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Delineating hydrologic response units in large upland catchments and its evaluation using soil moisture simulations

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A B S T R A C T

We present here a basis for delineating Hydrologic Response Units (HRUs) to capture heterogeneity in the catchment's topography, landforms and geomorphologic attributes. To delineate topologically connected HRUs, the catchment is divided into four landforms and sub-basins. These four major landforms represent macroscopic changes in the catchment landscapes, using thresholds derived from a range of terrain analysis techniques – the Cumulative Area Distribution (CAD) curve, average local slope, curvature, Compound Topographic Index (CTI) and the MultiResolution Valley Bottom Flatness (MRVBF) index. The adequacy of the HRUs delineation approach is ascertained by soil moisture movement modelling in the unsaturated zone based on a two-dimensional solution of Richards' equation, across multiple cross-sections of the catchment. The modelling results of the four landform delineated cross-sections are compared with those from the simplest case of a single landform delineated cross-section and with the most complex case of cross-sections divided on a pixel basis. The modelling results indicate gain in accuracy when using the four landform formulation compared to the use of a single landform, and little loss of accuracy compared to simulations on a pixel basis. This study investigates the stability of this HRUs delineation methodology using the data for the Maclaughlin, Bombala and Delegate catchments of the Snowy River at Burnt Hut, New South Wales, Australia.

1. Introduction

The minimum spatial resolution in catchment modelling which adequately represents the spatial heterogeneity of a catchment has received considerable attention in the literature (Bathurst, 1986; Bongartz, 2003; Flugel, 1995; Pierson et al., 1994; Reggiani and Rientjes, 2005; Singh and Woolhiser, 2002; Tao and Kouwen, 1989; Vieux, 1993; Wolock, 1995; Wood et al., 1988; Zhang and Montgomery, 1994). Bathurst (1986) suggested that the grid spacing and time step are the two most important structural parameters for a distributed hydrologic model application. It is desirable to make them both as large as possible to minimize computing requirements. At the same time, the larger the value assigned, the greater is the possibility of inaccurate representation of the catchment and its hydrological response. Bathurst (1986) used the SHE model on the Wye catchment of 10.55 km^2 area and suggested dividing the catchment into elements no larger than 1% of the total area to ensure that each element was more or less homogeneous.

The impact of spatial Digital Elevation Model (DEM) resolution on simulations was explored by Tao and Kouwen (1989) with 5 km × 5 km and 10 km × 10 km grid cell sizes in the 3520 km^2 Grand River catchment in Canada, finding that changes in grid size had no significant effects on model results. Bruneau et al. (1995) analyzed the impact of spatial resolutions using TOPMODEL (Beven and Kirkby, 1979) on the 12 km^2 Coetdan experimental catchment in France with input derived from a DEM. They suggested that the 50 m grid cell size is the optimum size for hydrologic modelling. Vieux (1993) investigated DEM aggregation and smoothing effects on surface runoff modelling and found that errors are propagated if the apparent slope is flattened or the flow path is shortened. Zhang and Montgomery (1994) investigated the effect of DEM grid size on the portrayal of the land surface and hydrological simulations on the Mettman Ridge (0.3 km^2) and Tennessee valley (1.2 km^2) catchments in the United States. For both the catchments, they found that the DEM grid size significantly affects computed topographic parameters and the simulated hydrographs. They suggested that a grid size smaller than the

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hillslope length was necessary to adequately simulate the hillslope hydrological processes. In a recent paper for selected flat wetland areas in the Murray basin in South-Eastern Australia, Vaze et al. (2010) demonstrated that the topographic information obtained from a high resolution Lidar (1 m) and its aggregation (2, 5, 10 and 25 m) exhibit greater accuracy than the 25 m resolution contour derived DEM. However, the availability of high resolution Lidar data is limited, particularly in steep areas and thus not considered as an alternative for the results presented here.

Wood et al. (1988) introduced the concept of Representative Elementary Area (REA) in the context of hydrologic modelling at the catchment scale in the USA. The investigation focused on the Coweeta River experimental catchment (17 km^2). For modelling the hydrologic response they used the TOPMODEL and concluded that REA exists in the context of catchment hydrologic responses and is strongly influenced by the topography. The variability of soils and rainfall has only a secondary role in determining the size of REA.

Reggiani et al. (1999, 1998, 2000) and Reggiani and Rientjes (2005) introduced the concept of a Representative Elementary Watershed (REW) for integrated hydrological modelling. In this approach, the microscale conservation equations of mass, momentum and energy are mapped on the megascale by integration over the REW. The authors applied the REW approach on the 494 km^2 catchment of the River Geer in Belgium, delineating 73 REW on the basis of Strahler's stream order 2. The REW approach provides an alternative by proposing a flux-based method that makes use of appropriately chosen control volumes. In broad terms the approach is oriented towards specifying the fluxes across the volume boundaries, rather than towards trying to increase the detail of the process description within the REW.

Flugel (1995) delineated Hydrologic Response Units (HRUs) to capture the spatial physiographic heterogeneity of the catchment but the delineated HRUs were not topological connected. Summerell et al. (2005) delineated four major landforms in six catchments of Australia on the basis of hydrological terrain analysis. They used the UPNESS index from the Fuzzy Landscape Analysis Geographic Information System (FLAG) model (Roberts et al., 1997). As this metric did not take into account the relative positions of the various landforms, it led to landforms that were not contiguous within Strahler's first order sub-basins. Argent et al. (2007) introduced the concept of Functional Units (FUs) in which they divided the entire catchment in FUs based on land use/cover (forest, crop, urban), management, position in the catchment, hydrological response or other spatial features. The concept of FUs is not significantly different than the HRUs concept developed by Flugel (1995).

In upland catchments, the upslope areas typically have shallow conductive soils and higher rainfall and generate significant runoff which is transmitted either as deep drainage or lateral flux (surface or sub-surface runoff) to mid and low slopes. Hydrologic modelling of hillslopes under varying geomorphic settings is important to understand the behaviour of hydrologic response of the catchment and has been an active area of research in last few years (Bogaart and Troch, 2006; Hilberts et al., 2007; Lyon and Troch, 2007).

Earlier studies have indicated that while aggregation of spatial features leads to inaccuracy and disaggregation increases the computational time, if the aggregation is carried out in a logical way then the optimum solution between accuracy and computational effort is possible (Bathurst, 1986; Flugel, 1995; Tao and Kouwen, 1989; Wood et al., 1988; Zhang and Montgomery, 1994). In the HRU and other aggregation schemes used previously, the size of the aggregated spatial structures is larger than the hillslope length, which has implications for adequate representation of the hillslope hydrologic processes, particularly for upland catchments. Zhang and Montgomery (1994) suggested that the hillslope processes are more adequately represented when the aggregated entities are smaller than the hillslope length. The hillslope hydrological processes control the runoff generation mechanisms for the catchment and therefore an appropriate representation of the hillslope processes is essential. Further, the existing alternatives for HRUs delineation either lack topological connectivity across the units, or require artificial nodes to ensure this connection. The topological connectivity of HRUs is important in catchment hydrologic modelling to transfer the fluxes from an upper HRUs to the lower HRUs and finally to the stream. The prime aim of this study is to delineate contiguous topologically connected HRUs for large catchments which can adequately represent the hillslope hydrological processes and provides a basis for numerically efficient semi-distributed catchment hydrology modelling. The method for HRUs delineation consists of delineating contiguous landforms, and then integrating within the Strahler's stream order based topologically connected sub-basins.

The paper is organized as follows. Section 2 describes the information about the data used in the study. Section 3 describes the proposed HRUs delineation approach. The proposed basis for HRUs delineation is supported by soil moisture modelling and presented in Section 4, followed by conclusions in Section 5.

2. Study area

2.1. Catchment area

The Snowy River is located in the Snowy Monaro region to the west of the town of Bombala in south-eastern New South Wales (NSW), Australia. The catchment area of the Snowy River at Burnt Hut is 7135 km^2. Three sub-catchments, Maclaughlin, Bombala and Delegate having catchment areas 459, 1364 and 1135 km^2 respectively have been considered for this study, as illustrated in Fig. 1. This region has been under hydrologic investigation from last ten years. The water availability in this region is significantly affected because of change in land use during the last 50 years (Tuteja et al., 2007). The topographic relief of Maclaughlin catchment is 698 m which is higher than the topographic relief of Bombala and Delegate catchments (582 and 641 m respectively). DEM data of 25 m by 25 m resolution used in this research provided by the former Department of Environment, Climate Change and Water, NSW. This data was derived from contour and drainage data from NSW topographic maps.

2.2. Climate and land use

Climate surfaces available for the Australian continent using the methodology of Jeffrey et al. (2001) were used in this analysis. The catchments in Snowy Monaro region were delineated into four climate zones (A: $<$600 mm/yr, B: 600–750 mm/yr, C: 750–900 mm/yr, and D: $>$900 mm/yr) using the CLASS Spatial Analyst (Teng et al., 2008). Mean annual rainfall for the Delegate, Bombala, and Maclaughlin catchments is 859, 783, and 650 mm/yr, respectively (Tuteja et al., 2007). Mean annual pan evaporation for the respective catchments is 1027, 1000, and 1425 mm/yr. Daily rainfall, pan evaporation, radiation, maximum and minimum temperature for the period of 1975–2000 are used for the two-dimensional unsaturated soil moisture movement modelling across hillslope cross sections. Potential evapotranspiration was derived from pan evaporation data and the appropriate pan factor to correct for differences in radiation, temperature and vapour pressure deficit.

Tuteja et al. (2006) have divided the study catchments into five land use categories which are crop, native woody, pines, pasture and improved pasture, and prepared representative land use maps