Spatial disaggregation of catchment scale fluxes

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Abstract: Topography is an important physical driver of the hydrologic response of a catchment. Several topographic wetness indices have been used to relate different landscape elements to catchment behaviour. However, these methods do not take into account the effects of landuse, soils and climate without the use of a fully distributed model. A new downscaling method is presented that can be applied easily to spatially disaggregate catchment scale fluxes by taking into account the effects of topography, landuse, soils and climate. Total runoff at the outlet of the catchment can be partitioned into surface runoff and groundwater discharge. The surface runoff component can then be attributed to different landscape elements by combining the following using a downscaling procedure that conserves the mass under current conditions: (a) runoff efficiency for each landuse and soil type, (b) area under each landuse, and (c) topographic location. The runoff efficiency is defined as the ratio of long-term mean annual runoff comprising overland flow, shallow sub-surface flow and lateral throughflow from a given landuse compared with that from areas under annual pasture. Using an analogous procedure and by replacing runoff efficiency with the recharge efficiency, groundwater flow from the catchment can also be attributed to different landscape elements. The runoff and recharge efficiencies can be obtained either from the current knowledge of farming systems or from process modelling or both. The method can then be used to evaluate the effects of landuse change on flow at the catchment outlet. Implementation of this method is demonstrated on the Little River catchment located in the Macquarie Basin, New South Wales.

Keywords: *Landuse; Runoff; Topographic Wetness Index; Modelling*

1. INTRODUCTION

Investigation of vegetation effects in the atmosphere-soil-vegetation continuum on catchment scale water balance has been a subject of extensive observation and modelling across the world for many years (Vertessy et al., 1996). Process based one dimensional water balance models such as PERFECT (Littleboy et al., 1992) have been used in a GIS framework to investigate the effects of soils, landuse and land management practices on the near surface soil moisture dynamics and water balance components (eg. Ringrose-Voase and Cresswell, 2000). However, there is often a mismatch between the catchment scale fluxes and those obtained in a purely vertical analysis due to scale effects and no accounting for the lateral fluxes.

In upland areas with moderate to steep slopes, topography is an important variable that, in conjunction with the spatial distribution of soil types and landuse, affects water balance and the magnitude of lateral fluxes. Several topographic indices relating landscape position to surface and sub-surface runoff are commonly used (eg. Roberts et al., 1997). The most commonly used index is called the wetness index or the compound topographic index CTI (Beven and Kirkby, 1979) that can be used to quantify runoff potential of different landscape elements. This index can be used to relate depth of the (perched) water table at any location in the catchment to mean depth of the (perched) water table over the catchment. The wetness index incorporates the effect of topography but commonly does not account for the effects of soils and landuse. Therefore, a common situation encountered in catchment scale modelling is either inadequate accounting of the scale effects and lateral fluxes or inadequate accounting of the soil and vegetation effects. This paper describes a new downscaling methodology that accounts for topography as well as the effects of soils and vegetation in attributing runoff and recharge to different source areas.

2. MODELLING METHODOLOGY

2.1. Overview

The modelling methodology used in this study is based on the techniques developed in CATSALT version 1.5 (Vaze et al., in press; Tuteja et al., in press). A lumped rainfall runoff model SMAR (Kachroo, 1992) is first used to predict streamflow at the outlet of the catchment. The SMAR model consists of a water balance component and a routing component. The model contains a total of nine parameters of which there are five water balance parameters and four routing parameters. The parameters of the model are calibrated using the Nash and Sutcliffe R^2 efficiency criterion. The calibration methodology forces mass conservation between the observed and the estimated streamflow. On the basis of a specified daily climate forcing (rainfall and pan evaporation) and the observed daily streamflow time series, the model structure allows for estimation of the catchment scale fluxes ie. surface runoff, groundwater discharge and evapotranspiration.

The distribution methodology described in Section 2.2 requires information on the relative effects of landuse representative over the range of soil types and climate zones on the surface runoff and groundwater discharge. Partitioning of the water balance components on a hillslope scale for a combination of soil types (usually 10-20), climate zones (usually 4-6) and slope classes (usually 4) is obtained using the Richard's equation based process model HYDRUS (Šimunek et al., 1999). A detailed description of the methodology for HYDRUS implementation is given in Tuteja et al. (in press).

2.2. Downscaling method

The downscaling method described here to spatially disaggregate surface runoff and groundwater discharge to different source areas is not necessarily restricted to the use of SMAR and HYDRUS. Any robust rainfall-runoff model can be used instead of SMAR for estimation of the surface runoff and groundwater discharge. Likewise any robust farming system model or expert knowledge or both can be used instead of HYDRUS.

From SMAR simulations the estimates of total daily-simulated streamflow Q(t) ($L^3.T^{-1}$), daily-simulated surface runoff $Q^r(t)$ ($L^3.T^{-1}$) and the daily-simulated groundwater discharge $Q^g(t)$ ($L^3.T^{-1}$) are available. Runoff is distributed on the basis of landuse and topography using the following methodology. Five dryland landuses are considered: trees, perennial pastures, annual pastures, cropping and other (eg. urban, wetland etc.). Surface runoff from the area under each landuse $Q_i^r(t)$ ($L^3.T^{-1}$) depends on area and the relative landuse efficiency of runoff generation.

$$Q_i^r(t) = \left(\frac{\dfrac{p_i}{\sum_{j=1}^{5} p_j} \cdot \dfrac{A_i^{T+\delta T}}{\sum_{j=1}^{5} A_j^{T+\delta T}}}{\sum_{k=1}^{5} \dfrac{p_k}{\sum_{j=1}^{5} p_j} \cdot \dfrac{A_k^T}{\sum_{j=1}^{5} A_j^T}} \right) Q^r(t) \qquad (1)$$

where, *i, j* and *k* refers to the landuse, A_i^T, A_j^T, A_k^T refers to the area under each *current* landuse in the catchment (L^2), $A_i^{T+\delta T}$ and $A_j^{T+\delta T}$ refers to the area under each *future* landuse change scenario (L^2), p_i , p_j and p_k refer to the runoff efficiency of landuses i, j and k relative to annual pasture (dimensionless).

The runoff efficiency p_i is defined as the ratio of long-term mean annual runoff from areas under landuse i compared with that from areas under annual pasture. The ratio $p_i/\Sigma p_j$, j=1,2,..5 incorporates the *scaled* effect of landuse i on runoff generation and the ratios $A_i^{T+\delta T}/\Sigma A_j^{T+\delta T}$, j=1,2,..5 and $A_i^T/\Sigma A_j^T$, j=1,2,..5 incorporates the *scaled* effect of the area under a specified future landuse change scenario at time T+δT and current landuse scenario T. When δT equals zero, the areas $A_i^{T+\delta T}$ collapse to the respective current landuse areas A_i^T. Under such conditions runoff volume conservation from the catchment is guaranteed ie. ΣQ_i^r, i=1,2,..5 equals $Q^r(t)$. However, under changed landuse scenario runoff volume will not be conserved (*eg.* if the area under annual pasture is changed to trees, the result is higher evapotranspiration and therefore a reduced runoff efficiency of trees relative to annual pasture).

The effect of landuse on the groundwater component can be estimated by substituting for p_i in (1), the efficiency of the landuse i to groundwater recharge with respect to annual pasture denoted by m_i (see Tuteja et al., in press). The effect of topography is introduced using the TOPMODEL wetness index (Beven and Kirkby, 1979) to disaggregate surface runoff within a given landuse:

$$y = \ln\left(\frac{a}{\tan\beta} \right) \qquad (2)$$

where, y = wetness index at a given pixel location (L), a = upstream contributing area at the given location per unit contour length (L), and tanβ = slope of the landscape at the given location (dimensionless).

Many schemes are available for calculating the upstream contributing area (*eg.* Quinn et al., 1991; Tarboton, 1997). Tarboton (1997) proposed a new multiple flow path algorithm, called the D∞ method, that performed better than most other methods. This method was used for estimating the upstream contributing area in this study.

The wetness index from (2) can be divided into *lmax* number of classes with a predefined uniform class interval. The wetness index for all pixel locations is disaggregated on the basis of landuse ie. a probability distribution function (pdf) of the topographic wetness index is constructed for each landuse by masking other landuses. Surface runoff $Q_i^r(t)$ obtained from (1) for each landuse i is then used to obtain surface runoff from each wetness index class l for the specified landuse area $Q_{il}^r(t)$ ($L^3.T^{-1}$) as in (3).

$$Q_{il}^r(t) = \frac{\sum_{p=1}^{p\max} y_{il}(p)}{\sum_{l=1}^{l\max}\sum_{p=1}^{p\max} y_{il}(p)} Q_i^r(t) = w_{il} Q_i^r(t) \tag{3}$$

where, $y_{il}(p)$ = wetness index of each pixel p within landuse i and wetness index class l, *pmax* = number of pixels within each landuse i and wetness index classes l, w_{il} = scaled wetness index of the wetness index class l and landuse i (dimensionless), *lmax* refers to maximum number of the wetness index classes.

Two basic assumptions are inherent in the above methodology. Firstly, the effects of non-linearity in the hydrograph due to climate effects are accounted for through SMAR. Therefore it is reasonable to use the efficiency values based on annual averages to incorporate the relative effects of landuse. Secondly, soil property variation affect partitioning of the vertical and lateral fluxes through the use of landuse efficiency parameters. These parameters vary spatially and temporally and their variations are available through HYDRUS. Even though these parameters are available, for practical reasons they are averaged in time and space within a sub-catchment.

3. STUDY AREA AND DATA

The Little River is located in the Macquarie catchment and contains streamflow data at three gauging stations (Figure 1). The catchment is divided into three sub-catchments: Little River at Obley (421048, 577 km^2), Buckinbah Creek at Yeoval (421059, 734 km^2) and the residual catchment (688 km^2) downstream of Obley and Yeoval and upstream of Arthurville (421176). Climate data for the period 1975-2000 (26 years) was used in both the modelling scales for consistency requirements. Four climate zones were used in the study: < 650 mm/y (zone A), 650-700 mm/y (zone B), 700-750 mm/y (zone C) and > 750 mm/y (zone D). Climate data was used at a 5 km grid and is sourced from the Silo database archived at Queensland Department of Natural Resources (Jeffrey et al., 2001).

Spatial distribution of the different soil types and the soil hydraulic properties were estimated using the methodology described by Murphy et al. (this issue). Proportions of different soil types in the Little River catchment are - Lithosols (5 percent), well drained Red Chromosols (34 percent), very leaky shallow Chromosols (8 percent) and Siliceous sands (18 percent) (Figure 5 from Murphy et al., this issue). Combination of these soil types on different slope classes results in larger leakage rates in the Little River catchment relative to the nearby Mandagery and Upper Castlereagh catchments (Tuteja et al., in press).

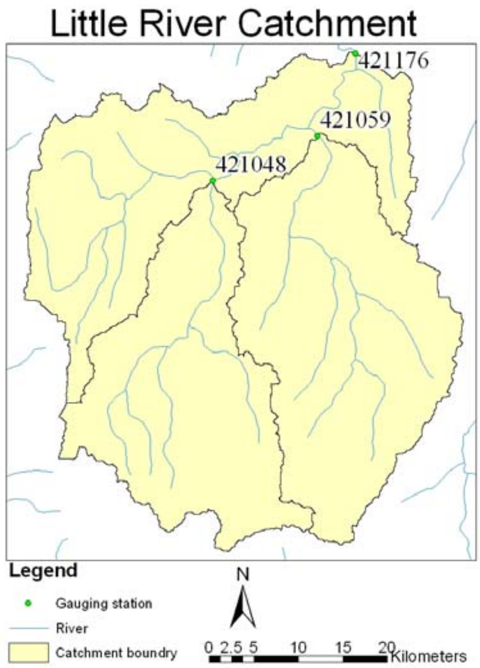

Figure 1. Map of the Little River catchment Little River at Obley (421048), Buckinbah Creek at Yeoval (421059) and the complete catchment at Arthurville (421176).

Four landuses were considered for modelling: trees, dryland cropping, annual pasture and perennial pasture (Figure 2). The landuse data is sourced from the Australian Landuse Classification System ALCC (Barson et al., 2000) and the DLWC Landuse maps for the catchment.

The spatial distribution of the wetness index, also known as the compound topographic index (CTI), was estimated from (2) for each landscape element and varies in the range 0-20 (Figure 3).

4. RESULTS AND DISCUSSION

4.1. Model setup and implementation

Hillslope scale modelling using HYDRUS was conducted for 14 soil types ranging from Siliceous Sands and Lithosols down to Chromosols and Sodosols. LAI used to partition potential evapotranspiration into potential soil evaporation and potential plant transpiration was obtained from the PERFECT model (Littleboy et al., 1992).

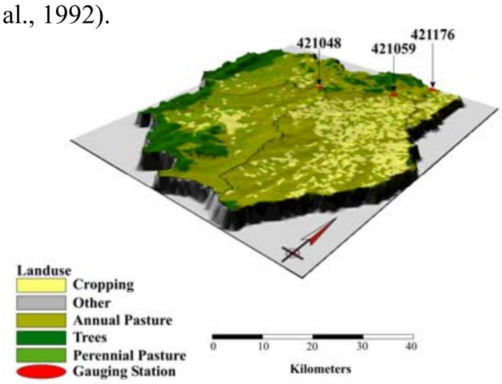

Figure 2. Landuse map of the Little River catchment. Sourced from Australian Landuse Classification System ALCC (Barson et al., 2000; Stewart et al., 2001).

The vertical domain modelled using HYDRUS in the case of pasture and cropping was 2.3m. Four soil layers used in the study were 0-20 cm, 20-40 cm, 40-70 cm and 70-230 cm. A free drainage boundary condition was used at the bottom of the soil profile. In the case of trees, simulations were adapted from the work done on Mandagery catchment located in the same physiographic region (Tuteja et al, in press).

The leakage rates under the soil profile are shown in Figure 4. Soils in the Little River catchment are in general leaky/permeable and in parts of the catchment where soils are formed over granites, leakage under the root zone leaves the catchment mainly through lateral saturated pathways. This is particularly true for the sub-catchment at Obley (421048) (Peter Baker, pers. comm.).

Hydraulic conductivity contrasts between the bottom soil layer and the underlying geology primarily initiates lateral flux below the root zone under variably saturated conditions. Average of the ratio of the saturated hydraulic conductivity of the deepest soil layer and the underlying geology for all soil types in the Little River catchment is about 11. Under unsaturated conditions, this ratio provides a measure of the anisotropy which is likely to vary between 1 and 5 (Khaleel et al., 2002).

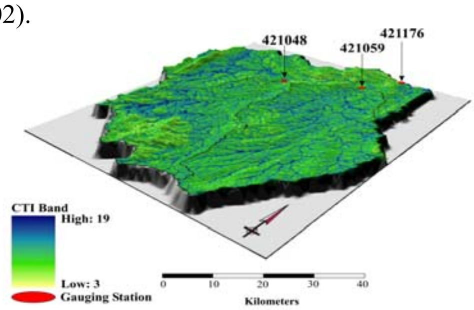

Figure 3. Wetness index map of the Little River catchment estimated from equation (2) and the D∞ method of Tarboton (1997).

Assuming a somewhat moderate anisotropy ratio of 4 for the Little River catchment, the recharge rate to the groundwater system for the sub-catchments at Obley, Buckinbah and the residual sub-catchment can be estimated (Table 1).

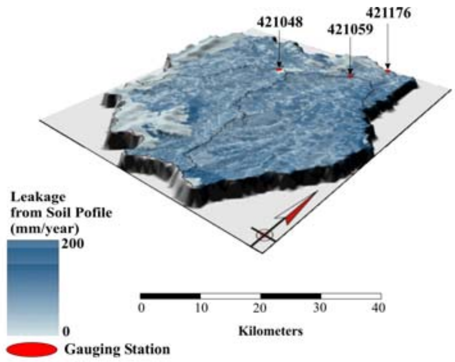

Figure 4. Leakage map of the Little River catchment estimated from HYDRUS simulations for 14 soil types, 4 climate zones and 4 landuses.

Daily surface and groundwater runoff was obtained from the sub-catchment scale modelling using SMAR (Table 1). The groundwater runoff for the sub-catchments obtained from SMAR match reasonably well with the groundwater recharge estimates from the hillslope scale modelling (with the exception of Buckinbah Creek at Yeoval, 421059). About 70 to 75 percent of the moisture leaking under the root zone is estimated to leave the catchment through lateral saturated pathways.

Table 1. Comparison of the mean annual fluxes from the hillslope scale and the catchment scale modelling (all fluxes in mm/y).

Hillslope scale modelling (HYDRUS)		Catchment scale modelling (SMAR)	
	Recharge	Surface runoff	Ground water runoff
421048	12.9	61.0	8.5
421059	22.9	26.5	13.8
Residual	12.1	32.9	8.9

4.2. Spatial Disaggregation of the runoff

The landuse efficiency parameters p_i and m_i for each landuse were averaged over the sub-catchments (Table 2). These were also compared with the respective values from the Mandagery catchment and other published data (Tuteja et al., in press).

Table 2. The runoff efficiency (p_i) and the recharge efficiency (m_i) obtained from this study and from the published data.

Trees	PP	Crop	Source
p_i	p_i	p_i	
0.5-0.67	0.6^{A}	1.19-2.31	Tuteja et al. (in press)
	0.71^{L}, 0.56^{P}, 0.44^{N}	2.4^{Y2} 1.6^{Y3}	Johnston et al. (1999)
0-0.2			Vertessy & Bassard (1999)
0.5-0.7	0.6^{A}	0.8-1.3	Ringrose-Voase & Cresswell (2000)
0.2^{A}	0.57-0.91	1.01-1.13	HYDRUS (this study)
m_i	m_i	m_I	
0-0.1	0.5^{A}	1.5-2.8	Tuteja et al. (in press)
0-0.3	0.5^{A}	1.0-2.6	Ringrose-Voase & Cresswell (2000)
0-0.1	0.25-0.52	1.17-1.38	HYDRUS (this study)

Note: - PP – Perennial pasture, L–Lucerne, P–Phalaris, N–Native, Y2/3–annual pasture followed by wheat in a 2/3 year crop rotation; A–assumed; simulated data from Ringrose-Voase & Cresswell is averaged across 20 soil types and 3 climate zones; parameters from Vertessy and Bassard (1999) obtained from equations 1 & 2; all HYDRUS results were obtained from this study.

Using the respective parameters p_i and m_i for each landuse with (1), (2) and (3) and the sub-catchment flux values from Table 1, the spatial disaggregation of the mean annual surface runoff for the entire Little River catchment can be obtained (Figure 5). The effect of tree cover and low CTI values can be seen on the runoff yield. Relatively high runoff values from the sub-catchment at Obley (421048) compared to the other two sub-catchments is because of higher mean annual streamflow that is enhanced by lateral throughflow from granites. The differences in runoff magnitudes at sub-catchment boundaries indicate the need for a higher CTI weighting in (1) compared to the landuse weighting. The effect of any landuse change scenario on catchment yield in a spatial context can easily be examined using (1-3).

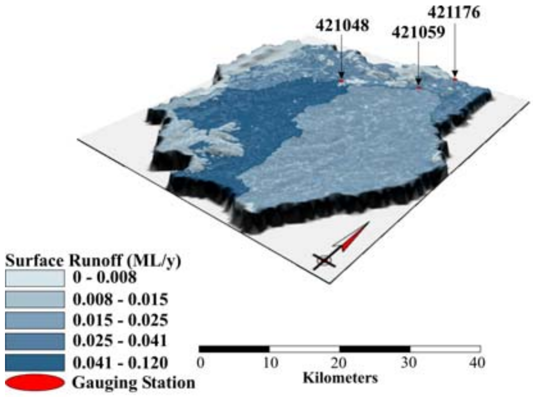

Figure 5. Spatial disaggregation map of the surface runoff (ML/y) for the Little River catchment.

5. CONCLUSIONS

A new and innovative method of disaggregating runoff at the sub-catchment outlet to different landscape elements is presented. The method allows for the scale effects and heterogeneity within the catchment by incorporating the effects of landuse, topography and soils. The proposed new algorithms enable effective transfer of information across the scale and warrant consideration. Implementation of the spatial disaggregation methodology guarantees mass conservation at the outlet of each sub-catchment.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge valuable contributions of the following: Allan Nicholson, Andrew Wooldridge, Brian Murphy, Guy Geeves, Peter Barker, Dugald Black, Darryl Lindner, Mark Littleboy, Paul Southwell, Lester Lynch and many staff from Central West Region, DSNR. Support of Peter Baker (BRS) is acknowledged. NSW Government funded the work under the Salinity Strategy.

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