Including the Influence of Groundwater Exchanges in a Lumped Rainfall-Runoff Model

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EXTENDED ABSTRACT

Traditionally, surface and ground water resources have been managed as separate resources in Australia, with the result that interactions between the two components have not been duly considered in the development of management strategies. A more integrated approach is required to evaluate the impacts of groundwater extraction on streamflow regime, and eliminate the potential for over-allocation of resources due to double-accounting of the available resource. Models, which represent the exchanges of water between surface and ground water systems, are needed to inform integrated water resource management.

In this paper, the IHACRES_GW model developed by Ivkovic *et al.* (2005a) and Ivkovic (2006) has been coupled with the catchment moisture deficit (CMD) version of the IHACRES non-linear module (Croke and Jakeman, 2004). The question posed is what kind of non-linear model structure is required that will permit the use of climate data to explore ephemeral stream behaviour and the impacts of groundwater extractions on flow regime.

Results from running the coupled model with Ivkovic's (2006) parameters and a partially-calibrated CMD model (GW_CMD in Figure 1) show that although the coupled model reproduces total streamflow over the simulation period well, the flow regime is poorly represented (Figure 1). The observed flow record has fewer quickflow events, but with typically higher streamflow peaks and a much greater proportion of 'no flow' periods than the modelled streamflow. These results identified a need to modify the model and/or vary model parameter values in order to improve model performance. Here we focus on changing the CMD module, and leave the GW parameters unchanged.

Sensitivity testing of the stress threshold parameter (*f*) shows it to have a significant impact on model performance, through its influence on the total water balance and the position of the groundwater table. The introduction of an effective rainfall threshold (*K*) for varying the parameters (ν_s and ν_q) that govern the partitioning of effective rainfall between slow and quick flow pathways significantly impacts the number of quickflow events, but at the expense of baseflow estimation. Figure 1 shows improvements in the representation of flow ephemerality when *f*=1.2 and *K*=0.1, but these changes do not go far enough.

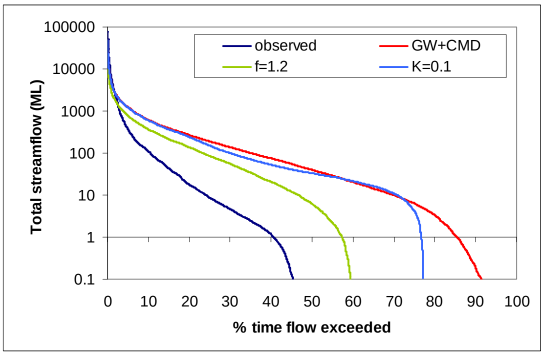

Figure 1. Flow duration curves (FDC) of observed and modelled streamflow in Coxs Creek (1988-2003). The *f*=1.2 and *K*=0.1 FDCs demonstrate how varying the stress threshold parameter, *f*, and introducing an effective rainfall threshold, *K*, can improve the flow regime result.

A full calibration of the model should produce a set of parameter values that will provide a better prediction of streamflow behaviour and baseflow contributions over time, but Ivkovic's (2006) experience suggests that other changes might be necessary and more effective in improving model calibration and performance. These include exploring alternative methods for deriving a catchment-averaged rainfall time-series, and breaking Coxs Creek catchment into sub-catchments and calibrating them each individually. Both of these methods will increase the representation of spatial variability, which is not necessarily achieved very well using a single set of parameter values.

1. INTRODUCTION

Until recently, the management of groundwater resources in Australia has tended to be handled as a separate resource management issue from that of surface water, despite the inter-connectedness of these water systems. During wet periods, when groundwater tables become elevated and streams flow for sustained periods, separate management of surface and ground water does not necessarily create a problem in terms of water resource availability. During extended periods of drought, however, the agricultural demand for water is not necessarily met through rainfall, and groundwater and streamflow become critical sources of water to sustain production. Groundwater extractions cause groundwater tables to fall, which impacts upon streamflow by reducing baseflow, or causing baseflow to cease for periods of time. Lowering of the water table can have serious consequences for the livelihood of town residents, irrigators and groundwater-dependent ecosystems that rely on a regular streamflow. By not managing surface and ground water resources as a single resource, double-accounting of the available water resource is a potential risk, because the shared component can be counted as both a groundwater resource and a surface water resource.

The modelling of surface and ground water systems has also tended to be done separately. Few models have been developed which represent the surface and ground water systems as an inter-connected, dynamic system. In surface runoff models, groundwater is often represented via a loss term, which accounts for unexplained water in closing the water balance. In groundwater models, fluxes of water to the surface water are represented through pre-defined boundary conditions. The lack of integration reflects, in part, the different temporal scales needed to represent surface and ground water processes: surface water models operate on a relatively short time-step, hourly or daily, that allows the rise and fall of rainfall events to be captured; groundwater models operate on longer time-steps, weeks or months, because groundwater aquifers exhibit less flashy behaviour. The collection of groundwater data tends to be more infrequent, partly due to lack of resourcing for groundwater monitoring, but also because the response times of groundwater systems to changes in system variables are slower than for streams.

More recently, the threat to water resource security in Australia has spurred the development of models that integrate surface and ground water processes within the one framework. Ivkovic *et al.* (2005a) took the IHACRES rainfall-runoff model and added a groundwater module to form IHACRES_GW, in order to better represent the streamflow response in ephemeral systems. The stated aim of this work was to quantify the impact that groundwater extraction has had on streamflow in the Coxs Creek catchment, by comparing streamflow patterns pre- and post- the commencement of groundwater use for irrigation.

This paper summarises the IHACRES_GW model developed by Ivkovic (2005a; 2006) and tested in the Coxs Creek catchment, and describes recent modifications to the modelled system intended to improve the performance of the model when coupled with the CMD version of the IHACRES non-linear loss module (Croke and Jakeman, 2004). The aim is to refine the non-linear model structure, such that the model can use climate data to explore ephemeral stream behaviour and the impacts of groundwater extraction on flow regime. We start with a couple of modifications to the model to better represent our conceptual understanding of the system. Some results are then presented, which illustrate the sensitivity of modelled streamflow to varying the stress threshold, f, and the effective rainfall threshold, K, a new term in the CMD module. Some other modifications, which might be needed to tailor the coupled model for predictive purposes, are also proposed.

Ultimately, the aim is to develop a transferable version of IHACRES for ephemeral stream systems, which adequately captures the timing and duration of baseflow episodes, without introducing a level of complexity that cannot be supported by the available data, or goes beyond what is necessary to inform management decisions.

2. THE STUDY AREA

The Coxs Creek is a tributary of the Namoi River in northern NSW, which, since the 1960s, has been a major cotton producer and heavily reliant on the available water resource, both surface and ground water. The Coxs catchment spans an area of 4040 km2, with a catchment-averaged annual rainfall of about 600 mm. The rainfall distribution is highly variable and this is reflected in the changing streamflow duration throughout the catchment, ranging from almost 100% of the time in the headwater catchments to approximately 33% of the time at Boggabri, the catchment outlet (Ivkovic, 2006).

Ivkovic *et al.* (2005b) have characterised the various reaches of Coxs Creek into two types based on the connectivity of the surface and ground water systems. In the headwater catchments, the streams are classed as gaining streams, reflecting the mostly permanent connection of the shallow groundwater aquifers with the stream and the dominance of groundwater fluxes to the stream. Further downstream, the connection between surface and ground water systems becomes more variable and the direction of water flux varies over space and time. These lower reaches are classed as variably gaining-losing reaches.

3. IHACRES

The IHACRES model is a conceptual rainfall-runoff model consisting of two modules: a non-linear loss module which converts measured rainfall (*P*) to effective rainfall (*U*) defined as the amount that contributes to streamflow; and a linear routing module, which uses a recursive relation at each time-step to model streamflow (*Q*) as a linear combination of antecedent streamflow and effective rainfall (Jakeman *et al*., 1990, see Figure 2). Several versions of the model have been developed and successfully applied to catchments within Australia and elsewhere, but the formulation of the model (i.e. streamflow represented as the sum of two exponential decay functions, which do not allow the possibility of zero streamflow) means that intermittent and ephemeral stream systems cannot be modelled well.

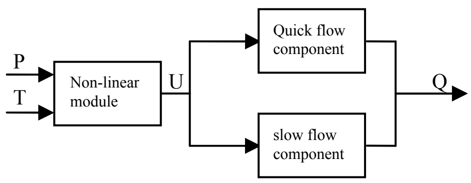

Figure 2. The IHACRES model structure.

The IHACRES_CMD (Croke and Jakeman, 2004), uses a catchment moisture deficit (CMD) accounting scheme in the calculation of evapotranspiration, and hence effective rainfall, on the same time-step that rainfall and temperature (maximum daily) variables are available. It is this version that will form the basis for integration with IHACRES_GW.

3.1. IHACRES_GW

IHACRES_GW was developed to represent groundwater impacts on streamflow more explicitly than in earlier IHACRES formulations. The IHACRES_GW model structure is shown in Figure 3. Conceptually, effective rainfall is partitioned between a surface runoff (or quickflow) component and recharge to a groundwater store. Losses to the groundwater system are represented

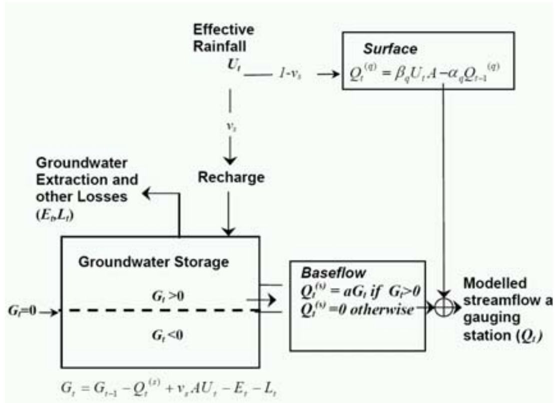

Figure 3. The IHACRES_GW model structure (Ivkovic, 2006).

by three different terms in the water balance: a baseflow (Q_s) contribution to streamflow; a groundwater extraction term (*E*) and an unaccounted loss term (*L*). Baseflow (Q_s) occurs only if the groundwater storage term (*G*) is greater than 0, which conceptually is when the groundwater aquifer intersects the stream channel. The use of a threshold value, $G = 0$, to define the switching off or on of baseflow, allows ephemeral flow behaviour to be represented.

Initial attempts to use the full IHACRES model as the basis for the groundwater module development were found to give very poor results. This was attributed, in part, to sparse rainfall data coverage and the derivation of an input rainfall time-series that did not adequately reflect rainfall behaviour across the catchment (Ivkovic, 2006). Croke *et al*. (2006) encountered similar problems modelling some other Namoi River basin catchments. As a consequence, Ivkovic (2006) focussed on calibrating just the linear routing model to which the groundwater module was coupled. Observed streamflow records were used to derive an effective rainfall time-series for input into the model, yielding good results across a range of performance indicators. Most significantly, the model was able to capture the timing in the switch between baseflow and no baseflow periods and reproduce the volume of baseflow contributed to streamflow on a daily basis.

While this formulation is adequate for evaluating the magnitude of streamflow impacts caused by historical groundwater extractions in Coxs Creek catchment (Ivkovic, 2005a), it cannot be used in a predictive role, owing to the circularity of its formulation (i.e. using the quickflow derived from observed streamflow to generate model inputs for predicting variations in baseflow.

4. COUPLING IHACRES_GW WITH IHACRES_CMD

IHACRES_CMD was run for Coxs Creek, using daily rainfall and maximum temperature (T_{max}) time-series with the IHACRES_GW calibrated parameter set for 1988-2003 (Ivkovic, 2006), a period with groundwater extractions (Table 1). These parameters govern the proportion of effective rainfall that takes a slow flow path, v_s, the recession coefficients for slow, τ_s, and quickflow, τ_q, and daily loss to groundwater, L. The CMD model parameters are a drainage threshold, d, a temperature coefficient, t, and a stress threshold, f.. Sensitivity testing (Croke and Jakeman, 2004) has shown that the model is not very sensitive to d, providing the value is sufficiently large (>~200 mm). The recommended value of d = 200 mm was adopted here. A temperature coefficient value of e = 0.166 was used, based on Chapman (2001), which showed that the relationship between daily potential evaporation (PE) and T_{max} at sites across Australia could be approximated by PE = 0.166*T_{max}. While there is significant scatter in the T_{max} versus PE relationship, this will not significantly affect model performance, as the model is not sensitive to short timescale (less than a week) fluctuations in the evaporation rate. The stress threshold parameter, f, governs the rate of evapotranspiration, which is a function of vegetation cover. A partial calibration of the model was undertaken to determine the value of f, based on minimising model bias.

Table 1. IHACRES_GW calibrated parameter values for Coxs Creek (Ivkovic, 2006).

Parameter	Value
v_s	0.1
τ_s	25 days
τ_q	1.4 days
L	3 ML/day

Using these parameter values, we obtained a modelled streamflow time-series for 1988 to 2003, which captures the total volume of streamflow for the period, but appears to under-predict baseflow and over-predict the frequency of quickflow events. Figure 4 shows that at different times during the modelled period, baseflow predictions are too low, too high, persist for too long or occur when there is no observed flow. The flow duration curves for the observed and modelled streamflows (Figure 1) highlight the difference in flow regime with streamflow occurring 40% of the time in the observed record, compared to 85% of the time in the modelled record.

The greater frequency of modelled events than observed events (Figure 4) suggests problems with

Figure 4. Sections of the observed, modelled flow and modelled baseflow time-series, based on a semi-calibrated parameter set.

the input rainfall data, the calculation of effective rainfall, U, and/or the partitioning of U between slow and fast flow pathways. In Ivkovic's (2005a) approach, U is calculated from filtered quickflow, which means there is a one-to-one correspondence between the frequency of modelled and observed streamflow events. When U is calculated using the CMD non-linear loss module, the frequency and magnitude of rainfall events in the input data govern streamflow generation. Mismatches arise due to the considerable uncertainty in rainfall data and the mathematical formulation for estimating U from P and the catchment moisture deficit.

The under-prediction of baseflow suggests the proportion of effective rainfall partitioned to the slow flow path (v_s) is too low or the daily groundwater loss rate is too high. Since the calibrated value (Ivkovic, 2006) for daily groundwater loss is small (3 ML), significant improvements are unlikely from re-calibrating this term. However, using a different parameter set, the significance of the groundwater loss term could increase. Mismatches in the timing of baseflow events suggest assumptions about groundwater extraction, assumed to be a constant daily rate during a fixed irrigation season, and the constant partitioning of effective rainfall between quick and slow pathways are not appropriate.

In the next sections, we introduce two changes to the coupled model and investigate the sensitivity of model predictions to some of the parameters in the CMD module. While the focus is on adjustments to the CMD module, a small change is made to the linear loss module, which allows quickflow to switch on and off.

4.1. Streamflow losses to groundwater

An artefact of using exponential decay functions to describe the quick and slow flow recession curves is that modelled flows can never drop to zero. The groundwater module of Ivkovic (2006) overcomes this by incorporating two groundwater loss terms (groundwater extraction and unaccounted losses) into the model formulation, thus allowing baseflow to switch on and off with fluctuations in the groundwater table around G = 0. Here we have made a similar modification to the quickflow component, such that for $G < 0$, quickflow is assumed to infiltrate to the groundwater store, at a rate governed by the infiltration area, A_i, and the saturated hydraulic conductivity, K_{sat}, of the channel substrate. We have used $A_i = 0.04$ km^2 and K_{sat} = 2400 mm/day, which results in a potential loss rate of 96 ML/day. The quickflow losses introduced are relatively small and have a negligible impact on total streamflow, but are significant in allowing streamflow to cease.

4.2. Non-constant partitioning between surface and ground water pathways

The current formulation of the CMD module assumes that the partitioning of effective rainfall between quick and slow flow pathways is constant through time. This assumption has been made to minimise model complexity, but it might be a significant source of error in catchments with a highly variable rainfall regime. Differences in the sizes and intensities of rainfall events are known to affect the partitioning of runoff between surface (quick) and sub-surface (slow) flow pathways. To maintain simplicity, we introduce a threshold effective rainfall parameter K, below which no quickflow is assumed to occur:

For $U < K$, $\quad v_q = 0,\ v_s = 1.$

This adjustment is intended to accommodate the occurrence of 'streamflow generating' events, which are dominated by recharge to groundwater, and potentially a baseflow response. The formulation represents the system as having two discrete states, rather than using a more complex, continuous relationship between U and v_s.

Varying K between 0 and 1 showed that both the number of quickflow events and the volume of baseflow are very sensitive to this value, although the total water balance is approximately conserved. Any improvements in the prediction of event frequency came at the expense of baseflow performance, with modelled baseflow exceeding observed flow most of the time. This is illustrated in Figure 5 for K = 0.2 for a section of the simulation period. The increase in baseflow with increasing K causes the duration of flow to increase with values of $K > 0.5$, resulting in

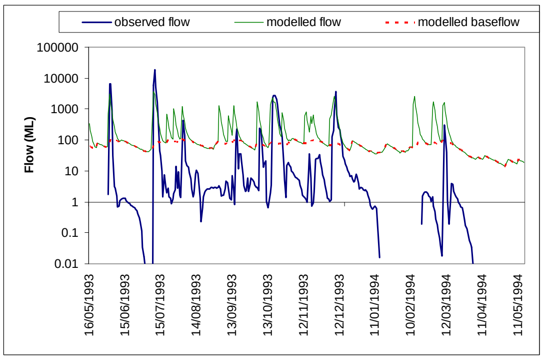

Figure 5. Hydrographs showing the impacts on modelled baseflow and streamflow of introducing an effective rainfall threshold (K = 0.2) for varying the partitioning coefficient, v_s.

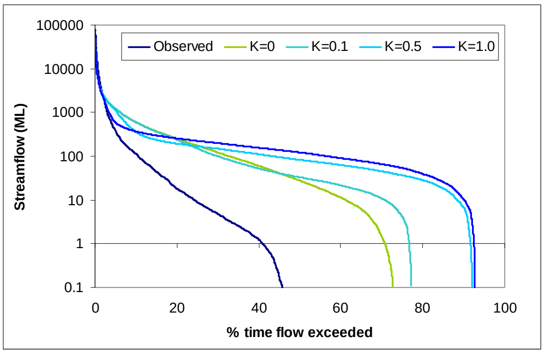

Figure 6. The impact on flow duration of varying the effective rainfall threshold, *K*.

streamflow >90% of the time, compared to 40% for the observed record (Figure 6).

4.3. Varying the stress threshold, *f*

The sensitivity of the model to varying the stress threshold value was tested for *f* = 0.5, 0.8, 1.0 and 1.2, using *K* = 0.2 and *L* = 3. The flow duration curves in Figure 7 show that the duration of streamflow is very sensitive to the *f* parameter. Changes in the magnitude of flow are distributed relatively uniformly across the flow range, resulting in significant impacts on the total streamflow volume during the simulation period. The modelled streamflow ranged from 730% (*f*=0.5) and 57% (*f*=1.2) of the observed flow.

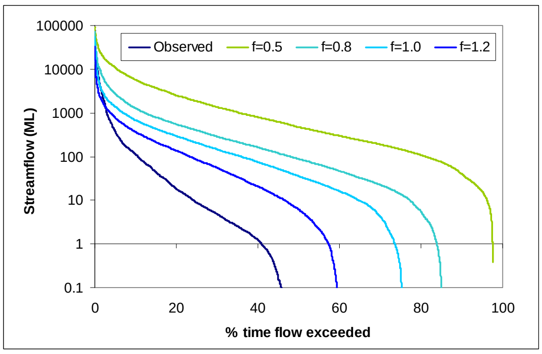

Figure 7. The impact on flow duration of varying the stress threshold, *f*.

5. DISCUSSION

Results from coupling the calibrated groundwater module of Ivkovic *et al.* (2005b) to the partially-calibrated CMD module in IHACRES suggest modifications to the CMD module will be necessary, if climate data are to be used to predict ephemeral streamflow behaviour and evaluate the impacts of groundwater extractions on flow regime. While total streamflow volumes during the simulation period were broadly similar, the duration of flow in the modelled system was significantly longer (85% of the time) than the observed record (40% of the time).

The introduction of an effective rainfall threshold, *K*, below which all the effective rainfall is partitioned to the slow flow pathway, helped to reduce the frequency of modelled quickflow events, but came at a cost in terms of increasing baseflow and, hence, streamflow perenniality (Figure 6). The stress threshold, *f*, which determines the rate of evapotranspiration from the catchment and, hence, effective rainfall and total streamflow volumes, was found to have a significant impact on flow duration, but even the calibrated value of 1.05 was not able to sufficiently reduce the duration of modelled flows (Figure 7).

A full calibration of the model is the obvious next step. Increases in baseflow caused by the introduction of an effective rainfall threshold or a lower stress threshold could, for example, be offset by increasing the groundwater loss term in the groundwater module. However, other changes might also be necessary to significantly improve model performance. .

The spatially-lumped input rainfall time-series has been mentioned as a significant source of model uncertainty. This is a perennial problem in rainfall-runoff modelling of data poor catchments, especially where the rainfall distribution is both spatially and temporally variable, as for Coxs Creek. An alternative method for deriving a catchment-averaged rainfall time-series is certainly an avenue to be explored. Time-series flow data are available for a number of other gauges in the Coxs Creek catchment and calibrations on the individual sub-catchments, using different rainfall time-series inputs for each sub-catchment, might better capture the influence of spatial variability on streamflow response. Additional data has the potential to improve model performance, based on standard objective functions (e.g. Nash & Sutcliffe, 1970), yet it can also introduce greater uncertainty. The decision to go to a more disaggregated spatial representation of the focus catchment will need to be informed by the information to noise ratio (Croke, 2007). If this ratio is less than 1, the degradation from data uncertainty exceeds any improvement in model performance from having more information.

Another source of uncertainty stems from the reliability of the gauged data at low flows. The gauging station is located where a gravel bed characterises the channel substrate. Flow can occur through unconsolidated sediments, such as sand and gravel beds. While, an additional loss term could be incorporated to account for this difference to improve model performance, it does not reduce the uncertainty inherent in the observed flow record.

Additional sources of hydrologic data to inform model development and calibration include historical bore data and groundwater level data currently being collected as part of the Cotton Catchment Communities Cooperative Research Centre (Cotton CRC) groundwater-surface water interactions project in the Coxs Creek catchment. Occurring in parallel with the IHACRES development, and constituting part of the same Cotton CRC project, is the development of a calibrated groundwater model for Coxs Creek, using MODHMS. It is anticipated that groundwater bore data, summarised in the MODHMS model can assist in calibrating the IHACRES model, and conversely IHACRES simulations of streamflow can assist with calibration of the groundwater model.

6. CONCLUSION

The IHACRES_GW model of Ivkovic (2006) has been linked with the IHACRES CMD module so that the influence of climate change and variability on the impacts of groundwater extraction on streamflow can be simulated. Due to uncertainty in the rainfall data for the catchment, the reproduction of flow peaks and the observed baseflow are poor, though the general characteristics of the baseflow are reasonably reproduced.

Some potential improvements to the model have been tested, particularly the loss of surface flow when groundwater levels are low, and the partitioning of effective rainfall between the quick and slow flow stores. Other possible improvements will be tested to determine which are the most effective. Alternatively, some of the spatial variability that is lost through averaging rainfall data across a large catchment area could be reinstated by disaggregating the catchment into sub-catchments and calibrating IHACRES using a number of rainfall time-series and sets of calibrated parameters. This option really only has merit, if the uncertainty introduced into the model is smaller than the improvement in model performance. In catchments with poor data sets, the increase in uncertainty can often exceed the improvement in model performance.

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