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A new approach for delineation of hydrologic response units in large catchments

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Abstract: This study aims to develop a catchment scale semi-distributed runoff generation model that can simulate flow under changing landuse and climatic conditions. The computational efficiency of the model is one of the key considerations behind its development. To reduce model run-time and still retain appropriate representation of the relevant physical processes, we aim to divide the catchment into topologically connected multiple homogeneous spatial units, referred to as Hydrologic Response Units (HRUs). These HRUs represent the spatial heterogeneity of the catchment in terms of topographical, physiographical and geomorphological characteristics of the catchment.

The connectivity of landforms with the stream network is a prime concern. This new approach includes landform delineation using area-aggregated slope relationship, the Compound Topographic Index (CTI), average local slope, the Multi Resolution Valley Bottom Flatness (MRVBF) index and the surface curvature. The catchment is divided into four major landforms called the landform-upslope, -midslope, -footslope and -alluvial flats. The upslope landform is dominated by the diffusive flow generation processes and the midslope-landform represents transition of diffusive to fluvial processes. These zones are classified by area-aggregated slope relationship. The landform -footslope and -alluvial flats are saturation zones and dominated by fluvial processes and they are classified by average local slope, CTI, MRVBF index and surface curvature. The catchment will also be divided in homogeneous sub-basins on the basis of topographical and physiographical features. This study is still under progress. To allow for runoff and soil moisture connectivity between landscape elements and the streams, the homogeneous sub-basins delineated catchment using Strahler's stream order will be overlaid by four landforms that will describe the underpinning spatial architecture of the proposed semi-distributed catchment model. At present, the study investigates the stability of this delineation using data of the Maclaughlin sub-catchment of the Snowy River at Burnt Hut, New South Wales. The methodology has also been applied to the adjacent Delegate and Bombala sub-catchments. Future work will entail using this delineation in the context of a semi-distributed rainfall runoff model and simulating the effect of changes in land use and climatic conditions on flow and soil moisture.

Keywords: *Hydrologic Response Units (HRUs), Compound Topographic Index (CTI), Multiresolution Valley Bottom Flatness Index (MRVBF), Landforms, Homogeneous Sub-basins*

1. INTRODUCTION

This study aims to develop a semi-distributed hydrologic modelling alternative that allows for efficient simulation of streamflow, soil moisture and evapotranspiration for long term climate, land use and land management conditions for large catchments. A conceptual framework of one such model is illustrated in Figure-1. A key element of this semi-distributed hydrological model is the consideration of lateral flow transfers in unsaturated zone from the steeper upslope elements of the catchment to the flatter saturated sections closer to the stream. This paper presents an approach for delineating these elements, which are referred as Hydrologic Response Units or HRUs in the remainder of this paper. HRUs are distributed, heterogeneously structured entities having a common climate, land use and underlying pedo-topo-geological associations controlling their hydrological dynamics (Flugel, 1995). To delineate these HRUs, we consider the use of topographical and geomorphological attributes. These attributes include average local slope, surface curvature, the area-slope relationship, the Compound Topographic Index (CTI) and the Multiresolution Valley Bottom Flatness (MRVBF) index. The HRU delineation approach is developed using data from Maclaughlin, Delegate and Bombala sub-catchments of Snowy River at Burnt Hut South-Eastern New South Wales and found to be reasonably consistent in its application for the study cases considered.

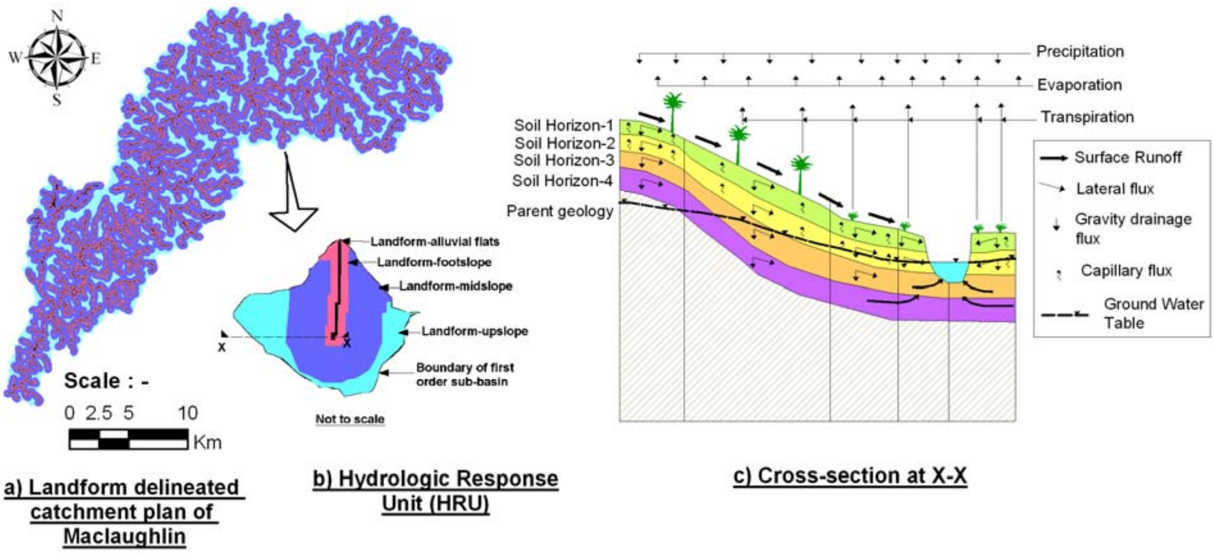

Figure 1. Schematic of proposed model

To delineate HRUs, the geomorphology of the catchment is explored. The geomorphology of the catchment determines the flow paths within the catchments (Willgoose and Perera, 2001). Traditionally, geomorphic descriptors such as area-slope relationship and the cumulative area distribution are used to demarcate the catchment into regions dominated by diffusive and fluvial processes (Hancock and Evans, 2006). The area-slope relationship of the catchment is explored and a new method to demarcate diffusive and fluvial dominated regions is presented.

The local slope, surface curvature (Zevenbergen and Thorne, 1987), the Compound Topographic Index (CTI) (Beven and Kirkby, 1979) and the Multiresolution Valley Bottom Flatness (MRVBF) index (Gallant and Dowling, 2003) are explored on a 1 pixel (25 m) wide strip running parallel to the river network. This exploration captures the heterogeneity of the catchment in terms of topographical and geomorphological attributes and is then used for HRUs delineation.

The availability of geospatial digital data and advancement of Geographical Information System (GIS) has traditionally attracted researchers to explore new techniques to delineate HRUs (Bongartz, 2003; Flugel, 1995; Leavesley, 1983). The use of advanced GIS tools for capturing the spatial heterogeneity of the catchment by considering updated topographical and geomorphological attributes is the focus of this paper.

2. STUDY REGION

The Snowy River at Burnt Hut covers an area of 7135 km^2 in the Snowy Monaro region to the west of the town of Bombala in South-Eastern New South Wales, Australia. The study area consists of Maclaughlin, Delegate and Bombala sub catchments having catchment area 459, 1135 and 1364 km^2 respectively. The significant change in land use i.e. vegetation type and pattern over the last 50 years affected the water availability in this region (Tuteja et al., 2007). This region is selected for the study because over the last few years studies of landuse impacts have been carried out in this region and detailed information and data are available (e.g. DEM data of size 25 m by 25 m, soil type, geology maps, landuse and climate data). These data have been obtained from the Department of Environment and Climate Change, NSW. While most of the analyses presented in this paper are from the Maclaughlin catchment, the analyses for the Delegate and Bombala catchments using this methodology have also been completed.

3. AREA - AGGREGATED SLOPE RELATIONSHIP

In the last few years, significant researches have been carried out on extracting geomorphological descriptors from Digital Elevation Models and their application in hydrological sciences (Cohen et al., 2008; Hancock, 2005; Hancock and Evans, 2006). The most focused geomorphological descriptors are area-slope relationship and cumulative area distribution plots. The relationship between the upslope contributing area at a point versus local slope at that point is called the area-slope relationship. However, the cumulative area distribution is a function defining the proportion of the catchment which has a drainage area greater than or equal to a specified drainage area. The cumulative area distribution describes the spatial distribution of areas and drainage network aggregation properties within a catchment (Hancock, 2005). Hancock and Evans (2006) have worked on 20 ha and 50 ha catchments of uniform geology located in Tin Camp Creek, Northern Territory, Australia. They demarcated diffusive processes dominated region from those influenced by more incised fluvial processes on the basis of area-slope relationship and cumulative area distribution plots.

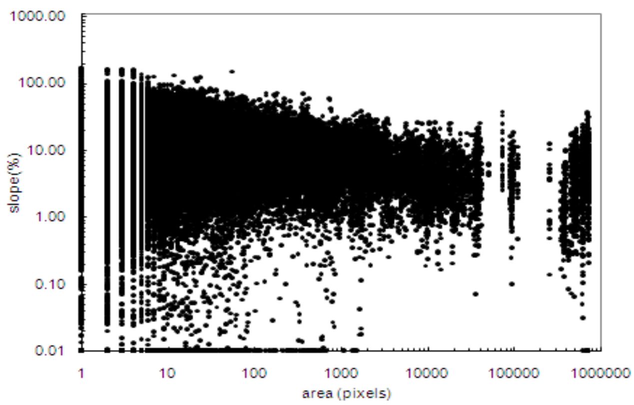

Figure 2. Area-slope relationship for Maclaughlin catchment

A large catchment of heterogeneous geology has been explored here. The Maclaughlin catchment consists of five broad geology classes - Adamellite, Granodiorite, Palaeozoic, Basalt and Alluvium. The proportion of the catchment with Alluvium is negligible and therefore it is not considered in the study. The area-slope relationship shows considerable scatter (Figure-2). Initially it was thought that the main reason for this scatter was the heterogeneity in geology classes. However, the area-slope relationship of each geology was explored separately, and these also showed considerable scatter. It confirms that the heterogeneity in geology classes is not a major factor affecting scatter in the area-slope relationship. Instead increased scatter is due to the large area of the catchment. In large catchments there are always some land patches where the slopes are excessively steep or almost flat and so resulting in increased band width of the area-slope relationship. To reduce this scatter, the plots of average slope of 20x20 surrounding pixels and 30x30 surrounding pixels were plotted. While the scatter reduced slightly, the diffusive (convex) and fluvial (log-log linear) zones were still not distinctly visible.

A new concept of area-aggregated slope (Figure-3a) is introduced, where aggregated slope at an area represents the average slope of all pixels having contributing area greater than or equal to that area. The area-aggregated slope in log-log scale (Figure-3a) for the entire Maclaughlin catchment and for each geology, exhibits two regions described by the convex and log-log linear curves. The semi-log plot of area-aggregated slope (Figure-3b) made the regions more distinct. On the basis of field measurements of channel positions, Hancock and Evans (2006) found that the areas of catchment which fall in the convex shape of the cumulative area distribution curve (Figure-3c) are diffusive processes dominated regions and the areas which fall in the log-log linear shape of the cumulative area distribution curve are fluvial processes dominated regions. For the entire Maclaughlin catchment, the cumulative area distribution curve (Figure-3c) shows that the regions dominated by diffusive processes fall in the range of 1 to 25 pixels contributing area whereas fluvial processes dominate at locations with the contributing area of 25 pixels or more. The plot of area-aggregated slope in log-log scale (Figure-3a) for the entire Maclaughlin catchment also shows that the same threshold of about 25 pixels can be used to demarcate the convex (diffusive) and log-log linear (fluvial) curves. Therefore, the area-aggregated slope plot can also be used to demarcate the diffusive and fluvial regions in large catchments. The plots of area-aggregated slope in log-log scale and semi-log scale (Figure-3a-b) also show that the threshold used to demarcate diffusive and fluvial regions is broadly similar for different geologies. These plots are also indicative of the steepness and/or flatness of the geologies. As an example, Granodiorite is the steepest geology of the catchment and Adamellite is the flattest, and the slopes of the moderately steep geologies fall in between these two extremes. The area-aggregated slope relationship is consistent for Delegate and Bombala catchments also.

In catchments, the location where hillslope ends and the channel begins is called the channel head. Downstream of the channel head, the channel takes its proper shape and the stream network formation starts. On the basis of field measurements of channel head positions, Hancock and Evans (2006) found that the critical slope or drainage area for initiation of channel occurs at the same threshold area as that for differentiating the convex (diffusive) and log-log linear (fluvial) zones, which is 25 pixels for Maclaughlin catchment.

In large catchments, the number of channel heads is very high and a single value of critical slope or drainage area for initiation of all channels can not apply. A transition zone exists between the diffusive and fluvial zones where the majority of channel heads fall. The point where curvature is changing sign in the semi-log plot of the area-aggregated slope (Figure-3, b) is an indicator of starting of the transition zone. To strengthen this idea, twenty five stream networks have been delineated with contributing area threshold varying from 1 to 25 pixels. Visual examination of these stream networks shows that the stream networks are not distinct for the threshold areas of 1 to 7 pixels and most of the first order streams are merging together. However a slightly distinct patterns of the stream networks start at a threshold area of 8 pixels, which is at the point where curvature is changing sign in semi-log plot of the area-aggregated slope (Figure-3, b). A more distinct stream network is formed at a threshold area of 25 pixels.

To further support the concept of transition zone, a few cross sections are drawn perpendicular to first order streams at their upstream ends. These streams are selected randomly from two stream networks, first corresponding to 8 pixels threshold and second corresponding to 25 pixels threshold. The cross sections of different streams at 8 pixels threshold indicate that only few streams have taken proper channel shape, whereas a majority of streams have taken proper channel shape at 25 pixels threshold. This indicates that a transition zone exists between diffusive and fluvial dominated zones and therefore threshold area of 8 pixels is used to delineate transition zone of the

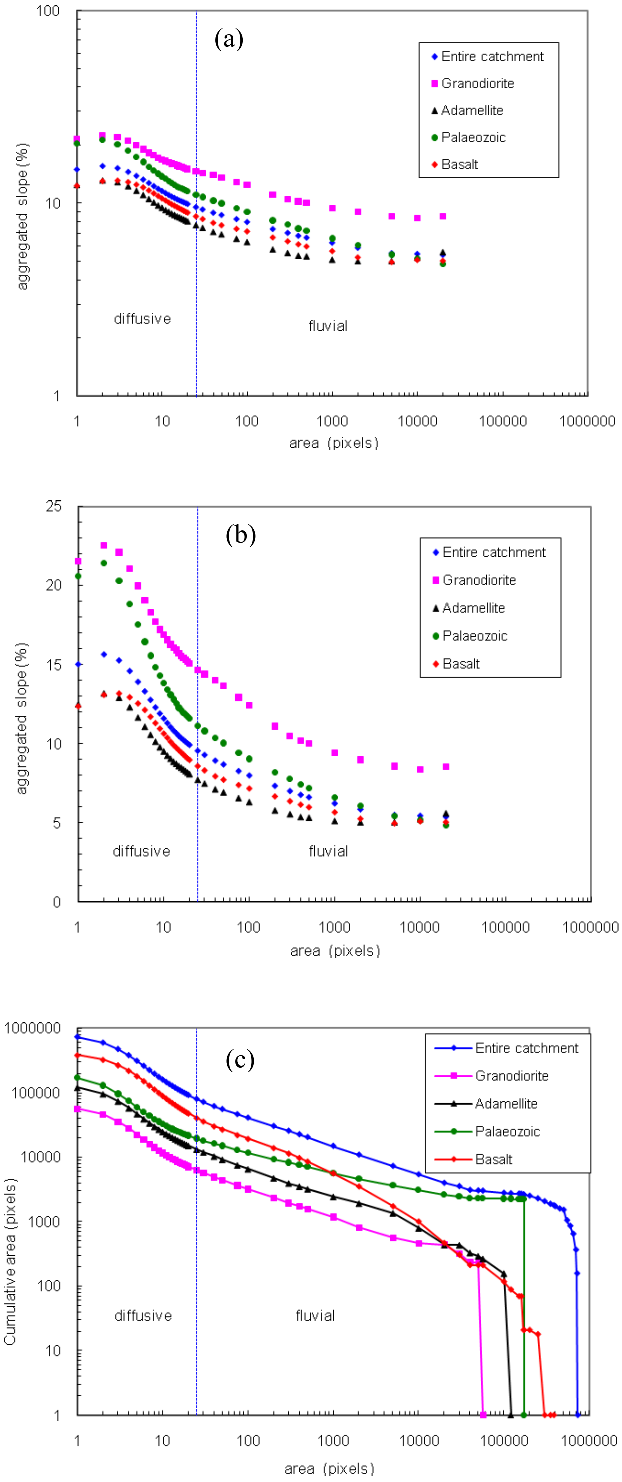

Figure 3. Area-aggregated slope relationship in log-log scale (a), semi log scale (b) and cumulative area distribution (c) for the entire Maclaughlin catchment and for all geologies

landforms in the Maclaughlin catchment.

4. LANDFORM DELINEATION

To capture the spatial heterogeneity of the hillslope elements, the catchment is divided in four landforms. These landforms are delineated by considering similar behaviour of topographical and geomorphological attributes.

After considering the effects on morphometric properties of different threshold areas in delineating the river network the threshold of 300 pixels is selected for the river network delineation in the Maclaughlin catchment (Helmlinger et al., 1993). The entire Maclaughlin catchment is divided into several strips running parallel to the river network. The width of these strips is 1 pixel (25 m), and these strips are used to explore topographical and geomorphological attributes.

Slope is an important topographical and geomorphological descriptor of a catchment, which can be used to differentiate hillslopes and channels and flat and steep terrain. It also controls hydrological processes. The average local slope on 1 pixel wide strips running parallel to river network are calculated (Figure-4a), which is indicative of the change in average slope across the catchment from the river in an upslope direction. Up to 25 m distance from the centre of the river, the average local slope is significantly low because of flat river banks, flood plains and low slope areas near main river channels. The steepest slope is calculated at 50 to 75 m strip and after that it decreased gradually. The trend of slope is the same for the entire catchment and for all geologies, although the magnitude of the slope is different depending on the steepness of a given geology (e.g. highest values corresponded to Granodiorite which is the steepest geology).

The Compound Topographic Index (CTI) is defined as ln(a/tanβ), where a is the local upslope area draining through a certain point per unit contour length and tanβ is the local slope. This index was developed within TOPMODEL (Beven and Kirkby, 1979). The CTI was based on the assumption that topography controls the movement of water in sloped terrain and thus the spatial patterns of soil moisture. The average CTI is also explored on 1 pixel wide strips running parallel to the river network for the entire catchment and for each geology (Figure-4b). The plot shows significantly higher values of CTI in converging flat terrain near the river network and starts reducing when going farther away from the river network. After a distance of 75 m, the average CTI values are almost constant. The pattern of the graph is similar for the entire catchment, as well as for each geology, although there are minor differences in the values of average CTI for different geologies because of the steepness and flatness of the geology.

The Multiresolution Valley Bottom Flatness (MRVBF) index identifies valley bottoms using a slope classification constrained to convergent areas (Gallant and Dowling, 2003). The average MRVBF index is also calculated on 1 pixel wide strips running parallel to the river network for the entire Maclaughlin catchment (Figure-4b). The average MRVBF index is quite high (1.8 to 2.0) up to 25 m from the centre of the river which indicates that the valley bottoms or flat areas are located in this region. The average value of MRVBF drops sharply over the next

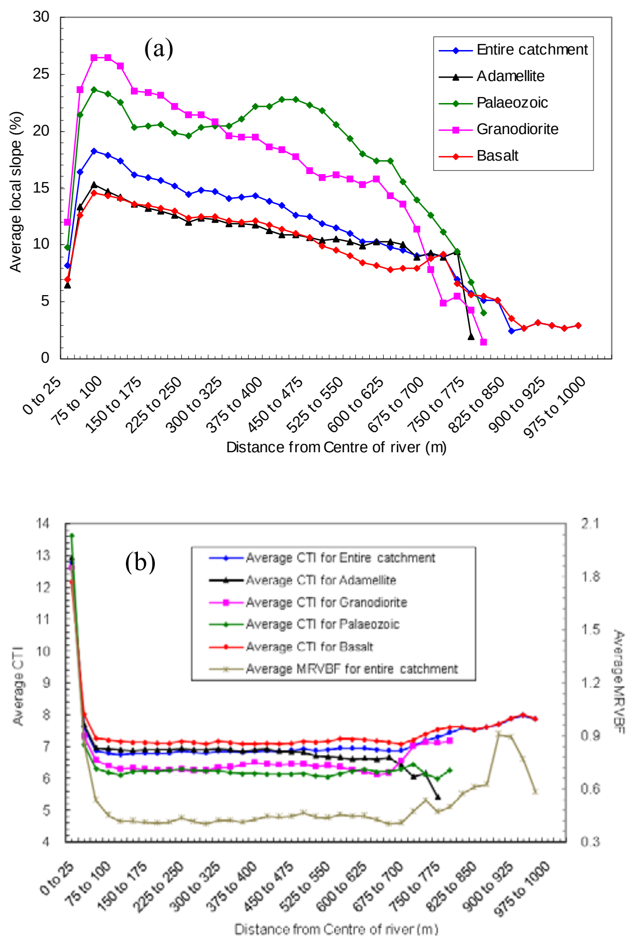

Figure 4. Distance from centre of river versus average local slope (a) and distance from centre of river versus average CTI (b) for the entire Maclaughlin catchment and for all geologies

50m from centre of the river (i.e. up to 75m), which indicates the transition from valley bottoms to hillslopes. After 100 m it almost becomes constant, which shows that hillslopes dominate in this region.

Topographic convergence and divergence are first order controls on hillslope and catchment hydrological responses. Surface curvature is the first derivative of slope (Zevenbergen and Thorne, 1987), which indicates whether a given part of surface is convex or concave. Convex parts of surfaces like ridges are generally exposed and drain to other areas and concave parts of surfaces like channels accept drainage from other areas. Again 1 pixel wide strips running parallel to the river network are used to explore surface curvature for the Maclaughlin catchment. For the 0 to 25 m strip, the magnitude of curvature is negative showing the concavity of the surface. From 25 m to 75 m, the magnitude of curvature suddenly increases and changes sign from negative to positive indicating the transition from concave to convex. Beyond 100 m distance, the variation in curvature is almost negligible and falls in the convex region.

The average upslope areas or flow accumulation areas (pixels) are also calculated on 1 pixel wide strips running parallel to the river network. These also showed higher values in the vicinity of river network and decreased away from the river network. As described in the previous section, the threshold area of 8 pixels gives an indication of the start of the transition zone between diffusive and fluvial processes dominated regions, corresponding to this threshold of 8 pixels the distance from the centre of the river is worked out which is 350m. This distance is used to demarcate diffusive and fluvial dominated regions.

Table-1. Landform classification

Types of Landform	Distance from centre of the river (m)
Landform-alluvial flats	0 to 25
Landform-footslope	25 to 75
Landform-midslope	75 to 350
Landform-upslope	greater than 350

From the above exploration of topographical and geomorphological attributes, four landforms are delineated for the Maclaughlin catchment (Figure-1, a-b). It is observed that up to 25 m from the river network, the values of average local slope, CTI, MRVBF and curvature are significantly different from other parts of the catchment. The average local slope is very low in this region because this region consists of river channels and flood plains which are comparatively flatter than other parts of catchment. The average CTI and MRVBF values are higher in this region because flow is converging and all valley bottoms are located in this area. The average curvature is negative and lowest in magnitude which shows the surfaces are concave in this region. This 0 to 25 m strip is treated as one landform and called the landform-alluvial flats. From 25 to 75 m, the average local slope and curvature are suddenly increased and beyond 75 m, changes are gradual, where as the average CTI and MRVBF are suddenly dropped within 25 to 75 m and after 75 m these are almost constant. It shows that the 25 to 75 m region is the transition region between channels and hillslopes, channels are ended and hillslopes are started and the flow characteristics are changed from converging to diverging. This 25 to 75 m region is considered as second landform called as landform-footslope. The third and fourth landforms are separated by a threshold at about 350 m which is calculated in last section corresponding to the start of a transition zone between diffusive and fluvial dominated regions. The third landform is from 75 to 350 m and called the landform-midslope, and the fourth landform from is 350 m and beyond and called the landform-upslope. The types of landform and their distances from the centre of the river are presented in Table-1. The study is repeated for Delegate and Bombala catchments and results obtained are consistent with Maclaughlin catchment.

5. DELINEATION OF HOMOGENEOUS SUB-BASINS AND FUTURE STUDIES

This study is still under progress. It is planned to overlay delineated landforms over the stream network described by the Strahler's convention to evaluate the effects of HRUs on soil moisture and fluxes (Figure-1). This work is proposed to be done using water balance simulations for cross-sections across various 1st, 2nd and higher ordered sub-catchments with and without the delineated landforms under a range of boundary conditions (free drainage, specified head and specified gradient). Our aim is to extend the above study to include a broader range of catchments and develop a generic rationale for HRUs delineation using a mix of the topographical and geomorphological attributes as illustrated here. Future work will also entail using this delineation in the context of a semi-distributed rainfall runoff model for simulating the effect on flow of changes in land use and climatic conditions.

6. CONCLUSIONS

The study is performed for the Maclaughlin, Delegate and Bombala sub-catchments of the Snowy River in NSW. The area-slope relationship of these large catchments of heterogeneous geology is explored. Significant scatter is found in the area-slope relationship which is because of the size of the catchment and the heterogeneity in the component geologies. The area-aggregated slope in log-log scale and semi-log scale are explored for the entire catchment and for each geology. In log-log scale it shows two regions, convex curve and log-log linear curve. When this curve is compared with the cumulative area distribution curve used to demarcate convex (diffusive) and log-log linear (fluvial) regions then the threshold for demarcating convex (diffusive) and log-log linear (fluvial) regions is found same. This indicates that the area-aggregated slope curve can also be used to demarcate diffusive and fluvial dominated regions. The area-aggregated slope curve also differentiate the steepness and flatness of different geologies of the catchment.

The local slope and CTI are explored on 1 pixel wide strips running parallel to the river network for the entire Maclaughlin catchment and for each geology. The MRVBF index and curvature are explored for the entire catchment only. On the basis of the behaviour of these explorations, the Maclaughlin catchment is divided in four landforms called landform-alluvial flats, footslope, midslope and upslope. The distances of these landforms from the centre of the river are presented in Table-1. This study is also repeated for the Delegate and Bombala catchments and the results obtained are consistent with the ones for the Maclaughlin catchment presented here. Finally, the newly developed methodology for delineating hydrologic response units using commonly available terrain analysis methods is promising and warrants consideration for development of the numerically efficient hydrological models.

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