Spatial and temporal water balance estimates using a GIS

W.D. Welsh

Bureau of Rural Sciences, GPO Box 858, Canberra, ACT 2601 Australia
Integrated Catchment Assessment and Management Centre, School of Resources, Environment and Society, The Australian National University, Canberra, ACT 0200 Australia
E-mail: wendy.welsh@brs.gov.au

ABSTRACT: This paper describes Geographic Information System (GIS)-based algorithms that were developed to provide simple estimates of the water balance for a coastal aquifer near Bowen, Queensland. The 220 km^2 area is data-rich with 260 observation bores plus stream gauging, metering of irrigation bores and detailed land use mapping. The analysis proved cost and time effective and provided important insights to the groundwater dynamics of the case study area. The approach is generally applicable to data-rich aquifers.

INTRODUCTION

Traditionally, aquifer water balances have been determined very approximately using back of the envelope methods, or more accurately by constructing complete numerical groundwater flow models using a package such as MODFLOW (McDonald & Harbaugh 1988). This paper applies an alternative GIS-based approach, which is more accurate than the first method and less time-consuming than the second, to the coastal Don River Delta Aquifer located near Bowen, Queensland. The method is considered to have general applicability to other data-rich aquifers.

The 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. An expansion of the area under irrigation has led to increased groundwater demand, particularly during prolonged dry periods. The strongly seasonal rainfall is infrequent and unreliable with high annual variability and an average of nearly 300 dry days per year (Welsh 2002).

Overpumping of the aquifer can cause seawater intrusion and hence contamination of the groundwater, which would then be unsuitable for irrigation until diluted by future groundwater flow-through. Understanding the groundwater dynamics provides a good basis for managing the water resources sustainably. Results of the Don River Delta Aquifer spatial and temporal water balance analysis and related sensitivity analysis conducted to achieve this objective are presented in this paper.

DATA AND HYDROLOGIC FRAMEWORK

The Don River Delta irrigation area (Figure 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) and was assigned a horizontal hydraulic conductivity (Kh) of 20 m/day. Production bores are screened in both layers. Preferential groundwater flow occurs in the more transmissive zones of the infilled channels formed by the unweathered granite that is assumed to be hydraulic basement.

There are 260 dedicated observation bores in the study area whose water level measurements were interpolated to derive the water table surfaces. A further 454 irrigation bores are metered and were read 4 to 5 times annually; 469 stock and domestic bores were not metered. The bore flows were summed for the water balance calculations. The aquifer is unconfined and groundwater flow is from the south toward the coast.

Using standard conductivities for the lithologies (Freeze and Cherry 1979), 726 bores with lithological logs and six bores with pump test transmissivities were used to calculate estimates of Kh of the alluvial sediments in the saturated zone. These varied from 0.1 to 100 m/day and were used in lateral flow calculations.

The lithological logs were also used, along with maps of surface geology and bottom elevation of the alluvial sediments from the Queensland Water Resources Commission (1988), to determine the aquifer geometry. The volume bounded by the water table, aquifer basement and the study area boundary was used in the storage calculations. 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.

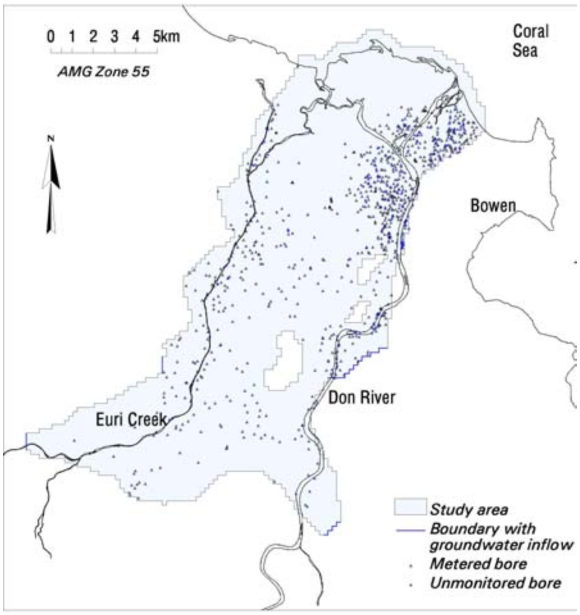

Figure 1 Location of production bores within the Don River Delta Aquifer study area.

Soil type was mapped by Northcote et al. (1960-68) and soil properties were mapped in the National Land and Water Resources Audit (NLWRA 2001). Land use was surveyed over an area of more than 50,000 hectares at a scale of 1:25,000 in 2000 (Dawson 2001). Soil type and land use were used in the evapotranspiration calculations.

Daily rainfall records, which were summed and used to constrain deep drainage recharge in the calculations, are available for the Bowen Airport weather station. Pan evaporation, which was summed and used in the evapotranspiration calculations is available for the Bowen Salt Works.

MODELLING APPROACH

The conceptual model is of an unconfined aquifer that drains into the sea and is tapped mostly for irrigation purposes. It is recharged by rainfall, irrigation flow-through and river leakage. Groundwater also discharges into the river when the water table is higher than the river stage. Evapotranspiration is significant.

The simulation model calculates water balance components over space and time. As detailed crop information was not available, deep drainage recharge is back calculated using aquifer storage and the other water balance components.

The 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 the recharge or discharge based on the water level difference, except evapotranspiration, which uses water table depth to regulate discharge.

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 flow. Areas of outcropping basement are not included.

The study area was discretised into polygons whose sizes were part-influenced by the density of the data, but also chosen to give a broad estimate of the spatial variation of the water balance components.

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.

Coastal outflows

Estimates of fresh water discharge to the sea were calculated for 14 coastal polygons (Figure 2) oriented parallel to the direction of groundwater flow for each 28-day interval. Each polygon is treated as a tube with a gradient given by the drop in hydraulic head over the average polygon length and a cross-section area as the average polygon width by 41 times the average height of fresh water. This uses the Ghyben-Herzberg Concept and it is assumed that the average hydraulic head represents the average depth of fresh water. The equation is:

$$Lo = \frac{41Kh.w.h.H}{L} \quad (1)$$

(after Queensland Department of Natural Resources and Mines 2000). Symbols are explained in Table 1. Figure 3 plots the total coastal outflows against rainfall for each 28-day period.

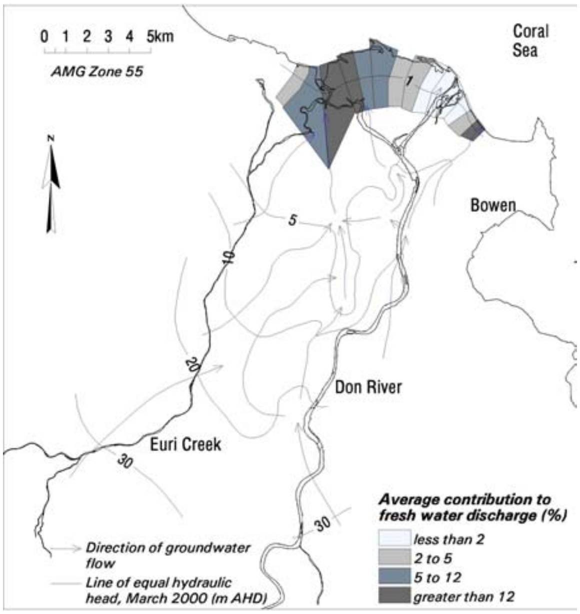

Figure 2 Coastal discharge polygons and groundwater flow directions.

River interactions

Water flow between the Don River / Euri Creek and the aquifer was calculated for 16 and 9 polygons respectively for each 28-day period. 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. Flow is assumed to be vertically in and out of the river through the riverbed sediments:

$$Riv = \frac{A.Kz(rh - wt)}{T} \quad (2)$$

(after McDonald & Harbaugh 1988). A negative *Riv* represents groundwater discharging into the river; a positive *Riv* represents river water recharging the aquifer. Figure 4 illustrates the total river components for each 28-day period.

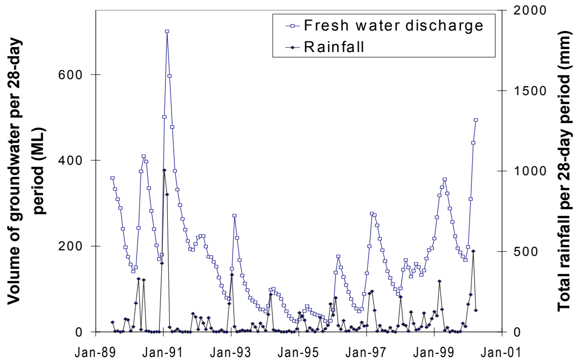

Figure 3 Estimated volume of groundwater flowing to the coast per 28-day period.

Table 1 Symbols used in this paper

A	Area of the riverbed
B	Flow rate of combined water extraction bores
dx	Cell edge length perpendicular to the flow direction
dy	Cell edge length parallel to the direction of flow
dz	Saturated thickness of the aquifer
E	Evapotranspiration rate
ED	Depth at which evapotranspiration ceases
EVR	Maximum rate of evapotranspiration
h	Average hydraulic head (above sea level)
H	Maximum hydraulic head (above sea level)
Hi	Hydraulic head inside study area boundary
Ho	Hydraulic head outside study area boundary
Kh	Average horizontal hydraulic conductivity
Kz	Vertical hydraulic conductivity of riverbed sediments
L	Average polygon length
Li	Lateral inflow rate
Lo	Lateral (coastal) outflow rate
R	Rainfall and irrigation deep drainage rate
rh	River stage
Riv	River leakage flow rate
ΔS	Change in groundwater storage
topo	Ground surface elevation
T	Thickness of riverbed sediments
w	Average polygon width
wt	Water table elevation

Evapotranspiration

Evapotranspiration is a combination of evaporation from open bodies of water, evaporation from soil surfaces and transpiration from the soil by plants. The rate of evapotranspiration is estimated as a proportion of measured evaporation and is a function of soil type, land use and extinction depth. When the plant root zone intersects the water table, evapotranspiration is calculated as:

$$E = EVR\left(\frac{ED - (topo - wt)}{ED}\right) \quad (3)$$

(after McDonald & Harbaugh 1988). When the root zone is entirely above the water table evapotranspiration is assumed to be zero.

Evapotranspiration was calculated for each 28-day period with the study area discretised into approximately 5000 cells, each 200m x 200m. The highest rates of evapotranspiration occur near the coast and adjacent to the rivers where the watertable is shallowest.

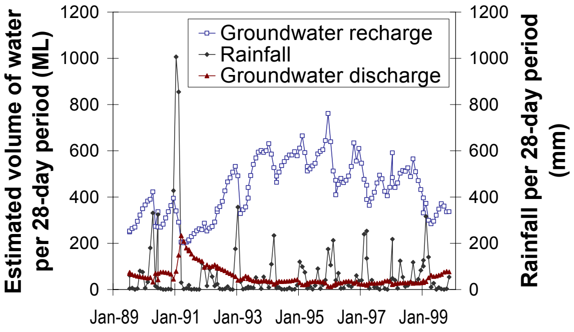

Figure 4 Estimated groundwater discharge into the rivers and recharge from the rivers for each 28-day period.

Lateral inflows

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

$$Li = \frac{dx.dz.Kh(Ho - Hi)}{dy} \quad (4)$$

Storage

Aquifer storage is the volume of saturated media between the water table and hydraulic basement multiplied by the specific yield. Groundwater volumes were calculated at 28-day intervals using time-varying hydraulic head surfaces and the hydraulic basement surface in the GIS.

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.

This component of recharge is calculated as a lumped parameter (Figure 5) invoking the relation:

$$\Delta S = Inflows - Outflows \quad (5)$$

To obtain an estimate for rainfall and irrigation deep drainage (R) equations 1 to 5 are re-arranged as follows:

$$R = \Delta S + B + Lo + E - Li - Riv \quad (6)$$

This equation describes the water balance for each time period. Since recharge and evapotranspiration are considered separately, specific yield was modified to ensure that deep drainage recharge rates were never negative for any 28-day period.

The calculations, as illustrated in figure 5, 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 have a significant effect on recharge.

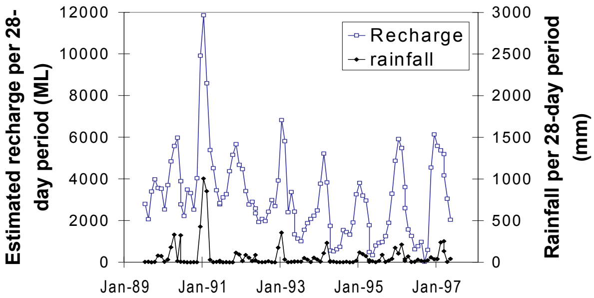

Figure 5 Deep drainage recharge calculated from changes in storage and the other water balance components.

SENSITIVITY ANALYSES

The effect of changes on parameter values to the study area water balance was determined for weathered granite Kh, unmetered bore flow rates, riverbed thickness and conductivity, specific yield and evapotranspiration parameters. With each sensitivity analysis the remaining components of the model were recalculated, providing calibrated sensitivities. Figure 6 shows the response of total flows to the parameter value changes.

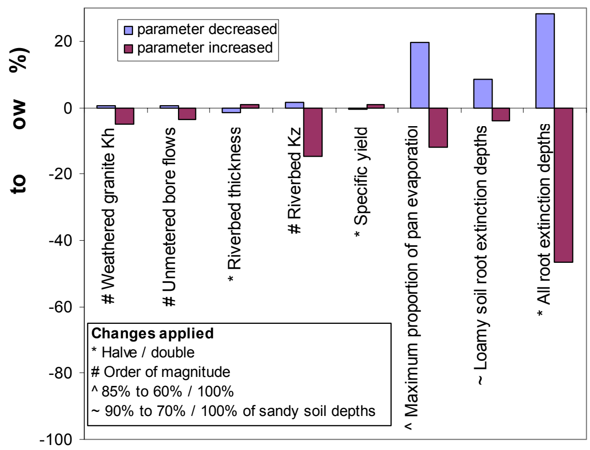

Figure 6 Mean changes in total flows for the sensitivity analyses.

Changes to weathered granite Kh and riverbed thickness caused significant differences in the lateral flows and river leakages respectively, but only small differences in the total water balance. 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 the riverbed vertical hydraulic conductivity (Kz), which is a logarithmically distributed parameter.

Evapotranspiration occurs over the whole study area and is the largest component of the water balance outflows. The maximum rate of evapotranspiration, assumed to be 85% of the pan evaporation rate and varied from 60% to 100%, had a significant impact. The root extinction depth matrix (Table 2) is the most sensitive parameter. Depths for loamy soils, assumed to be 90% of the depths for sandy soils and varied from 70% to 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 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.

Table 2 Estimated root extinction depths

Root extinction depth (m)	Vegetation type
5	Native trees
1	Cleared pasture
1.5	Improved pasture
2	Irrigated horticulture
2	Near-shore native vegetation
2	Mangroves

RESULTS

The estimated water balance for the study area for selected periods is shown in Table 3. The 12/1/1991 period has the highest rainfall, 1/5/1993 is in the dry season prior to the mandated move from flood to trickle irrigation and has the greatest groundwater pumping, and 11/11/1995 has the lowest water table. A time series for some of the water balance components is shown in Figure 7. Deep drainage recharge, evapotranspiration and bore discharge are the largest components and show the most seasonal variation.

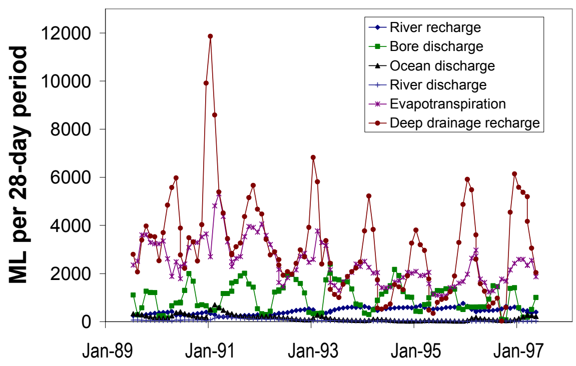

Figure 7 Time series of average water balance component values.

The estimates 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%, fresh water 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

Table 3 Estimated water balance for a selection of 28-day periods for the study area. Volumes are ML per 28-days.

Component	12/1/91	1/5/93	11/11/95	Average Jul-89 to May-97
Inflows:				
Deep drainage	11,861	2427	3287	3138
Rivers	339	395	644	435
Lateral flows	32	30	27	30
Total	12,232	2852	3958	3603
Outflows:				
Rivers	78	54	28	59
Lateral flows	501	131	21	163
Water bores	478	2391	564	1004
Evapotrans.	2698	2158	1604	2407
Total	3755	4734	2217	3633
In - Out	8477	-1882	1741	-30

DISCUSSION AND CONCLUSIONS

This paper presents algorithms that provide simple estimates of the water balance for the Don River Delta Aquifer. A GIS is critical to the method, being used to spatially interpolate point data and to calculate aquifer volumes.

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

The water balance is based on the application of Darcy's Law for the individual water balance components. Although simplifications of natural conditions, these equations seem to capture the important flows.

Spatial and temporal water balance estimates quantify 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 case study sensitivity analyses suggest that this water balance is relatively insensitive to all estimated parameters except those associated with evapotranspiration. Monitoring the implied proportion of rainfall required to balance the evapotranspiration provides bounds for the evapotranspiration parameters.

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.

ACKNOWLEDGMENTS

The hydrologic data used in this work was provided by the Queensland Department of Natural Resources, Mines and Energy.

REFERENCE LIST

Baskaran, S, Brodie, RS, Budd, KL & Plazinska, AJ 2001, *Assessment of Groundwater quality and origin of saline groundwaters in the coastal aquifers of Bowen area, North Queensland.* Bureau of Rural Sciences, Canberra.

Dawson, DE 2001, *Agricultural and veterinary chemical usage in the Bowen horticultural area in Queensland.* Bureau of Rural Sciences, Canberra. Unpublished report.

Freeze, RA & Cherry, JA 1979, *Groundwater.* Prentice-Hall Inc., Englewood Cliffs, N.J., U.S.A.

McDonald, MG & Harbaugh, AW 1988, *A modular three-dimensional finite-difference ground-water flow model.* Techniques of Water-Resources Investigations of the United States Geological Survey. Book 6, Chapter A1. US Department of the Interior, USA.

National Land and Water Resources Audit 2001, *Australian Agriculture Assessment 2001,* vol. 1, a theme report for the National Land and Water Resources Audit, Canberra.

Northcote, KH with Beckmann, GG, Bettenay, E, Churchward, HM, van Dijk, DC, Dimmock, GM, Hubble, GD, Isbell, RF, McArthur, WM, Murtha, GG, Nicolls, KD, Paton, TR, Thompson, CH, Webb, AA, & Wright, MJ 1960-68. *Atlas of Australian soils, sheets 1 to 10, with explanatory data.* CSIRO and Melbourne University Press, Melbourne.

Queensland Department of Natural Resources and Mines 2000, *Water Management in the Lower Burdekin, Phase 2 (incorporating Phase 1): Groundwater Model Conceptualisation.* Department of Natural Resources and Mines, Queensland. Unpublished report.

Water Resources Commission 1988. *Review of Water Resources Bowen Area.* Unpublished report.

Welsh, WD 2002, *Conceptual hydrogeological model and water balance estimates for the Bowen irrigation area, Queensland.* Bureau of Rural Sciences, Canberra.