HYDROLOGICAL PROCESSES
Hydrol. Process. **19**, 1727–1749 (2005)
Published online 23 February 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5632

The use of digital elevation models in the identification and characterization of catchments over different grid scales

G. R. Hancock*
School of Environmental and Life Sciences, The University of Newcastle, Callaghan, NSW 2308, Australia

Abstract:

This study examines the ability of well-known hydrological and geomorphological descriptors and statistics to differentiate between catchments with spatially varying geology, size and shape subject to the same climate in the Northern Territory, Australia. The effect of digital elevation model grid resolution on these statistics is also examined. Results demonstrate that catchment descriptors such as the area–slope relationship, cumulative area distribution and hypsometric curve can differentiate between catchments with different geology and resultant morphology, but catchment network statistics are insensitive to differences in geology. Examination of the effects of digital elevation model grid scale demonstrates that while considerable catchment information can be gained at digital elevation grids greater than 10 m by 10 m, hillslope and hydrological detail can be lost. Geomorphic descriptors such as the area–slope relationship, cumulative area distribution, width function and Strahler statistics were shown to be sensitive to digital elevation model grid scale, but the hypsometric curve was not. Consequently, caution is needed when deciding on an appropriate grid resolution as well as the interpretation and analysis of catchment properties at grid scales greater than that for optimal hillslope and area aggregation definition. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS digital elevation model; geomorphology; hydrology; catchment statistics; hillslope processes

INTRODUCTION

It is well recognized that catchment form and function is shaped by the interaction between geology and climate (Wolock and Price, 1994; Holmes *et al*., 2000; Willgoose and Perera, 2001). Catchment hydrology responds to catchment shape and erosion (Kirkby and Chorley, 1967; Dunne and Black, 1970; Anderson and Burt, 1978; Moore *et al*., 1993; DaRos and Borga, 1997; McMaster, 2002). From an engineering hydrology point of view, a catchment can often be described by a hydrograph and if a hydrological model can describe this hydrograph then a catchment is adequately characterized. From a geomorphological perspective, the description of a catchment (and the ability to compare catchments) is a much deeper question that not only includes the ability to understand runoff processes (i.e. the hydrograph) but also catchment form (i.e. hillslope length and shape, soil catena) (Hancock, 2003).

Observation of geology, vegetation and erosion processes will often provide insights into the mechanisms that control catchment form and function, with the catchment being organized according to simple laws (i.e. Shreve, 1966; Rodriguez-Iturbe and Valdez, 1979). Nevertheless, there is a need for more detailed characterization of catchment form and function than simply using observation and field mapping. There is also the deeper question of what are the essential characteristics of a catchment. How do we qualitatively and quantitatively differentiate between different landscapes (Hancock, 2003)?

* Correspondence to: Dr G. R. Hancock, School of Environmental and Life Sciences, The University of Newcastle, Callaghan, 2308, Australia. E-mail: gggh@alinga.newcastle.edu.au

Received 5 September 2003
Accepted 19 April 2004

A catchment has characteristic signatures that are expressed as a product of the underlying geology and climate. Visual comparison between landscapes is the first step in assessing similarities or otherwise of catchment form and function. Nevertheless quantification, or the ability to statistically analyse landscapes (Hancock, 2003; Willgoose *et al.*, 2003), is especially necessary in the rapidly moving disciplines of hydrological and landscape evolution modelling, where it is essential to be able to compare field and computer-simulated landscapes using statistically defensible methodologies at appropriate scales (for a review of some of these models see Coulthard, 2001) (Kalma and Sivapalan, 1995; Sposito, 1998; Wolock and McCabe, 2000; Schoorl *et al.*, 2000; Thompson *et al.*, 2001). This also applies to the mining industry, where areas of the Earth's surface, ranging in size from a few hectares to many square kilometres, are disturbed by earth-moving equipment and require reconstruction (Hancock, 2004). What are the essential components of a landscape that allow us to re-engineer a stable, self-sustaining landform that blends in with the surrounding disturbed landscape and at what scales should landscapes be examined (Hancock *et al.*, 2002; Hancock, 2004)?

The ability to understand catchment processes is also reliant on the digital elevation model scale and reliability of landscape data input (Kenward *et al.*, 2000; Thompson *et al.*, 2001; McMaster, 2002). Advances in numerical models to monitor and predict hydrology and geomorphology rely heavily on digital elevation models and their integrity, yet the strengths and limitations of these data sets have not been fully investigated or understood (Moore *et al.*, 1991; Moore and Grayson, 1991; Zhang and Montgomery, 1994; Walker and Willgoose, 1999; Fryer *et al.*, 1994; Lane *et al.*, 1994; Gyasi-Agyei *et al.*, 1995; Quinn *et al.*, 1995; Willgoose and Perera, 2001). In the past decade there has been a plethora of studies examining the effect of different digital elevation model grid scales on the ability of a digital elevation model to accurately and reliably represent catchment form and function (for example, Zhang and Montgomery, 1994; Walker and Willgoose, 1999 plus numerous others). At what digital elevation model grid size is it appropriate to examine catchment behaviour and landscape features (Thieken *et al.*, 1999; Zhang *et al.*, 1999; Schoorl *et al.*, 2000; Wolock and McCabe, 2000; Thompson *et al.*, 2001; McMaster, 2002)? What particular geomorphic properties are reliable in describing catchments at a particular scale? Can geomorphic and hydrological measures and descriptors be used to identify different catchment processes and aid in the calibration of erosion models (Hancock *et al.*, 2002)? The author believes that these questions have not been adequately addressed.

In the past, the area–slope relationship, cumulative area distribution and hypsometric curve have been used to understand and compare catchments (Hancock and Willgoose, 2001, 2002; Hancock, 2003; Willgoose *et al.*, 2003). These geomorphic descriptors are believed to be integrative measures which graphically describe the surface morphology of a catchment, therefore integrating catchment geology, climate and vegetation over geological time. Questions remain as to how we can actively differentiate between catchments as a result of their surface expression or geomorphology from remotely sensed data.

The purpose of this study is to examine differences in these catchment descriptors in adjacent catchments subject to the same climate but having different geology. The effect of different digital elevation model grid scales on these descriptors will also be examined.

STUDY SITE

Tin Camp Creek is a natural site in Arnhem Land, Northern Territory, Australia (Figure 1). This site is important as it is considered that Tin Camp Creek is one of the few sites worldwide where the management regime has not changed in recent history (the site has not been significantly impacted by European settlement), so the historical hydrology and erosion that shaped the landform can be reasonably assumed to be as today, subject to caveats about long-term climate fluctuations. The catchment has a geology very similar to the ERA Ranger uranium mine and is thought to be an analogue for the long-term rehabilitated post-mining landscape, and consequently has undergone extensive examination in recent years (Riley and Williams, 1991; Hancock *et al.*, 2002; Hancock, 2003; Willgoose *et al.*, 2003).

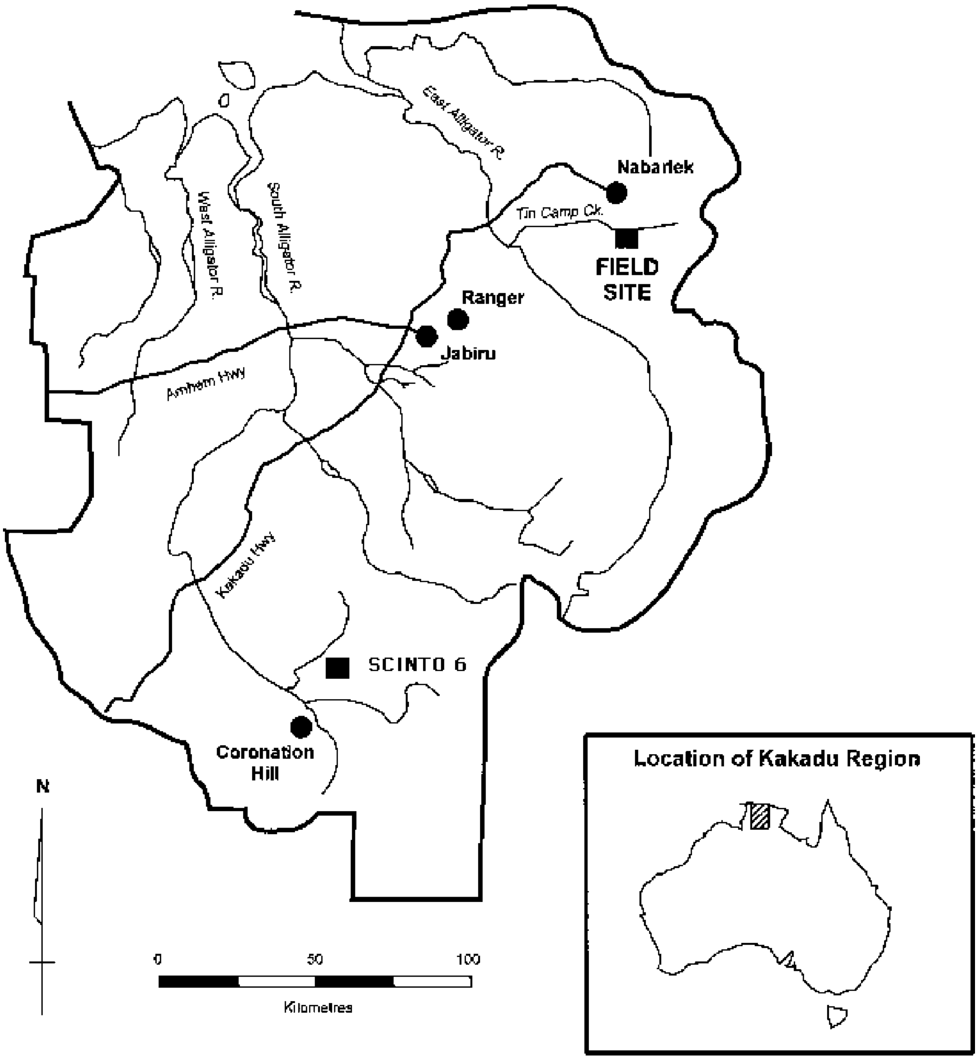


Figure 1. Location of the Tin Camp Creek field site

The Tin Camp Creek area in Arnhem Land is presently a tectonically inactive, or stable, area. Tin Camp Creek is part of the Ararat Land System (Story *et al.*, 1976) and developed in the late Cainozoic by the retreat of the Arnhem Land escarpment, and has resulted in a landscape which is actively being dissected. The catchment consists of three land units with unit 1 having closely dissected short steep slopes 10–100 m long and gradients generally between 15 and 50%. Unit 2 contains narrow colluvial foot slopes and occasional colluvial patches on foot slopes, and unit 3 contains steep linear ridges with quartz metasediment flanks and closely dissected rolling-to-hilly terrain, developed on mica schists. The soils are red loamy earths and shallow gravelly loam with some micaceous silty yellow earths and minor solodic soils on alluvial flats (Riley and Williams, 1991). There is considerable geological heterogeneity over the study area and the landscape displayed large differences in catchment morphology as a result of spatially varying geology and erosion rates. Examination of the geology of the Tin Camp Creek area reveals a complex faulted landscape with spatially varying rock types (Needham, 1988).

METHODS

Tin Camp Creek landscape data (X, Y, Z coordinates) were determined by digital photogrammetry by AIRESEARCH Pty Ltd, Darwin, and were supplied as 240 000 irregularly spaced data points within an irregularly shaped boundary. To place the data onto a regular grid, Delaunay triangulation was used to interpolate the landscape elevation data onto a 10 m by 10 m grid, producing a data set of approximately 82 000 points. This method ensures that triangles close to equilateral are generated and overlays the grid on top of this triangulation (Sloan, 1987). In the construction of the triangulation no account is taken of constraints such as blue lines, etc. This 10 m by 10 m spacing was equivalent to the average spacing of the original AIRESEARCH data over the catchments examined. Further digital elevation models were produced at 20 m by 20 m, 30 m by 30 m and 40 m by 40 m grid spacing, providing a multi-scale hierarchical approach to examining digital elevation model resolution (Bevan, 1995; Schoorl *et al*., 2000; Yang *et al*., 2001). A smaller resolution grid (i.e. 5 m by 5 m) could have been produced by interpolation, but as the 10 m by 10 m grid spacing matches the average spacing of the original ungridded data, the 10 m by 10 m resolution provides a natural limit to the grid size reduction. In this study the Tarboton *et al*. (1989) method was used to remove all pits in the data.

Subcatchments which drained into the main stream network were selected from the Tin Camp Creek digital elevation model for analysis of catchment properties (Figures 2 to 4). These catchments encompassed a range of different sizes, landscape morphology, geology and shape (Table I). Catchments were examined for their geological homogeneity or heterogeneity by use of available geological survey data and also by field investigation (Hancock *et al*., 2002). The catchments examined were also adjacent to each other so that any climatic differences were minimized.

Four adjacent catchments were selected which covered a range of catchment sizes, shapes, geology and relief (Figures 2 to 4, Table I). Catchments C1-homo and C2-homo were geologically homogeneous with closely dissected rolling-to-hilly terrain developed on mica schists within unit 1 of the Ararat Land System (Riley and Williams, 1991; Story *et al*., 1976). Catchments C1-hetero and C2-hetero were geologically heterogeneous and both had approximately 25% of their catchment area composed of steep linear ridges with quartz dike cores and metasediment flanks, with the remaining 75% having similar geology and topography to the homogeneous catchments. These catchments contained units 1, 2 and 3 of the Ararat Land System (Story *et al*., 1976).

RESULTS

In this paper the catchments are assessed using both qualitative (visual) and quantitative measures. Quantitative measures examined are the area–slope relationship, hypsometric curve, cumulative area distribution and width function. Other quantitative measures such as network statistics, catchment energy and runoff generation are also examined.

Qualitative assessment

Qualitative or visual assessment of catchment morphology has been shown to provide an important first step in assessing and comparing catchments (Hancock *et al*., 2002; Hancock, 2003). If a catchment visually

Table I. Homogeneous and heterogeneous geology catchments examined at Tin Camp Creek

Catchment	Geology	Area (ha)	Relief (m)
C1-homo	homogeneous	51	43
C2-homo	homogeneous	24	39
C1-hetero	heterogeneous	192	100
C2-hetero	heterogeneous	32	144

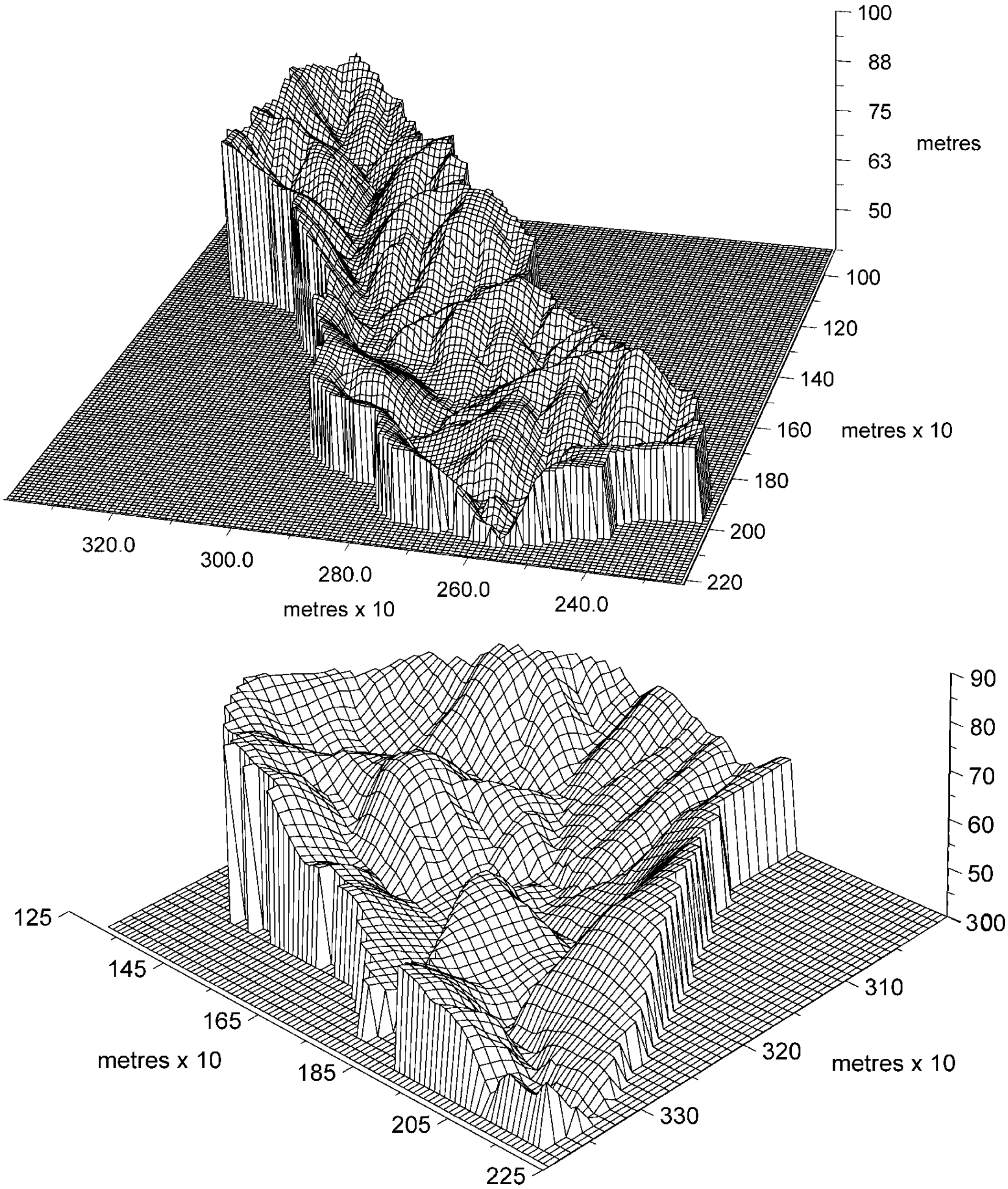


Figure 2. Tin Camp Creek catchments with homogeneous geology, catchment C1-homo (top) and C2-homo (bottom)

looks different from a neighbour that is subject to the same climate, then it is likely to be geomorphologically quantitatively different (Hancock, 2003).

The homogeneous and heterogeneous Tin Camp Creek catchments display strong differences in surface morphology (Table I, Figures 2 and 3). The homogeneous catchments display well-rounded hillslopes of regular curvature and hillslope length over the entire domain with relatively low relief. The catchments are well dissected by a regularly spaced drainage network. The heterogeneous catchments have well-rounded hillslopes in the lower reaches, where geology is the same as the homogeneous catchment, but there is a

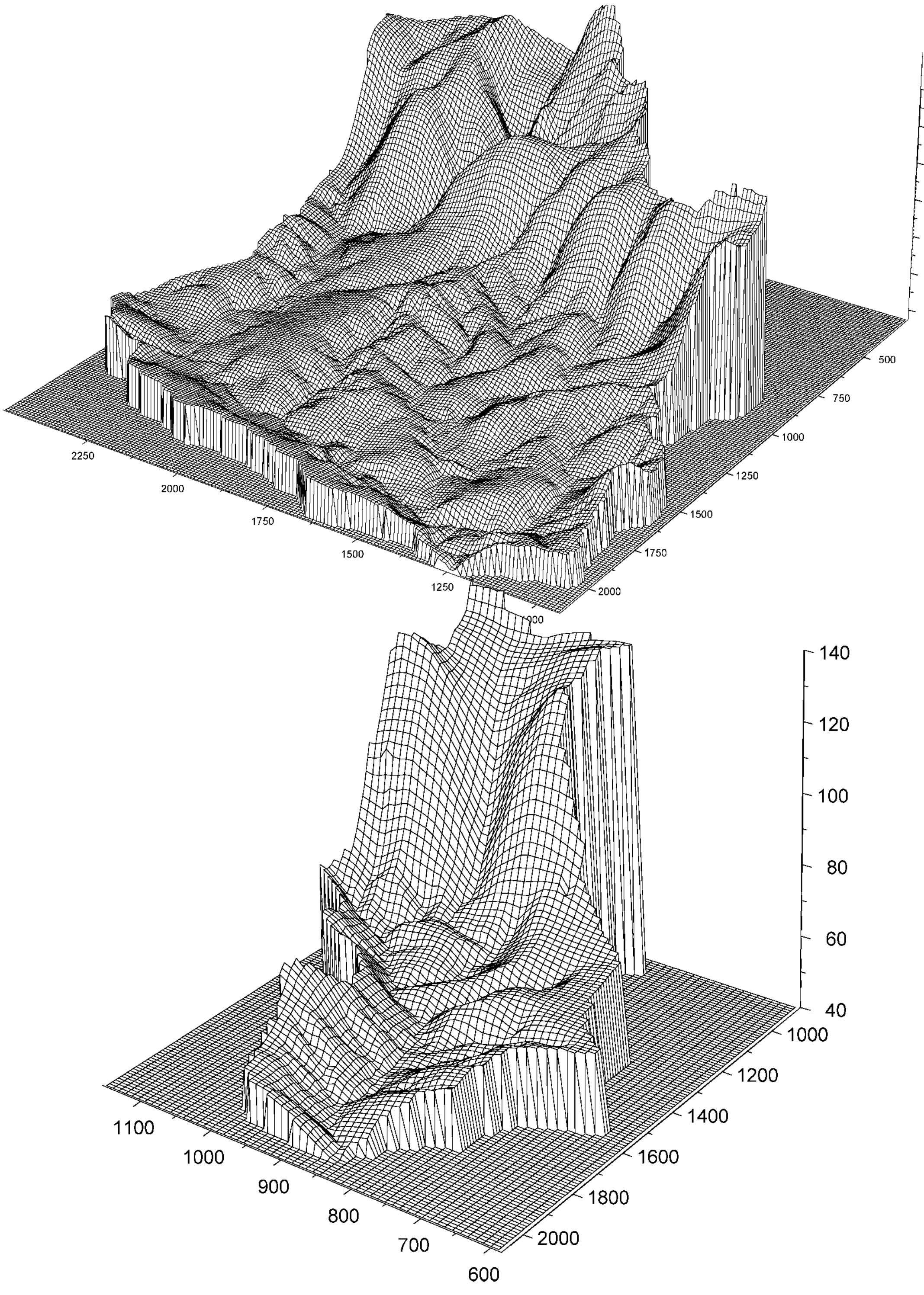


Figure 3. Tin Camp Creek catchments with heterogeneous geology, catchment C1-hetero (top) and C2-hetero (bottom). All dimensions are metres

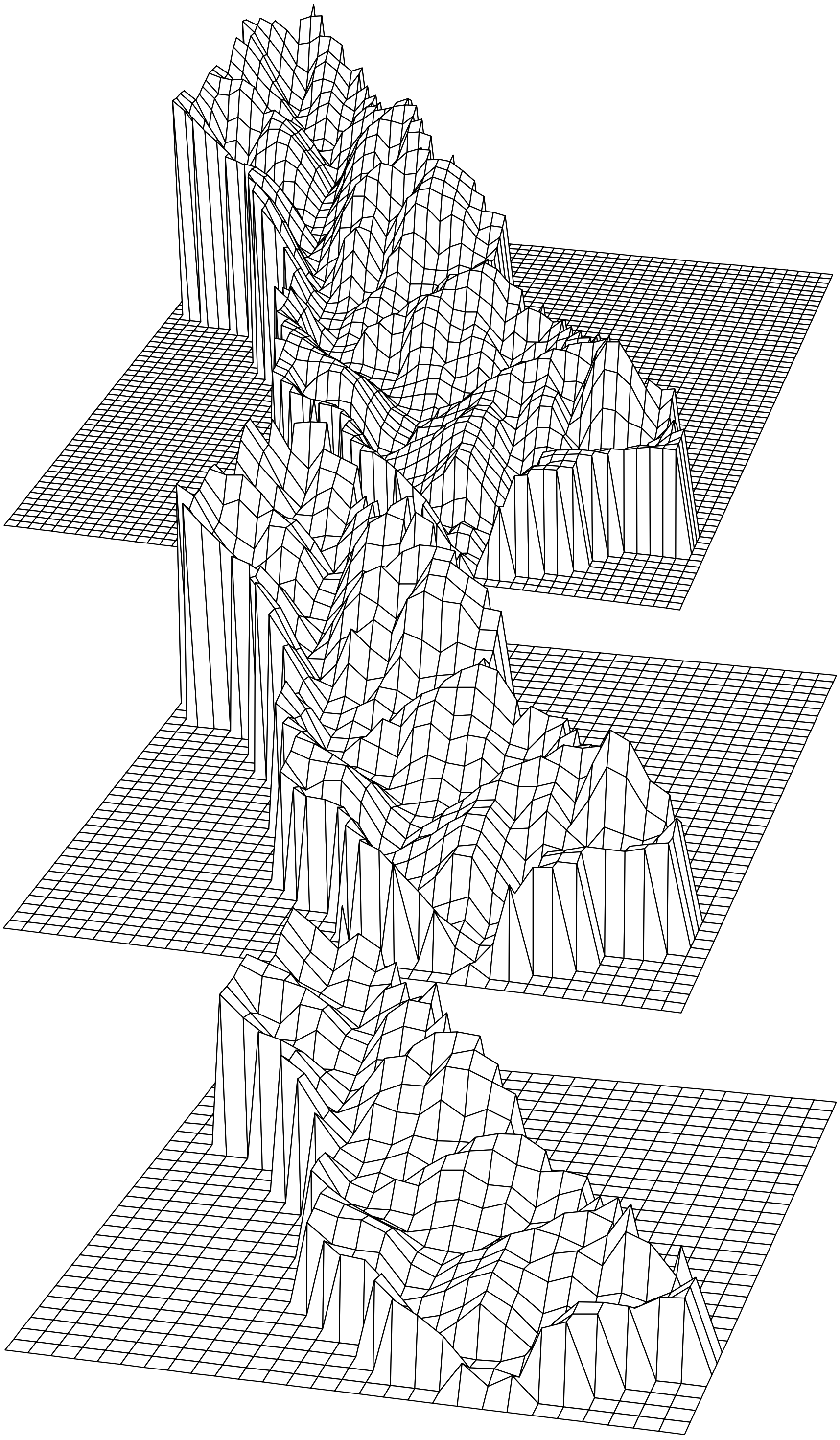


Figure 4. Digital elevation model of the Tin Camp Creek catchment C1-homo using a 20 m (top), 30 m (middle) and 40 m (bottom) digital elevation model grid spacing

strong break in slope between the more erosion-resistant upslope and schistose lower catchment area. In the lower catchment area the hillslopes are more highly dissected and appear to have a more dense drainage network than the upslope areas. The slope lengths of the upslope sandstone sections of the heterogeneous catchments are considerably longer than the lower schistose catchment areas.

Visual examination of the catchments with different grid spacings demonstrates a loss of surface morphological detail as grid scale increases (Figure 4). At a grid scale of 20 m the catchment displays some measure of hillslope curvature, but at higher grid sizes much resolution is lost. At a grid spacing of 30 m (and greater) the catchment appears as a set of linked linear facets with hillslope curvature being poorly represented. Much of the hillslope and channel detail has been lost. The result is similar for the other catchments.

Area–slope relationship

The area–slope relationship is the relationship between the area draining through a point versus the slope at the point. It quantifies the local topographic gradient as a function of drainage area. For example:

$$A^{\alpha}S = \text{constant} \tag{1}$$

where A is the contributing area to the point of interest, S is the slope of the point of interest. The area–slope relationship is considered to be a fundamental geomorphic relationship, with the value of α ranging between 0·4 and 0·7 for natural catchments (Hack, 1957; Flint, 1974; Gupta and Waymire, 1989; Tarboton *et al.*, 1992; Willgoose *et al.*, 1991; Montgomery and Foufoula-Georgiou, 1993; Willgoose, 1994; Moglen and Bras, 1995a,b; Montgomery and Dietrich, 1988, 1989, 1994).

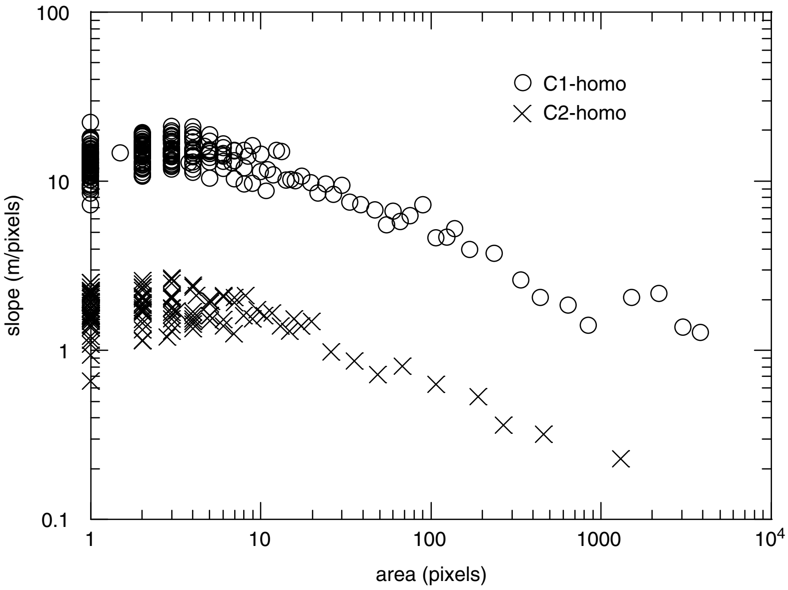
Two distinct regions of the relationship are typically observed. Small catchment areas are dominated by rainsplash, interrill erosion, soil creep or other erosive processes that tend to round or smooth the landscape. As the catchment area becomes larger, a break in gradient of the curve occurs. This is where slope decreases as catchment area increases. This region of the catchment is dominated by fluvial erosive processes, that is, those processes that tend to incise the landscape.

The area–slope relationship for Tin Camp Creek for catchments with homogeneous geology (Figure 5) displays a tightly grouped data set in both the diffusive (concave) and log–log linear (fluvial) erosion-dominated sections of the curve (Hancock *et al.*, 2002). The data set is typical of other area–slope data in soil-mantled fluvially dominated landscapes with uniform geology. Both the data sets have a diffusive region of approximately 10 pixels, with the y-intercept range being 0·6–2·0 and the slope of the fluvially dominated region being 0·42 (Hancock *et al.*, 2002) (Table II).

The heterogeneous geology catchment displays considerable scatter in the area–slope data at areas approximately less than 10 pixels, and is reflected in the y-intercept (0·7–4·0). In the case of C1-hetero there appear to be two bands in the data. It is speculated that these bands are the result of the differing geologies, with the higher data representing the areas of more erosion-resistant geology in the upslope areas of the catchments and the lower data representing the weathering schistose soils. The fluvially dominated region (Figure 5) is largely log–log linear and has slopes of 0·34 and 0·40 (Table II), this being similar to that of the homogeneous geology catchment. This comparable slope in the fluvially dominated region between the homogeneous and heterogeneous catchments is a result of the fluvially dominated areas of both the homogeneous and heterogeneous catchments being on the same geology.

There also appears to be increased scatter in the fluvially dominated regions for the geological heterogeneous catchments. This increased scatter is likely to be the result of firstly, remnant patches of more erosion-resistant material in the lower reaches of the catchment that is largely dominated by the schistose material and secondly, a combination of both sandstone and schistose material in the lower catchment areas which, as a result of deposition and transport, results in a landscape with different erodibilities and consequent morphology.

An examination of the area–slope data for the different grid spacings demonstrates that as grid size increases, detail in the area–slope relationship is lost (Figure 6). At a grid spacing of 20 m much of the curvature in the diffusive region is lost and at 30 m the area–slope relationship is log–log linear for its entire domain.



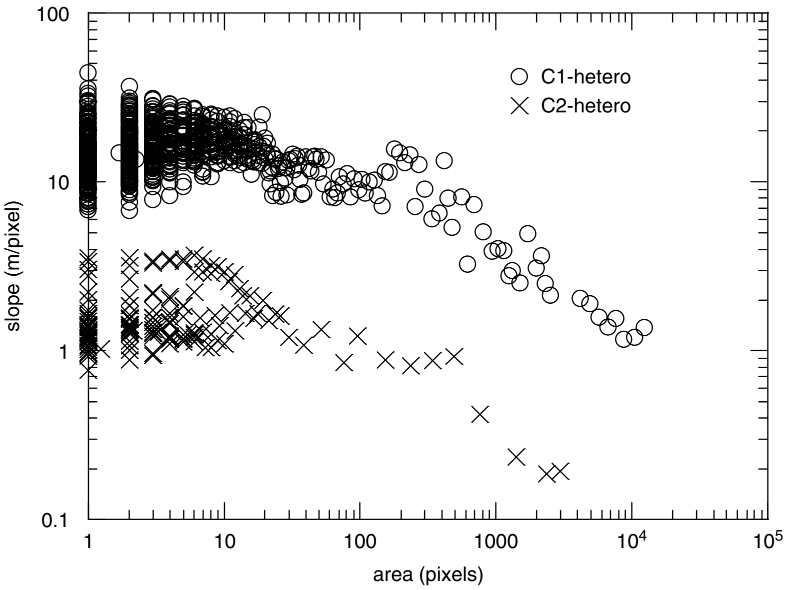


Figure 5. Area–slope relationship for the Tin Camp Creek catchments with homogeneous (top) and heterogeneous (bottom) geology. The data for the catchments C1-homo and C1-hetero have been multiplied by 10 for ease of comparison

Despite the loss of hillslope detail, the slope of the fluvially dominated region is stable over all grid spacings. A similar result was found for the other catchments.

Cumulative area distribution

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 and describes the spatial distribution of areas and drainage network aggregation properties within a catchment. The cumulative area distribution has been used as a means

Table II. Statistics for geological homogeneous and heterogeneous catchments at Tin Camp Creek

Catchment	Hypsometric integral	α	Bifurcation ratio	Slope ratio	Length ratio	Area ratio	OCN energy	Network convergence
C1-homo	0·46	0·42	5·65	1·26	1·27	5·65	17 050	1·49
C2-homo	0·40	0·42	5·37	1·35	1·14	4·21	7813	1·42
C1-hetero	0·25	0·34	5·46	1·14	1·24	4·91	82 956	1·36
C2-hetero	0·25	0·40	5·61	1·18	1·21	5·31	11 214	1·35

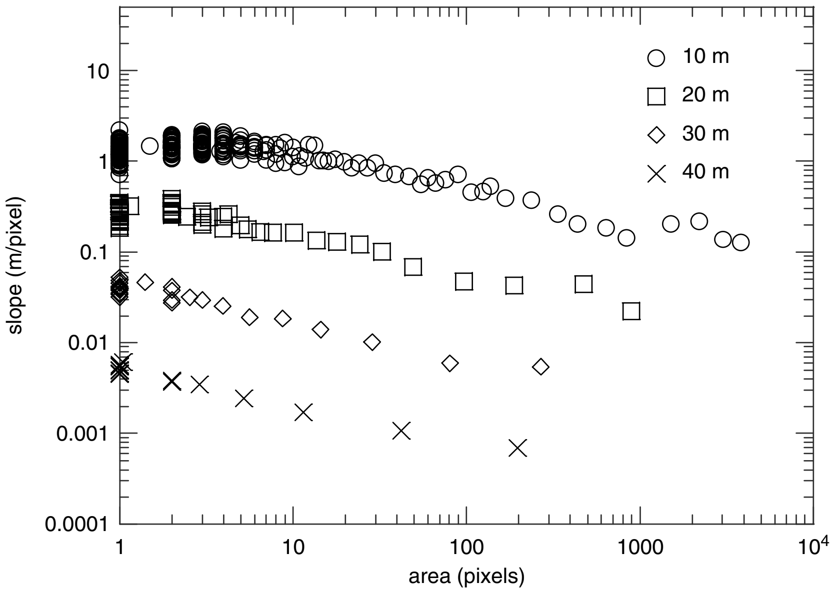


Figure 6. Area–slope relationship for the Tin Camp Creek catchment C1-homo at different digital elevation model grid sizes

of characterizing the flow aggregation structure of channel networks (Rodriguez *et al.*, 1992; LaBarbera and Roth, 1994). The cumulative area distribution is similar to the area–slope relationship in that it provides the ability to examine the relationship between diffusive and fluvial processes. Similar to the hypsometric curve, the cumulative area distribution is indirectly related to the area–slope relationship, as the distribution of areas in a catchment is related to its area–elevation properties.

The cumulative area distribution typically has a form that consists of three regions. Region one represents those small areas of the catchment where rainsplash or interrill erosion is the dominant erosive mechanism, it is also the region of hillslope flow aggregation. This region is largely influenced by the diffusive erosion processes (Hancock and Willgoose, 2001; Hancock *et al.*, 2002). Region two represents catchment areas dominated by channelized flow. This region is generally observed to be approximately log–log linear and is influenced by the value of α in the area–slope relationship (Willgoose, 1994). Region three consists of that part of the catchment dominated by large channels near the catchment outlet. Large area contributions are made in this part of the catchment, where the ordinate of the distribution function rapidly decreases as a result of increasing drainage area.

The cumulative area distribution for both the homogeneous and heterogeneous catchments at Tin Camp Creek displays three regions typical of those observed for other fluvially dominated catchments (Hancock *et al.*, 2002) (Figure 7, top). At areas approximately less than 10, the geological homogeneous and heterogeneous data has convex curvature, representing diffusive-dominated areas of the hillslope. Nevertheless, a subtle

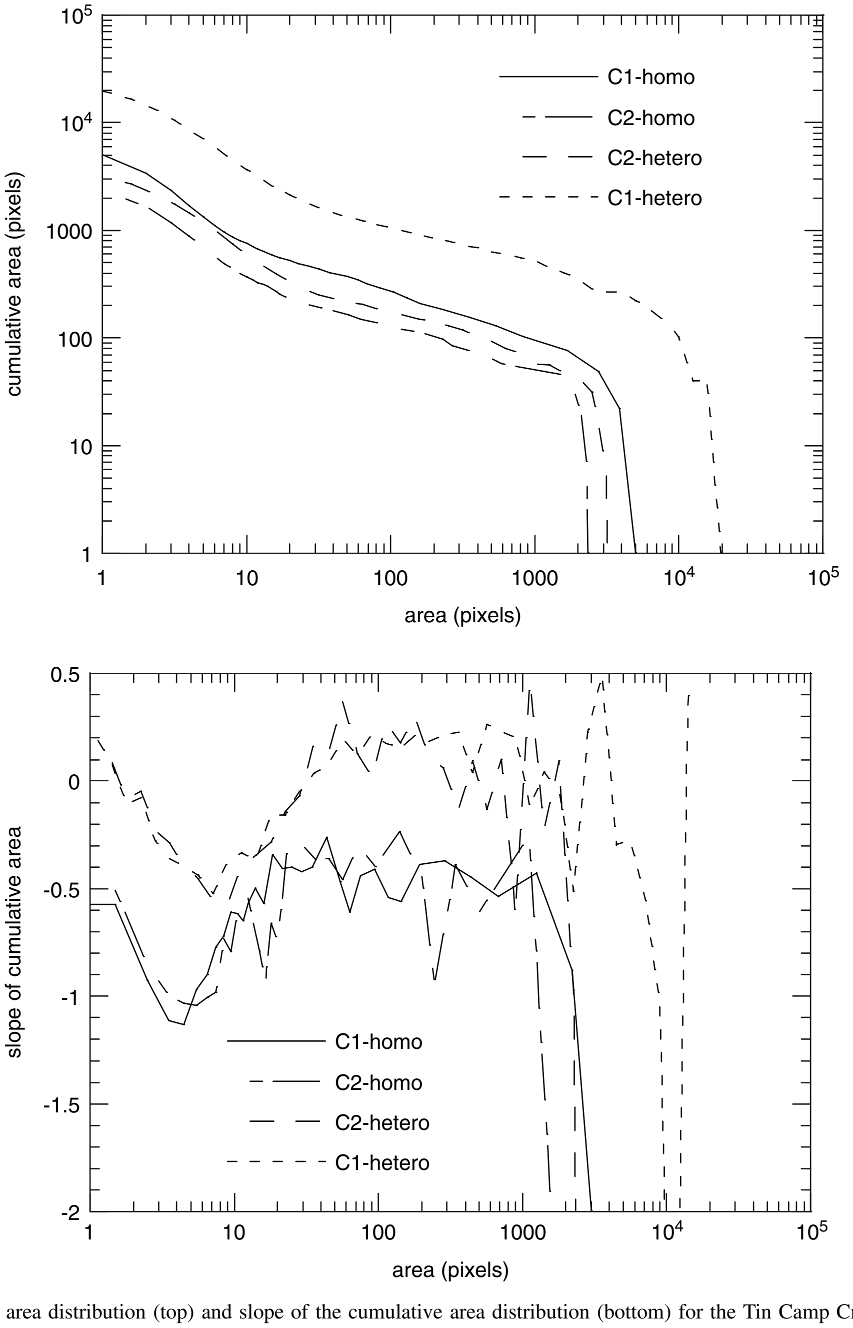


Figure 7. Cumulative area distribution (top) and slope of the cumulative area distribution (bottom) for the Tin Camp Creek catchment with homogeneous and heterogeneous geology

distinction can be observed between the diffusive regions of the homogeneous and heterogeneous data, in that the diffusive region of the heterogeneous catchments extends for slightly greater areas than the homogeneous data. In both the homogeneous and heterogeneous catchments at areas greater than 10, data display log–log linear behaviour, representing catchment areas dominated by fluvial processes followed by a sharp break in slope as large catchment areas congregate. The slope of the fluvially dominated component of the data is very similar for all data, suggesting a very similar aggregation of catchment areas in the homogeneous and heterogeneous catchments in the fluvially dominated regions of the catchments.

To further examine differences in the cumulative area distribution, the slope of the cumulative area distribution was examined (Figure 7, bottom). Both the homogeneous and heterogeneous catchments have characteristic behaviour. Figure 7 (bottom) demonstrates that the diffusion-dominated region of the homogeneous geology catchments extends for an area of approximately 11 pixels, whereas the heterogeneous geology catchment extends for approximately 50 pixels until a constant slope occurs for both the homogeneous and heterogeneous catchments. Figure 7 confirms that the slopes of the fluvially dominated regions of the Tin Camp Creek catchments are very similar to each other. These results demonstrate that the slope of the cumulative area distribution is a more sensitive tool for detecting changes in area–aggregation than the cumulative area distribution itself.

An examination of the cumulative area distribution for the different grid spacings demonstrates that the data maintains its characteristic three-region behaviour over the range of scales examined (Figure 8, top). Examination of the slope of the cumulative area distribution (Figure 8, bottom) demonstrates that the slope of the fluvially dominated region of the curve is constant for the different grid spacings, but considerable detail is lost in representation of the diffusion-dominated region when moving from the 10 m to the 20 m grid. There appears to be little difference between the 30 m and the 40 m grid in the small areas of the catchment, suggesting that the representation and distribution of areas at these grid spacings is invariant at the grid scales examined.

Hypsometric curve

The hypsometric curve (Langbein, 1947) is a non-dimensional area–elevation curve which allows a ready comparison of catchments with different area and steepness. The hypsometric curve has been used as an indicator of the geomorphic maturity of catchments and landforms (Strahler, 1952, 1964). Strahler (1952, 1964) divided landforms into youth, mature and monadnock characteristic shapes, reflecting increasing catchment age. Willgoose and Hancock (1998) demonstrated that these characteristic shapes were also consistent with different catchment erosion processes, catchment geometry and network form.

The hypsometric curves for the homogeneous and heterogeneous catchments at Tin Camp Creek display strong differences (Figure 9). The hypsometric curves for the homogeneous geology catchments display a mature profile with a smoothly declining curve as area increases and a well-defined toe at large catchment areas. The data is typical of a fluvially dominated landscape, with two-dimensional flows and roughly equal width and length (Willgoose and Hancock, 1998). The hypsometric integrals of 0·46 and 0·40 for C1-homo and C2-homo, respectively are within the range of 0·4–0·6 suggested by Strahler (1952, 1964) for mature catchments (Table II).

The heterogeneous geology catchments display a very irregular curve, with a rapid drop in the upper reaches of the catchment and then relatively flat as area increases. This rapid drop in the upper reaches represents the more erosion-resistant geology, whereas in the lower reaches the geology is less erosion resistant. The distinct break in slope indicates the catchment area where the geological transition occurs. These curves both have hypsometric integrals of 0·25, this being lower than that suggested by Strahler (1952, 1964) (Table II).

Comparison of the hypsometric curve for the homogeneous and heterogeneous catchments over the different grid scales demonstrates little difference between the data sets (Figure 10). This suggests that the distribution of area and elevation in a catchment is scale-invariant, and that the hypsometric curve is insensitive to grid scale within the range of 10–40 m. The hypsometric curve provides little information on the loss of hillslope and channel definition as grid size increases.

Catchment networking and energy properties

Descriptors of channel networking properties used here are the width function, network convergence and Strahler statistics. The width function (Surkan, 1968) is a plot of the number of channels at a given distance

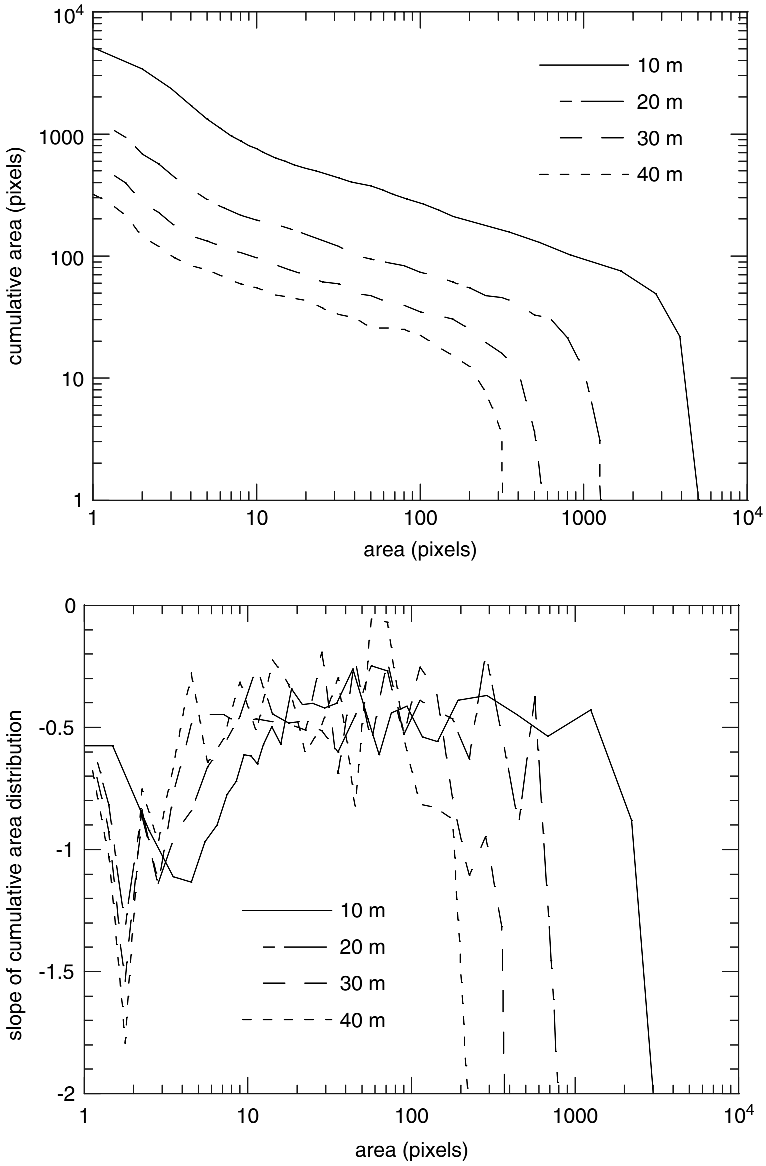


Figure 8. Cumulative area distribution (top) and slope of the cumulative area distribution (bottom) for the Tin Camp Creek catchment C1-homo at different digital elevation model grid sizes

from the basin outlet, measured along the network (Naden, 1992). A slightly more general interpretation is adopted here, which is easier to apply for digital terrain maps. The width function used is the number of drainage paths (whether they be channel or hillslope) at a given distance from the outlet, as it is difficult to determine what is channel and what is hillslope on a digital terrain map.

Catchment drainage network convergence for a gridded digital terrain map is the average number of channels draining into a point in a catchment. Convergence statistics provide, in addition to the width function, a further method of analysing catchment drainage and network properties (Perera and Willgoose, 1998; Ibbitt *et al.*, 1999).

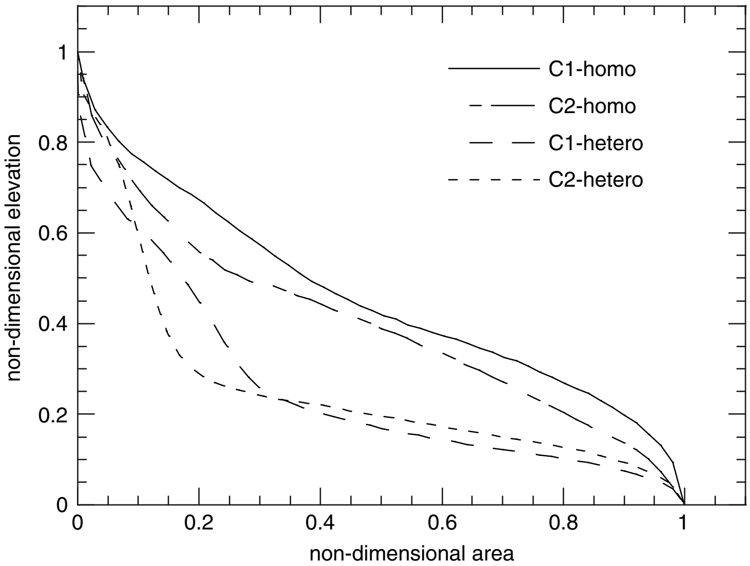


Figure 9. Hypsometric curve for catchments with homogeneous and heterogeneous geology

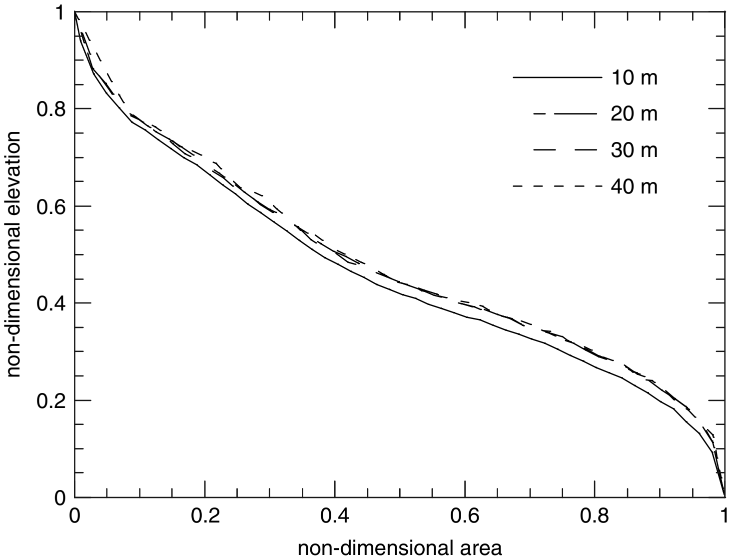


Figure 10. Hypsometric curve for the Tin Camp Creek catchment C1-homo at different digital elevation model grid sizes

Catchments differ in potential energy as a result of catchment size and relief. A simple method of comparing catchment energy is an examination of catchment relief and area. The greater the catchment area and the larger the relief, the more energy a catchment will have (Table I). Energy was also examined using the Optimal Channel Networks (OCN) concept of Rodriguez-Iturbe and Rinaldo (1997) (Table II). In this study, OCN energy is defined as

$$\sum_{i}^{N} l_i A_i^{0.5} \tag{2}$$

where i is the link index, N the number of links, and l and A are the length and area of each link. It is normally defined for the channel network only (Rigon *et al.*, 1994), but is used here over the whole catchment to eliminate the energy's sensitivity to the drainage density of the catchment. The differences in OCN energy between different catchments reflect the differences in catchment area, with the larger catchments having more energy.

The width function displays considerable spatial variability as a result of both catchment shape and catchment size (the data was normalized by dividing distance and width by maximum distance and width, respectively) (Figure 11, bottom). This reflects the different catchment shapes and resultant different drainage network. It is believed that at the present time there is limited information to be gained from the width function other than to say that the width function is an expression of catchment shape.

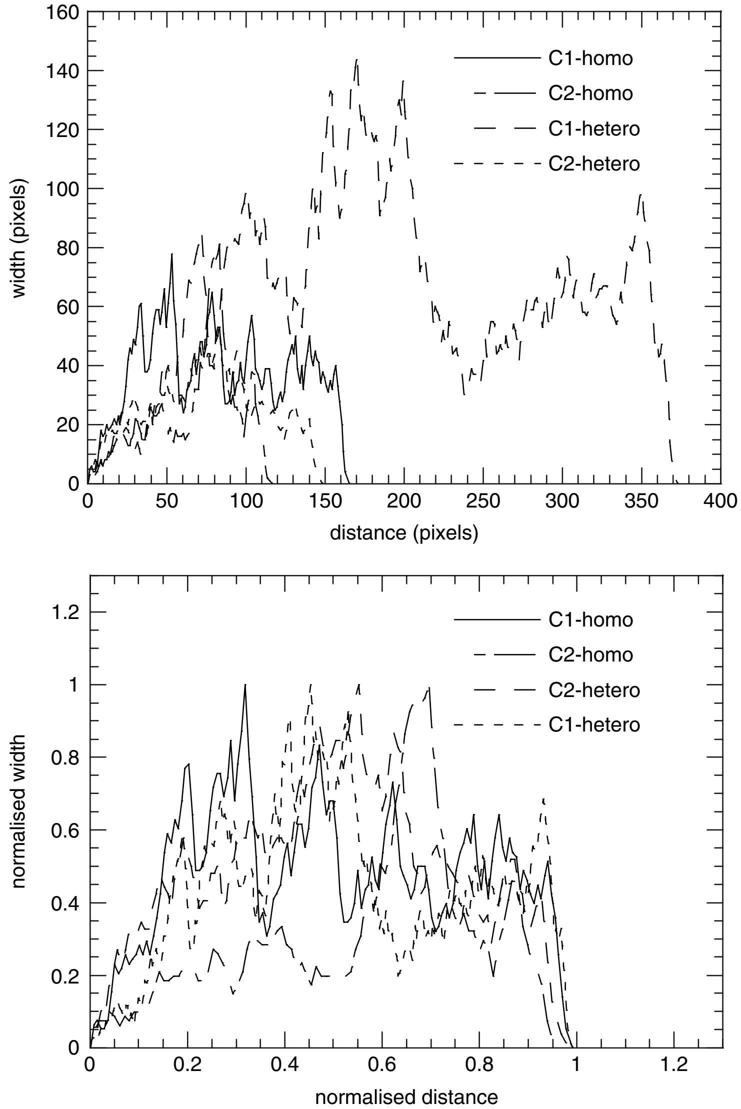


Figure 11. Width function for the homogeneous and heterogeneous geology catchments at Tin Camp Creek (top) and normalized width functions for the same data (bottom)

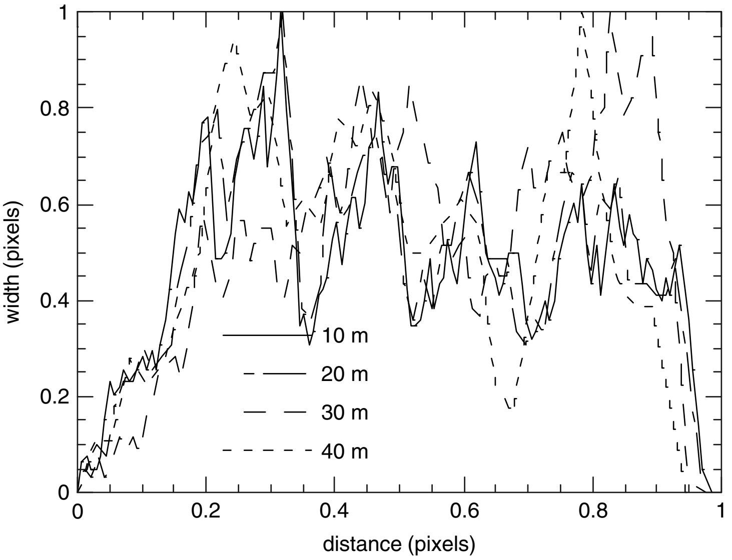


Figure 12. Normalized width function for the Tin Camp Creek catchment C1-homo at different digital elevation model grid sizes

Table III. Catchment statistics for C1-homo using different digital elevation model grid spacings

Grid size	Bifurcation ratio	Slope ratio	Length ratio	Area ratio	Stream order	Network convergence	OCN energy
10 m	5·65	1·26	1·27	5·65	6	1·49	17 050
20 m	6·05	1·55	1·66	6·48	5	1·86	3 711
30 m	6·11	1·83	1·81	6·48	5	2·05	1 530
40 m	7·36	2·19	2·17	7·94	4	2·45	821

Differences in the width function occur as digital elevation model grid size increases. Figure 12 demonstrates that the width function largely maintains its shape up to a 20 m grid, but at greater sizes the shape begins to change. A similar result was found for the other catchments. The width function appears to be a sensitive indicator of differences in grid spacing (Yang *et al*., 2001).

Convergence statistics (Table II) for Tin Camp Creek demonstrate that the heterogeneous catchments have a slightly lower network convergence than the homogeneous catchments. This suggests that the homogeneous geology catchments have a slightly more branched network than the heterogeneous catchments, and may reflect the greater average dissection of the homogeneous catchments. Nevertheless, the difference is not strong. Table III demonstrates that as catchment grid spacing increases so does the network convergence value, suggesting that grid size has an effect on drainage network characterization. This change in network characterization and consequent network convergence can be observed in Figure 13, where at a grid spacing of 10 m the hillslopes are represented by long linear flow paths, and as grid size increases the length of the flow path decreases and the tendency of the network to branch increases. A similar result was found for all other catchments.

Strahler bifurcation, length, slope and area ratios (Strahler, 1964) were examined for the catchments (Table II). Drainage density is not examined in this study as it was too difficult to determine what was hillslope and what was channel. Strahler network statistics display no strong differences between the geological homogeneous and heterogeneous catchments and are of little use in identifying differences in catchment morphology. Nevertheless, as catchment grid spacing increases the maximum stream order of the

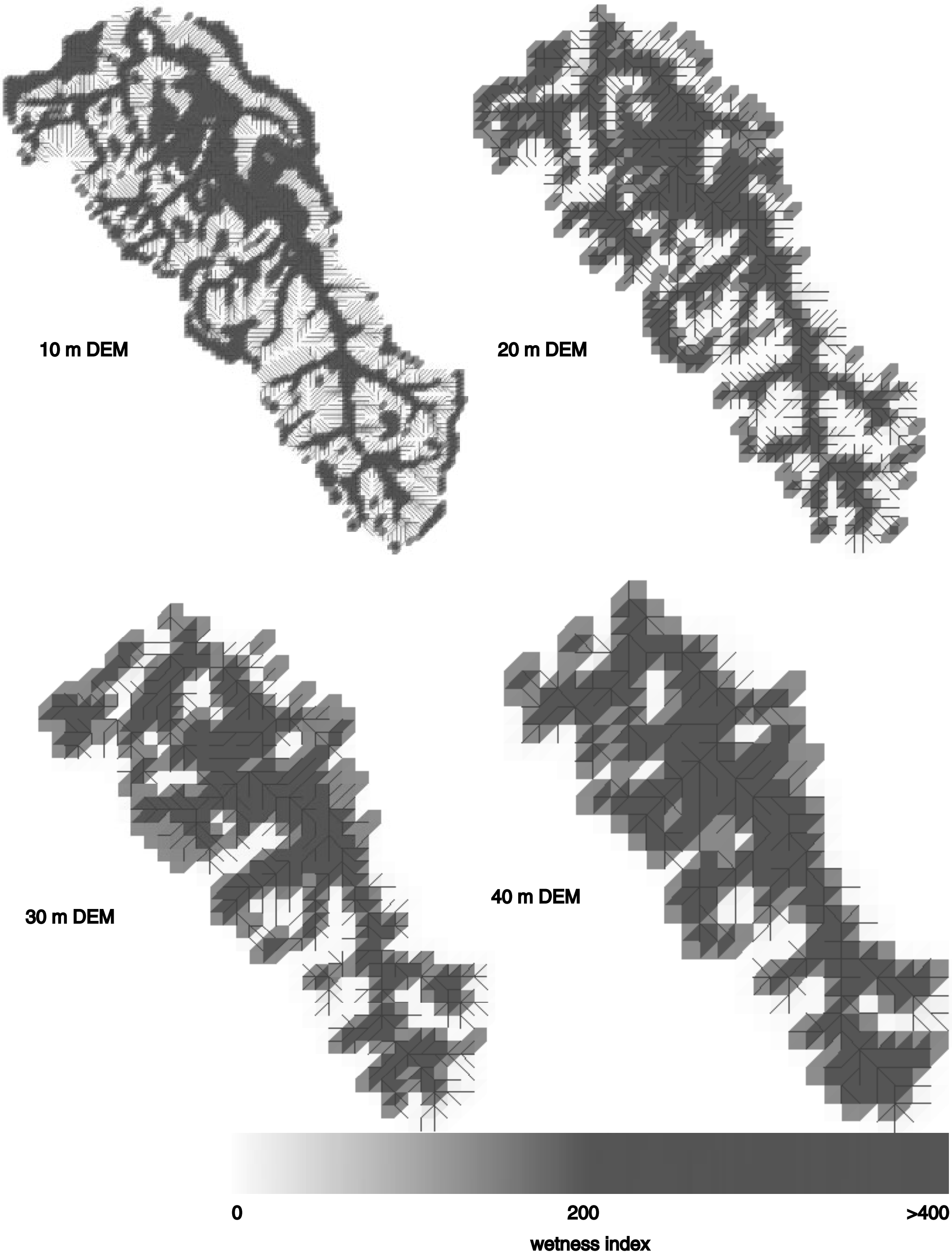


Figure 13. Drainage network and wetness index for catchment C1-homo over a range of digital elevation model grid scales

catchments decreases while the bifurcation, slope length and area ratios increase for both the homogeneous and heterogeneous catchments (Table III). This demonstrates that choice of digital elevation model grid spacing has a direct impact on Strahler network properties and is reflecting the more branched network as grid size increases (Figure 13).

An increase in grid spacing reduces OCN energy (Table III). Nevertheless, when corrected for grid size OCN, energy decreases. This difference in energy with grid size reflects the differences in catchment area aggregation definition as a result of the different grid spacings.

Catchment hydrology and digital elevation model grid size

In order to assess the impact of different digital elevation model grid scales on runoff properties of the catchments, the Hydrogeomorphic Steady State (HGSS) model of Willgoose and Perera (2001) was used. This model incorporates catchment organization and geomorphological relations, such as the cumulative area distribution and area–slope relationship (Willgoose and Perera, 2001). In this study the wetness index λ_i is used to describe the relative area of the catchment saturated when water saturates the total depth of the soil profile. Wetness indices have been used extensively to assess the runoff properties of catchments (Moore *et al*., 1991; Wolock and McCabe, 2000). The saturation of the soil profile and resultant saturation excess runoff is a typical runoff process in the monsoonal tropical climate of the Northern Territory. The wetness index (λ_i) is calculated by

$$\lambda_i = \frac{A_{\mathrm{i}}^{1+\alpha}}{C} \tag{3}$$

where A_i is catchment area draining through a point, α and C are the exponent and constant in the area–slope relationship [Equation (1)] for the entire catchment.

The wetness index was overlaid on the drainage network for catchment C1-homo for different grid spacings (Figure 13). In this case α and C are taken from the C1-homo catchment (Table II). The results demonstrate that the 10 m and 20 m grid spacings produce saturated areas along the major drainage lines (areas that would be expected to be saturated each season) but at greater grid spacings much detail is lost, and at 30 m and 40 m grid sizes the major drainage lines are not linked by saturated areas.

DISCUSSION

In this study a range of catchment sizes and shapes have been examined for characteristic geomorphological signatures using a range of both graphical and statistical tools. This study has shown that the area–slope relationship, hypsometric curve and cumulative area distribution can be used to distinguish between catchments with differing geologies. Other geomorphic measures such as the width function, Strahler statistics, network convergence and OCN energy provide little information. The examination of the different digital elevation model grid scales on the behaviour of these geomorphological measures demonstrates that some are scale-dependent while others are scale-invariant.

It is recognized that this analysis examines only catchments from one region subject to the same climate with a limited range of geology. Nevertheless, the study provides insights into the usefulness of current geomorphic descriptors in understanding catchment behaviour. The methods used in this study outline the strengths and weaknesses of the various statistics. It is recognized that further work is needed to fully evaluate the usefulness of these catchment properties (McMaster, 2002).

Catchment differentiation using geological and hydrological measures

The area–slope relationship demonstrates that there are two different hillslope curvatures at small catchment areas occurring within the Tin Camp Creek catchment. The different land units of the catchment have different characteristic curvature as a result of the different geologies. It has been demonstrated in previous studies that, when modelling this hillslope curvature, different diffusive erosion parameters are needed to obtain an area–slope relationship that matches that of the field data (Hancock *et al*., 2002; Hancock, 2003). In the fluvially dominated areas of both catchments, the area–slope relationship is very similar as both catchments have developed on schistose material. Therefore, to numerically model the geologically heterogeneous catchments, both sets of erosion model parameters would be necessary to capture the behaviour of the area–slope data (Hancock *et al*., 2002).

Increased scatter in the area–slope relationship in the fluvially dominated area of the heterogeneous catchment is likely to be an expression of mixed geology, with remnants of the more resistant upper slope geology still being present in the lower catchment reaches. It is also likely that the scatter may be a result of the freshly weathered and deposited material from both the upslope areas of the catchment and the more weathered material on the lower slopes. This mix of materials and their deposition and weathering may have an important impact on the area–slope data. The observation that scatter in the area–slope relationship occurs in catchments with heterogeneous geology also offers an explanation for the observed scatter found in past studies (Willgoose, 1994; Willgoose *et al*., 2003).

The cumulative area distribution demonstrates strong differences between the geologically different catchments in the diffusive-dominated region. As found for the area–slope relationship, the diffusive-dominated region of the cumulative area distribution for the geologically heterogeneous catchments is larger than that of the homogeneous catchments. A visual examination of the catchments demonstrates that the heterogeneous catchments have, on average, longer hillslopes than those of the homogeneous catchments. Accordingly, the cumulative area distribution (as found for the area–slope relationship) is a good tool for understanding differences in the diffusive-dominated regions of a catchment. The constant slope of both the cumulative area distribution and the area–slope relationship in the fluvially dominated regions of the catchments examined, despite the differences in geology in the upper reaches of the spatially heterogeneous catchments, confirms the consistency of erosion processes in the fluvially dominated region of the catchments as the slope of this region has been shown to change with different erosion processes.

While the hypsometric curve provides no indication of the likely erosion processes in a catchment, it can be used to infer the underlying geology and state of catchment evolution. The data demonstrates that in a catchment with uniform geology, a curve that matches the classical mature profile of Strahler will result. A catchment with steep topography in the upper reaches and lower topography downslope will result in a very different profile. Therefore, the hypsometric curve is a useful tool when comparing catchments.

An examination of the Strahler and network convergence statistics demonstrates that there is little difference between the homogeneous and heterogeneous catchments, and while the homogeneous catchments have a slightly higher network convergence than the geologically heterogeneous catchments, little information can be gained from these statistics. As found in previous studies, the width function is of limited benefit and provides an assessment of catchment shape only (Hancock, 2003).

Effect of digital elevation model grid scale

The hierarchical scaling approach used in this study has allowed an assessment of the strengths and weaknesses of the hydrological and geomorphological measures (Schoorl *et al*., 2000). Visual assessment of the catchments over a range of digital elevation model grid scales demonstrates that much hillslope detail is lost at digital elevation model grid sizes greater than 10 m. The catchments lose definition of hillslope curvature and become much more linear (Gallant and Hutchinson, 1996). This suggests that a visual assessment of a catchment digital elevation model may suffice as an appropriate way of judging the maximum grid size to capture hillslope detail. The applicability of the 10 m grid is also supported by the catchment statistics examined in this study over the range of grid scales. Consequently, as found by Zhang and Montgomery (1994), a grid scale of 10 m captures sufficient hillslope detail for the terrain examined. In this study, grids smaller than 10 m are not examined as this would require interpolation of data.

The results also show that choice of digital elevation model grid size is important in determining all the geomorphic measures examined in this study, except for the hypsometric curve. A grid size should be selected which is considerably less than that of the average hillslope length (Zhang and Montgomery, 1994; Wolock and Price, 1994; Yang *et al*., 2001; McMaster, 2002). Nevertheless, the behaviour of the area–slope relationship and the cumulative area distribution at Tin Camp Creek is scale-invariant at areas dominated by fluvial processes. Previous studies have shown that the slope of the fluvially dominated region is related to the erosion process that occurs in this region of the catchment (Willgoose, 1994). The area–slope relationship has been used in the past to derive parameters for erosion model calibration and infer the erosion process (Hancock *et al*., 2002; Hancock, 2003; Willgoose *et al*., 2003). The loss of detail in the width function and wetness index demonstrates that hydrological properties are likely to be poorly represented at grid scales greater than 20 m.

Nevertheless, considerable information can be gained at grid scales greater than 10 m by 10 m as the hypsometric curve is scale-invariant and the area–slope relationship and cumulative area distribution are scale-invariant in the fluvially dominated regions of the data sets. The slope of the cumulative area distribution (Figure 8) suggests that at grid sizes greater than 20 m the definition of diffusive-dominated areas does not deteriorate any further. Accordingly, these results demonstrate that care must be taken when extracting catchment information from a digital elevation model and that the reliability of the information must be related to grid size (Tarboton *et al*., 1991; Thieken, 1999; Wolock and Price, 1994; Wolock and McCabe, 2000; Schoorl *et al*., 2000; Yang *et al*., 2001; McMaster, 2002). The process used in this study provides a methodology where visual assessment as well as the use of geomorphological and hydrological measures can be used to determine an appropriate grid scale which best captures landscape features.

Therefore, if sufficient hillslope detail is captured at a resolution of 10 m by 10 m for reliable geomorphological and hydrological assessment to be made, there may be no need for finer grid resolution with its accompanying fourfold increase in number of grid points with each halving in grid size (and resultant data storage and handling issues). This is an important issue, as LIDAR and InSAR can provide reliable digital elevation models at grid resolutions of centimetres (Smith, 2002). The usefulness of such small grid resolution for geomorphology and hydrology needs to be questioned.

CONCLUSION

In understanding any catchment, visual assessment (both field examination and also mapping) is the first and easiest way to distinguish similarities and differences in catchment form and function. Nevertheless, in many cases visual assessment is not sufficient. Further analysis using graphical or other semi-quantitative measures may be needed to assess differences in catchment form and function.

This study demonstrates that well-accepted geomorphic descriptors such as the area–slope relationship, cumulative area distribution and hypsometric curve can be used to differentiate between catchments with differing underlying geology. An assessment such as this, using remotely sensed data, can provide important background information on catchment geology and geomorphology. Field examination is still required to confirm statistical and graphical data, but geomorphological descriptors such as the area–slope relationship, hypsometric curve and cumulative area distribution can be used reliably to provide background information on geology and erosion processes, while the hypsometric curve can provide important information on the relative proportions of catchment area with large relief differences over a range of digital elevation model scales. Channel network statistics (such as Strahler and network convergence), together with the width function, provided little information on differences in catchment properties between the geological homogeneous and heterogeneous catchments.

Examination of the area–slope relationship, cumulative area distribution, width function and Strahler statistics showed them to be sensitive to digital elevation model grid scale, while the hypsometric curve was not. Results also demonstrate that catchment digital elevation model grid size is important for the reliable capture of hillslope properties. In this study a digital elevation model grid scale of 10 m by 10 m was found to be appropriate. Hillslope detail was lost at grid scales greater than 10 m. Nevertheless, considerable catchment information can be obtained from digital elevation models at larger grid scales. Consequently, currently available digital elevation models at grid scales greater than an appropriate grid scale for the catchment property of interest may have a considerable loss of catchment detail.

ACKNOWLEDGEMENTS

The advice and support of Ken Evans and Dene Moliere (*eriss*), the two anonymous reviewers and comments of David O'Brien are greatly appreciated. Conversations with Garry Willgoose are gratefully acknowledged.

REFERENCES

Anderson MG, Burt TP. 1978. The role of topography in controlling throughflow generation. *Earth Surface Processes* **3**: 331–344.
Bevan K. 1995. Linking parameters across scales: subgrid parameterizations and scale dependent hydrological models. *Hydrological Processes* **9**: 507–525.
Coulthard TJ. 2001. Landscape evolution models: a software review. *Hydrological Processes* **15**: 165–173.
DaRos D, Borga M. 1997. Use of digital elevation model data for the derivation of the geomorphological instantaneous unit hydrograph. *Hydrological Processes* **11**: 13–33.
Dunne T, Black R. 1970. Partial area contributions to storm runoff in a New England watershed. *Water Resources Research* **6**: 1297–1311.
Flint JJ. 1974. Stream gradient as a function of order, magnitude and discharge. *Water Resources Research* **10**(5): 969–973.
Fryer JG, Chandler JH, Cooper MAR. 1994. Short communication on the accuracy of heighting from aerial photographs and maps: implications for process modelers. *Earth Surface Processes and Landforms* **19**: 577–583.
Gallant J, Hutchinson MF. 1996. Towards an understanding of landscape scale and structure. In *Proceedings, Third International Workshop/Conference on Integrating GIS and Environmental Modelling*, Santa Fe, NM, 21–26 January. National Centre for Geographic Information and Analysis, Santa Barbara, CA.
Gupta VK, Waymire E. 1989. On the formation of an analytic approach to hydrologic response and similarity at the basin scale. *Journal of Hydrology* **65**: 95–123.
Gyasi-Agyei Y, Willgoose GR, DeTroch FP. 1995. Effect of vertical resolution and map scale of digital elevation model on geomorphological parameters used in hydrology. *Hydrological Processes* **9**: 363–382.
Hack JT. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. *United States Geological Survey Professional Paper* **292**(B): 45–97.
Hancock GR. 2003. The effect of catchment aspect ratio on geomorphological descriptors. In *Prediction in Geomorphology*, Wilcock P, Iverson R (eds). American Geophysical Union: Washington, DC.
Hancock GR. 2004. The use of landscape evolution models in mining rehabilitation design. *Environmental Geology* DOI: 10.1007/s00254-004-1030-3.
Hancock GR, Willgoose GR. 2001. The use of a landscape simulator in the validation of the SIBERIA landscape evolution model, steady state landforms. *Water Resources Research* **37**(7): 1981–1992.
Hancock GR, Willgoose GR. 2002. The use of a landscape simulator in the validation of the SIBERIA landscape evolution model: transient landforms. *Earth Surface Processes and Landforms* **27**: 1321–1334.
Hancock GR, Willgoose GR, Evans KG. 2002. Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia, field catchment. *Earth Surface Processes and Landforms* **27**(2): 125–143.
Holmes KW, Chadwick OA, Kyriakidis PC. 2000. Error in a USGS 30-meter digital elevation model and its impact on terrain modelling. *Journal of Hydrology* **233**: 154–173.
Ibbitt RP, Willgoose GR, Duncan MJ. 1999. Channel network simulation models compared with data from the Ashley River, New Zealand. *Water Resources Research* **35**(12): 3875–3890.
Kalma JD, Sivapalan M. 1995. *Scale Issues in Hydrological Modelling*. John Wiley & Sons: New York.
Kenward T, Lettenmaier DP, Wood EF, Fielding E. 2000. Effects of digital elevation model accuracy on hydrologic predictions. *Remote Sensing of Environment* **74**: 432–444.
Kirkby M, Chorley R. 1967. Throughflow, overland flow and erosion. *Bulletin of the International Association of Science and Hydrology* **12**: 73–80.
LaBarbera P, Roth G. 1994. Invariance and scaling properties in the distributions of contributing area and energy in drainage basins. *Hydrological Processes* **8**: 125–135.
Lane SN, Chandler JH, Richards KS. 1994. Developments in monitoring and modelling small scale river bed topography. *Earth Surface Processes and Landforms* **19**: 349–368.
Langbein WB. 1947. Topographic characteristics of drainage basins. *US Geological Society Water Supply Paper* 968-C, Washington, DC.
McMaster KJ. 2002. Effects of digital elevation model resolution on derived stream network positions. *Water Resources Research* **38**(4): 13–1–13-8.
Moglen GE, Bras RL. 1994. *Simulation of observed topography using a physically based basin evolution model, TR340*. Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA.
Moglen GE, Bras RL. 1995a. Effect of Spatial Heterogeneities on Geomorphic Expression in a Model of Basin Evolution. *Water Resources Research* **31**(10): 2613–2623.

Moglen GE, Bras RL. 1995b. The Importance of Spatially Heterogeneous Erosivity and the Cumulative Area Distribution. *Geomorphology* **12**(3): 173–185.

Montgomery DR, Dietrich WE. 1988. Where do channels begin? *Nature* **336**: 232–234.

Montgomery DR, Dietrich WE. 1989. Source areas, drainage density and channel initiation. *Water Resources Research* **25**(8): 1907–1918.

Montgomery DR, Dietrich WE. 1994. Landscape dissection and drainage area–slope thresholds. In *Process Models and Theoretical Geomorphology*, Kirkby MJ (ed.). John Wiley & Sons: Chichester, UK.

Montgomery DR, Foufoula-Georgiou E. 1993. Channel network source presentation using digital elevation models. *Water Resources Research* **29**(12): 3925–3934.

Moore ID, Grayson RB. 1991. Terrain-based catchment partitioning and runoff prediction using vector elevation data. *Water Resources Research* **27**(6): 1117–1191.

Moore ID, Grayson RB, Ladson AR. 1991. Digital terrain modelling: a review of hydrological, geomorphological and biological applications. *Hydrological Processes* **5**: 3–30.

Moore ID, Turner AK, Wilson JP, Jenson S, Band LE. 1993. GIS and land-surface–subsurface process modelling. In *Environmental Modelling with GIS*, Goodchild M, Parks B, Steyaert L (eds). Oxford University Press: New York; 196–230.

Naden PS. 1992. Spatial variability in flood estimation for large catchments: the exploitation of channel network structure. *Journal of Hydrological Sciences* **37**(1): 53–71.

Needham RS. 1988. *Geology of the Alligator Rivers uranium field, Northern Territory*. Bulletin 224, Australian Government Publishing Service, Canberra.

Perera HJ, Willgoose GR. 1998. A physical explanation of the cumulative area distribution curve. *Water Resources Research* **34**(5): 1335–1343.

Quinn PF, Beven KJ, Lamb R. 1995. The ln(a/tanb) index. How do you calculate it and how to use it within the TOPMODEL framework. *Hydrological Processes* **9**: 161–182.

Rigon R, Rinaldo A, Rodriguez-Iturbe I. 1994. On landscape self-organisation. *Journal of Geophysical Research* **99**(B6): 11 971–11 993.

Riley SJ, Williams DK. 1991. Thresholds of gullying, Arnhem Land, Northern Territory. *Malaysian Journal of Tropical Agriculture* **22**(2): 133–143.

Rodriguez-Iturbe I, Rinaldo A. 1997. *Fractal River Basins Chance and Self Organisation*. Cambridge University Press: Cambridge.

Rodriguez-Iturbe I, Valdes JB. 1979. The geomorphologic structure of hydrologic response. *Water Resources Research* **15**: 1409–1420.

Rodriguez I, Ijjasz Vasquez EJ, Bras RL, Tarboton DG. 1992. Distributions of discharge, mass and energy in river basins. *Water Resources Research* **28**(4): 1089–1093.

Schoorl JM, Sonneveld MPW, Veldkamp A. 2000. Three-dimensional landscape process modelling: the effect of DEM resolution. *Earth Surface Processes and Landforms* **25**: 1025–1034.

Shreve RL. 1966. Statistical law of stream numbers. *Journal of Geology* **74**: 17–37.

Sloan SWA. 1987. Fast algorithm for constructing Delaunay triangulations in the plane. *Advanced Engineering Software for Workstations* **9**(1): 34–55.

Smith LC. 2002. Emerging applications of interferometric synthetic aperture radar (InSAR) in geomorphology and hydrology. *Annals of the Association of American Geographers* **92**(3): 385–398.

Sposito G. 1998. *Scale Dependence and Scale Invariance in Hydrology*. Cambridge University Press: New York.

Story R, Galloway RW, McAlpine JR, Aldrick JM, Williams MAJ. 1976. *Lands of the Alligator Rivers area, Northern Territory*. Land Research Series no. 38, CSIRO.

Strahler AN. 1952. Hypsometric (area–altitude) analysis of erosional topography. *Geological Society of America Bulletin* **63**: 1117–1142.

Strahler AN. 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, Chow VT (ed.). McGraw-Hill: New York; 4·40–4·74.

Surkan AJ. 1968. Synthetic hydrographs: effects of network geometry. *Water Resources Research* **5**(1): 112–128.

Tarboton DG, Bras RL, Rodriguez-Iturbe I. 1989. *The analysis of river basins and channel networks using digital terrain data, TR 326*. Department of Civil and Environmental Engineering, Massachusetts Institute of Technology: Boston.

Tarboton DG, Bras RL, Rodriguez-Iturbe I. 1992. A physical basis for drainage density. *Geomorphology* **5**(1/2): 59–76.

Thieken AH, Lucke A, Dieggruger B, Richter O. 1999. Scaling input data by GIS for hydrological modelling. *Hydrological Processes* **13**: 611–630.

Thompson JA, Bell JC, Butler CA. 2001. Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil–landscape modelling. *Geoderma* **100**: 67–89.

Walker JP, Willgoose GR. 1999. On the effect of digital elevation model accuracy on hydrology and geomorphology. *Water Resources Research* **35**(7): 2259–2268.

Willgoose GR. 1994. A physical explanation for an observed area–slope–elevation relationship for catchments with declining relief. *Water Resources Research* **30**(2): 151–159.

Willgoose GR, Hancock G. 1998. Revisiting the hypsometric curve as an indicator of form and process in transport limited catchment. *Earth Surface Processes and Landforms* **23**: 611–623.

Willgoose GR, Perera H. 2001. A simple model of saturation excess runoff generation based on geomorphology, steady state soil moisture. *Water Resources Research* **37**(1): 147–155.

Willgoose GR, Hancock GR, Kuczera G. 2003. Variability of catchment statistics. In *Prediction in Geomorphology*, Wilcock P, Iverson R (eds). American Geophysical Union: Washington, DC.

Willgoose GR, Bras RL, Rodriguez-Iturbe I. 1991. A physical explanation of an observed link area–slope relationship. *Water Resources Research* **27**(7): 1697–1702.

Wolock DM, McCabe GJ. 2000. Differences in topographic characteristics computed from 100- and 1000-m resolution digital elevation model data. *Hydrological Processes* **14**: 987–1002.

Wolock DM, Price CV. 1994. Effects of digital elevation model map scale and data resolution on a topography-based watershed model. *Water Resources Research* **30**(11): 3041–3052.

Yang D, Herath S, Musiake K. 2001. Spatial resolution sensitivity of catchment geomorphologic properties and the effect on hydrological simulation. *Hydrological Processes* **15**: 2085–2099.

Zhang W, Montgomery DR. 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. *Water Resources Research* **30**(4): 1019–1028.

Zhang X, Drake NA, Wainwright J, Mulligan M. 1999. Comparison of slope estimates from low resolution DEMs: scaling issues and a fractal method for their solution. *Earth Surface Processes and Landforms* **24**: 763–779.

