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Use of a simple surface–groundwater interaction model to inform water management

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Allocations of river and groundwater have been traditionally managed separately in Australia and many other parts of the world even though in many regions groundwater and river systems are hydraulically connected. Groundwater extractions in areas where river systems are hydraulically connected can cause substantial impacts to river flows particularly base flows or low flows, which are considered to be ecologically important. Traditional groundwater modelling approaches tend to be undertaken on time-scales of weeks or months and are not sufficient to demonstrate the impacts of groundwater extractions in many river systems, particularly where flows are ephemeral. The impacts of groundwater extraction on surface water flows is considered using a simple, conceptual, lumped-parameter modelling approach called IHACRES_GW. The Coxs Creek catchment in the Namoi River Basin, New South Wales is used as a case study. Groundwater extractions are having significant impacts on base flows in this area and current policies will not be effective in reducing these impacts. These findings demonstrate the potential of such a modelling approach, when used in conjunction with traditional groundwater models, in setting allocation limits to assess impacts on river flows.

KEY WORDS: hydrological model, Namoi River Basin, surface–groundwater interactions, water allocation.

INTRODUCTION

The allocation of river water and groundwater resources has traditionally been managed separately in Australia, even though in many regions groundwater and river systems are hydraulically connected. Groundwater extraction from aquifers that are connected with river systems can alter river hydrology by reducing the base flow, or low flow, component of river flows. This may have adverse consequences for riverine ecosystem health, the viability of environmental flow releases and the security of water resources. Comprehensive reviews of the physical interactions that occur between groundwater and surface water systems have been provided by Winter *et al.* (1998), Winter (1999), Woessner (2000) and Sophocleous (2002). Reviews which emphasise the ecological significance of groundwater–surface water interactions can be found in Brunke & Gonser (1997) and Boulton *et al.* (1998).

In Australia, the over-allocation of water resources has led to the implementation of water reforms, and this has posed a number of challenges to catchment managers, especially in highly developed, over-allocated catchments that are reliant on surface and groundwater irrigation such as the Namoi catchment in New South Wales (Figure 1).

In order to ensure that adequate water remained within the Murray–Darling Basin river systems, the Murray–Darling Basin Management Committee announced the Murray–Darling Basin Ministerial Cap in July 1995 (the Cap). The Cap gave an upper limit on the amount of water that could be taken from surface water systems and limited this to the amount of water that would have been diverted with 1993/94 levels of development. While a Cap was placed on surface water diversions, no Cap was placed on groundwater extractions in the context of their impact on surface water flows.

The sustainability of the nation's groundwater resources became an additional concern as part of the water reform agenda. Key recommendations from the Agricultural and Resource Management Council of Australia and New Zealand included (ARMCANZ 1996): (i) groundwater management policies should be directed at achieving sustainable use of the resource; (ii) groundwater and surface water resource management should be better integrated; and (iii) where allocations exceed the sustainable yield, strategies should be developed to reduce abstractions to sustainable levels within time frames that minimise permanent damage to the resource.

Water reforms in New South Wales have been implemented through a number of planning processes and policy documents, most recently the Water Sharing Plans. In catchments such as the Namoi River system these plans were enacted through separate processes resulting in plans for unregulated surface waters, regulated surface waters, and two sets of groundwater management plans (Upper and Lower catchment).

The water reform process has resulted in decreased water entitlements for water users in the catchment in

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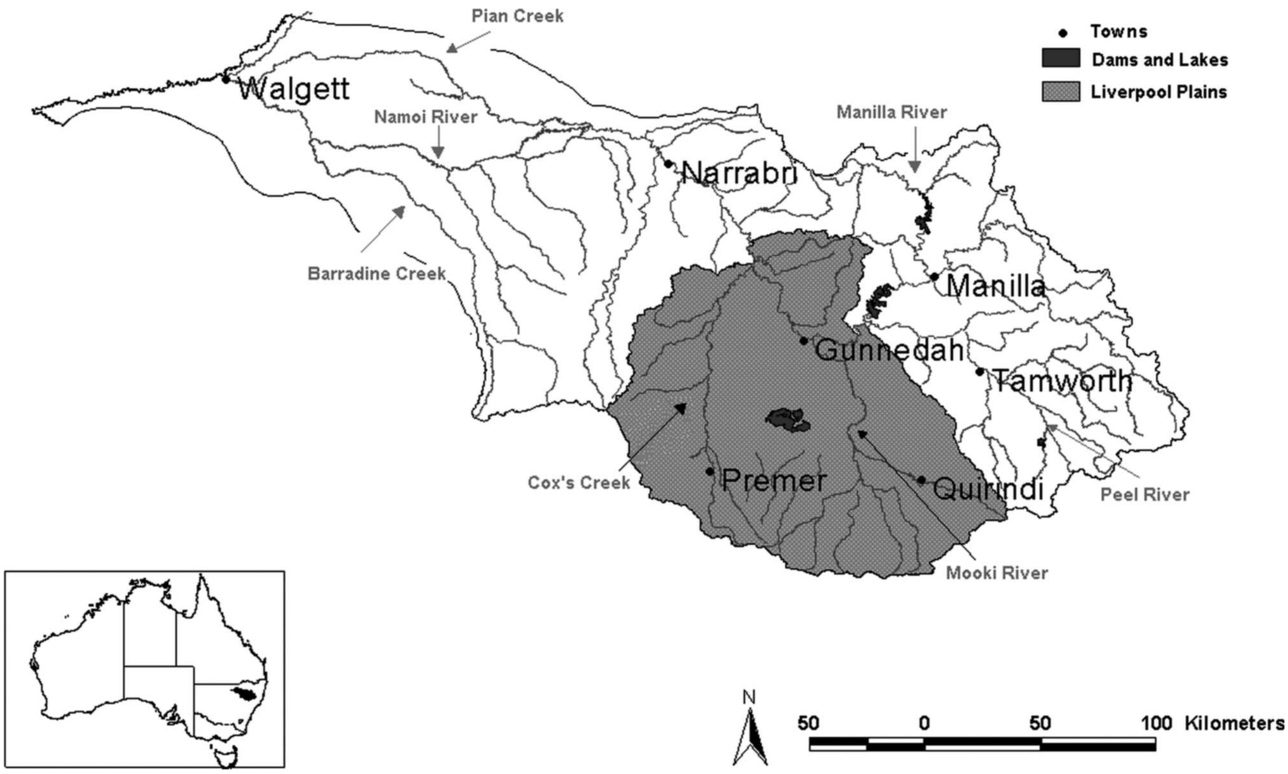

Figure 1 Namoi Catchment, New South Wales.

order to promote resource security and sustainability. Moreover, the National Water Initiative (2004) requires that the connectivity between surface and groundwater resources is recognised, and that connected systems are managed as a single resource. However, a broad-scale understanding of the interactions between the groundwater and river systems remains lacking. Some of the management questions for which answers are required in order to effectively implement appropriate water reform policies include: (i) what have been the impacts of the historical rates of groundwater extraction on river flows; (ii) can the impacts be quantified in order to appropriately consider risks to water security and riverine ecosystem health; (iii) how do the impacts vary with varying rates of groundwater extraction, and what is the implication for the Cap on surface water diversions; (iv) what role does climatic variability play in influencing the impacts observed; and (v) are the groundwater allocation provisions in the water-sharing plans sustainable?

This paper uses a simple surface water–groundwater interaction model to consider these issues. A case study catchment, Coxs Creek, in the highly developed Namoi River Basin is used to demonstrate the model and illustrate the nature of the impacts of groundwater extraction on surface water flows.

PREVIOUS MODELLING APPROACHES

The journal literature covers a wide range of empirical, conceptual and physically based modelling approaches for application in aquifer–river interaction studies, with each modelling approach differing in terms of the degree to which physical processes are represented, the data requirements and associated data/computational costs, the model capabilities and the form of model outputs. Each modelling approach will have its strengths and limitations. Often there is no 'best' model for all applications, and the most appropriate model will depend on the intended use and data availability. Surface–groundwater modelling has commonly tended to take either a surface water or groundwater focus, with the non-primary domain represented adequately, but in less detail.

However, new generations of modelling tools are starting to become more fully integrated, and these types of fully coupled models are often considered to be superior in managing water resources. The coupling of groundwater and surface water models at catchment scales presents a number of technical challenges. The two main technical challenges in applying fully coupled surface and groundwater models are associated with spatial and temporal discretisation (Camp Dresser & McKee Inc. 2001), as well as the flow and head variability between surface and subsurface flow systems and their respective mathematical representations (Werner *et al.* 2006). Codes also need to be adequately accurate, efficient and robust to manage the large computational demands associated with dual domain simulation (Werner *et al.* 2006). Overly complicated models that consider large numbers of spatially distributed processes run the risk of having a high degree of uncertainty associated with model inputs, which may be translated through to the model outputs, thus resulting in lower predictive capability, particularly at larger catchment scales

(Beven 1993, 2001). Surface water models often use small time increments (minutes to days) to capture rapid hydrological changes while groundwater models require longer time periods (weeks to months) to simulate slower groundwater movement and solute transport. Given the larger data requirements of fully integrated models appropriate for considering river–aquifer interaction processes, model simulation will require more time for development, calibration and simulation relative to a surface or groundwater model and the costs will be considerably greater (Camp, Dresser & McKee Inc. 2001). Consequently, the use of a fully integrated surface water/groundwater model is not appropriate for all projects, and the specific type of model needs to be considered for each project depending on the particular purpose.

A number of quasi-3D, spatially distributed groundwater models, mostly using the MODFLOW package (McDonald & Harbaugh 1988), have been developed for use in the Namoi catchment (Lawson & Treloar Pty Ltd 1988; Merrick 1989, 2001, 2003; Debashish *et al.* 1996; Salotti 1997; Kalf & Associates Pty Ltd and National Centre for Groundwater Management 2000; McNeilage 2006). These models were developed primarily with the focus of estimating sustainable groundwater yields, and as a result these models did not consider surface water processes in any detail; nor did they assess the spatio-temporal interactions that occur between groundwater and river systems on a shorter time steps (e.g. daily). Recently CSIRO (2007) reported on the water availability in the Namoi Catchment through water-balance accounting using pre-existing State-operated rainfall–runoff models together with groundwater models run on a monthly time step: these models were not directly coupled. Nevertheless, the study results were able to provide insights into the groundwater–river dynamics occurring within the catchment and to highlight some of the implications for water availability into the future.

The computational demands of running complex models at shorter time steps have generally hampered the routine use of fully coupled, physically based surface–groundwater models in the Namoi and other catchments. Yet important aquifer–river interaction processes commonly occur at a daily time step in ephemeral types of river systems that commonly characterise semi-arid catchments, and these processes will not be adequately modelled when utilising weekly to monthly time steps that are more commonly employed in groundwater-based modelling. The use of lengthier time steps can result in an underestimation of the impacts of groundwater extraction on river flows when modelling ephemeral river systems.

An alternative modelling approach is to utilise a simpler, spatially lumped model such as that achieved by combining a rainfall–runoff model with a simple groundwater model. The use of a simple model in the evaluation of water-sharing plans may be preferable for a number of reasons including: (i) the relative ease of using more simple models at larger scales, such as required when considering catchment-scale water budgets; (ii) the facility to model stream flows, including base flows, on a daily time step; (iii) the lower constraints on data and time requirements to parameterise a simple model; and (iv) the relative reduction in the uncertainties associated with model validation/simulation when compared with those of over-parameterised models.

A simple, coupled aquifer–river model, IHACRES_GW, has been developed and applied for use within an integrated assessment of water allocation options and is further discussed in this paper. This relatively simple type of modelling approach can be seen as being complementary to the more traditional groundwater modelling approaches and/or more recent developments in fully coupled surface–groundwater modelling, with each approach yielding different insights into a particular system.

IHACRES_GW MODEL DESCRIPTION

The IHACRES_GW model (Ivkovic *et al.* 2005b) includes a dynamic, spatially lumped rainfall–runoff model, IHACRES (Jakeman & Hornberger 1993), combined with a groundwater bucket module that maintains a continuous water-balance account of groundwater storage volumes relative to the reference point at which groundwater contributes to stream flow (as observed from stream gauging station data) at the catchment outlet. Thus, the IHACRES_GW model allows for the impact of groundwater extraction and other groundwater losses to be modelled at the sub-catchment scale. This simple model quantifies the water balances for the catchment area upstream of the stream gauging station using stream flow and groundwater extraction data. It was developed for use in unregulated, gauged catchments that demonstrate strong aquifer–river connectivity, and where groundwater extractions predominantly occur upstream of the gauging station.

The main assumptions of the IHACRES_GW model are: (i) the slow flow component of the linear module represents base flow expressed as an exponential decay function; (ii) the base flow contribution to stream flow can be estimated using mathematical filtering and the base flow represents groundwater discharge; (iii) the proportion of effective rainfall that recharges the groundwater storage is constant in time; (iv) all base flow comes from a single groundwater store or, if there are two or more stores, their behaviour is similar to that of a single store; (v) base flow contributions to stream flow occur immediately when groundwater storage levels are above the stream gauging station measuring point, and hence, there are negligible hysteresis effects associated with the amount of groundwater held in storage and the associated hydraulic gradients; (vi) bank storage effects on the stream flow hydrograph are a relatively minor component of the filtered base flow signature; (vii) losses from groundwater other than extraction are constant (i.e. not dependent on groundwater storage or other factors); (viii) groundwater extraction and other modelled losses impact on groundwater storage volumes during the same time step; (ix) transient groundwater flow and the distance of extraction bores from the river do not significantly influence the timing of the base flow contribution from groundwater storage to stream flow; (x) groundwater extraction influences predominantly occur upstream of the stream gauging station at the outlet of a drainage system (groundwater extraction influences downstream of the gauging station will present as additional groundwater losses); and (xi) groundwater flow across the catchment boundary will present as an additional volume of loss or as a gain to groundwater storage volumes.

The influence of some of these assumptions on model results is discussed below after the model results are presented.

CASE STUDY: COXS CREEK

Catchment description

The Namoi River catchment covers an area of ~42 000 km^2 in northeast-central New South Wales. It is arguably Australia's most developed irrigation area. Both river and groundwater resources are heavily utilised in the catchment to support substantial cotton and lucerne industries, as well as various other cropping regimes. The Namoi River stretches for over 350 km and flows from east to west. One of the major unregulated tributaries to the Namoi River is the Coxs Creek, which is the focus for this paper. Average annual rainfall in the Namoi catchment ranges from 1100 mm at the top of the Dividing Range in the east of the catchment to less than 470 mm at Walgett in the far west. The Coxs Creek catchment has an annual rainfall of about 600 mm. Annual average potential evaporation ranges from 1750 mm in the western part of the catchment to less than 1000 mm in the east. Rainfall is extremely variable between years and seasons, and generally exhibits a summer-dominated pattern.

The Coxs Creek alluvium is the largest aquifer type in the subcatchment and sits in a narrow alluvial valley about 10 km wide and 72 km in length (Figure 2). The subcatchment is divided into two groundwater management zones, zone 2 and zone 9. The maximum thickness of the alluvium is 140 m in the Boggabri area (Broughton 1994). The aquifers are divided into an upper Narrabri Formation and a lower Gunnedah Formation. The Gunnedah Formation contains gravel and sand, while the Narrabri Formation contains mostly clay and silt. Both aquifers are semiconfined, and the two formations are in vertical hydraulic contact. The alluvium has a range of transmissivities ranging from 21 to 1300 m^2/d. Recharge to the Gunnedah Formation is at the southern, upstream end of the aquifer where

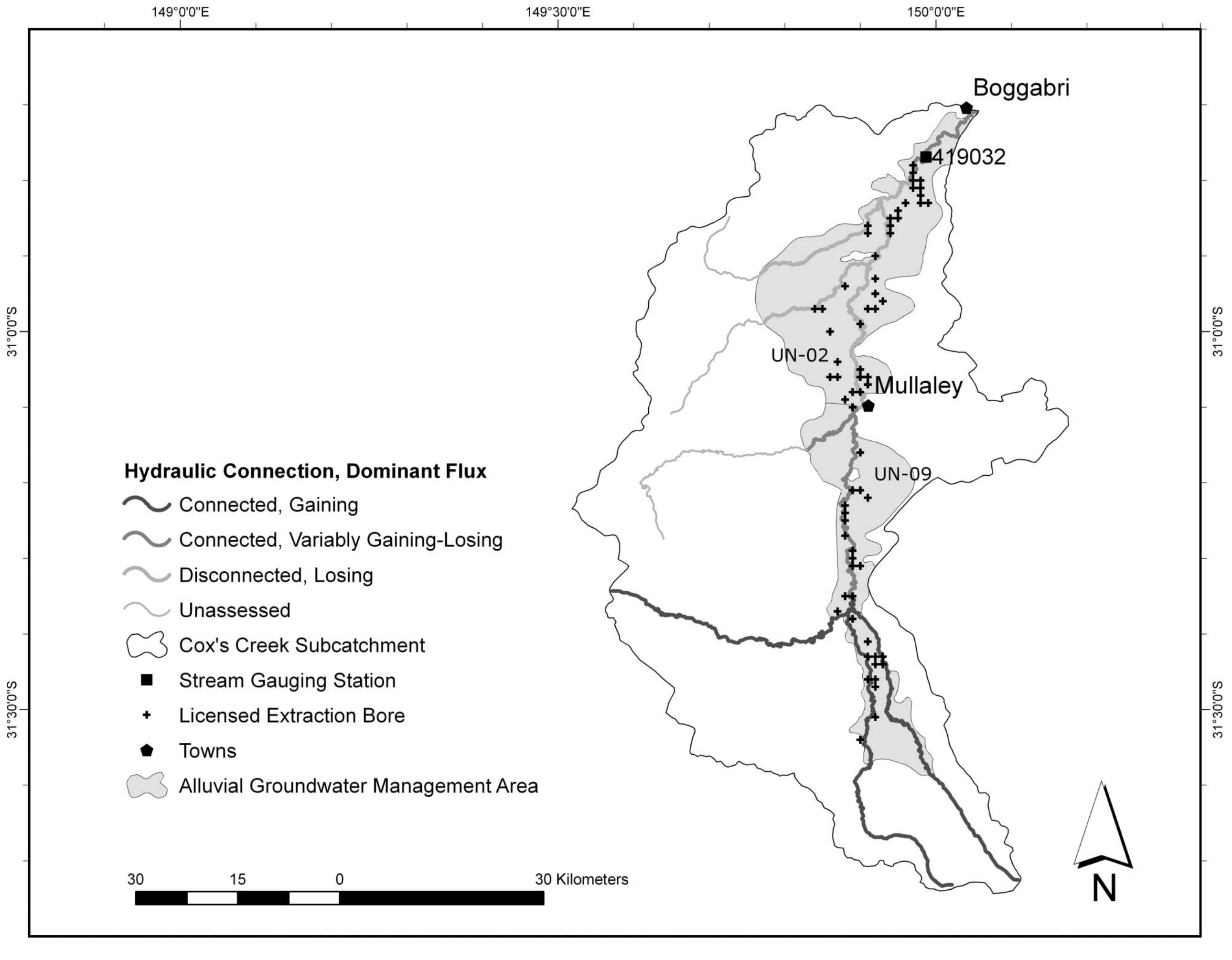

Figure 2 Location of Coxs Creek subcatchment, groundwater management zones 9 and 2, extraction bores and gauging station 419032.

extensive alluvial fans have been deposited by the upland creeks on the lower hill slopes of the ranges. Diffuse recharge and occasional flooding on the alluvial plain contributes recharge to the Narrabri Formation. A degree of upward flow to the Narrabri Formation also occurs through vertical leakage from the pressurised Gunnedah aquifer, which receives upward vertical leakage from the underlying basalt bedrock aquifer (Dyce & Richardson 1997). Groundwater flow is in a northerly direction towards the Namoi River. Extraction bores primarily tap the Gunnedah Formation aquifers and are located close to Coxs Creek.

Extraction limits for these zones were determined from their estimated average annual recharge (EAAR) as calculated by the Department of Water and Energy. In zone 2 this has meant that allocations have been reduced from 23 801 ML/a by 70% to an EAAR of 7200 ML/a. In zone 9, use has been limited to well below the EAAR of 11 400 ML/a. The average use in this zone is just 690 ML/a, and the maximum recorded use for any year was 2320 ML/a.

Analysis design

The IHACRES_GW model was tested in the Coxs Creek subcatchment at gauging station 419032, located at the catchment outlet at Boggabri (Figure 2). The upstream catchment represents an area of 4040 km^2. This river reach has been categorised by Ivkovic *et al.* (2005a) as a variably connected–disconnected aquifer–river system that alternates between gaining and losing. The river is an ephemeral stream system with flows 37% of the time (as determined from the gauged flows). The average flow over the length of the stream flow record (1965–2003) is 254 ML/d, with a base flow contribution over the whole length of the record that is approximately 9% of total average flows (Ivkovic 2006).

The IHACRES_GW model was calibrated to daily stream flow data at gauging station 419032. The period for calibration selected was 1/6/1965 to 30/6/1980, spanning a period of ~15 years with a continuous record of daily stream flow data. The river flows during this period of time were considered to be representative of pre-groundwater extraction conditions. Groundwater extraction data were available from 1985 onwards, and it is understood that prior to around 1980 there were relatively small amounts of groundwater extraction.

The period for model simulation was 2/9/1988 to 9/12/2003, spanning 15.3 years. This period was selected because daily stream flow and yearly groundwater extraction data (converted to a daily average over the 1 September–31 March irrigation season) were available over the whole record (Figure 3). Simulations were run on a daily time step using the calibrated model parameters. Outside the irrigation season, groundwater extractions were set to zero. The mean annual rainfall over the 1965–2003 period is shown in Figure 4.

RESULTS OF ANALYSIS OF HISTORICAL EXTRACTIONS

The IHACRES_GW model was used to simulate two scenarios over the 1988–2003 period. One scenario included observed values of groundwater extraction and the other scenario the absence of groundwater extraction. The modelled groundwater storages for the two scenarios are shown in Figure 5.

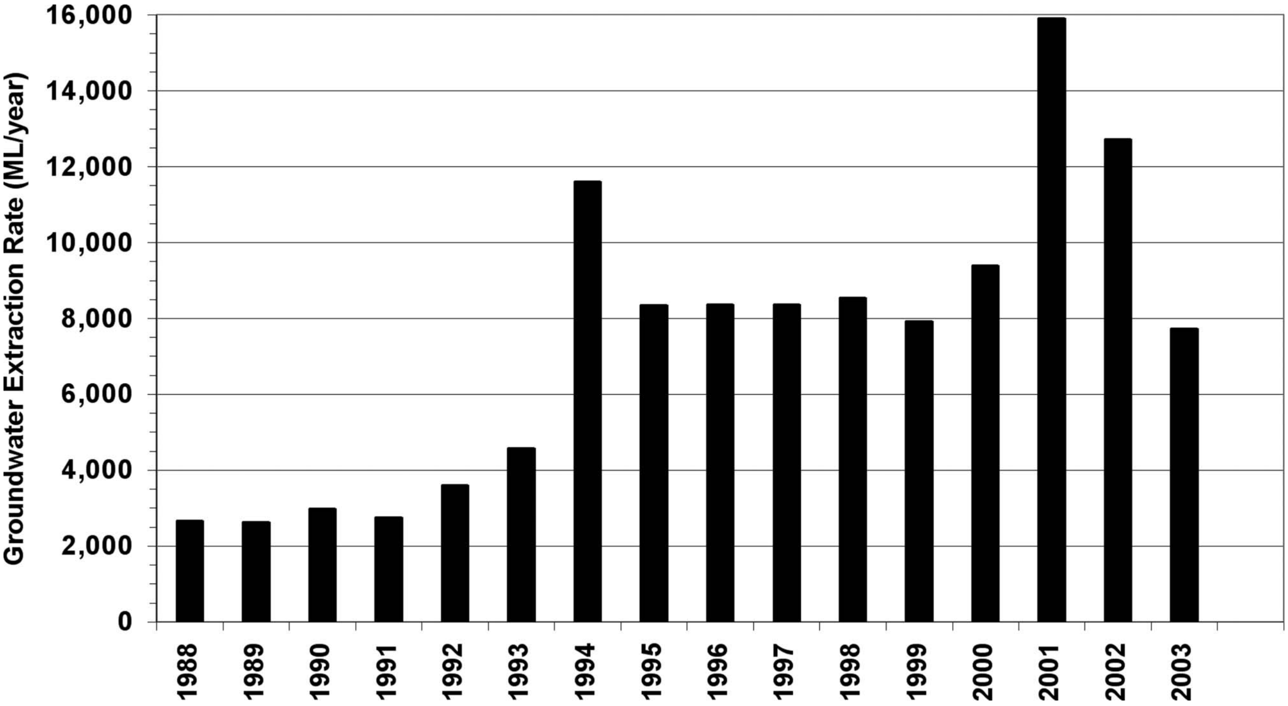

Figure 3 Reported annual groundwater extraction rates over the 1988–2003 simulation period (New South Wales Department of Water and Energy database).

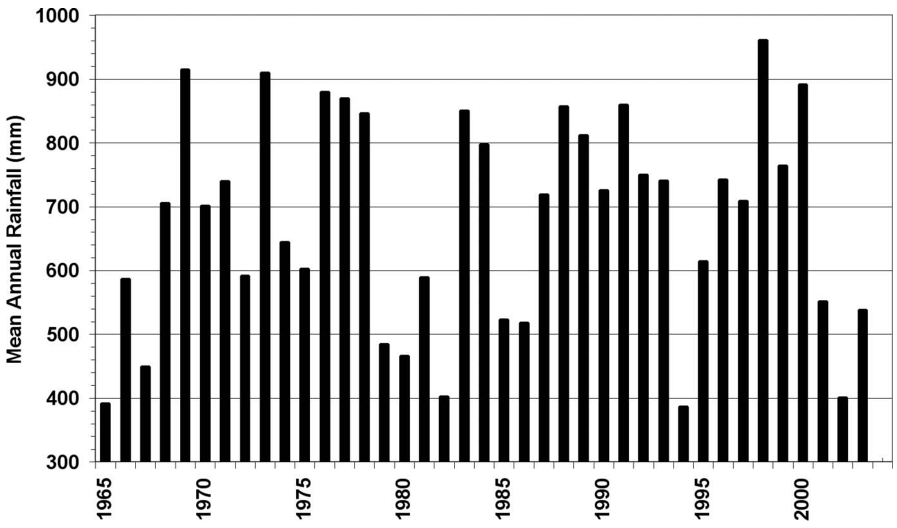

Figure 4 Mean annual rainfall for the 1 June 1965 to 9 December 2003 period.

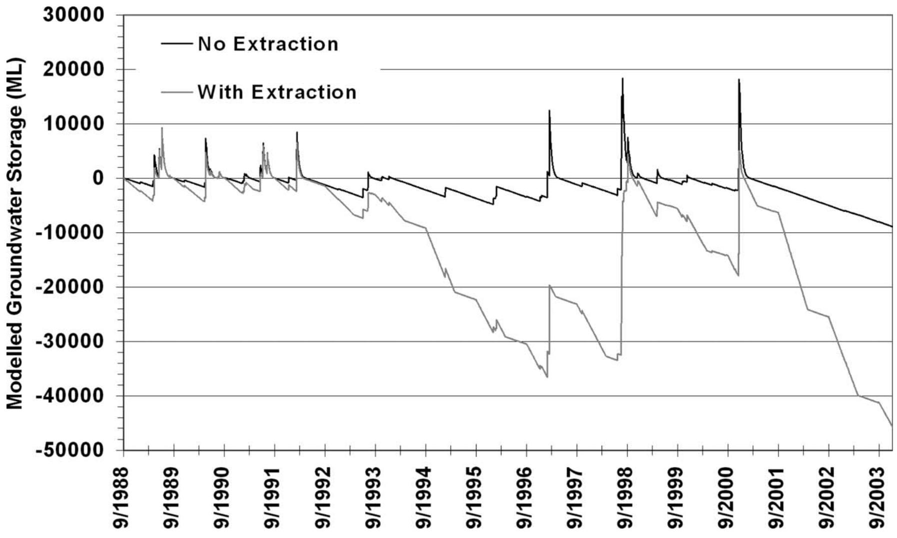

Figure 5 Modelled groundwater storages for simulation scenarios, with and without extraction.

The periods when groundwater storage volumes are above the zero reference point (Figure 5) coincide with stream flow periods that have a measurable base flow component in the stream hydrograph. Two key impacts are seen in this figure: (i) a number of base flow events, i.e. with positive groundwater storage values, have been missed as a consequence of groundwater extraction; and (ii) in many instances the magnitude of the base flow contribution has been reduced.

Table 1 summarises the impacts of groundwater extraction on stream flows during the simulation period. The model simulations indicate that groundwater extraction has resulted in reduced base flow contributions to flow ranging from zero to a maximum value of 1205 ML/d peak instantaneous flow, which is about five times the average annual stream flow measured at the gauging station. The total reduction in base flow over the 15 year modelling simulation period (2/9/1988 to 9/12/2003) as a consequence of extraction was estimated as 78.3 GL, representing 5% of the 1643 GL of modelled stream flow in the absence of extraction. This is equivalent to about 5220 ML/a. Extraction rates over this period varied between 2630 and 15 920 ML/a, with an average extraction rate of 7390 ML/a.

The modelled median reduction in base flows (calculated for periods with base flow only) was 15 ML/d, and the average reduction was 73 ML/d. The largest reductions in base flows were associated with dry/drought periods (Figure 4) that were characterised by greater than average volumes of groundwater extraction that resulted in significant declines in groundwater storage volumes. There were 1066 days that received reduced base flow discharges in comparison with the 'no extraction' scenario. Daily base flow contributions to stream flow as a result of groundwater extraction were reduced by between 14 and 100%, with an average reduction of 37% over the 15 year modelling period. The total reduction in base flow over the whole 15 year simulation period was ~78.3 GL. The overall impact of groundwater extraction on the duration of stream flows has been to reduce the probability of flows lower than 100 ML/d by between 2 and 4% (Figure 6). The full impacts from the recent (post-2001) drought period remain to be seen and quantified.

The application of IHACRES_GW demonstrates that a simple, dynamic, spatially lumped model is able to simulate the effects of groundwater extraction on the frequency, timing and magnitude of base flow events. The model suggests that the impacts of extraction on overall groundwater storage volumes and associated base flow discharges at the catchment outlet is a function of the net recharge to the exploited aquifer system versus loss as a consequence of extraction and other groundwater losses.

DISCUSSION

The previous section illustrates results of the IHACRES_GW model when used to consider the impacts of historical rates of groundwater extraction in the Coxs Creek subcatchment. This section considers the implications of these results for policy and the role of climate in the ability of a system to recover from extraction. It also considers limitations of the model and their implications for the results.

Table 1 Summary of impacts of groundwater extraction on flows over simulation period (2 September 1988 to 9 December 2003).

Measure	Impact	Proportional
Extractions		
Minimum groundwater extraction over simulation period	2630 ML/a	–
Maximum groundwater extraction over simulation period	15 290 ML/a	–
Average groundwater extraction over simulation period	7390 ML/a	–
Impacts on flow		
Total base flow lost	78.3 GL	5% of total stream flow
Days of base flow impacted	1066	19% of all days
Minimum reduction in base flow on impacted days		14%
Maximum reduction in base flow on impacted days		100%
Average reduction in base flow on impacted days	73 ML/d	37%
Median reduction in base flow on impacted days	15 ML/d	–

Role of climate

The simulation results shown in Figure 5 demonstrate that it can take decades or longer to recharge aquifers to pre-drought storage levels when groundwater resources have been heavily exploited. Conversely, during wetter climatic periods associated with flooding and large amounts of recharge, groundwater storages can be replenished relatively quickly (Figure 4). Although groundwater recharge rates are not required for estimating safe pumping rates, they are critical for an accurate assessment of groundwater–river interactions and sustainability assessments, as discussed by Devlin & Sophocleous (2005). In this study, the IHACRES_GW model has estimated groundwater recharge based on the partitioning of 0.09% of the volume of effective rainfall to groundwater storage, determined during model calibration, which has allowed for appropriate consideration of groundwater recharge on a daily time step.

The variability in groundwater storage volumes as a consequence of climate variability and associated groundwater recharge rates is also critical to determining sustainable pumping rates and sustainable groundwater allocation.

The significance of base flows to riverine ecosystems requires further study and consideration within the Namoi River catchment. Groundwater storage declines have clearly impacted upon base flow discharges, and declines in storage may equate to lower groundwater levels, which might also have an impact on vegetation and other ecosystems reliant on shallow groundwater systems.

Implications for Murray–Darling Basin Ministerial Cap

The IHACRES_GW model was used to model the impacts of varying rates of extraction on groundwater storage volumes and the consequent reductions in base flow over the 15 year simulation. Figure 7 demonstrates that the relationship between the rate of groundwater

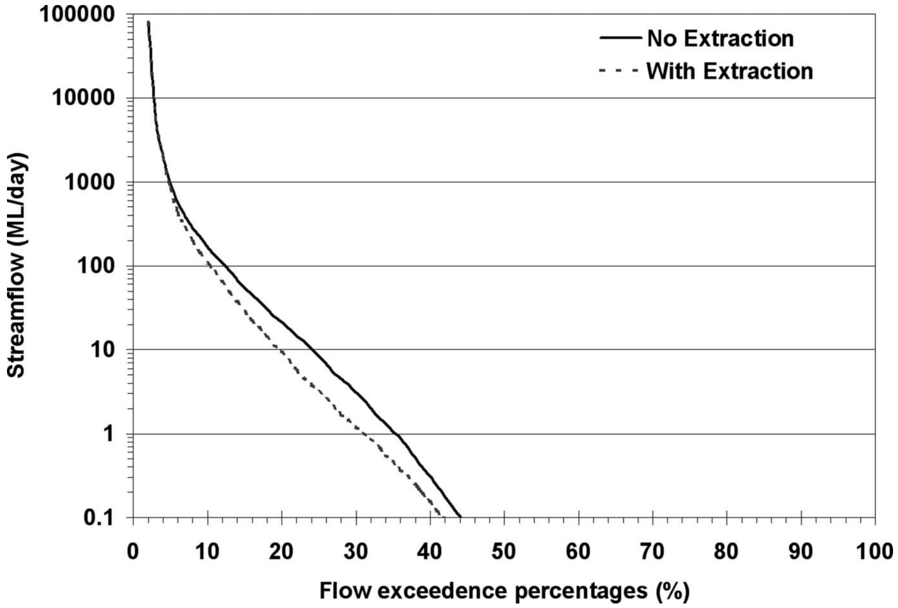

Figure 6 Flow exceedence percentages for stream flow simulation scenarios with and without groundwater extraction.

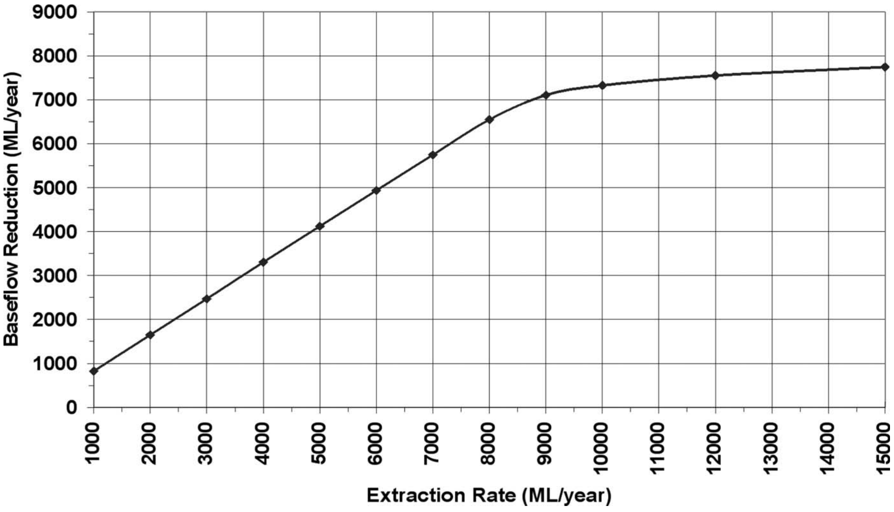

Figure 7 Modelled reductions in base flow for varying rates of groundwater extraction over the 2 September 1988 to 9 December 2003 simulation period.

extraction and the resultant decline in base flow is highly linear ($y = 0.82x$) up to an extraction rate of about 9000 ML/a.

At extraction rates above 9000 ML/a, the reductions in base flow start to level off. This is because groundwater storage levels decline to such an extent that disconnection increasingly occurs between the groundwater and river system, hence the flattening of the slope in Figure 7. If long-term pumping rates were to exceed 9000 ML/a, then this would eventually result in the river reach becoming a disconnected–losing system. Despite the fact that the reductions in base flow at extraction rates greater than 9000 ML/a start to level off, extractions from disconnected aquifer–river systems will still result in captured groundwater discharges, and these volumes of water will no longer have the potential to discharge further down the catchment. This might eventually impact upon the river system downgradient in areas where the exploited aquifer and river system eventually become connected.

In summary, the modelling results suggest that groundwater extraction in the Coxs Creek catchment will have the effect of reducing base flow discharges in the order of 82% of the volume of groundwater extracted (for rates up to 9000 ML/a), though the impacts might be greater or lesser than this figure depending on the particular climatic period. The remaining 18% of the total volume of groundwater extraction is assumed to be impacting on the available volumes of subsurface throughflow below the level of the gauging station. The magnitude in the reduction of base flows will need to be considered in light of the objectives of the Murray–Darling Basin Ministerial Cap on surface water diversions (Murray–Darling Basin Ministerial Council 2000), as well as in water account budgets and in water allocation plans more generally.

Implications for water-sharing plans

The IHACRES_GW model has been used to assess the impacts of the currently reported sustainable yield (or EAAR which is the estimated average annual recharge) in the existing groundwater sharing plans for the Upper Namoi (DLWC 2002). The model simulations suggest that the reported rate of 7200 ML/a for zone 2 of the Coxs Creek would reduce base flow discharges by approximately 6000 ML/a.

The combined reported EAAR of 18 600 ML/a for zones 2 and 9 could adversely impact upon river flows given that the modelling results suggest that for extraction rates above 9000 ML/a the groundwater and river systems would become disconnected. Although the volumes of groundwater extracted in zone 9 are currently well below the estimated average annual recharge of 11 400 ML/a (Brownbill 2000), any future increases to groundwater extraction within this zone will impact down gradient and affect zone 2 by reducing the volumes of groundwater available as throughflow as a consequence of captured discharges. This would exacerbate the water security of an already over-allocated zone 2.

The IHACRES_GW model simulations suggest that the extraction limits within the current water-sharing plans are set too high, and that a limit of between 7200 and 8000 ML/a might be more appropriate over the whole subcatchment, i.e. including both zone 2 and zone 9. This would allow for replenishment of groundwater stores over a few large rainfall–runoff–recharge events, and hence maintain connection between the groundwater and river systems upon resumption of wetter climatic periods. Based on these modelling results, it is suggested that the sustainable yield calculations for the subcatchment be revised. The groundwater allocation entitlements laid out in the water-sharing plans currently do not consider the impact of extraction on the frequency, timing and magnitude of the base flow events, and, should ecosystem water requirements be defined, then these figures may need to be reviewed.

Model strengths and limitations

A spatially lumped modelling approach in the management of water resources has a number of limitations including those arising from the lack of spatial considerations, such as a lack of discrimination of the effects of pumping from bores very close to the river system from those further away. However, it offers a number of advantages, including: (i) facilitating a better understanding of large-scale water management issues; (ii) assessing the impacts of water allocation and groundwater extraction on river flows at the catchment scale; and (iii) informing water-sharing plans. In particular, this type of modelling approach lends itself to integrated assessments of water allocation options in which hydrological, ecological and socio-economic data sets are combined, and where data are commonly aggregated to a larger scale of interest in response to the requirements of policy makers. This approach also allows a daily time step to be used in considering impacts. This is important for ephemeral river systems in particular, where important aquifer–river interactions processes occur over short periods of time. While such a spatially lumped approach would not be appropriate in isolation for the management of a water resource, it is expected that coupling this approach with a more spatially detailed groundwater modelling approach will provide significant insights when managing surface and groundwater resources conjunctively.

The IHACRES_GW model has been tested in the Coxs Creek subcatchment, which is a long, narrow semiconfined alluvial valley constrained by bedrock. These types of systems commonly demonstrate little to no time lags between the onset of groundwater pumping and the impact upon a river system (Braaten & Gates 2004). A comparison of model performance within both wide and narrow, as well as in semiconfined and unconfined alluvial valleys would provide insights into the wider applicability of the model. The model is well suited to modelling unregulated and gauged river systems in narrow, semiconfined as well as narrow, shallow, unconfined alluvial valleys that have strong aquifer–river connectivity and where groundwater extractions predominantly occur upstream of a gauging station located at the catchment outlet. It is not appropriate for use in regulated systems in its current configuration.

CONCLUSIONS

The application of the IHACRES_GW model in the Coxs Creek subcatchment demonstrates that groundwater extraction affects the frequency, timing and magnitude of base flow events, and that the impacts vary not only as a consequence of the extraction rates and other losses to groundwater storage, but also according to the groundwater recharge rates. The legacy that historical rates of extraction have on overall groundwater storage volumes and associated base-flow discharges is a function of the net recharge to the exploited aquifer system versus loss as a consequence of extraction and other groundwater losses. It can take decades or longer to recharge aquifers to pre-drought storage levels if groundwater resources have been heavily and/or overly exploited. Conversely, during wetter climatic periods, particularly when associated with flooding and increased groundwater recharge, groundwater storages may be replenished within a relatively short time. Although groundwater recharge rates are not required for estimating sustainable pumping rates, they are critical for an accurate assessment of groundwater–river interactions and sustainability assessments.

Application of the IHACRES_GW model to the Coxs Creek catchment has been able to show that the estimated sustainable yields of 7200 ML for zone 2 and 18 600 ML/a for the combined zones 2 and 9, covering the entire Coxs Creek catchment are likely to have significant impacts on surface water resources in the area. The lower limit in zone 2 is likely to reduce base flows by 6000 ML/a and lead to slower recoveries of the river system following drought periods. The model shows that for extraction rates greater than 9000 ML/a the groundwater and surface water systems would be permanently disconnected. It suggests that a limit of between 7200 and 8000 ML/a across the whole subcatchment (including both zone 2 and zone 9) would be most appropriate.

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