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Groundwater component of the WaterCAST catchment modelling framework

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Abstract: Greater pressure on water resources and the environment as well as the need to better model stream flow constituent generation has led to more interest in low-flow conditions. Rainfall-runoff models have traditionally focused on estimating total stream flows with less emphasis on modelling the groundwater component. There is a need for approaches to be developed which more explicitly consider the impacts of surface water – groundwater interactions on the prediction of stream flow.

The WaterCAST model (developed by the eWATER CRC) aims to link changes in catchment management and climatic variability to stream flow quantity and quality within upland catchments and to predict stream flows from unregulated tributaries for subsequent use as input to regulated river management models. This paper describes the development and application of a groundwater module to be used as part of WaterCAST.

The groundwater module lumps the water-balance results from multiple 1-D modelling runs (which allows the ability to model land-use changes), explicitly includes variation in groundwater delays across the modelled area, stream losses, and can be calibrated to fit gauged flows. Preliminary work at a monthly time scale gave good results in the Tarcutta catchment (NSW, Australia), providing an excellent match for low flows.

Keywords: *baseflow, catchment water-balance model, groundwater–surface water interactions, eWater*

1. INTRODUCTION

Catchment models have traditionally focused on estimating total stream flows with less emphasis on modelling the groundwater component. Greater pressure on water resources and the environment, as well as the need to better model constituent generation, has led to more interest in low-flow conditions, particularly how these are impacted by groundwater – surface water interactions.

Existing rainfall-runoff models (e.g. SMAR/Sacramento: O'Connell *et al.* 1970, Burnash and Ferral 1972) have been designed to provide estimates of daily flows. They are lumped conceptual models and are typically calibrated to a particular gauging station, and designed to suit perennial, gaining streams. Climate is the only temporal change considered by these models. In order to model the impacts of changes in land-use, a more complex type of model should be developed which allows for changes (such as plantation area change, groundwater pumping, impact of bushfires) to be modelled. It is tempting to use fully distributed hydrologic models for this purpose, although care needs to be taken that the data is available to take advantage of the additional complexity, i.e. that the model is fit for purpose. This is particularly important when modelling areas of 1000s of km^2.

Models such as 2CSalt (Stenson *et al.* 2005) combine the water-balance estimates from 1-D modelling (PERFECT: Littleboy *et al.* 1992) within a relatively simple catchment framework, to provide estimates of monthly flows. Some of the ideas and structure from 2CSalt have been further developed in this paper with the aim of providing a daily flow model, which links land-use to water-balance terms, and incorporates groundwater lags, and capacity to model losses such as losing streams and the effects of groundwater pumping.

Modelling of groundwater – surface water interactions is needed in areas with ephemeral or losing streams or intensive groundwater extractions. Ivkovic (2005) adapted the dynamic spatially lumped IHACRES (Jakeman and Hornberger 1993) rainfall-runoff model to include groundwater pumping impacts. This IHACRES_GW model has been applied in the Namoi catchment (Herron and Croke 2007, Ivkovic *et al.* 2009), and has further highlighted the need to include the impacts of groundwater pumping in surface flow models.

WaterCAST is being developed by the eWATER CRC, and links changes in catchment management and climatic variability to stream quantity and quality from upland catchments. The groundwater module is intended to be applied across upland areas composed mainly of local groundwater flow systems (GFS: Coram *et al.* 2000), and is used to provide daily stream flow. One the purposes of WaterCAST is to provide stream flows from unregulated tributaries, as input for river management models (e.g. RiverManager or IQQM: Simons *et al.* 1996) which operate at a daily time-step.

In this paper we describe the development and application of a groundwater module to be used as part of a broader WaterCAST catchment water generation model. The aim of this module is to improve the predictive capacity of surface flow models with special emphasis on low flows. The underlying parameters and equations are presented, and the initial application of the prototype model to the Tarcutta catchment (Murrumbidgee, NSW, Australia) is outlined.

2. CONCEPTUAL MODEL

The conceptual model used in this paper builds on the structure of the 2CSalt model (Stenson *et al.* 2005) and BC2C (Gilfedder *et al.* 2009). A gauged catchment is subdivided into sub-catchments using terrain analysis of surface topography and a knowledge of the scale of the underlying GFS.

Each sub-catchment is further divided into Functional Units (FUs) which are defined as areas with the same combination of soil, land-use and climate. For each of these FU types, the model requires a daily time-series of runoff, subsurface lateral flow, and recharge as input from a separately run water-balance model.

To generate the FU water balances, the PERFECT model (Littleboy *et al.* 1992) has been used. PERFECT is a 1-D water balance model, which considers crop water use, soil parameters, and calculates surface runoff, ET, and deep drainage. The PERFECT results from each FU are summed to the sub-catchment level.

The groundwater module described in this paper works at a sub-catchment scale and accepts daily deep drainage which is split into groundwater recharge and shallow lateral-flow using the approach of Rassam and Littleboy (2003) from each FU within the sub-catchment. Groundwater response time-scales are calculated for each sub-catchment using GFS parameters. A six parameter model is then used to delay each of the input terms to provide a daily output of base flow to the river.

3. MODELLED PROCESSES

The processes described in this section are a mixture of groundwater and non-groundwater components. Fig. 1 provides a simplified overview of the water pathways. There are currently six calibration parameters in the prototype groundwater module, which give us a degree of freedom which will enable us to capture all the processes that should be modelled. With further testing and application, some of these may be kept constant, or removed from a particular catchment application if not required.

α	scaling term for groundwater response time
β	lateral flow response time
γ	varying the split between lateral flow and recharge
P	scaling of 1D water balance outputs
D	loss to deep regional aquifers
L	other loss from stream

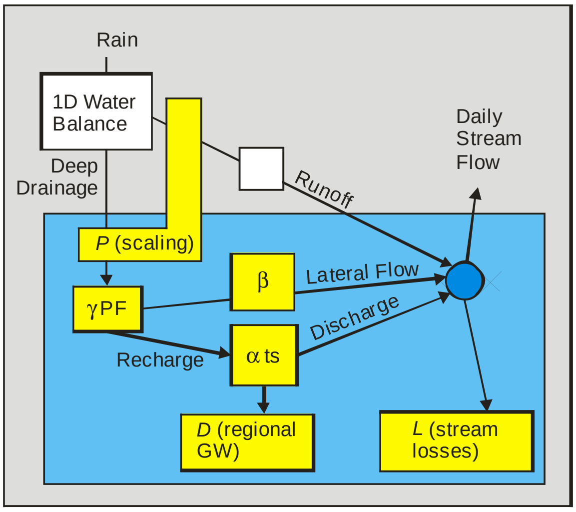

Figure 1: Simplified flowchart of conceptual model (calibration parameters shown in yellow).

3.1. Rainfall Scaling

There can be inconsistencies in the measured rainfall data used to drive the catchment runoff model; e.g. in parts of the Namoi (Croke *et al.* 2006, Herron & Croke 2007). This could be handled by changing rainfall in the 1-D water balance model, although due to long run times this would need to be a separate exercise. Instead, the groundwater module can allow for this with a scaling parameter (P), although it is likely that it will be set P=1 in most catchments. The groundwater module uses P to scale deep drainage and runoff from the lumped 1-D Water balance models:

$$DD = DD_{1D} * P \quad , \qquad (1)$$

$$RO = RO_{1D} * P \quad , \qquad (2)$$

where DD_{1D} is the lumped deep drainage output from 1D water balance models, DD is the deep drainage used by the module, RO_{1D} is the lumped runoff output from 1D water balance models, and RO is the lumped runoff used by the module. If calibration/optimisation leads to a value of P which is not close to unity, it is likely that the re-running of the 1-D Water balance model with modified rainfall would be undertaken.

3.2. Sub-surface Partitioning Factor

DD is split into lateral flow, and groundwater recharge using a partitioning fraction (PF). PF is determined using the method of Rassam & Littleboy (2003), which was also used in the 2CSalt model (Stenson *et al.* 2005). The partitioning can also be scaled using γ (calibration parameter) if desired:

$$R = DD * \gamma\, PF \quad , \qquad (3)$$

$$LF = DD * \gamma\, (1 - PF) \quad , \qquad (4)$$

where R = groundwater recharge; LF = lateral flow (shallow subsurface); $0<PF<1$; γ = calibration parameter.

3.3. Groundwater delay

A linear-storage-discharge relationship is used to predict groundwater response at a sub-catchment level. A groundwater storage term (V) is calculated for each time-step but this is used to provide the response only, and is not meant to be considered explicitly.

$$D_{GW}(t) = \alpha * 1/t_s * (R(t) + V_{GW}(t\text{-}1)) \qquad [V_{GW}>=0] \quad , \qquad (5)$$

$$V_{GW}(t) = V_{GW}(t\text{-}1) + R(t) - D_{GW}(t) \qquad , \qquad (6)$$

where t is time; D_{GW} = Groundwater discharge to river (ML/day); α = calibration parameter; R = Recharge (ML/day); V_{GW} = storage term; t_s = groundwater timescale (day).

The groundwater timescale is determined in a similar manner to the BC2C model (Gilfedder *et al.*, 2009). This uses the idealised groundwater analogue that was developed by Walker *et al.* (2005), which captures some of the features of real, sloping aquifer systems (see Fig. 2). It provides a simple approach for estimating the response of aquifers to changes in recharge, and for predicting the time-scale between changes in recharge and subsequent changes in discharge.

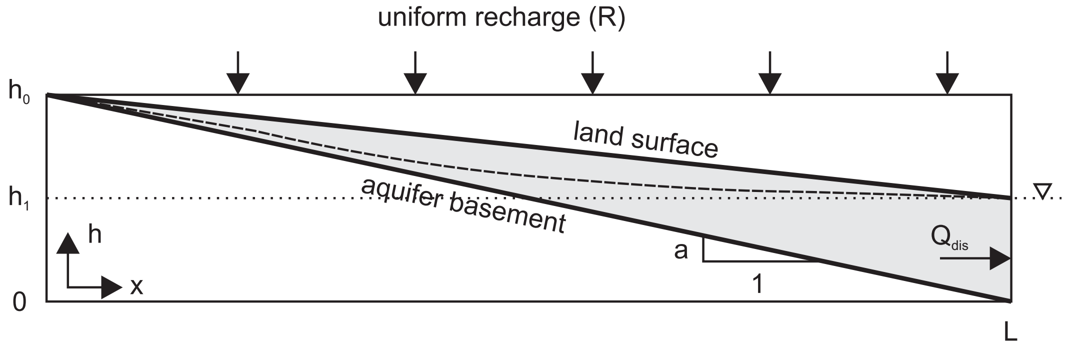

Figure 2: Idealised groundwater analogue of sloping aquifer, with surface head drop (h_0-h_1) over the flow length (L), and aquifer thickness at the outlet (h_1). [from Walker *et al.* (in prep)].

Much of the literature on flow over sloping beds have a full-thickness seepage face as the downstream-end boundary condition (e.g. Schmid and Luthin 1964, Childs 1971, Towner 1975, and more recently Verhoest and Troch 2000). This leads to a convex groundwater profile. The method in Walker *et al.* (in prep) maintains the constant head boundary at the land surface at the aquifer outlet – mimicking a river overlying a thick and saturated zone. This boundary condition tends to result in a concave groundwater profile.

While the extended Dupuit-Forchheimer assumption of streamlines parallel to the bed is typically used for modelling flow over sloping beds (e.g. Wooding and Chapman 1966, Childs 1971), Chapman (1980) considered that the horizontal streamline assumptions remained satisfactory up to a bed-slope of at least 10 degrees. Henderson and Wooding (1964) provided a solution for groundwater discharge from a steeply sloping aquifer using the classical Dupuit-Forchheimer assumption of horizontal streamlines. In Walker *et al.* (in prep) the mathematics is modified to allow for the inclusion of much flatter aquifers – with a focus on estimating changes in groundwater flux to a stream.

$$t_s = S\,L\,/\,2\,K\,a \quad , \qquad (7)$$

$$a = (\Delta h+d)/L \quad , \qquad (8)$$

where S = storativity; L = groundwater flow length (m); K = saturated hydraulic conductivity (m/day); a = aquifer basement slope ($a = h_0/L$); Δh = change in elevation of land surface (m); d = aquifer thickness (m).

The calibration parameter (α) is applied globally, while the t_s is calculated for each individual sub-catchment. Thus, the variability of groundwater responses across the catchment is maintained, but can be adjusted to provide a better fit to gauged information.

3.4. Lateral Flow delay

The module uses a linear-storage-discharge relationship to predict lateral flow response. A storage term (V_{LF}) is calculated for each time-step but this is used to provide the response only, and is not considered explicitly.

$$D_{LF}(t) = \beta * (LF(t) + V_{LF}(t-1)) \quad [V_{LF}>=0] \quad , \qquad (9)$$

$$V_{LF}(t) = V_{LF}(t-1) + LF(t) - D_{LF}(t) \quad , \qquad (10)$$

where D_{LF} = Lateral Flow discharge to river (ML/day); β = calibration parameter; LF = lateral flow input (ML/day); V_{LF} = storage term.

3.5. Losses

In addition to the groundwater and lateral flow delays, the module will allow for three different types of "loss". This can be used to help match low-flow periods, and are:

1) Recharge to deep regional groundwater (*D*) (i.e. discharge not seen at stream gauge). Not all recharge appears as stream flow (e.g. recharge to regional GFS, which may discharge much further away in the catchment, or directly to ocean).
2) Losses from stream itself (*L*). This can be used to improve the modelling of zero-flow periods, in areas which are losing streams. It provides the capacity to model losing streams, including no-flow periods that are likely to occur after prolonged dry periods.
3) Groundwater pumping. Additional losses occur in areas with extensive groundwater development. These losses are calculated using classical stream depletion models (e.g. Glover and Balmer 1954) which require knowledge of pumping rates, distance of bore from stream/gauge, and aquifer parameters. The module recognises both local and regional impacts of pumping, depending on the depth of the bore.

3.6. Modelled Streamflow

The modelled streamflow will be:

$$Q = D_{LF} + D_{GW} + RO - D - L \quad , \qquad (11)$$

where Q = streamflow (ML/d); D_{LF} = discharge to stream from "lateral flow"; D_{GW} =discharge to stream from groundwater; RO = runoff (ML/d) (from water balance model), D = loss to deep groundwater, L = stream loss. The following section compares the modelled predictions to measured flows.

4. APPLICATION TO TARCUTTA CATCHMENT

Tarcutta Creek is part of the Murrumbidgee catchment in the South West Slopes area of NSW, Australia. The *Tarcutta @ Old Borambola* gauging station (410047) is unregulated, and has a contributing area of 1630 km^2, an estimated "forest cover" of 32%, and an annual rainfall range of approximately 580-1200 mm (Gilfedder *et al.* 2007). At this gauge, the river is a perennial connected-gaining stream, with limited groundwater extractions. For the model runs, the catchment was broken into 81 sub-catchments, each with an individually estimated t_s which in this case ranged between 0.8 yr and 176 yr (median=6 yr, mean=17 yr).

The catchment was chosen for the initial application as it has been used for previous modelling work, and the climate / land-use / soil datasets were already assembled for the 2CSalt project (Gilfedder *et al.* 2007). Since the 2CSalt model operated at a monthly time-step, the initial modelling runs were also carried out monthly. Daily flows were obtained from the NSW Government (2008) and summed to give monthly flows for this preliminary application.

4.1. Preliminary application: Monthly Flows

As an initial test of the module, we used a monthly time-step for the period 1960-1990, and compared this to gauged flow data for the period 1980-1990. This allowed a 20 year warm-up period – important for the groundwater storages to move towards a dynamic equilibrium.

Preliminary monthly runs were undertaken using a spreadsheet version of the module for Tarcutta (see Fig. 3 and 4). The spreadsheet's solver was used to find a value of α with the least mean sum of the square of the differences between modelled and observed (α=160), while the other parameters were kept fixed (β=1, γ=1, P=1, D=0, L=0). No weightings were used to remove the bias towards high flows.

The main aim with the monthly modelling was to make sure that the mechanics of the module were working. The match between modelled and observed was excellent (note the y-axis is a LOG scale), although we recognise that modelling monthly flows is easier than daily flows.

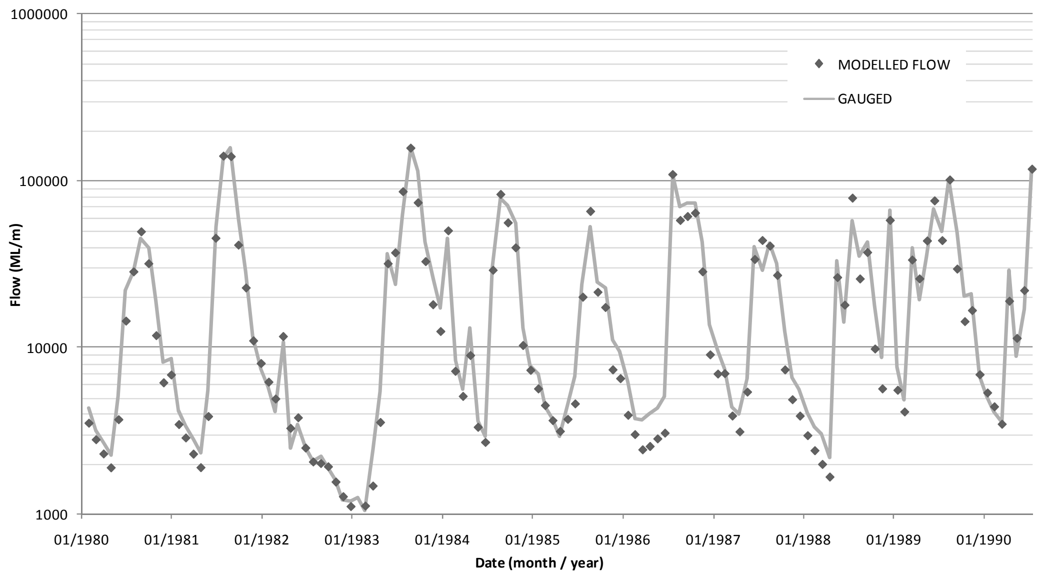

Figure 3: Monthly flow (modelled and observed) (α=160, β=1, γ=1, P=1, D=0, L=0) [note log scale].

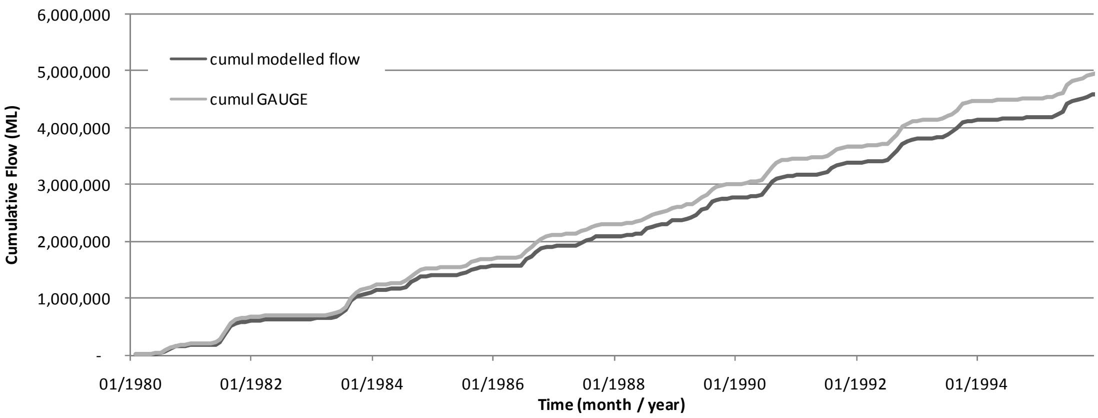

Figure 4: Cumulative flow (modelled and observed) (α=160, β=1, γ=1, P=1, D=0, L=0).

FURTHER DEVELOPMENTS AND CONCLUDING REMARKS

A module has been developed which combines the water-balance terms from 1-D modelling, explicitly includes variation in groundwater delays across the modelled area, and can be calibrated to fit daily gauged flows. This module is intended to improve prediction of low-flows, and to provide input to regulated river models, as part of the WaterCAST model.

The code has already been adapted to allow its calibration parameters to be optimised using PEST (Doherty 1994), although we have not undertaken the runs yet. Work will be undertaken to investigate different objective functions, which place emphasis on low flows.

The work is currently in progress – and future efforts are directed towards:

- Parameterisation / optimisation using different objective functions with PEST
- Application across multiple catchments – to provide guidance on parameterisation
- Revision of the calibration parameters – and fixing or removing some if possible.
- Implementation of groundwater pumping impacts calculations.

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