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Analysis of process controls on streamflow response in an Australian tropical catchment

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Abstract This study investigates the dominant processes that may be responsible for the observed streamflow response in the Seventeen Mile Creek, a tropical catchment of Northern Territory, Australia. To achieve this, the available rainfall and runoff data from this catchment are analysed through the systematic development of rainfall–runoff models of appropriate complexity, by means of the "downward or top-down approach". We start with simple model constructs, and progressively increase model complexity and improved process representation, and at each step of the way, the predictions of the models are evaluated against signatures of observed runoff variability, using standard measures of goodness of fit. This systematic examination of observed streamflow variability leads to considerable physical insights into the dominant process controls, and can be extremely valuable towards the choice and development of models of appropriate complexity. The results obtained from this modelling study show that the soils within the catchment have a high storage capacity, which contributes to a significant fraction of delayed runoff, whereas saturation excess overland flow occurs only after heavy rainfall events during the wet season. Sensitivity analyses have been conducted to determine the effects of interactions between soil depth and temporal rainfall variability on the runoff regime. They show that on the one hand the catchment total runoff is more sensitive to rainfall variations than to soil variations, while on the other hand the runoff components appear more influenced by soil depth changes.

Key words bucket model; downward approach; hydrological process; tropical catchment; ungauged basin

INTRODUCTION

Modern society is starting to require more and more accurate streamflow predictions in order to guarantee sustainable environmental management, and to prevent and control natural disasters such as floods and droughts. Unfortunately, drainage basins in many parts of the world are ungauged or poorly gauged, and their hydrological behaviour is poorly understood. The application of many hydrological models for predictions in poorly gauged and ungauged basins suffers from structural arbitrariness and over-parameterization (Klemes, 1983), resulting in the problem of equifinality (Beven, 2002, 2005). In this context, systematic analysis of any available data in data-poor regions can yield valuable insights into the dominant processes governing catchment streamflow response, and can assist in the development of parsimonious, physically realistic models that can be used in predictions. The downward or top-down approach (Sivapalan & Young, 2005) represents a model-based approach to insightful analysis of observed rainfall–runoff behaviour. It involves starting with simple models that directly link rainfall to runoff at the time and space scales of interest, and then increasing the complexity of the model through systematic and step-by-step incorporation of appropriate process descriptions at progressively smaller scales, in this way identifying the sources of observed variability in the streamflow regime (Klemes, 1983; Wittenberg & Sivapalan, 1999; Jothityangoon *et al.*, 2001; Atkinson *et al.*, 2002; Farmer *et al.*, 2003). In this case, the models that are chosen are of the conceptual or bucket model type (Manabe, 1969; Milly, 1994a,b), which are often sufficient to explain observed patterns of streamflow response. These models, being lumped or semi-distributed, are characterized by small number of parameters which retain a conceptual/physical meaning even though they cannot always be directly measured in the field.

The present article proposes the application of the downward approach to gain insights into the dominant runoff generation processes within Seventeen Mile Creek, a tropical catchment located in Northern Territory, Australia. The available hydrological information is first analysed to obtain a preliminary indication about the physical processes that underlie the observed streamflow response. Subsequently, standard application of the downward approach is adopted to derive the structure of the bucket model of appropriate complexity.

The results from this study will provide an improved insight into the hydrology of this region, and the hydrology of tropical catchments in general. Moreover, the possibility to identify key hydrological features in tropical catchments, combined with similar studies from other catchments around the world, may contribute to our efforts at a rational classification of catchments for regional hydrological studies and predictions, which is an acknowledged aspect of the PUB initiative (McDonnell & Woods, 2004).

THE STUDY CATCHMENT

Seventeen Mile Creek is a tributary of Katherine River, in the Northern Territory of Australia. The study catchment is part of the Nitmiluk National Park and has an area of 619 km^2 at Waterfall View, where a discharge gauging station, which collected data from 1 October 1975 to 30 September 1994, is located. Over the same time span, rainfall data were monitored by the Northern Territory Department of Infrastructure, Planning and Environment (DIPE), using two raingauges (Fig. 1): the first at Below Falls (DIPE code R8140160), and the second at Upper Catchment (DIPE code R8140159). As both the rainfall time series are affected by missing and poor quality data, as described by the DIPE, a single more reliable composite series was obtained from them and used in this study. The climate of the region is monsoonal, with 90% of the rainfall falling between October and April, called the wet season.

Potential evapotranspiration (*pet*) data at the daily time scale was provided by the Bureau of Meteorology of Australia from three stations located within a 200 km radius from the watershed barycentre, namely: Mango Farm, Wooliana and Douglas, and at

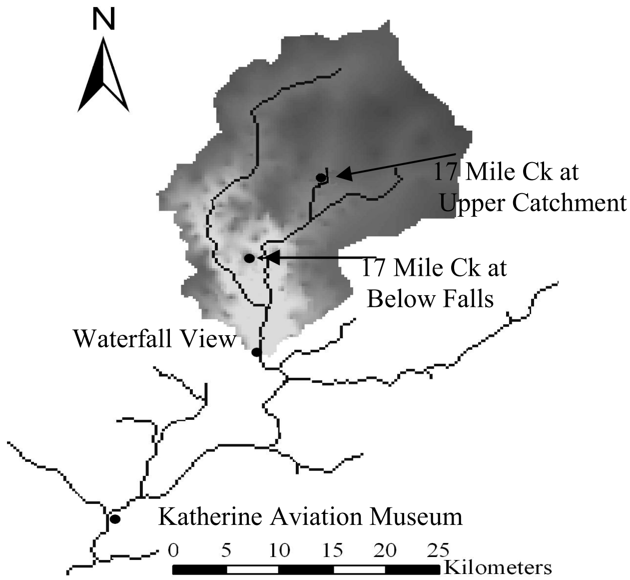

Fig. 1 Seventeen Mile Creek catchment.

Katherine Aviation Museum, used to rescale the data from the other three. The daily data are then downscaled to the hourly ones by assuming that the hourly *pet* is constant within each day. The mean annual *pet*, over the considered observation period, is 2295 mm and does not change markedly from one year to another. On the other hand, annual rainfall and runoff experience a significant inter-annual variability.

PRELIMINARY ANALYSIS OF THE RAINFALL AND RIVER FLOW REGIME

Following the downward approach, a detailed analysis of the time series of the main hydrological variables was carried out first. The framework of the Budyko curve (Budyko, 1974) was used to represent the annual water balance of the catchment, and to identify anomalous years. The index of aridity (the ratio of annual potential evapotranspiration to annual precipitation) varies from 1.2 to 3.5 and on this basis the catchment can be classified as arid. The ratio of annual evaporation to annual rainfall varies between 0.7 and 0.95, as expected in monsoonal climatic regions.

Further analysis revealed that the monthly (within-year) variations of potential evapotranspiration and rainfall were opposite in phase. Figure 2 shows the progress of cumulative rainfall and runoff over one hydrological year, which is assumed to begin on 1 October, the month with the lowest runoff value. Although rainfall falls from the beginning of the wet season, the river flow commences only after 2 or 3 months (slightly different delays are experienced in different years). This behaviour reveals a variable initial water deficit and suggests that the surface runoff generation is probably dominated by saturation excess. Moreover, although there is no rainfall during the dry season, small but significant flows are also observed over this period. This delayed hydrological response is probably due to water storage within the Cretaceous deep aquifer that underlies the catchment.

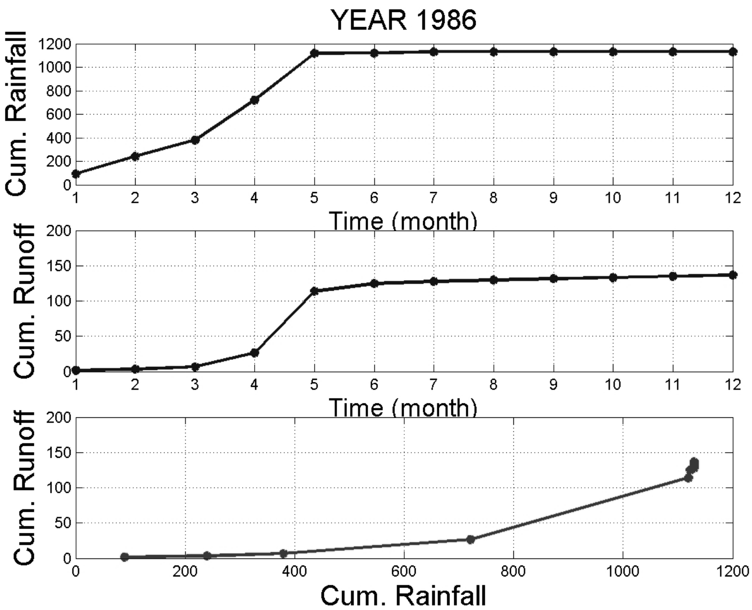

Fig. 2 Cumulative plots of monthly rainfall, river discharge and their ratio for the year 1986.

On the basis of the preliminary analysis above, it was concluded that a model for Seventeen Mile Creek should be able to account for delayed runoff, considering that the water storage operating within the catchment is significant. Moreover, the runoff generation model was deemed to be of the saturation excess type. This intuition was later confirmed by the first modelling attempt in which a Hortonian runoff excess model was examined without satisfactory results.

MODEL DEVELOPEMENT

The hydrological model for the Seventeen Mile Creek catchment was developed starting from a single bucket model. Model complexity was increased in subsequent steps when deemed necessary to match the signatures of observed streamflow variability, and also ascertained by means of the Nash & Sutcliffe (1970) coefficient of efficiency.

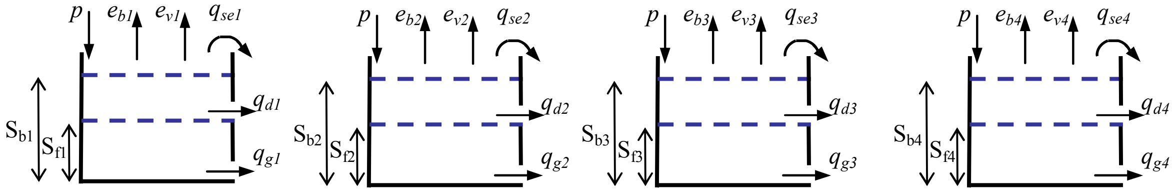

Fig. 3 Model structure: four buckets in parallel. Precipitation, saturation excess runoff, delayed runoff and groundwater flow, bare soil evaporation and vegetation transpiration are evaluated at each time step *t*.

After having implemented a series of alternative model structures (details not included here for reasons of brevity), a four bucket model was finally selected (Fig. 3) which accounts for: the precipitation $p(t)$ (mm h^{-1}), saturation excess overland flow $q_{se}(t)$ (mm h^{-1}), delayed runoff $q_d(t)$ (mm h^{-1}), and deep groundwater flow $q_g(t)$ (mm h^{-1}). Evapotranspiration is divided into bare soil evaporation $e_b(t)$ (mm h^{-1}) and transpiration $e_v(t)$ (mm h^{-1}). These are computed depending on the potential evapotranspiration over the watershed and the water content in each reservoir (see Jothityangkoon *et al.* (2001) for further details). In summary, the finite difference form of the water balance equation has the following expression:

$$\frac{\Delta s(t)}{\Delta t} = p(t) - q_{se}(t) - q_d(t) - q_g(t) - e_b(t) - e_v(t) \tag{1}$$

where $s(t)$ (mm) is the water stored in the bucket at time t. Each bucket is modelled separately and assumed to equally contribute to runoff generation (Atkinson *et al.*, 2003). In particular, saturation excess overland flow occurs only when the maximum soil water capacity of a bucket, S_b (mm), is exceeded and it is computed by the following expression:

$$q_{se}(t) = \left(s(t) - S_b\right)/\Delta t \qquad \text{if} \quad s(t) > S_b \tag{2}$$

A first guess value for S_b is obtained, for each bucket, by multiplying the corresponding mean soil depth, D (mm), by the mean soil porosity, φ [-]. Initial values of these two parameters are estimated on the basis of available qualitative information about the soil type over catchment portion covered by each bucket. Subsequently, they are manually adjusted (calibrated) to better simulate the observed discharge at annual, monthly and daily scales, and the final values are reported in Table 1. The initial soil water storage is calculated via an iterative procedure, requiring that its value at the end of the complete simulation cycle (after all considered year series) is equal to the initial value. This assumption appears reasonable as the dry season tends to completely dry the soil, thus almost no carry-over is recorded from one year to the subsequent one. The groundwater flow is computed at each time step by dividing the water storage by a time scale parameter related to the deep groundwater response. On the other hand the appropriately named delayed runoff $q_d(t)$ is described by a nonlinear function of storage, characterized by a threshold storage value s_f (mm), and two parameters a and b; the resulting relationship is given by:

$$q_d(t) = \left(\frac{s(t) - s_f}{a}\right)^{\frac{1}{b}} \qquad \text{if} \quad s(t) > s_f \tag{3}$$

The threshold s_f (mm) is obtained by multiplying the soil depth D by the soil's field capacity f_c [–]. The parameters a and b are estimated from analysis of streamflow recession curves using the methods of Wittenberg & Sivapalan (1998) and Atkinson *et al.* (2003). The formulations of bare soil evaporation and transpiration are taken from Jothityangkoon *et al.* (2001), and are not repeated here, again for reasons of brevity. It is worth pointing out that only parameters D and φ strongly influence the runoff generation process and they both have a strictly physical meaning, inferable from the available knowledge of soils. Parameter f_c also plays a relevant role at smaller

Table 1 Parameters values for the model.

Type of soil	*D* (mm)	φ (–)
1	900	0.15
2	3500	0.37
3	1800	0.28
4	2500	0.27
mean	2175	0.27

time scales, while the other parameters are used only to refine the hydrograph representation at daily scale.

RESULTS AND DISCUSSION

The model provides good fit with the observed values as represented in Figs 4 and 5 for the annual and daily scales, respectively. As only a single rainfall time series is available in the catchment and due to the scarce information on channel hydraulic characteristics of the basin, no routing is implemented in the model to increase the temporal resolution up to hourly scale, because the uncertainty in the observed data is believed not to permit finer representation. The hourly predictions then are aggregated to daily values and the Nash-Sutcliffe efficiency is calculated at the daily time step over the whole period, yielding a value of 0.72. Focusing on results of individual years, the best fit is obtained in years with high runoff, whereas the model does less well in years having low flows. In the latter case, inaccuracy due to missing or inadequate data is the dominant cause and compromises the results. However, it is important to note that in spite of this the model produced satisfactory efficiencies with minimal calibration. This suggests that the model is sufficient to identify the most important runoff generating mechanisms in this catchment, while more complex models might lead to considerable equifinality (Beven, 2002), in that they can induce erroneous conclusions with the model performances that might seem apparently satisfactory.

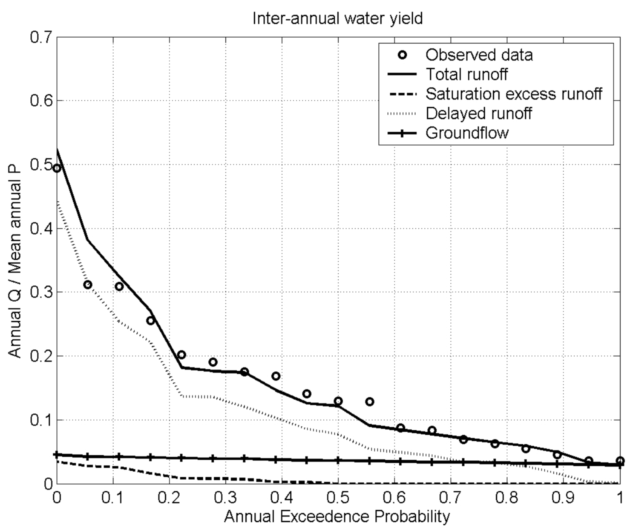

Fig. 4 Model results at annual time scale.

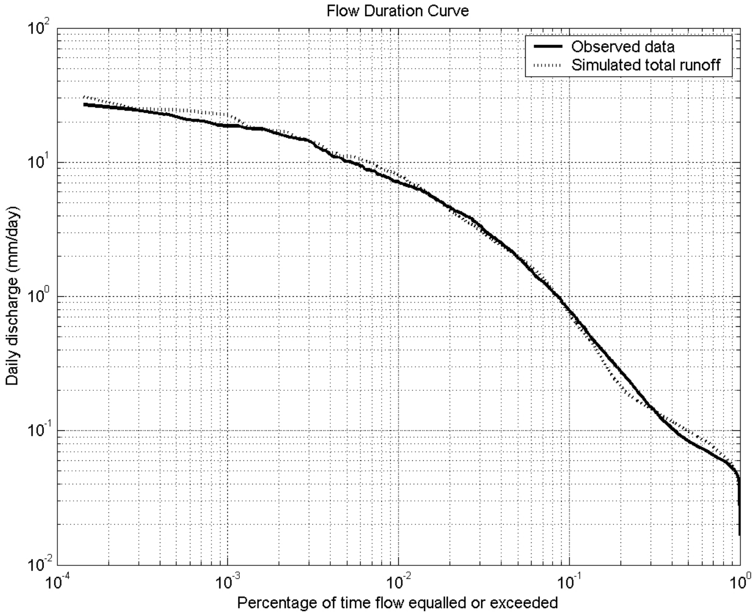

Fig. 5 Model results at daily time scale.

According to Fig. 4, the chosen multiple bucket model clearly highlights the importance of delayed runoff in the study catchment, whereas saturation excess runoff occurs only during heavy rainfall events. In fact, although the surface soils are thin, the presence of local deep aquifers, swampy areas, and the limited slope of the catchment tend to increase storage effects and generally contribute to the occurrence of delayed runoff.

Investigation of anomalous years

Despite having the same annual cumulative rainfall, some years display markedly different cumulative runoff. After more detailed analysis that included the examination of rainfall in the preceding years and seasons, we concluded that the reason for such variable hydrological behaviour must be sought in the characteristics of the temporal rainfall pattern occurring during each year. In fact, by considering the daily rainfall plots of 1977 and 1990 for example, we notice that the rainfall in 1977 occurs in the first part of the wet season, when the potential evapotranspiration is high and rainfall is sparsely distributed in time. This means that both the storage capacity and the threshold of delayed runoff generation can hardly be reached and therefore less runoff occurs. On the contrary, in 1990, which experienced the same annual precipitation as 1977, the major rainfall events occurred over a much shorter time span and therefore the above mentioned thresholds were easily reached.

Investigation of the effects of storminess

In order to better investigate the effects of rainfall temporal distribution, the bucket model is run for all the observation periods by feeding it with just one synthetic rainfall event per year. For such events a constant rainfall input is used which is supposed to last 100 days, with a total rainfall amount equal to the corresponding annual precipitation. The above described synthetic rainfall event is supposed to begin: (a) at the beginning; (b) in the middle; or (c) at the end of the wet season. The results show that case (c) generates the highest river discharge because of the decreasing trend of the potential evapotranspiration, reaching its lowest value at the end of the wet season. This result confirms that the temporal distribution of rainfall within the year plays a significant role in the streamflow generation response.

Sensitivity analysis

In order to understand the role played by selected model parameters in the streamflow generation response, the model is run over the whole observation period with three different scenarios: (a) decreasing the soil depths to 50%; (b) increasing the soil depths up to 200%, (c) decreasing and increasing rainfall depth up to 50%, in steps of 10%.

Decreasing the soil depths lowers the water storage capacity of the soil, leading to an increase of the saturation excess runoff and reducing the groundwater flow and delayed runoff, without affecting the annual and monthly cumulative river discharges. On the contrary, when the soil depth is significantly increased, the greater amount of water stored in the soil induces a decrease in the river discharge that is visible even at annual time scale, in part due to the augmentation of evapotranspiration. This latter consideration is not valid during dry years, when the saturation excess flow would not occur anyway, while the groundwater flow is increased due to the effects of the augmented water storage capacity of the soil. Rainfall depth variations cause corresponding generated runoff changes, which are more evident for saturation excess overland flow and for delayed runoff than to groundflow, but no compensation effect occurs between runoff components.

CONCLUSIONS

Using the “downward approach”, a parallel four bucket model is developed for a catchment in the Northern Territory, Australia and is then used to gain insights into the hydrological behaviour of the basin. In particular, delayed runoff, caused by the water retention within rock aquifers, is found to be the most important runoff generation mechanism in the basin. Saturation excess overland flow occurs only during high rainfall events in the wet season and cannot be caused by the underlain aquifer, which is known to release a smaller quantity than the one recorded here. Groundwater flow, released from the underlying Cretaceous aquifer, causes the water to flow for the entire dry season. The initial water deficit within the catchment at the beginning of the wet season is the reason for the 2–3 month delay in runoff initiation.

The bucket model is used to perform a sensitivity analysis with regard to soil depth, rainfall depth and rainfall occurrence. In the case of total volume of runoff generation, as long as the heterogeneity of the soil is respected, the catchment is more sensitive to rainfall variations, than to soil variations. This seems to be reasonable in tropical regions where the rainfall intensity is higher than in other climates. On the other hand, when it comes to the partitioning of the total runoff into its components, the catchment is more sensitive to soil depth.

Finally, anomalies in annual runoff are considered, with a comparative analysis of years in which the annual precipitation is the same, but recorded runoff is considerably different. This study showed that the cumulative runoff in the catchment was not dependent on previous dry season precipitation and runoff, but only on precipitation intensity and its occurrence within the present year. The same amount of rainfall in fact, produces higher runoff if it happens in a shorter period of time, allowing the storage capacity and/or the soil-water storage at field capacity to be exceeded. If it occurs later in the wet season, the potential evapotranspiration decreases, being opposite in phase with the rainfall, and hence more rainfall is converted into runoff. In conclusion, by implementing a simple bucket model, important features of the catchment behaviour have been highlighted, which permitted deeper knowledge and understanding of tropical basins in the Northern Territory of Australia. It is hoped that the knowledge and process understanding that has been gained can be used to characterize runoff generation behaviour elsewhere in this region, and to extrapolate to similar but ungauged basins in other similar regions of the world.

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