Overcoming the challenges of using a rainfall–runoff model to estimate the impacts of groundwater extraction on low flows in an ephemeral stream

K. M. Ivkovic, B. F. W. Croke and R. A. Kelly (née Letcher)

ABSTRACT

Simple modelling approaches such as a spatially lumped, rainfall–runoff model offer a number of advantages in the management of water resources including the relative ease with which groundwater and surface water accounts can be evaluated at the river-reach scale in data-poor areas. However, rainfall–runoff models are generally not well suited for use in ephemeral river systems because of their inability to simulate abrupt transitions from flow to no-flow periods and the highly non-linear rainfall–runoff relationships that exist in low yielding catchments. This paper discusses some of the challenges of using a rainfall–runoff model to assess the impacts of groundwater extraction on low flows within an ephemeral river system and demonstrates how these challenges were overcome during the development of the IHACRES_GW (Identification of Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data – with Ground Water store) model. Details on the model algorithms, calibration, validation and objective function fits are provided. The performance of the IHACRES_GW model in Cox's Creek (Namoi Valley, Australia), and 13 additional areas investigated, suggests that this simple modelling approach may be of considerable utility for water accounting, especially when attempting to evaluate the impacts of groundwater extraction on low flows in similar systems.

Key words | ephemeral stream, groundwater extraction, low flows, rainfall–runoff, surface–groundwater interactions, water accounting

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INTRODUCTION

The importance of managing connected groundwater and surface water resources as a single resource has been highlighted in Australian and international water reform legislation, and these requirements have necessitated a change to the way that water systems have traditionally been managed. One challenging area is in the modelling of aquifer–river volumetric exchanges, and in particular, accounting for low flows, which are especially critical when considering resource sustainability and ecosystem health in anthropogenically modified basins (Rassam 2011; McCallum *et al.* 2012).

A complementary approach to using complex, physically based, surface–groundwater interaction models is to use a simpler, conceptual, rainfall–runoff model to consider catchment-scale water balance accounts. In the past, hydrological models have tended to focus on estimating total river flows, with little emphasis on modelling the groundwater component of river flows (Fleckenstein *et al.* 2006). However, the importance of considering groundwater exchanges in rainfall–runoff models has increasingly been recognised (Tan & O'Conner 1996; Croke *et al.* 2000; Moore & Bell 2002; Le Moine *et al.* 2007; Herron & Croke 2009a; Ivkovic *et al.* 2009a; Pushpalatha *et al.* 2011; Gilfedder *et al.* 2012).

There is clearly an ongoing need to continue to test and trial simple approaches that require limited data when assessing groundwater contributions to river flows in order to more efficiently meet water management policy objectives, particularly

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in data-poor areas (Larocque *et al.* 2010). Some of the main benefits of using simple rainfall–runoff models for catchment-scale water balance accounting are that they have relatively low data requirements, are easy to use, and they often have greater predictive certainty when simulating flows. These models are also able to provide estimates of flows on short time-scales (e.g., daily or shorter), and as a result, they potentially have a greater ability to simulate the baseflow discharges that can occur within these shorter time frames. This is especially important when simulating the flow of ephemeral streams where surface–groundwater exchanges can be rapid.

The utility of using a simple surface–groundwater model to inform water management policy was discussed by Ivkovic *et al.* (2009a), where the conceptual, spatially lumped IHACRES_GW model was introduced. The IHACRES_GW model was used to quantify the historical impacts of groundwater extraction on river flows in the ephemeral Cox's Creek subcatchment in Australia. They found that baseflow discharges in the catchment had been reduced by approximately 82% of the volume of groundwater extracted, and that an average of 5% of the total streamflow volume (78.3 GL) had been lost to the river as a consequence of groundwater extractions over the 15-year simulation period.

While the considerable strengths of using a simple modelling approach were highlighted by Ivkovic *et al.* (2009a), they provided little information on the development of the IHACRES_GW model used in their study. Nor did they provide the background on the model testing calibration and validation. This paper discusses some of the challenges of using a rainfall–runoff model when assessing the impacts of groundwater extraction on low flows within an ephemeral river system and shows how these challenges were overcome through the development of the IHACRES_GW model. Details on the model algorithms, calibration, validation and objective function fits are provided using the same datasets used in the Ivkovic *et al.* (2009a) investigation.

CHALLENGES OF USING RAINFALL–RUNOFF MODELS TO ASSESS LOW FLOWS WITHIN EPHEMERAL RIVER SYSTEMS

There are a number of advantages of using conceptual, rainfall–runoff models for catchment-scale water accounting, as previously discussed; however, rainfall–runoff models are generally not well suited to modelling low flows within ephemeral river systems. This is because: (1) rainfall–runoff modelled steamflows typically use exponentially decaying stores in the formulation of the unit hydrograph, and therefore do not allow for the possibility of zero flows; and (2) rainfall–runoff relationships in semi-arid to arid catchments are characterised by strong non-linearities that lead to considerable uncertainty when estimating effective rainfall depths and predicting streamflow (Ye *et al.* 1997). In many cases, the uncertainty in estimating effective rainfall using a non-linear module exceeds the volumes of groundwater being extracted within the catchment, making it difficult – or even impossible – to assess the impacts of groundwater extraction on low flows using a rainfall–runoff model in low yielding catchments.

In order for rainfall–runoff models to be successfully used for water accounting in low-yielding catchments, they must have the capacity to simulate ephemeral river flows, which often terminate abruptly, or else which may be sustained by baseflows for varying periods of time. To effectively simulate these processes, a rainfall–runoff model must be able to account for the changes in groundwater storage that occur as a consequence of groundwater extractions and other catchment losses. In particular, it is important to maintain a water balance account of groundwater stores throughout no-flow periods in order to be able to correctly simulate the resumption to a flow period. The transition between flow and no-flow periods is especially important to assess in catchments where groundwater extractions may be impacting on low flows and where extractions result in variable groundwater–river connectivity (Ivkovic 2009b).

OBJECTIVES

In order for rainfall–runoff models to be able to provide useful outputs in the study of low flow behaviour within ephemeral streams they must be able to provide:

1. an accurate simulation of both high and low flows, including the correct timing in the switch between baseflow and no-flow transitions at the river reach scale on a daily time-step; and

2. an ongoing water balance account of the changes in groundwater storages arising from groundwater extraction and other losses, even during no-flow periods, and the influences of these losses on low flows on a daily time-step.

A primary research objective was to consider whether an existing rainfall–runoff model could be modified to meet these requirements, and then to rigorously test the modified model for its performance.

APPLICATION CASE-STUDY: NAMOI RIVER CATCHMENT, AUSTRALIA

The Namoi River catchment is one of Australia's most developed irrigation areas where both river and alluvial groundwater resources are heavily utilised for irrigation (Figure 1). One of the major unregulated tributaries to the Namoi River is the Cox's Creek, which was the case-study area selected (Figure 2). The Cox's Creek subcatchment represents an area of 4,040 km^2, and it has an average annual rainfall of 600 mm and an average potential evapotranspiration of 1,900 mm (Zhang *et al.* 1997). The rainfall distribution is highly variable, and this is reflected in the streamflow duration throughout the catchment. The Cox's Creek river reach has been categorised by Ivkovic (2009b) as a variably connected–disconnected aquifer–river system that is variably gaining–losing (Figure 2). The Cox's Creek is an ephemeral river system, with flows measured 37% of the time at the catchment outlet at Boggabri. The average flow over the streamflow record (1965–2003) is 254 ML/day, with baseflows contributing approximately 9% of flows (Ivkovic 2009b). The Cox's Creek alluvium sits within a narrow, bedrock-contained alluvial valley about 10 km wide and 72 km in length. The maximum thickness of the alluvium is 140 m in the Boggabri area (Broughton 1994).

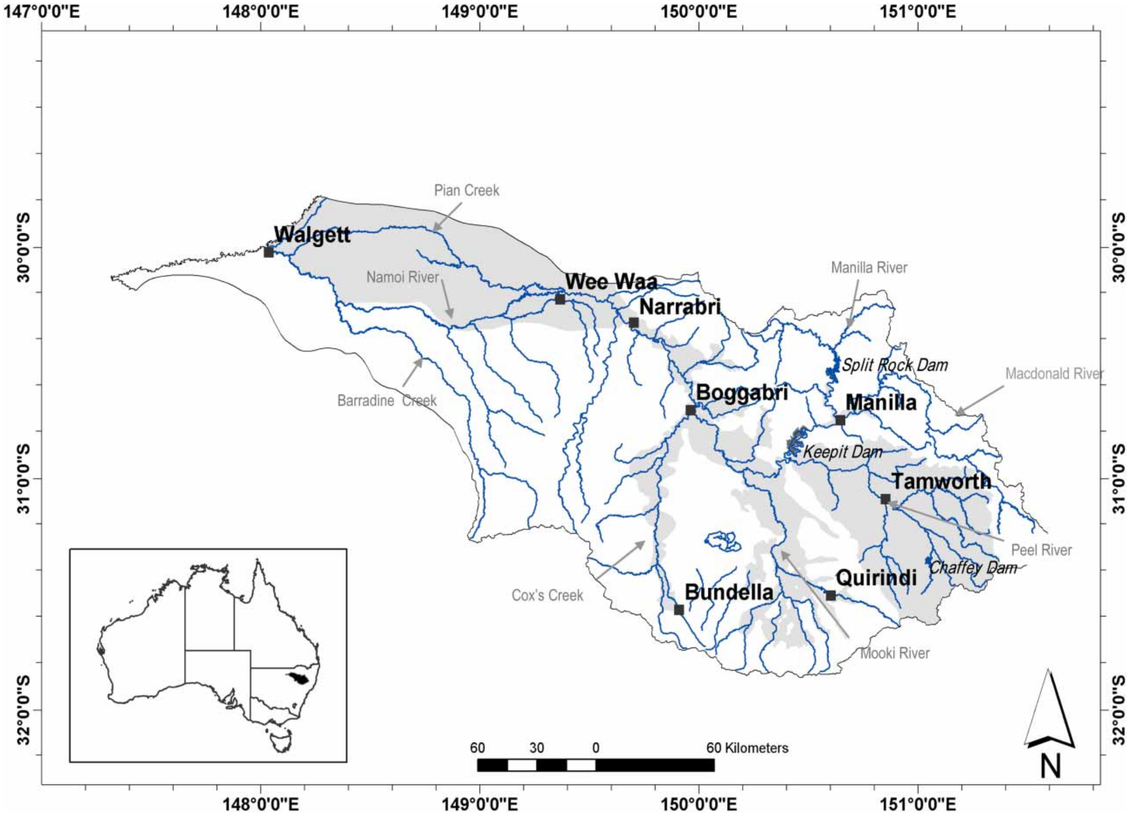

Figure 1 | Namoi River catchment, New South Wales, Australia.

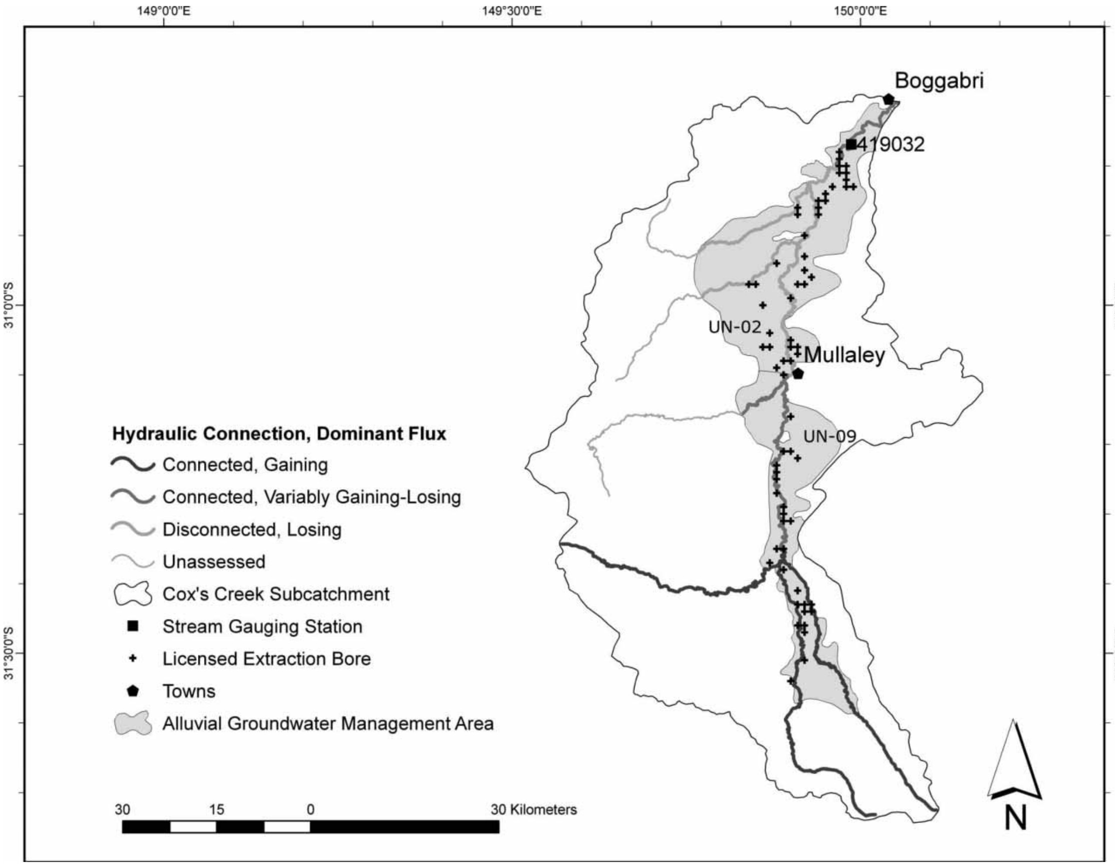

Figure 2 | Cox's Creek subcatchment, gauging station and extraction bores (after Ivkovic *et al.* (2009a)).

METHODS

Model selection

A number of existing rainfall–runoff models were reviewed with the specific purpose of meeting the two main model output criteria previously outlined above. One of the main considerations for model selection was parsimony. This is because simple rainfall–runoff models tend to give more robust results than more complex models when simulating flows (Perrin *et al.* 2001; Nalbantis *et al.* 2011). There are many examples of rainfall–runoff conceptual models that have been used to model storage–outflow relationships, such as the Sacramento (Burnash *et al.* 1973), HBV (Bergström 1976) and SIMHYD (Chiew *et al.* 2002) to name a few. However, the IHACRES model (Identification of Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) (Jakeman *et al.* 1990; Jakeman & Hornberger 1993) was ultimately selected for use in this investigation because it was among the models with the fewest parameters. The IHACRES model typically uses only three parameters for the linear unit hydrograph routing module, suggesting that its linear module could be more easily modified to meet the model output criteria. An overview of the IHACRES model follows in some detail below in order to show how the algorithm was later modified to include a groundwater store in the development of IHACRES_GW.

IHACRES model background

The structure of the linear routing module of the IHACRES model is based on transfer function theory that relates inputs to outputs through linear transformation equations (Young

1974; Whitehead & Young 1975). Most applications of IHACRES involve two stores arranged in parallel, one representing a quick flow pathway, and the other a slow flow pathway (Figure 3).

The quick flow pathway is used to infer the overland and shallow subsurface contributions to streamflow, and the slow flow pathway to infer the groundwater contributions to streamflow or baseflow. Refer to Figure 3, where $Q_t^{(q)}$ and $Q_t^{(s)}$ represent the modelled quick and slow flow volumes at time-step t, and Q_t represents the modelled total streamflow. The parameters β_q and β_s govern the height of the unit hydrograph peaks of the quick and slow flow components, respectively, and U_t is the effective rainfall depth at time-step t. The A term represents the catchment area and is used to convert units of effective rainfall in mm to units of streamflow in megalitres (ML). The parameters α_q and α_s define the rates of quick and slow flow recession. $Q_{t-1}^{(q)}$ and $Q_{t-1}^{(s)}$ are the modelled quick and slow flow volumes from the previous time-step.

The partitioning of effective rainfall into its quick and slow flow components is assumed to be linear and constant in time. Thus, if v_s represents the fraction of effective rainfall that is partitioned as slow flow, conservation of mass requires that the fraction partitioned as quick flow v_q is 1–v_s. The depth of recharge to the slow flow store is implicitly considered by v_s, and its value is calibrated along with the parameters representing the unit hydrograph.

The parameters α_q and α_s define the recession characteristics of the hydrographs, and they can also be expressed as time constants, τ_q and τ_s for the quick and slow flow components, respectively, of streamflow decay:

$$\tau_q = \frac{-\Delta}{\mathrm{In}(-\alpha_q)} \tag{1}$$

$$\tau_s = \frac{-\Delta}{\mathrm{In}(-\alpha_s)} \tag{2}$$

where Δ is the sampling interval. The derivation of τ_q and τ_s is given in Jakeman *et al.* (1990). The time constants are estimated for the sampling interval, and as a result the calibrated value is dependent upon the sampling interval and time-step as was shown by Littlewood & Croke (2008, 2013), so care should be taken in interpreting the time constants obtained as being representative of the conditions being investigated.

Introduction of a groundwater store

The IHACRES model was modified to include a groundwater store and the resultant model was entitled IHACRES_GW (Ivkovic *et al.* 2009a). The IHACRES_GW model is based on the IHACRES rainfall–runoff model, as outlined above. However, in IHACRES_GW the slow transfer function component of the IHACRES model, which makes no allowance conceptually for an aquifer, has been replaced with a store

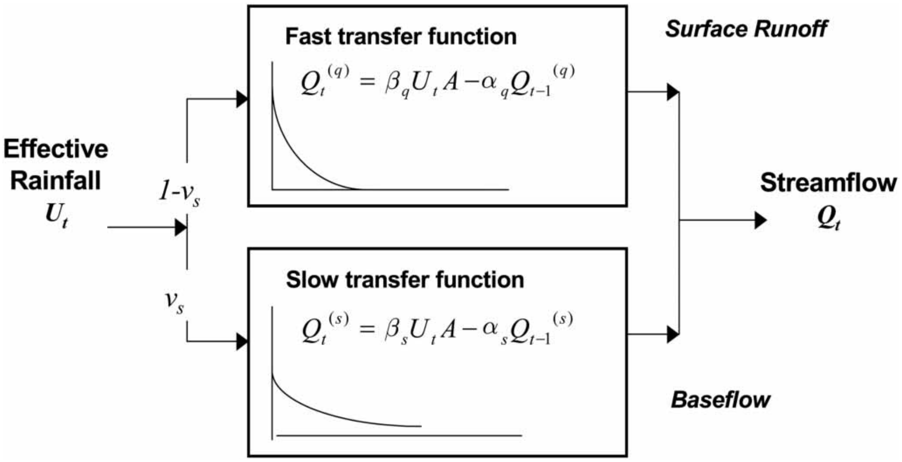

Figure 3 | IHACRES linear routing model structure.

that more explicitly accounts for the presence of groundwater (Figure 4). The conceptual model was derived from ideas initially developed in Croke *et al.* (2000).

In the IHACRES_GW model, groundwater storage is conceptualised as a single reservoir with its areal extent represented by the catchment area above the stream gauging station of interest. As one can see from Figure 4, the depth of water that recharges the groundwater store is determined by the proportion of effective rainfall that is partitioned as slow flow, which is a calibrated value. The remaining fraction of effective rainfall is apportioned to quick flow. (Note that the methodology for estimating effective rainfall for input to IHACRES_GW is discussed later in this paper.) The volume of water released from groundwater storage to the river system is represented by the slow flow component of streamflow, and is assumed to be baseflow. Groundwater extraction and other losses behave as additional outflows from the groundwater store. The main assumptions of the IHACRES_GW model were provided in the Ivkovic *et al.* (2009a) paper.

The details of the derivation of the IHACRES_GW model algorithms follow, and it is important to note that these changes could be made to any rainfall–runoff model that uses exponentially decaying stores to represent the total unit hydrograph.

Derivation of the IHACRES_GW model

The exponentially decaying slow flow component in the IHACRES model can be reformulated to consider the total volume of groundwater by adopting a linear relationship between groundwater storage and baseflow (Boussinesq 1877; Maillet 1905; Chapman 2003):

$$Q_t^{(s)} = \left\{ \begin{matrix} aG_t & \mathit{if} \quad G_t > 0 \\ 0 & \mathit{otherwise} \end{matrix} \right\} \tag{3}$$

where:

$Q_t^{(s)}$ Modelled slow flow inferred as baseflow at time-step t (ML/time-step).

G_t Volume of groundwater (ML) stored above the catchment outlet at time-step t.

a The value of this parameter gives the linear relationship between groundwater storage and the contribution of groundwater discharge to baseflow.

This representation of the baseflow results in an exponentially decaying store (i.e., behaves identically to the formulation in IHACRES). Replacing the IHACRES slow transfer function in this way allows the inclusion of

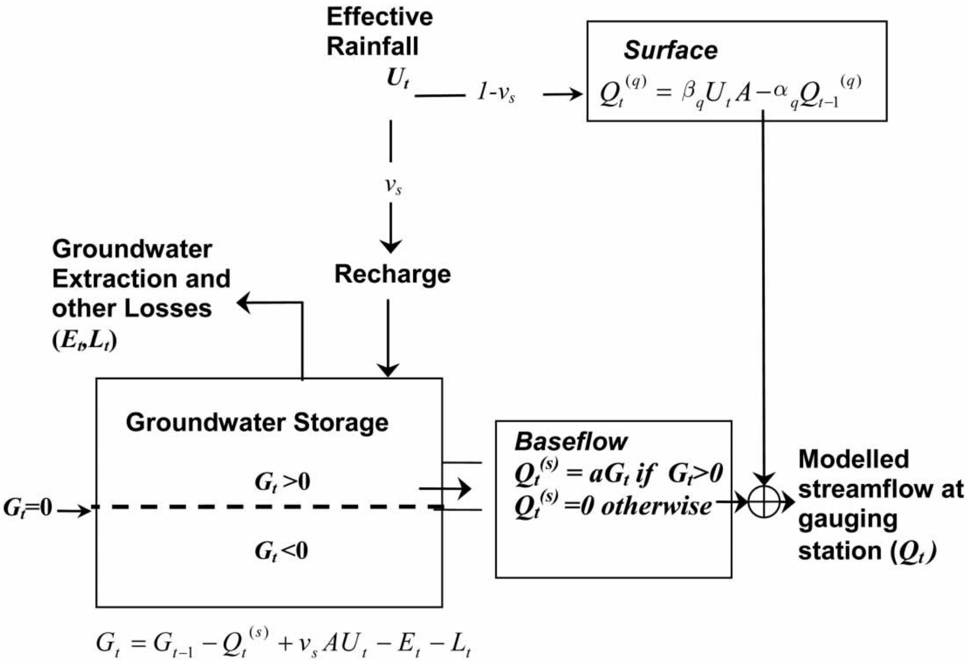

Figure 4 | IHACRES_GW model structure.

extractions and other losses in the mass balance equation for groundwater storage:

$$G_t = G_{t-1} - Q_t^{(s)} + v_s A U_t - E_t - L_t \tag{4}$$

where E_t is the groundwater extraction at time-step t, and is based on annual extraction data, converted to a daily rate and lumped for the catchment area. L_t represents any losses from groundwater storage at time-step t, including subsurface outflow below the level of the stream gauging station, evapotranspiration and other losses (or gains if the loss term is negative such as would be the case with irrigation returns and river infiltration) and is a calibrated term that remains constant at each time-step.

The $Q_t^{(s)}$ term in Equation (4) can be substituted with aG from Equation (3) yielding:

$$G_t = \begin{cases} G_{t-1} - aG_t + v_s A U_t - E_t - L_t, & \text{if} \quad G_t > 0 \\ G_{t-1} + v_s A U_t - E_t - L_t & \text{otherwise} \end{cases} \tag{5}$$

This can be arranged as:

$$G_t = \begin{cases} \dfrac{1}{1+a}(G_{t-1} + v_s A U_t - E_t - L_t) & \text{if} \quad G_t > 0 \\ G_{t-1} + v_s A U_t - E_t - L_t & \text{otherwise} \end{cases} \tag{6}$$

Solving for the above equations allows for a continuous accounting of groundwater storage volumes to be maintained.

Multiplying Equation (6) through by a allows for $Q_t^{(s)}$ to be calculated by Equation (3), resulting in:

$$Q_t^{(s)} = \begin{cases} \dfrac{1}{1+a} Q_{t-1}^{(s)} + \dfrac{a}{1+a}(v_s A U_t - E_t - L_t) & \text{if} \quad G_t > 0 \\ 0 \quad \text{otherwise} \end{cases} \tag{7}$$

Equation (7) has a similar functional form to the equation for the slow transfer function shown in Figure 1, but without the added extraction and loss terms. It therefore follows that:

$$\alpha_s = \frac{-1}{1+a} \tag{8}$$

$$\beta_s = v_s \frac{a}{1+a} \tag{9}$$

Solving Equation (8) in terms of a yields:

$$a = \frac{-(\alpha_s + 1)}{\alpha_s} \tag{10}$$

The baseflow contribution at time-step t is then calculated by solving Equation (6) for G_t, where G_t is greater than zero, and then by multiplying through by a as shown in Equation (3). If G_t is less than zero, then the baseflow is zero. The parameter a is calculated with Equation (10) using the calibrated τ_s parameter derived from running the IHACRES_GW model over a number of years in which streamflow events demonstrate some baseflow components to flow, and solving for α_s using Equation (2).

To summarise, the IHACRES_GW model requires the calibration of four parameters, τ_q, τ_s, v_s and L_t,. The calibration process is discussed in more detail later in the paper as part of the model testing.

Estimating effective rainfall

A non-linear loss module, such as the Catchment Moisture Deficit (CMD) module (Croke & Jakeman 2004), is usually used to transform observed rainfall and temperature data to effective rainfall depth when using IHACRES. However, the spatial coverage of raingauges throughout many catchments in Australia is poor and the rainfall patterns often tend to be non-uniform. An analysis of the input rainfall time-series generated using a standard weighted Thiessen polygon (Croke *et al.* 2011) approach in the Cox's Creek catchment revealed mismatches between observed streamflow events and the occurrence of rainfall, which imposed major limits on model performance when using the CMD module with IHACRES_GW (Herron & Croke 2009a). As previously mentioned, the highly non-linear relationships between rainfall and runoff in low yielding catchments commonly result in poor estimates of effective rainfall depth when using non-linear models. In addition, ephemeral catchments have more zero flow days and typically fewer streamflow events, and therefore the streamflow series provides less information for parameter estimation. Furthermore, there is no information on the catchment's soil moisture status during dry periods (Ye *et al.* 1997).

In our assessments of ephemeral river catchments in the Namoi Catchment, it was noted that the consequent errors in estimating catchment average rainfall increased the uncertainty in the non-linear loss module to the extent that the influence of groundwater extraction using the IHACRES_GW linear module was masked. Taking the Cox's Creek catchment as an example, where the average extraction rate during the irrigation season is on the order of 7,390 ML/year, over a catchment area of 4,040 km^2 this volume equates to less than 1.8 mm/year of extraction. The estimated average effective rainfall depth over the simulation period was 36.7 mm/year. It would be expected that the uncertainty in effective rainfall depth would be greater than 10% (i.e., greater than ~4 mm) when using a non-linear module. And yet, it is important to note that the impacts of 1.8 mm/year extraction within the Cox's Creek catchment were shown by Ivkovic *et al.* (2009a) to have a considerable impact on low flows.

Given the high uncertainty of estimating catchment yield using a non-linear module, a top-down modelling approach was employed that relied on the streamflow data to estimate effective rainfall. This involved filtering the observed streamflow series to generate its quick and slow components using the box-car minimum baseflow filter technique described by Croke *et al.* (2001).

The mathematical box-car minimum baseflow filter method is applied in two steps. The first step involves running a filter using a width of $2w+1$ time-steps ($w=2$), where at each time-step t, the minimum of the observed flows from time-step $t-w$ to $t+w$ is determined. In the next step, the resulting time series is smoothed using a box-car filter of the same width (i.e., five time-steps), which is the width also used by the Institute of Hydrology Base Flow Index (BFI) filter (Gustard *et al.* 1992). The filtered stream flow values were then used to estimate the baseflow volume contribution to the stream, and as discussed in Littlewood (2008, 2009), the filtered value is sensitive to the data interval assessed. The quick flow contribution to streamflow was then estimated by subtracting the filtered baseflow, using the method outlined above, from the total flow for each time-step. The effective rainfall was then calculated by:

$$U_t = \begin{cases} \dfrac{Q_t^{(\mathrm{qf})} + \alpha_q Q_{t-1}^{(q)}}{\beta_q A} & \text{if} \quad Q_t > Q_{t-1} \\ 0 \ \text{otherwise} \end{cases} \tag{11}$$

where U_t is the effective rainfall and $Q_t^{(\mathrm{qf})}$ is the filtered quick flow at time-step t. α_q is the quick flow recession rate, β_q is the height of the unit hydrograph peak for quick flow, and A is the catchment area (Croke 2006).

Assumptions in this formulation are: (i) that the filtered quick flow volume provides the effective rainfall input to the model; (ii) that for effective rainfall to be generated there must be a measurable quick flow (because of the way effective rainfall is estimated in Equation (11)); and, furthermore, (iii) that the quick flow signature has not changed over time in response to groundwater extraction. These assumptions render the calculation of effective rainfall in this way to be only suited to ephemeral river systems which are quick flow dominated and yet exhibit an intermittent baseflow signal, such as the situation we are considering here.

A sensitivity analysis described by Ivkovic (2006) showed that the calculated effective rainfall depth influenced the modelled streamflow, and in turn, the choice of parameter values selected when calibrating the IHACRES_GW model influenced the effective rainfall depth. This is expected given the inter-relationships evident in Equation (11). Importantly though, the errors were relatively small and found to be within the bounds of -0.5 to 2.3 ML/day (≤ 0.2 to 1% of mean flows) for 10% perturbations relative to the optimal reference parameter values.

Using Equation (11) to calculate effective rainfall for model input to IHACRES_GW had the critical benefit of reducing the uncertainty in effective rainfall depth, which as previously stated, was greater than the influence of groundwater extractions on modelled streamflow. Moreover, employing this approach allowed for a more thorough testing of the performance of the IHACRES_GW linear model structure, as will now be discussed.

Model calibration and performance criteria

The calibration of the four parameters, τ_q, τ_s, υ_s and L_t, was performed through a manual trial-and-error process using visual inspection of the observed flows and flow duration. Modelled versus observed flows were visually assessed in log space in order to focus on the low flow component of model fits. The visual calibration was complemented by analysing five performance criteria, namely R^2, R^2_{slow}, R^2_{inv}, relative bias (RB) and RB_{slow} (defined below) during the manual calibration process. Confusion matrices (Dunham 2002), a type of contingency table, were also analysed to assess the timing in the switch between baseflow and no-flow periods on a daily time-step; they provided an indicator of the proportions of correctly and incorrectly classified flows for the presence of baseflow (>0.1 ML/day). The objective functions utilised for this investigation are described below.

R^2 is the coefficient of efficiency described by Nash & Sutcliffe (1970) as:

$$R^2 = 1 - \frac{\sum_{t=1}^{n} (O_t - M_t)^2}{\sum_{t=1}^{n} (O_t - O)^2}$$

where O_t is the observed value at time t, M_t is the predicted value at time t, O is the mean of the O_t and n is the number of daily time-steps in the record being simulated. The R^2 values were calculated for total streamflow and filtered baseflow (R^2_{slow}) using the minima filter previously described. R^2 is biased towards reproducing high flows, not baseflow behaviour, so it was of limited interest in terms of calibrating the model except to ensure the overall acceptability of model performance. The R^2_{slow}, however, was of particular interest because it gave an indication of how well the slow flow volumes modelled by IHACRES_GW compared with filter-derived slow flow values (based on observed streamflow) using the minima filter.

A similar statistic to the coefficient of efficiency is the R^2_{inv} which is calculated as:

$$R^2_{\text{inv}} = 1 - \frac{\sum_{t=1}^{n} \left(\frac{1}{1+Q_t} - \frac{1}{1+M_t} \right)^2}{\sum_{t=1}^{n} \left(\frac{1}{1+Q_t} - \frac{1}{1+O} \right)^2}$$

R^2_{inv} measures the fit to mostly low flows (Pushpalatha *et al.* 2012). The addition of 1 to the observed and modelled flows enables the inclusion of time-steps with zero flows. The selection of the value 1 was somewhat arbitrary, and in this investigation represents about 1/400th of the mean flow to emphasise the behaviour of the model at the flow to no-flow transition.

The relative bias (RB) was also assessed, which is given by:

$$\text{RB} = \frac{\frac{1}{n} \sum_{t=1}^{n} (O_t - M_t)}{O}$$

RB measures are useful in assessing streamflow volumes over the length of the modelled period. RB was calculated for both the modelled streamflow as well as for comparing the modelled slow flow relative to filter-generated slow flow volumes (RB_{slow}) using the minima filter.

RESULTS

Model calibration

The IHACRES_GW model was calibrated to daily streamflow data for gauging station 419032 (Boggabri) at the outlet of the Cox's Creek subcatchment (Figure 2). The period for calibration selected was 1 June 1965 to 30 June 1980 (15 years) using a continuous record of daily streamflow data, as was outlined by Ivkovic *et al.* (2009a). The river flows during this period of time were considered to be representative of pre-groundwater extraction conditions. The model calibration was commenced at the onset of a baseflow event when groundwater storage volumes would be expected to be close to the zero reference point. A 50-day warm-up period was used.

The order of the calibration was to first fit the τ_q parameter, to which the model is most sensitive, with emphasis on fitting towards the end of a baseflow recession period. Second, v_s was calibrated, followed by the τ_s parameter. The L_t parameter was fitted last, and had the overall effect of shortening the duration of the baseflow recession. The calibration parameters providing the best model fit are shown in Table 1.

A visual inspection of the modelled output showed a good match to the stream hydrograph recession behaviour.

Table 1 | Calibration period parameter values and objective function fits (1/6/1965 to 30/6/1980)

Parameters	Calibrated values	Objective functions	Fits
v_s	0.09	R^2	0.89
τ_s	15 days	R^2_{slow}	0.62
τ_q	0.9 days	R^2_{inv}	0.79
L_t	6 ML/day	RB	0.28
		RB_{slow}	0.48

A typical streamflow record is shown in Figure 5 and highlights the influence of the loss term (L_t). Note that the reproduction of the high flows is very good due to the manner of estimating the effective rainfall, and is therefore not a good indicator of the model fit. Rather, it is the behaviour of the model following the flow peaks that is of primary interest in this case.

The values for R^2 and RB for the 15-year calibration period are very good, as would be expected, given that effective rainfall was calculated using a filter-derived quick flow value (refer to Equation (11)). However, the fits to the high flows are not perfect due to having constrained effective rainfall to only days with an increase in observed flow, as well as the non-stationarity in the unit hydrograph. The R^2_{slow} and R^2_{inv} statistics, which focus on low flow behaviour, suggest that the model is capturing the recession volumes of baseflows well on a daily time-step. The RB_{slow} statistics, however, indicate that the overall volume of baseflow predicted over the 15-year calibration period is about half the volume estimated from the filtered streamflow.

The underprediction of low flows is also evident in the flow duration curve (Figure 6). Some underprediction is due in part to the fact that low flow events below 8 ML/day were not reliably recorded at the gauging station between 1965 and 1980, which resulted in either no data, or else data infilling had been employed using a constant value of around 8 ML/day. This affected about 10% of the data (a similar finding was noted for the other gauging stations within the Namoi Catchment over this period of time). Because effective rainfall is calculated using Equation (11), effective rainfall input to IHACRES_GW is constrained to only those days where an increase in streamflow is observed, or else it is assumed to be zero. The data-infilling with constant values had the effect of resulting in zero effective rainfall input over those days (since no increases in streamflow were observed), and thus there is also zero groundwater recharge, further reducing low flow contributions to modelled streamflow. An additional source of uncertainty includes sources of recharge to the aquifer from outside of the catchment, or at greater depth within the catchment. For example, Dyce & Richardson (1997) reported that some upward vertical leakage from the underlying basalt bedrock aquifer may be occurring in parts of the Cox's Creek catchment, although these volumes have not been quantified.

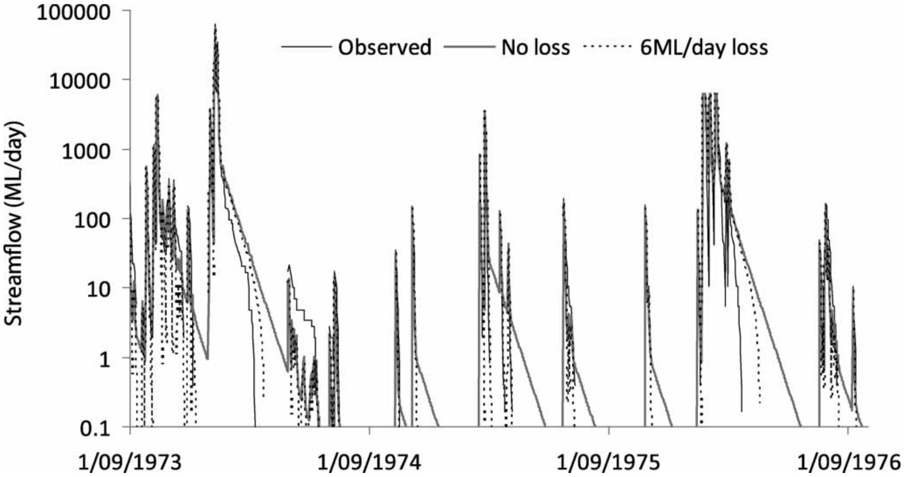

Figure 5 | Observed and modelled streamflow at Gauging Station 419032, Cox's Creek at Boggabri for September 1973–1976 portion of the calibration period.

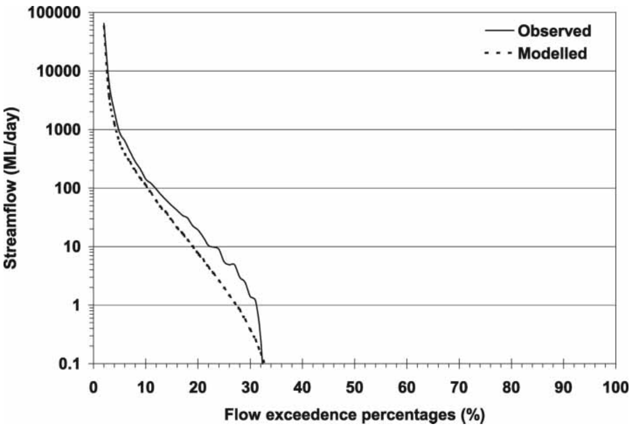

Figure 6 | Flow exceedence percentages for observed and modelled streamflow for the 1/6/1965 to 30/6/1980 calibration period.

The evaluation of modelled and minima filtered low flows relative to the 0.01 ML/day threshold value indicated that the proportion of modelled flows with incorrect recession timings (e.g., filtered >0.01 ML/day and modelled <0.01 ML/day; and filtered <0.01 ML/day and modelled >0.01 ML/day) was 6.6%. The proportion of time where a minima filter-derived baseflow was estimated, but not modelled was 2.1%. These percentages suggest that the model performed well in terms of capturing the baseflow to no-flow transitions. By contrast, if no groundwater losses were included in the model run (Figure 5), 49% of the total proportion of flows are incorrectly modelled. These data suggest that the IHACRES_GW model configuration is more capable of simulating the rapid transition from a flow to no-flow periods.

Model simulation

Model simulation in this investigation consisted of running the model forward with calibrated parameters using input data from a period that did not include any data from the calibration period. The term simulation, rather than validation, is used in this instance because groundwater extraction data were used for the simulation (and were not used in the pre-extraction calibration period). The period selected for model simulation using IHACRES_GW was 2 September 1988 to 9 December 2003 (15.3 years) as discussed by Ivkovic *et al.* (2009a). This period was selected because daily streamflow and yearly groundwater extraction data (converted to a daily average over the irrigation season) were available over the record. Simulations were run on a daily time-step using the calibrated model parameters (Table 1). Groundwater extraction data were used as an additional loss from groundwater storage (E_t). The model was not calibrated to this period, so this simulation also serves as a test/validation of the calibrated model. Outside of the irrigation season groundwater extraction was set to zero, while the constant loss term (L_t) remained 6 ML/day based on the calibration period.

The model fits assessed by our five performance statistics for the simulation period are provided in Table 2. An improvement in R^2, R^2_{slow} and RB is evident together with a slight decrease in R^2_{inv} and $\mathrm{RB}_{\mathrm{slow}}$ in comparison to the calibration period (Table 1). The value of $\mathrm{RB}_{\mathrm{slow}}$ indicates that the baseflow volumes over the simulation period are approximately one-third of those estimated by the minima-derived filter. The confusion matrix for flows greater than 0.01 ML/day gives the proportion of modelled flows with incorrect recession timings as 7.4%. The proportion where baseflow was estimated but not modelled was 5.9% (an increase from the 2.1% found for the calibration period).

These performance measures indicate that the model still performed well in terms of capturing the behaviour of the baseflow recessions, as well as the transitions from flow to no-flow events over the simulation period, despite the fact that the model was not calibrated to this period.

A plot of observed versus modelled streamflow for a representative portion of the simulation period is shown in Figure 7, and demonstrates that the model is representing the overall streamflow recession behaviour reasonably well. However, it is also apparent that the modelled flows are underestimated for periods where observed flows last for a couple of months or longer, e.g., the baseflow-dominated periods, consistent with the value of the $\mathrm{RB}_{\mathrm{slow}}$ objective function fit of 0.36. The residual differences reflect

Table 2 | Simulation period objective function fits (2/9/1988 to 9/12/2003)

Evaluation criteria	Fits
R^2	0.96
R^2_{slow}	0.75
R^2_{inv}	0.70
RB	0.10
$\mathrm{RB}_{\mathrm{slow}}$	0.36

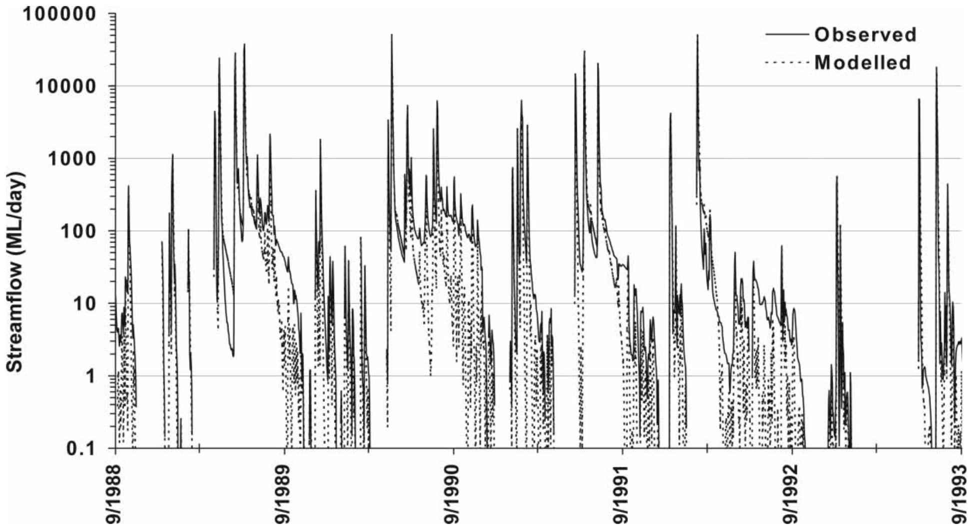

Figure 7 | Observed and modelled stream flow at Gauging Station 419032, Cox's Creek at Boggabri for the September 1988–1993 portion of the simulation period.

an underestimation of very high flows and a too rapid decay of baseflow recession.

The flow exceedence percentages for streamflows below 100 ML are accordingly underpredicted between 2 and 14% (Figure 8). Despite the tendency of the model to underpredict low flows, one would expect that the differences between model outputs for a range of extraction scenarios, using the model as a base-case, would be much smaller than the uncertainties in the predictions themselves as discussed by Reichert & Borsuk (2005).

A possible reason for the underestimation of baseflows over the simulation period may have been because the parameter values derived during the calibration period (Table 1) were no longer applicable for the developed period. This hypothesis was tested by a recalibration to the 1988–2003 post-groundwater development period data. The recalibration showed an increase in the v_s, τ_s and τ_q parameters and a decrease in L_t, with slightly improved objective function and visual fits (Table 3). There were no improvements noted in the model performance of switching behaviour. The changes in parameter values suggest that groundwater extraction and irrigation have resulted in increased recharge, most likely from deep drainage and induced and captured forms of recharge, which have resulted in a consequent slowing down in the baseflow recession rates. However, given that the IHACRES_GW model was calibrated to pre-development data, and yet managed to predict the overall streamflow behaviour well in a

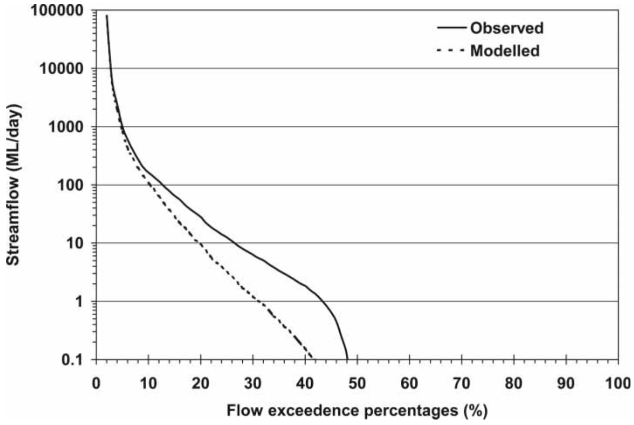

Figure 8 | Flow exceedence percentages for observed and modelled streamflow for the simulation period (2/91988 to 9/12/2003).

Table 3 | Calibration period parameter values and objective function fits for post development period (2/9/1988 to 9/12/2003)

Parameters	Calibrated values	Objective functions	Fits
v_s	0.1	R^2	0.94
τ_s	25 days	R^2_{slow}	0.72
τ_q	1.4 days	R^2_{inv}	0.79
L_t	3 ML/day	RB	−0.1
		$\mathrm{RB}_{\mathrm{slow}}$	−0.2

post-development state outside of the calibration period, suggests a degree of robustness in the model structure.

FURTHER TESTING OF IHACRES_GW

The IHACRES_GW model was subsequently tested in a further 13 semi-arid, narrow, semi-confined alluvial aquifer catchments in Australia (Zhu 2010). The IHACRES_GW model was found to perform well in the seven variably connected gaining–losing and losing reaches (R^2_{inv} values of 0.972–0.877) and the five connected gaining reaches (R^2_{inv} 0.876–0.691). However, IHACRES_GW performed poorly in the connected-gaining, permanently flowing perennial river system ($R^2_{\mathrm{inv}} = 0.156$), consistent with the fact that the IHACRES_GW model is not suited to groundwater-dominated (e.g., perennial) streams.

The IHACRES_GW model was also tested in the Messara Valley, Crete where it was coupled with the CMD nonlinear module (Herron & Croke 2009b). The ephemeral river investigated was similarly situated within a narrow, contained alluvial valley. No information was provided about the hydrogeology of the Messara Valley in Herron & Croke's study (2009b), making it impossible to know whether the aquifer configuration was consistent with a two-store model such as IHACRES_GW. Herron & Croke (2009b) reported they required the addition of a third store to represent a perched aquifer system in order to calibrate their model. The resultant IHACRES_3S (3-storage) model was found to satisfactorily reproduce streamflow volumes and patterns using the complete data record (i.e., no data remained for validation). The IHACRES_3S model was subsequently used to investigate the impact of climate variability on catchment hydrology in Australia by Kim *et al.* (2011). They found that the subcatchments located in the lower rainfall regimes showed poor to average model performance using the IHACRES_3S model. This finding is consistent with the problems IHACRES_GW attempted to overcome by using streamflow to calculate effective rainfall, as discussed in this paper. Zhu (2010) further reported that the additional model complexity of the IHACRES_3S model was not warranted in the Australian catchments they investigated when streamflow data were used to calculate effective rainfall.

CONCLUSIONS

Two main challenges associated with using a rainfall–runoff model to estimate the impacts of groundwater extraction on low flows in an ephemeral stream were investigated during the development of the IHACRES_GW (Ivkovic *et al.* 2009a) model.

The first challenge was to be able to correctly simulate the transitions between baseflows and no-flow periods within an ephemeral stream, and to be able to correctly account for changes in groundwater storages arising from groundwater extraction and other losses. To address these problems, the slow transfer function component of the IHACRES model was replaced with a groundwater store. The derivation is fully described in this paper, and could be applied to any rainfall–runoff model that represents baseflow as one or more exponentially decaying stores.

The second challenge was to address the uncertainty in estimated effective rainfall depths when using a non-linear module due to the highly non-linear rainfall–runoff relationships typically found in low yielding catchments. This problem was overcome by using streamflow data to estimate effective rainfall depth. Such an approach is best suited for use in areas where the error in the rainfall data is high as a consequence of poor spatial coverage of raingauges and non-uniform rainfall patterns. Using streamflow data to estimate effective rainfall depth has the benefit of allowing for greater certainty in the low flow simulation of runoff-dominated catchments; however, this approach is not suitable for use in groundwater-dominated (i.e., perennial) river systems.

Model testing of IHACRES_GW demonstrated that it was able to effectively simulate the transition between baseflow and no-flow periods in rivers exhibiting variable groundwater–river connection in low yielding catchments. The model also demonstrated that baseflow volumes could be simulated on a daily time-step, although, the model commonly underpredicted baseflow volumes by between 2 and 14%.

Ongoing research of the IHACRES_GW and IHACRES_3S models is continuing in order to improve aspects of rainfall–runoff model performance in low yielding catchments. The IHACRES_GW model approach of using streamflow to estimate effective rainfall depth requires further evaluation, including the possibility of generating effective rainfall when streamflow volumes are constant and decreasing, rather than only when there is an observed increase. Other research directions include modifying the linear module structure to have a variable partitioning between quick and slow flow components in order to capture any event-dependent variability present in the total unit hydrograph and the use of a variable loss parameter (L_t). Other considerations include modifying the non-linear CMD module so it produces a greater effective rainfall depth for large rainfall events in order to better represent the sharper form of the unit hydrograph peak observed with these types of events (Kim *et al.* 2011). A formal analysis of the predictive uncertainty (data, parameter and model structure) of the IHACRES model and its derivations is currently in progress (Blakers *et al.* 2011).

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