11 November 1995 has the lowest water table. A time series plot of the water balance components except lateral inflow and groundwater storage, which are the smallest and largest components, is shown in Fig. 11.

The model results suggest that, on average:

(1) Deep drainage from rainfall and irrigation is about 87%, river leakage is about 12% and lateral groundwater inflow into the study area is less than 1% of the recharge
(2) Evapotranspiration is about 66%, water bores are about 28%, freshwater flow to the ocean is about 4% and drainage into the rivers is about 2% of the groundwater losses
(3) Groundwater pumping uses about 6 times the amount of fresh groundwater that flows out to the sea
(4) Don River and Euri Creek contribute close to half of the volume of groundwater that is removed by pumping
(5) About 7 times more river water replenishes the aquifer than groundwater is lost to the river

The annualised average water balance figures for July 1989 to May 1997 are illustrated in Fig. 12.

4. Discussion and conclusions

A numerical groundwater modelling study has been described using the ten step framework of Jakeman et al. (2006). This approach encourages good, disciplined model-development practice. Using the ten steps to document the model focused attention on each important element of the modelling. This highlighted that, due to the nature of the study, the uncertainty in model results and an assessment of the calibration have not been quantified.

The algorithms presented are mostly based on Darcy's Law and provide simple estimates of the water balance for the Don River Aquifer. A GIS is critical to the method, being used to spatially interpolate point data and to calculate aquifer volumes. The equations capture the important flows while simplifying the groundwater system.

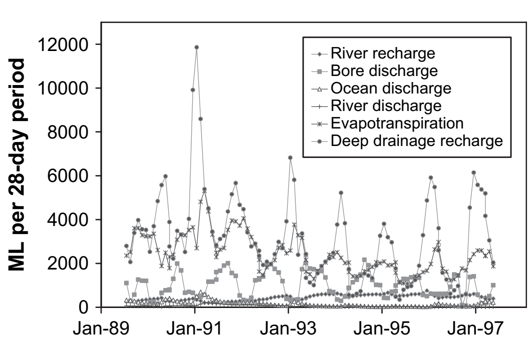

Fig. 11. Time series of average water balance component values.

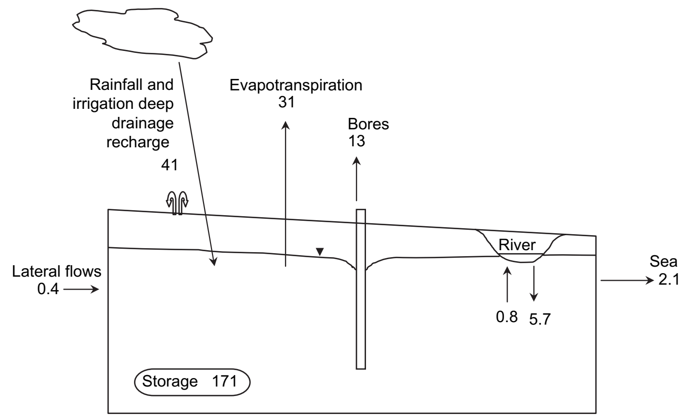

Fig. 12. Estimated annual average water balance (GL) for the period July 1989 to May 1997.

Spatial and temporal water balance estimates quantify the components of the conceptual model. They provide groundwater managers with information on the quantitative effect of climate and the interactions between surface and groundwater. The GIS-based method can be a useful step between the conceptual and numerical groundwater model.

The data requirements of both GIS-based and full numerical models are similar, but the former relies almost entirely on measured data. The GIS-based method is more time-efficient but only generates water balances. Water surfaces, such as MODFLOW generates, could provide an additional means of checking model input.

The case study sensitivity analyses suggest that this water balance is relatively insensitive to all estimated parameters except those associated with evapotranspiration. However, the iterative cycle of back calculating recharge from the other parameters, converting it to a proportion of rainfall, deciding if this is feasible, then re-adjusting the evapotranspiration parameters provided bounds for the evapotranspiration.

The study shows the effect on the hydrologic components of the 1991 flood and the more subtle effects of the reduced level of pumping from 1993. It estimates the contributions of the individual hydrologic components to the water balance, both spatially and temporally.

A narrow, 4 km long, north-south oriented area with a flat groundwater gradient, shown by the 5 m contour in Fig. 2, was unexpected. The groundwater flow directions inferred from the hydraulic head surface imply that groundwater from more than half of the study area passes through the northern end of this feature. More groundwater monitoring bores could verify this unusual feature.

A useful enhancement to the model would be the separation of evapotranspiration from the river–aquifer interactions.

Since the original work was completed QDNRM&W have drilled more bore holes and are updating the water balance model. They hope to then have a MODFLOW model developed independent of the water balance model. They plan to use the water balance model in the evaluation of the MODFLOW model. They will be modifying their groundwater management policies and are hoping to increase compliance by irrigators with water allocation limits (personal communication, Gary Jensen, QDNRM&W, November 2005).

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