Topographic parameterization in continental hydrology: a study in scale

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Abstract:
Digital elevation models (DEMs) are useful and popular tools from which topographic parameters can be quickly and efficiently extracted for various hydrologic applications. DEMs coupled with automated methods for extracting topographic information provide a powerful means of parameterizing hydrologic models over a wide range of scales. However, choosing appropriate DEM scales for particular hydrologic modeling applications is limited by a lack of understanding of the effects of scale and grid resolution on land-surface representation. The scale effects of aggregation on square-grid DEMs of two continental-scale basins are examined. Base DEMs of the Mackenzie and Missouri River basins are extracted from the HYDRO1k DEM of North America. Successively coarser grids of 2, 4, 8, ... 64 km were generated from the 'base' DEMs using simple linear averaging. TOPAZ (Topographic Parameterization) was applied to the base and aggregated DEMs using constant critical source area and minimum source channel length values to extract topographic variables at varying scales or resolutions. The effects of changing DEM resolution are examined by considering changes in the spatial distribution and statistical properties of selected topographic variables of hydrological importance. The effects of increasing grid size on basin and drainage network delineation, and derived topographic variables, tends to be non-linear. In particular, changes in overall basin extent and drainage network configuration make it impractical to apply a simple scaling function to estimate variable values for fine-resolution DEMs from those derived from coarse-resolution DEMs. Results also suggest the resolution to which a DEM can be reduced by aggregation and still provide useful topographic information for continental-scale hydrologic modelling is that at which the mean hydraulic slope falls to approximately 1%. In this study, that generally occurred at a resolution of about 10 km. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS digital elevation model; modelling; hydrological modelling; grid cell; resolution; geomorphometry; hydrology

INTRODUCTION
Digital elevation models (DEMs) are increasingly being used in hydrology. Automated methods are available for delineating a basin, channel network and a variety of topographic parameters from DEMs (Tribe, 1992; Martz and Garbrecht, 1998). This information is readily transformed into meaningful input for hydrologic applications (Lacroix et al., 2002). However, scale-related issues continue to be a concern for hydrologic modellers and researchers attempting to model continental-scale processes and land–atmosphere interactions. A lack of understanding of the nature and extent of grid-scale effects on the properties of drainage basins and networks continues to limit the potential use of coarse-resolution DEMs in continental-scale hydrology.

Recent advances in automated DEM analysis techniques and the increased availability of global datasets have allowed researchers to perform in-depth examinations of various scale-related issues (e.g. grid-scale effects on drainage properties). Such studies require a rapid and efficient means of segmenting and parameterizing basins over a wide range scales, which involves identifying the channel network and drainage boundaries and measuring the properties of the drainage network and its contributing areas. Ultimately,
automated techniques depend on: (1) a method of defining surface drainage (simulating overland flow) over the landscape, and (2) a means of dealing with depressions and flat areas, which are problematic in defining overland flow (Martz and Garbrecht, 1998).

Watershed modelling of relatively small catchments with high-resolution DEMs has been the dominant practice in the past. In recent years more attention has been given to modelling regional and continental-scale drainage basins to study various aspects of global water and energy exchanges (Kite, 1995). For modelling purposes, the direct segmentation and parameterization of such large basins (>10^5 km^2) from high-resolution DEMs is not practical, as it would result in unmanageable volumes of data and severe computational demands. The alternative of aggregating source DEMs, or the derived data, to coarser resolutions has seen limited application to regional and continental-scale hydrology, largely due to a lack of understanding of scale effects and grid resolution on land-surface representation.

Several previous studies have examined the effects of increasing grid size on basin and network delineation, and on topographic variable measurement (Hutchinson and Dowling, 1991; Veregin, 1997; Bates et al., 1998; Graham et al., 1999; Zhang et al., 1999; Ma et al., 2000; Wolock and McCabe, 2000). Grid sizes used in these studies range from 10 m to 100 km and typically examined one or two coarser resolution DEMs generated by averaging or resampling. Hutchinson and Dowling (1991) and Zhang et al. (1999) are the exception, in that they generate coarser grids from an initial source dataset.

In this study, the effects of increasing grid-cell size on the delineation of drainage boundaries and drainage networks, and derived topographic variables for several regional and continental-scale drainage basins, are examined. Two continental-scale DEMs with a horizontal resolution of 1 km are initially extracted from the HYDRO1k DEM of North America. These initial DEMs are then averaged to generate several coarser resolution DEMs to assess the impact of increasing grid size on basin boundaries, drainage networks and several topographic variables commonly used in hydrologic modelling and water resource management. The digital landscape analysis tool TOPAZ (Garbrecht and Martz, 2000) is used to segment and parameterize the initial and aggregated DEMs of the basins.

Even though widely accepted drainage enforcement techniques are available for use in DEM generation (Hutchinson, 1989, 1996), no such techniques were used in this study. As is often the case, the best available elevation data were already in raster format and independent stream and river data consistent with the topographic data were not available. This study was also focused on assessing the impact of simple aggregation or coarsening methods without the complication of drainage enforcement.

A better understanding of the effects of changing DEM resolution on the automated segmentation and parameterization of drainage basins was thought to be of value to the development of continental-scale hydrologic simulations. The possibility of substituting coarser DEMs for finer resolution DEMs for such purposes is attractive, because it would reduce data volume and computational demands. This could also have potential application to linking hydrologic and atmospheric models to assess the impact of climate change and variability on the global hydrologic cycle.

STUDY AREAS

Two study areas were chosen for this research: (1) the Mackenzie River basin, and (2) the Missouri River basin. The Mackenzie basin is located in northwestern Canada (Figure 1). The Mackenzie basin spans approximately 40° of longitude (140–103°W) and 15° latitude (70–55°N). The Mackenzie River system is the second largest river system in North America (Krauss, 1995) and flows more than 4000 km through northwestern Canada before entering the Beaufort Sea of the Arctic Ocean. The basin covers an area of approximately 1.8 x 10^6 km^2 with elevations ranging from 0 m (sea level) to approximately 3400 m at the southernmost tip of the basin. The basin is divided into six major sub-basins, three of which (Liard, Peace and Athabasca) have been examined as part of this study (Figure 2). These three sub-basins account for over 40% of the entire
Mackenzie drainage area. Three major freshwater lakes also occupy large areas along the eastern part of the Mackenzie basin, including Great Bear, Great Slave and Athabasca (Figure 2).

The Missouri basin occupies a majority of the northwestern USA (Figure 1), spanning approximately 25° longitude (120–90° W) and 15° latitude (50–35° N). The Missouri River basin drains over 1.3 x 10^6 km^2 or one-sixth of the USA (MRNRC, 1998). The Missouri River flows southeast from Three Forks, MT, for nearly 3800 km to its confluence with the Mississippi River near St Louis, MO (Leese, 1999). Elevations within the basin range from approximately 130 m, near the mouth of the Missouri, to 4300 m in the Rocky Mountains along the western edge of the basin. Three major sub-basins, the Yellowstone, Platte and Kansas, account for approximately 40% of the total area drained by the Missouri River system (Figure 3). These sub-basins are also examined in this study.

**METHODOLOGY**

Initial DEMs of the Mackenzie and Missouri River basins were derived from the HYDRO1k DEM of North America, as sub-DEMs. These DEMs have an initial horizontal grid spacing of 1 km and a vertical resolution of 1 m. The initial DEMs were then aggregated to coarser grid resolutions using simple averaging aggregation. Using this technique, additional DEMs of 2, 4, 8, 16, 32 and 64 km were generated for the Mackenzie and Missouri basins.
Figure 2. Location of the Liard, Peace, and Athabasca River basins. Source: shaded relief image; USGS EROS Data Center (1999)

The digital landscape analysis tool TOPAZ (Garbrecht and Martz, 2000) was used to pre-process the DEMs and perform the hydrographic segmentation and parameterization of the basins. TOPAZ uses a unique combination of outlet breaching and relief imposition (Martz and Garbrecht, 1998) to treat depressions and flat areas in the DEM. The basic principle of ‘breaching’ is to eliminate or reduce the size of a depression that can reasonably be expected to have resulted from elevation overestimates (Martz and Garbrecht, 1998).

The breaching algorithm determines if the elevations of one or two cells at the outlet of a depression may be lowered to simulate breaching of an obstruction (band of higher elevation within the valley bottom) blocking the drainage path in a valley bottom. An underlying assumption of the ‘breaching’ method is that obstructions caused by elevation overestimates will be of limited spatial extent (Martz and Garbrecht, 1998), thus the breaching length is limited to one or two cells. For this study, a ‘breaching length’ of two cells was implemented.

TOPAZ uses the deterministic eight neighbour (D8) method (Fairfield and Leymarie, 1991) and downslope flow routing and accumulation concepts (O’Callaghan and Mark, 1984; Martz and de Jong, 1988) to define surface drainage. The channel network is defined as all cells with a contributing area greater than a user-specified threshold. In TOPAZ, two parameters, critical source area (CSA) and minimum source channel length (MSCL), are used to control the configuration of the drainage network derived from a DEM (Martz and Garbrecht, 1992). The CSA value defines the minimum drainage area below which a source channel is initiated and maintained. The MSCL prunes the channel network of exterior links shorter than a specified threshold value.

To assess the impact of increasing the grid cell size on the delineation of the basin and drainage network, and derived variables, TOPAZ was applied to the base (1 km resolution) and aggregated DEMs using the same CSA (4096 km²) and MSCL (128 km) parameter values. The CSA and MSCL values used represent the area of one grid cell at 64 km resolution and the length of two grid cells at 64 km resolution, and produce
a channel network of maximum drainage density for a grid size of 64 km, the coarsest grid used in this study. Using these parameter values yields drainage networks approximately similar to the blue line on 1:7,500,000 topographic maps.

The effects of varying DEM resolution are examined by considering changes to the spatial distribution and statistical properties of the basin, network and derived topographic variables. Selected variables in this study include local (e.g. slope) and non-local or global variables (Martz and de Jong, 1988; Florinsky, 1998), e.g. basin and sub-basin area. For the purpose of comparison, basin and network properties obtained from the 1 km resolution DEMs are assumed to be the most accurate, and used as a reference for comparing results of the basin and network properties from the aggregated DEMs. Statistical properties reported in this study include basin area, total channel length, highest Strahler order, drainage density, and bifurcation ratio.

RESULTS

The basins and channel networks generated by the CSA and MSCL parameters at each DEM resolution are shown in Figures 4 and 5. Some descriptive statistics for the basins and networks are given in Tables I and II.

Mackenzie River basin

Figure 4 shows variations in the spatial distribution of the basin extent and network at each resolution for the Mackenzie River basin and the Liard, Peace, and Athabasca River sub-basins. Variations in basin extent and the network for the 2 to 8 km resolution grids tend to be relatively small when compared with the basin and network (for the whole Mackenzie basin) at 1 km resolution.
With increased grid size, there is a general decline in basin area, total channel length (calculated as the length of all channel segments) and drainage density (Table I). The CSA and MSCL parameters used for this study produce a maximum channel order of 4 (Table I) for the Mackenzie basin. At each resolution, the highest Strahler order remains constant and the bifurcation ratio is also fairly consistent.

A couple of notable changes to the basin and network configurations, affecting the Peace and Athabasca basins, are observed at resolutions of 2, 4, and 8 km (Figure 4). Elevation smoothing/aggregation results in the loss of the upper portion of the Peace channel network, along with a large area of high elevations. This is
because averaging has produced a blockage (higher elevations) within a narrow valley region, which obstructs the drainage path, and redirects a large part of the channel network and drainage area of the Athabasca basin (Figure 4) to the north, where it joins with the Peace basin.

There are two reasons for this: (1) the inability of the DEM to resolve a very narrow valley (only 1 km wide) at coarse resolutions, thus blocking the drainage path of the Athabasca network, and (2) the blockage results in the formation of a depression within the Athabasca basin that is adjacent to an area of lower elevation within the Peace basin near the Peace–Athabasca drainage divide. After breaching/filling of the depression by TOPAZ, flow from the Athabasca basin is redirected to the north towards the lowest available outlet.

The considerable changes in basin and network configurations with changes in DEM resolution for the Peace basin (Figure 4) have almost no impact on the basin and network statistics at 2 and 4 km resolutions (Table I) and have only a slight impact at 8 km resolution. At 8 km resolution the basin area increases by 12%, but the total channel length is reduced by only 2 km. The basin order is reduced from 3 to 2 and the bifurcation ratio increases from 3-0 to 7-0; this is because there is one less second-order channel in the network. Changes in basin and network configurations for the Athabasca basin (Figure 4) are much greater (Table I), with large reductions of about one-third in both basin area and total channel length. Basin order, drainage density and bifurcation ratio remain similar from 2 to 8 km resolutions (Table I).

Relative to the 1 km DEM, the basin and network configuration (Figure 4) change dramatically for the Mackenzie basin at resolutions of 16 to 64 km. Most important is the major change in the configuration of the

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Mackenzie basin stream network that first occurs at 16 km resolution and persists through to 64 km resolution. Smoothing/averaging of the 1 km DEM to resolutions of 16 to 64 km also produces a large depression in the eastern part of the Mackenzie basin.

This is a region of relatively low relief at 1 km resolution and is occupied by Great Slave Lake (Figure 2). After pre-processing (breaching/filling and relief imposition) the aggregated DEM, the flow paths of several main channels of the upper Mackenzie basin are directed into the region (Figure 4). The channels converge towards the centre of the flat area, and continue towards an outlet to the north and towards the region occupied by Great Bear Lake (Figure 2). From 16 to 64 km resolution, the total channel length is reduced by more than 4000 km (>25%), but basin area is reduced by only 6% or less (Table I).

Similar reductions in basin area (13 to 36%), and total channel length (23 to 53%) are shown for the Liard basin (Figure 4), at 16 to 64 km resolution. Owing to further changes in basin and network configuration, for the Peace basin at 16 to 64 km resolution (Figure 4), reductions in basin area (16 to 18%) and total channel length (23 to 53%) also result (Table I). Relative to the 1 km DEM (Figure 4), the Athabasca basin continues to be poorly reproduced at coarser resolutions (16 to 64 km), with large reductions in basin area (53%) and total channel length (57 to 71%) at 16 and 32 km (Table I).

The representation of the basin and network is also more generalized with increased grid size (Figure 4), i.e. as channels become straighter and shorter. The network statistics (basin order, drainage density and bifurcation ratio) are shown, in general, to be poor indicators of variations in basin and network configurations for the

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</table>
Mackenzie basin, as they remain relatively stable with increased grid size. This may be explained, in part, by the initial coarseness of the drainage network at 1 km resolution.

**Missouri River basin**

Figure 5 shows changes in the basin extent and network of the Missouri River basin and Yellowstone, Platte and Kansas River sub-basins as resolution becomes coarser. For the Missouri basin, the overall stability of basin and network configurations from 2 to 8 km resolutions is greater than the Mackenzie basin. Relative to the 1 km DEM, for the Missouri basin there is little change in basin and network configurations at 2 to 8 km resolutions. At 8 km resolution, the basin area is reduced by only 2% (Table II) and the total channel length is reduced by 13% (∼2000 km). These changes have no impact on the network statistics (Table II).

The Yellowstone, Platte and Kansas sub-basins also show little change in basin and network configuration (Figure 5) from 2 to 8 km resolutions, relative to the 1 km DEM, with the exception of the Platte basin at 8 km resolution. At 8 km resolution, the total channel length of Platte basin increases by only 50 km (2%); however, the area of the Platte basin increases by 15% (∼35 000 km²). This increase is because of additional flow from a large flat area, (the result of smoothing/averaging) near the headwater region of the Platte basin. Again, these changes have no impact on the network statistics (Table II) for the Platte basin. The basin and network configurations for the Yellowstone basin at resolutions of 2 to 8 km (Figure 5) are fairly similar to the 1 km DEM. The basin area is reduced by only 1% at 2 km resolution and less than 1% at 4 and 8 km resolutions. The total channel length of the Yellowstone basin, however, is reduced at 2 km, 4 km and 8 km resolutions by 5%, 10% and 13% respectively (Table II).

At 16 to 64 km resolutions, there are large changes in basin and network configuration for the Missouri basin (Figure 5) as a result of averaging. The entire northern portion of the Missouri basin and channel network (which includes the Yellowstone basin) has been removed completely at 16 km resolution, resulting in large reductions (Table II) in basin area (∼500 000 km² or 35%) and total channel length (∼5000 km or 44%). Again, this is because averaging results in blockages (areas of higher elevation) within the valley bottom. Unfortunately, the blockage cannot be removed by TOPAZ because of a lower available outlet to the north. Although it is not shown here, the entire upper portion of the Missouri network (at 16 km resolution) is redirected towards the north, where it joins with the Red River near the Canada–USA border and ultimately flows into Hudson Bay in northeastern Canada. At 32 and 64 km resolutions, even greater reductions in basin area (58% and 68%) and total channel length (∼68% and 67%) are observed; however, the network statistics are generally not impacted by these changes (Table II).

The Platte and Kansas basins (Figure 5) also show considerable variation in basin and network configuration at 16 and 64 km resolutions. This is due to the capture of most of the network and basin area of the Platte basin (by the Kansas basin) at these resolutions. This may be attributed to the coarseness of the DEM, that is, the DEM is unable to resolve between the channel and divide at these resolutions. Large increases in basin area (131% and 67%) and total channel length (119% and 54%) for the Kansas basin result. As a result of the joining of second-order networks, the order of the Kansas basin increases from 2 to 3 and the bifurcation ratio is reduced (Table II). For the Platte basin, the result is a large reduction in basin area (80% and 89%) and total channel length (85% and 88%), while the basin order is reduced from 3 to 1 (Table II). This is because only a small part of the channel leading to the outlet remains. As was the case with the Peace and Athabasca basins, capture of the Platte network by the Kansas network occurs where a channel segment of the Platte is very close to the drainage divide (at 1 km resolution) separating the basins.

**Topographic variables at each resolution**

Topography is a main source of heterogeneity or diversity in nature, and is one of the main contributing factors to the generation of run-off and the hydrologic response of watersheds to precipitation (Brasington and Richards, 1998). Important quantitative measures of relief (e.g. slope), area (e.g. basin) and length (e.g.
channel and overland flow) can be obtained from a defined basin and channel network (Strahler, 1964). These measures not only describe landforms, they also provide the basis for deriving topographic attributes from DEMs (Mark, 1975; Speight, 1968, 1980; Zevenbergen and Thorne, 1987) that contribute to many important hydrologic and sedimentary processes (Moore et al., 1991).

The following section shows results of deriving topographic variables from DEMs of increasing grid-cell size. The topographic variables provided by TOPAZ are commonly used in support of hydrologic analysis and include basin area, mean elevation, total number of sub-basins, mean sub-basin area, mean distance to nearest channel and outlet, mean drop to nearest channel and outlet, total channel length, and mean channel link length. For comparative purposes, the summarized values obtained for individual variables at 1 km resolution are assumed to be the most accurate. Variations in values with increased grid size are measured as the deviation (%) from values obtained at 1 km resolution (i.e. reference values).

**Basin and sub-basin properties**

Variations in basin area, mean elevation, total number of sub-basins, and mean sub-basin area with grid size for the Mackenzie, Liard, Peace and Athabasca basins are shown in Figure 6. The total area of the Mackenzie basin declines with grid size but remains fairly consistent (within ±6%) to 64 km resolution. The Liard basin area is within ±10% to 4 km resolution and ±11% at 8 km resolution, deviating further from the value at 1 km resolution for grid sizes of 16 to 64 km. The total area of the Peace basin is within ±10% at 4 km and ±12% at 8 km resolution as well, but also shows larger deviations after 8 km. The area for the Athabasca basin deviates considerably from the 1 km value due to the joining of the Athabasca network with the Peace network. The mean elevation (Figure 6) of the Mackenzie and Liard are within ±10% up to 64 km resolution, and for the Peace basin within ±10% to 8 km resolution. A large drop in mean elevation is consistently observed for the Athabasca basin from 2 to 64 km resolution, again due to the considerable change in basin extent.

![Basin properties for the Mackenzie, Liard, Peace and Athabasca basins at each resolution](image-url)
The total number of sub-basins and mean sub-basin area are generally more sensitive to changes in grid size than basin area and mean elevation (Figure 6). The total number of sub-basins is simply a measure of the number of channel links in the network, which is a product of the CSA and MSCL values used. That is, a specific drainage area is associated with each link in the network.

Figure 6 shows the Mackenzie basin as having the same number of sub-basins at 2 km resolution as there were at 1 km. However, the number of sub-basins is shown to decrease (Figure 6) with further aggregation. This is also the general trend for the Liard, Peace and Athabasca basins. As the total number of sub-basins decreases or the number of channel links is reduced, the mean sub-basin area increases (Figure 6). It should be noted that the Liard and Peace basins have only 15 sub-basins at 1 km resolution and the Athabasca nine sub-basins, due to coarseness of the network. Therefore, an increase or decrease of even two sub-basins (e.g. for the Peace basin) is a large deviation from the initial condition. At 16 km resolution the values tend to deviate considerably from those at 1 km resolution (Figure 6), although variables for the Liard basin remain fairly consistent to 16 km resolution, with greater fluctuation at resolutions of 32 and 64 km.

Results of the analysis of basin area, mean elevation, total number of sub-basins, and mean sub-basin area for the Missouri basin and sub-basins (Figure 7) show an even more striking trend. That is, variable values tend to be within ±10% of the reference values (at 1 km resolution) to 8 km resolution, with the exception of number of sub-basins and mean sub-basin area for the Platte basin. For the Missouri basin, a reduction in basin area of between 35 and 65% from 16 to 64 km resolution results in lower mean elevation and considerable reductions in total number of sub-basins, and mean sub-basin area. Owing to the capture of most of the Platte network by the Kansas network, at 16 and 64 km resolutions, large increases in variable values for the Kansas and a decrease in values for the Platte are observed (Figure 7). The area of the Kansas basin increases by more than 131%, while the area of the Platte basin is reduced by 80%. This has a considerable effect on the mean elevation, number of sub-basins and mean sub-basin areas (Figure 7) for the Kansas and Platte basins as well.

![Figure 7. Basin properties for the Missouri, Yellowstone, Platte and Kansas basins at each resolution](image-url)
Channel properties

Results for selected channel properties, including total channel length and mean link length for the Mackenzie, Liard, Peace and Athabasca basins at each resolution, are presented in Figure 8. The total channel length is calculated as the sum of all channel link lengths in the network. The mean link length is calculated as sum of all link lengths divided by the total number of channel links.

The total channel length tends to decrease with increasing grid size as a result of network generalization. Total channel lengths for the Mackenzie, Liard and Peace basins are generally within ±10% of the values at 1 km resolution, with a few individuals slightly outside ±10%. At 16 to 64 km resolutions, the total channel lengths for these basins deviate considerably from the 1 km values. Owing to the reduction in area for the Athabasca basin, the total channel length is reduced by more than 30% at 2 km resolution and continues to decrease further with increased grid size. The mean link lengths for the Mackenzie, Liard and Peace basins remain fairly consistent (within ±10%) to 32 km, with a couple of values outside ±10%. Again, the Athabasca gives the poorest results for mean link length at 2 to 64 km, with most values outside ±10%.

Results for the Missouri basin and its sub-basins (Figure 9) continue to show this general trend. Even though the total channel length declines with increased grid size, the values are within ±10% of the reference values (with a couple of values falling slightly outside) to 8 km resolution. At 16 km resolution, however, the total channel length for the Missouri, Platte and Kansas basins develops general inconsistencies, and large deviations from the values at 1 km resolution result.

Mean link lengths for the Missouri, Yellowstone, Platte, and Kansas basins (Figure 9) tend to decline for grid sizes of 2 to 8 km, although most values also tend to be within ±10% of the reference values, again with
a few individuals slightly outside ±10%. The instability of total channel length for the basins is reflected in the observed fluctuations of mean link length (Figure 9) for grids larger than 8 km.

**Overland flow length and elevation change**

Results for the mean distance to nearest channel and outlet and the mean drop to nearest channel and outlet are given for the Mackenzie, Liard, Peace, and Athabasca basins in Figure 10. The distance to nearest channel is calculated as the overland distance from each cell to the nearest channel it flows into. The distance to the outlet is calculated from each cell to the nearest channel it flows into, and the continuation down the channel network to the basin outlet. The change in elevation is calculated in a similar way, except that the drop in elevation from each cell is used. These values are then averaged over the entire basin.

As shown in Figure 10, these variables values also tend to decline with increasing grid size. Values for mean distance to nearest channel, for the Mackenzie and Peace basins, are generally within ±10% of the reference values (from the 1 km DEM) to a grid size 64 km, and to 4 km resolution for the Liard basin. Results for mean distance to nearest outlet for the Mackenzie, Liard and Peace basins are also consistent (within ±10%) to 8 km resolution when compared with the values at 1 km resolution.

Smoothing of the DEM appears to have a greater impact on values of mean drop to nearest channel (Figure 10), as these values deviate by more than ±10% for grid sizes larger than 2 km for the Mackenzie and Peace basins and 4 km for the Liard basin. The greatest impact is on values for the Athabasca basin, because of the dramatic change in basin and network configurations. The mean drop to nearest outlet, however, is generally consistent to (within ±10% of the reference values) to 8 km resolution for the Liard and Peace basins, whereas values for the Mackenzie basin are within ±11%. Again, the values deviate further from the values at 1 km resolution for grid sizes larger than 8 km.

Results for the mean distance to nearest channel and outlet and for the mean drop to nearest channel for the Missouri, Yellowstone, Platte, and Kansas basins also tend to decline with increased grid size. For the
Missouri and Kansas basins the mean distance to nearest channel remains within ±10% for resolutions up to 4 km (Figure 11), and tend to deviate more from the 1 km values at larger grid sizes. Values of mean distance to nearest channel for the Platte basin are within ±12% of the reference values to 4 km resolution, and for the Yellowstone basin within ±10% of the reference values to 32 km. The mean distance to nearest channel for the Platte is reduced to nearly zero (Figure 11) at 64 km resolution; this is because the basin consists of only six cells.

The mean distance to outlet for the Missouri, Yellowstone, Platte and Kansas basins is consistently within ±10% of the reference values to 8 km resolution. At 16 km resolution, large reductions in mean distance to outlet are observed for Missouri and Platte basins due to considerable losses in basin area. Also at 16 km resolution, the mean distance to outlet for the Kansas basin shows a large increase because of the increase in basin area. The Yellowstone basin also continues to show the most consistency to 16 km resolution (within ±10% of the reference values) for the mean distance to outlet.

Values of mean drop to nearest channel for the Missouri, Yellowstone, Platte and Kansas basins decline at similar rates to 8 km resolution. For these basins, the values tend to be within ±10% to 4 km resolution, and within ±15% at 8 km resolution, with greater variations in general for larger grid sizes. The mean drop to outlet for the Missouri, Yellowstone, Platte and Kansas basins remain consistent (within ±10% of the reference values) to 8 km resolution. For grids larger than 8 km resolution, large fluctuations are observed in the mean drop to outlet (Figure 11); the exception is the Yellowstone basin, which remains within ±10% of the values at 1 km for all resolutions.

Values of mean drop to outlet for the Missouri decline further from 16 to 64 km as a result of the losses in higher elevations with basin area. Large increases in mean drop to outlet are seen for the Kansas basin at 16 and 64 km resolution (a result of adding higher elevations with increased basin area). The Platte basin shows large reductions in mean drop to outlet because the loss of the higher elevations at 16 and 64 km resolutions.

Figure 11. Flow length and elevation drop properties for the Missouri, Yellowstone, Platte and Kansas basins at each resolution.
Slope measures at each resolution

Slope is a widely used topographic measurement that describes the nature of the land surface and, more importantly, influences the flow rates of water (Mark, 1975; Zevenbergen and Throne, 1987). The measurement of slope across the land surface is influenced by several factors (Chang and Tsai, 1991), including topography, the method of calculation and, more importantly for this study, the DEM resolution or grid-cell size. The latter factor is important because the calculation of slope is biased by the increase in distance between grid cells at coarser resolutions.

TOPAZ provides several measures of slope (Garbrecht and Martz, 2000). Two of these are used in this study; namely, terrain slope and hydraulic slope. In TOPAZ, terrain slope is calculated by suitable differentiation of a second-order polynomial function fitted to the current cell and its eight adjacent neighbours (Martz and de Jong, 1987). TOPAZ calculates the hydraulic slope as the average slope of all flow vectors entering and leaving each cell, weighted by the corresponding flow accumulation value. Results of the mean terrain slope (referred to as mean TSLOPE for simplicity) comparisons at each resolution are shown in Figure 12.

As expected, mean TSLOPE values are shown to decline with increased grid size as a result of smoothing/aggregation. At 1 km resolution, the Mackenzie basin and sub-basins have different mean TSLOPE (%) values. At 2 km resolution (one aggregation), the mean TSLOPE of the Mackenzie basin it is reduced by ~1%, and for the Liard, Peace and Athabasca basins it is reduced by an average of ~2%. This results in similar mean TSLOPE values for the Mackenzie and Peace basins at 2 km resolution. Interestingly, the mean TSLOPE values for the Mackenzie and Peace basins decline at similar rates (with similar values) to 64 km resolution.

At 2 km resolution, the Athabasca basin is shown to have much gentler slopes (mean TSLOPE of ~0.6%) due to the loss of the upper elevations of the basin, with relatively little change to 16 km resolution. The mean TSLOPE of the Liard basin continues to decline systematically (Figure 12) from 2 to 64 km resolution by approximately 2, 1, 0.6, 0.2 and 0.2%. At 16 km resolution, the Mackenzie basin and its sub-basins have fairly similar mean TSLOPE values (below 1%), which decline at similar rates to 64 km resolution.

Similar results can also be seen for the Missouri basin and sub-basins (Figure 12). The Missouri and Platte basins have similar mean TSLOPE values at 1 km resolution, which are reduced at similar rates to 8 km resolution. The loss of 35% of the Missouri basin at 16 km resolution appears to have little effect on the mean TSLOPE of the basin. This may be due to the similarity between mean TSLOPE values at 16 km resolution (well below 1%) for all basins, with the exception of the Yellowstone basin (~0.9%). In other words, there is less overall variation in basin elevations in lower relief areas because of the effect of the grid-cell size.

There is a noticeable drop in mean TSLOPE, however, for the Platte basin at 16 km resolution (Figure 12). This may be explained by the considerable reduction in basin area and a loss of most of the higher elevations.
with the joining of the Platte and Kansas networks at 16 km resolution. The addition of the higher elevations in the Kansas basin at 16 km resolution (Figure 12) is reflected by an increase in mean TSLOPE for the Kansas basin. Aggregation has a greater effect on higher values of mean TSLOPE (e.g. for the Yellowstone basin), which are reduced at a greater rate from 2 to 8 km resolutions than at 16 to 64 km resolutions (Figure 12).

Again, at 16 km resolutions, mean TSLOPE values for the Missouri basin and sub-basins are below 1%.

Results for the mean hydraulic slope (mean HSLOPE) are similar to the results for mean TSLOPE (Figures 12 and 13). As the grid size increases, the mean HSLOPE values decline, with the greatest impact on mean values from 2 to 8 km resolution. Owing to the difference in calculation, the values of mean HSLOPE (Figure 13) are, in general, higher than mean TSLOPE values (Figure 12) to 8 km resolution. This is likely because of the overall effect of several flow vectors (flow weighted) entering each cell, which are considered in the calculation of HSLOPE. From 32 to 64 km resolutions the values of mean TSLOPE and HSLOPE are similar, a result of the very coarse grid size.

Interestingly, mean HSLOPE values for the Mackenzie, Peace, Missouri and Platte basins fall to about ~1% at 8 km resolution, and are well below 1% from 16 to 64 km resolutions. The Liard and Yellowstone basins (two of the steepest sloped basins in this study) have mean HSLOPE values of ~1% at 16 km resolution, and are much less than 1% at 32 and 64 km. Results for the standard deviation or root-mean-square (RMS) of the hydraulic slope (Figure 14) for these basins are essentially the same.

This is of interest because the largest overall variations in basin and network patterns and derived topographic variables are observed for the Mackenzie, Peace, Missouri and Platte basins at 16 km resolution. The Peace Basin is included here, despite the difficulties in reproducing the basin and network at coarser
resolutions, because the basin and network configuration and most variable values are similar to those of
the 1 km DEM from 2 to 8 km resolutions, and shows further change at 16 to 64 km resolutions. Also,
the configuration of the basin and values of several derived variables for the Yellowstone basin (at 16 km
resolution) are fairly similar to those derived at 1 km resolution, but are much different at resolutions of 32
and 64 km.

The instability of drainage divides and stream networks apparent under the simple averaging method of
DEM aggregation used here prompted investigation of other approaches to aggregating flow-related attributes
to coarser spatial units. These include the application of ANUDEM (Hutchinson, 1996) to enforce ‘blue-
line’ drainage patterns in a coarser resolution DEM and adaptation of the ‘fuzzy’ flow aggregation technique
developed for the WATFLOOD hydrological model (Kouwen et al., 1993). Although only preliminary results
are available, these suggest that the network and basin instability observed in this study is not resolved by
standard drainage enforcement and that the fundamental problem arises from the reduction in topographic
information associated with reducing the number of grid cells. Fuzzy aggregation techniques, such as that used for WATFLOOD, appear to offer greater potential for aggregating
flow information across the range of scale or DEM resolution investigated here (Shaw, 2002).

CONCLUSIONS

Automated methods for parameterizing drainage basins offer the advantages of speed and efficiency and
reproducibility (Tribe, 1992). TOPAZ provides a sound and reliable means of delineating a basin, drainage
network and deriving topographic variables from a raster DEM, over a wide range of scales. Subsequently,
this information may be used for various hydrologic applications. In this study, initially derived DEM data are
scaled using simple aggregation to examine the impact on the delineation of a drainage basin and network,
and deriving several topographic variables. To isolate the effects of grid resolution, all DEMs were processed
using constant network configuration parameters.

The results of this study show that aggregation produces a smoother representation of the land surface.
As expected, this produces less variation in elevation, gentler slopes, shorter channels and shorter distances
to channels. This is complicated, however, by major changes in basin extent and channel network structure.
These can be very significant in some cases, and result in large fluctuations in variable values. Changes in
the spatial extent of basins, the structure of drainage networks and the consequent tendency for topographic
variables to change in a non-linear fashion with grid size make it impossible to derive reliable simple scaling
functions to adjust topographic variables measured from coarser DEMs to the values that would have been
measured from finer DEMs.

The substitution of coarse-resolution DEMs for continental-scale hydrology is constrained by the redirection
of flow across large flat areas, as observed from major changes in network structure for the Mackenzie basin
from 16 to 64 km resolutions. Coarse grid substitution is also constrained by elevation errors (a result of
averaging) or obstructions that block flow paths within valley bottoms. This becomes a problem as the valley
width approaches the size of the grid cell (e.g. the Peace and Athabasca basins at 2, 4 and 8 km resolutions, and
the Missouri basin at 16, 32 and 64 km resolutions). The poor definition of flow paths at coarser resolutions,
as found in this study, is in agreement with the findings of Veregin (1997). Owing to the increased generation
of vertical errors with aggregation, network structure tends to deviate considerably from that derived at finer
resolutions, indicating that flow path definition has become very unreliable.

Compared with the basin and network properties at 1 km resolution, the overall reproducibility of the
basin, network and topographic variables is relatively good for grid sizes up to 8 km and considerably less,
in general, with grid sizes larger than 8 km. Based on the comparisons of the basins, networks and derived
topographic variables for the aggregated DEMs (with those from the base DEMs), it is recommended that a
grid size of 10 km or less be used for continental hydrologic applications.
The decreasing slope with grid size found in this study is expected, and it is also consistent with previous studies, including those of Hutchinson and Dowling (1991), Bates et al. (1998), Zhang et al. (1999), Ma et al. (2000) and Wolock and McCabe (2000). The findings of this study suggest that a mean hydraulic slope of approximately 1% (for the basin) can be used to define a limit to DEM generalization for applications in continental-scale hydrology. This would appear to be a threshold for reproducing basin and network properties from coarser resolution DEMs to within 10% of those derived from finer resolution DEMs.

REFERENCES


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