Generation of Triangulated Irregular Networks Based on Hydrological Similarity

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Abstract: Distributed hydrologic models typically incorporate topographic data through the use of raster-based digital elevation models. The resampling of high-resolution grid data required to effectively use distributed models, however, can result in the distortion of terrain and hydrographic properties. In this study, we present a geographic information system approach for deriving multiple resolution meshes that conserve physiographic features while significantly reducing the number of computational nodes in a distributed hydrologic model. We utilize triangulated irregular networks (TINs) which serve to integrate information on the surface topography, hydrographic features and land surface characteristics into an adaptive representation of a basin. We discuss three approaches for constructing TIN models for hydrologic applications: (1) *Traditional*, (2) *hydrographic* and (3) *hydrological similarity* TINs. We focus on the generation of triangulated terrain models using the concept of hydrological similarity provided through a topographic or wetness index. This new method embeds an estimate of the steady-state hydrologic response directly into the basin terrain model. Through a series of case studies, we demonstrate the advantages of the multiple resolution approaches over a range of terrain characteristics, basin scales and elevation data products. Finally, we discuss the implications of TIN terrain representation for watershed simulation with the TIN-based Real-Time Integrated Basin Simulator model.

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Introduction

A representation of land surface topography is required in most system models of the Earth, including general circulation models, numerical weather prediction models, land surface models and distributed hydrologic models. Representation of the terrain differs among these types of models since the coupling between the physical processes and surface landforms varies considerably. In distributed hydrologic modeling, accurate depiction of terrain features is essential since the surface elevation properties (slope, curvature, aspect) determine the hydrologic response to meteorological forcing. In general, as the model domain increases in size, the resolution and accuracy retained in the terrain representation decrease to allow efficient model simulation. For climate, hydrology, and weather models operating at large spatial scales [e.g., $O\,(10^3-10^6\ \mathrm{km}^2)$], inaccurate depiction of the topography and of its spatial variability is recognized as an important source of model error (e.g., Wood et al. 1997; Koster et al. 2000; Warrach et al. 2002).

Traditionally, terrain data in hydrologic models has been represented in two ways: (1) Aggregating or resampling grid-based digital elevation models (DEMs) to coarser resolutions or (2) introducing a topographic distribution function that classifies catchment locations according to an elevation index. Both methods attempt to account for the spatial variability in topography without adding computational burden to hydrologic models that operate over large domains. Neither approach, however, can incorporate all the information on high-resolution topographic data currently available from land surveying, aerial photogrammetry (Gesch et al. 2002), synthetic aperture radar (Farr and Kobrick 2000) or light detecting and ranging (LIDAR) (Ritchie 1996). As a result, poorly resolved hydrologic models typically have terrain inaccuracies that propagate directly to model predictions of streamflow and soil moisture (e.g., Vieux 1993; Zhang and Montgomery 1994; Kuo et al. 1999). For these reasons, a computationally efficient method for representing high-resolution terrain with minimal loss of information is currently needed for hydrologic models that operate over large regions.

In order to best utilize high volumes of topographic data in hydrologic models, new techniques are required to efficiently sample elevation points and adaptively grid the model domain. The approach proposed in this study is the use of a multiple-resolution, triangulated irregular network (TIN) mesh to represent the surface terrain in a watershed model. Our motivation for exploring new procedures for generating TIN terrain models stems from the development and application of a distributed hydrologic model known as the TIN-based Real-Time Integrated Basin

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Simulator (tRIBS) (Ivanov et al. 2003a,b). The coupled surface-subsurface hydrology model takes advantage of the triangulated data structure described by Tucker et al. (2001b) to simulate the spatial and temporal basin response to complex rainfall patterns. The accurate representation of catchment features (e.g., hillslopes, streams, basin boundaries, floodplains) required in the distributed model stimulated the development of automated methods to generate the watershed terrain.

In this study, we present a geographical information system (GIS) methodology for constructing TIN terrain models over a range of basin scales. A set of hydrologically significant terrain models are developed by taking into account the topographic, hydrographic and hydrologic features characterizing a catchment. In the following, three approaches are described in sequence: *traditional, hydrographic* and *hydrological similarity* TINs. Traditional TINs are based exclusively on capturing terrain variability, while hydrographic and hydrological similarity TINs integrate additional criteria critical to hydrologic model application. Hydrographic TINs, for example, explicitly represent stream networks, basin boundaries, riparian or floodplain zones and landscape features, while selecting elevation nodes based on a slope-preserving criterion. Hydrological similarity TINs, on the other hand, implement a new method for sampling a dense DEM that results in an adaptive mesh resolution that resembles the spatial pattern of a hydrologic index. Each approach builds on the previous method and can be tailored to a specific basin based on the relevant hydrological processes. The resulting terrain models are computationally feasible with respect to the original DEM by significantly reducing the number of nodes (by an order of magnitude in many cases), while preserving the terrain attributes that are typically lost when coarsening raster-based elevation products.

This paper is organized as follows. First we describe triangulated irregular networks and review their advantages for distributed hydrologic modeling. Then the methodology for constructing traditional, hydrographic and hydrological similarity TINs is presented in detail, with particular emphasis on the new method for embedding hydrologic behavior into the model mesh. Next we outline the elevation data products utilized to assess the performance of the TIN terrain models over a series of distinct catchments. A comparative analysis is made between the TIN models and raster DEMs with an equivalent number of nodes to illustrate (1) the relative performance of TIN and DEM coarsening, (2) the impact of DEM quality on TIN generation, and (3) the effects of basin scale and terrain variability on TIN terrain models. Finally, we discuss various issues related to the use of hydrologically significant TINs in distributed modeling in light of our recent applications of the tRIBS model in mid-to-large scale basins (50–1500 km^2) (e.g., Ivanov et al. 2003a,b; Vivoni et al. 2003a,b).

Triangulated Irregular Networks

Topography can be represented using a number of computational structures, including contour lines, regular grids or triangulated irregular networks. The TIN data structure is a piece-wise linear interpolation of a set of points in x, y, z coordinates, that results in nonoverlapping triangular elements of varying size. Although several methods exist, Delaunay triangulation is a preferred technique since it provides a nearly unique and optimal triangulation (e.g., Watson and Philip 1984; Tsai 1993). For a set of points, the Delaunay criterion ensures that a circle that passes through three points on any triangle contains no additional points. *Constrained* Delaunay triangulation permits the inclusion of linear features such as channel networks or watershed boundaries directly in a terrain model (Tsai 1993). Using a point selection criterion and Delaunay triangulation, dense or high-resolution DEMs obtained from ground measurements or remote sensing can be sampled to construct triangulated terrain models.

Various factors motivate the use of irregular triangular elements to represent the watershed topography. The primary advantage is the variable resolution offered by the irregular domain (Kumler 1994), as opposed to the single resolution inherent in raster grids. Regions of high terrain variability can be modeled more precisely than areas of lower variability. Multiple resolutions translate into computational savings as the number of nodes is reduced in areas of low terrain variability (Goodrich et al. 1991). While the TIN data structure can be complex (Tucker et al. 2001b), the reduction achieved in the number of model nodes results in a significant savings that can allow TIN-based hydrology models to operate over large regions (e.g., Ivanov et al. 2003a,b). A second advantage is that TINs permit linear features to be preserved within the model mesh. This allows the terrain to mimic natural terrain breaklines, stream networks or boundaries between heterogeneous regions without introducing the raster artifacts inherent in grid methods. For a distributed hydrologic model, TINs allow the stream network and basin boundary to be precisely depicted within the watershed topography.

Despite these advantages, few studies have addressed methods for constructing TIN terrains for distributed hydrologic models. Efforts have focused primarily on watershed delineation using TINs (e.g., Palacios-Vélez and Cuevas-Renaud 1986; Jones et al. 1990; Nelson et al. 1994) and TIN-based distributed modeling (e.g., Goodrich et al. 1991; Palacios-Vélez and Cuevas-Renaud 1992; Tucker et al. 2001b). Discussions on how to generate TIN terrains prior to watershed modeling have been largely bypassed, in particular when dealing with real-world basins. Notable exceptions include the work of Tachikawa et al. (1994) and Nelson et al. (1999). In most hydrologic applications, however, TIN terrain modeling remains an ad hoc process based on sampling a DEM at a desired level of detail without explicitly considering hydrologic features such as stream channels and river cross sections, basin boundaries and floodplain or riparian zones.

The generation of TIN terrain models is facilitated by a geographic information system that allows the manipulation of elevation data in a variety of formats (e.g., points, vectors, grids, TIN) as well as other types of landscape coverages (e.g., hydrography, vegetation, soils). ArcInfo GIS, for example, has a set of TIN routines based on the Delaunay criterion that are popular for three-dimensional surface analysis (ERSI 1992). Methods for constrained Delaunay triangulation also permit the construction of TIN surfaces that incorporate linear features. In this study, we use ArcInfo GIS to develop TINs that preserve key hydrologic and topographic characteristics while minimizing the number of computational nodes. A reduction in domain size while preserving terrain attributes (elevation, slope and curvature distribution) translates directly into efficient and accurate hydrologic simulations with the tRIBS distributed model, particularly over large, complex watersheds (Ivanov et al. 2003a,b). In this study, we focus on the methods for selecting elevations points and incorporating hydrologic information into a TIN terrain model.

Methodology

The methods for constructing TINs presented in the following account for the catchment topography, hydrography and the

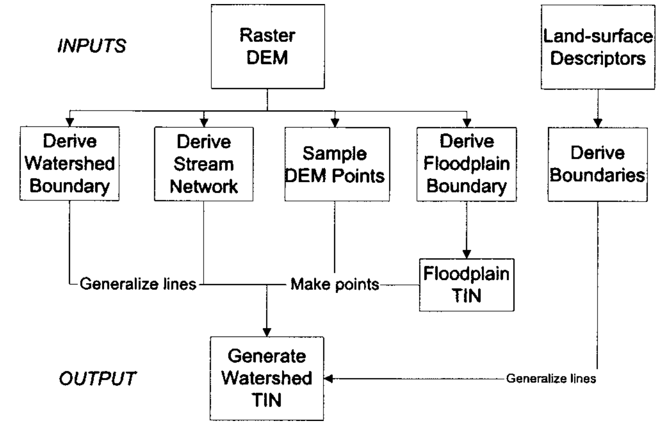

Fig. 1. Schematic of triangulated irregular network (TIN) generation process. Constrained Delaunay triangulation is used to generate the watershed TIN using sampled digital elevation model (DEM) points, linear features (basin boundary, stream network) and ancillary land surface descriptors (soils, vegetation, geology). The *traditional* TIN approach consists solely of sampling a DEM to generate a TIN (see Fig. 2). The *hydrographic* TIN approach combines DEM sampling using a topographic criterion (Latticetin) with linear features, floodplain representation and land surface descriptors (see Fig. 3). The *hydrological similarity* TIN approach utilizes the wetness index to sample the DEM instead of the topographic criterion and incorporates features that represent basin hydrography (watershed delineation, channels) (see Fig. 4).

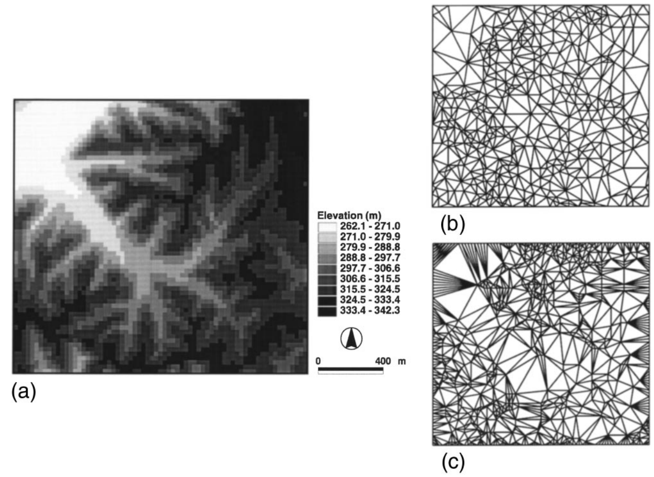

Fig. 2. Traditional TINs utilizing the topographic sampling methods for a given data reduction factor ($d = 0.1$ or 10% original DEM nodes). (a) USGS 30-m DEM within Peacheater Creek basin, Okla. (4,416 total cells); (b) TIN generated using the ArcInfo GIS Latticetin method ($z_r = 8$ m); (c) TIN generated using ArcInfo VIP method ($v = 16\%$). Both the Latticetin and VIP methods have an equivalent number of nodes (442 nodes) but differ substantially in significant points retained in the TIN. Comparisons to the original DEM (a) reveal RMSE values of 3.01 (Latticetin) and 7.22 m (VIP).

steady-state hydrologic response, as parameterized by a topographic or wetness index. The principal objective for generating hydrologically significant TIN terrain models is to capture the salient topographic and hydrologic features efficiently since feasibility is sought for hydrologic applications over large domains. A schematic of the three methods (traditional, hydrographic and hydrological similarity TINs) is presented in Fig. 1. In the following, we describe TIN terrain models that are progressively constrained by additional criteria derived from the raster DEM or other land surface descriptions (e.g., soils, vegetation, geology maps).

Topographic Approach: Traditional TINs

Topography exercises major control on the hydrologic response in watersheds (e.g., Wood et al. 1990; Ivanov et al. 2003b). With the availability of high-resolution raster DEMs, direct use of topographic data in hydrologic models is often sought. For large domain models, however, utilizing high-resolution grids requires a means by which to reduce data or coarsening to obtain reasonable computational performance (e.g., Wigmosta et al. 1994; Vázquez et al. 2002). For raster DEMs, data reduction is usually achieved through pixel aggregation at the expense of topographic detail (Vieux 1993). Similarly, large topographic data sets obtained through photogrammetrical methods or LIDAR typically require coarsening to reduce the number of irregularly spaced elevation points. In *traditional* TIN models, essential topographic information is captured by selectively sampling a high-resolution DEM according to a slope-preserving (or topographic) criterion. Specific criteria for selecting elevation points can vary widely among different surface simplification algorithms (see, for example, Heckbert and Garland 1997).

Various GIS methods exist for selecting critical elevations from dense DEMs using a slope-preserving criterion (Fig. 1, sample DEM points). Lee (1991) compared two approaches implemented in ArcInfo GIS, the very important point (VIP) and the drop heuristic (DH) methods. VIP is a *local* procedure based on determining the "significance" of a point relative to a 3×3 filter. The significance measure is the distance between the actual node elevation and interpolations obtained from its four neighboring transects. A specified percentage (v) of the significant elevation points is retained in the final triangulation. The DH method, on the other hand, is a *global* procedure that guarantees that a TIN model is within elevation tolerance (z_r in meters) of the DEM. The approach successively removes DEM points, and retains significant points that result in a TIN surface that exceeds the specified tolerance. A variant on the DH method is implemented in ArcInfo GIS as Latticetin (Lee 1991; ERSI 1992).

Lee (1991) evaluated the performance of the two methods, and concluded that the DH approach exhibited lower root mean-square errors (RMSEs) over a range of terrain resolutions. In our experience with generating TINs using the traditional approach, we have found that the Latticetin (DH) method is more robust, quantifiable and accurate. In order to compare the methods directly, preliminary parameter tests are required to select values of v or z_r such that an equivalent number of nodes is retained. In this study, we define the data reduction factor (d), the number of TIN nodes (n_t) divided by the number of DEM cells (n_g), as a measure of the coarsening performed in a TIN. As an example, Fig. 2 compares the VIP and Latticetin methods at an equivalent aggregation ($d = 0.1$) for a DEM within the Peacheater Creek, Okla. Notice that the Latticetin method results in a more regular triangle size distribution and a smoother hillslope to valley transition. By linearly interpolating each TIN onto a regular grid, we computed RMSE values of 7.22 (VIP) and 3.01 m (Latticetin) with respect to the original DEM. For this basin, both the horizontal resolution and vertical accuracy (RMSE) favor the selection of the Latticetin method at this level of aggregation ($d = 0.1$, $z_r = 8$ m and $v = 16\%$). Similar results were observed over a range of basins and at varying aggregation levels (not shown), thus confirming the conclusions of Lee (1991). For this reason, we only consider the Latticetin method for selecting nodes with a topographic criterion in the following discussions.

Incorporating Hydrographic and Landscape Features: Hydrographic Triangulated Irregular Network

Traditional TIN methods generally do not account for criteria other than the preservation of critical slopes. As a result, traditional techniques ignore hydrographic and landscape features that are desirable within hydrologic model domains. The general strategy for formulating *hydrographic* TINs combines the topographic DEM sampling used in the traditional approach (Latticetin method) with representations of surface streams, basin boundaries and floodplains in a constrained Delaunay triangulation. As shown in Fig. 1, the raster DEM is used to extract the channel network, watershed boundary and floodplain boundary, which combined with the sampled DEM points and other land surface features constitute the basis for the hydrographic TIN method. In the following, we discuss how linear coverages or natural breaklines used to map hydrographic and land surface data are preserved within the triangulated terrain model. For the tRIBS distributed model, direct representation of hydrographic criteria is essential for (1) determining the watershed domain boundary, (2) depicting streams accurately in the channel routing scheme, (3) resolving the variable source area within a river floodplain or riparian zone, and (4) minimizing the subelement variability of land surface properties (e.g., Tucker et al. 2001b; Ivanov et al. 2003a,b). To best illustrate the components in the hydrographic TIN method, the reader is referred to Fig. 1 for a general schematic and Fig. 3 for a detailed example.

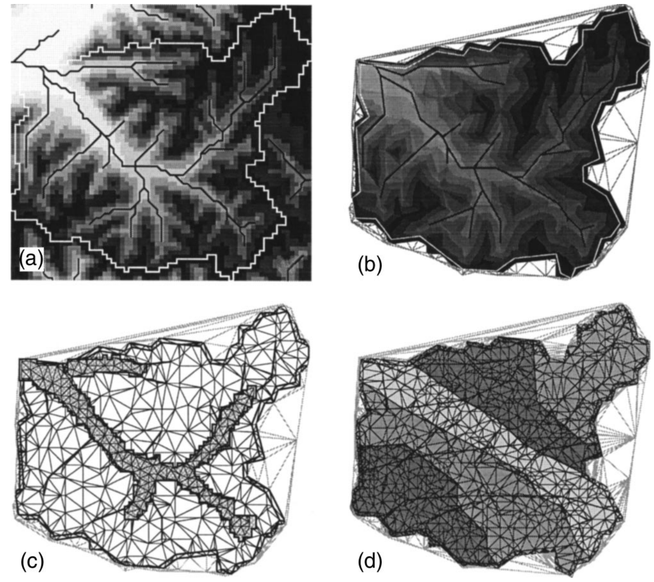

Fig. 3. Example of elements of the hydrographic triangulated irregular network (TIN) method. (a) Basin boundary (white polygon) and channel network (black lines) derived from the digital elevation model by selecting an outlet point and utilizing an area threshold of 50 pixels (30-m cell size) for stream cell selection; (b) hillshade view of the hydrographic TIN model derived using the Latticetin method ($z_r = 8$ m) and conforming to the generalized stream network (black line) and buffered catchment boundary (outer lines); (c) facet view of the floodplain boundary (gray region) and nested floodplain TIN embedded within a watershed TIN which also retains the basin streams and boundary; (d) facet view of the TIN model conforming to hydrologic response units derived from soils and vegetation classes (shaded regions). Note how the hydrologic response unit boundaries are retained within the TIN model, thus reducing the problem of subelement variability in land-surface properties.

Channel Network and Watershed Boundary

The watershed stream network and boundary are essential features that distinguish hydrographic TINs from triangulated models used for surface visualization. Channel networks can be delineated from high-resolution topographic data using a series of algorithms (e.g., O'Callaghan and Mark 1984; Jenson and Domingue 1988; Tarboton et al. 1991). In this study, a constant-area threshold method is used to classify DEM points as stream cells [Fig. 3(a)]. An iterative procedure ensures that the drainage density of the extracted network is equivalent to available hydrographic data. The stream network is preserved in the hydrographic TIN model by enforcing the triangulation to hard breaklines and sampling the DEM to obtain channel profile elevations (Tachikawa et al. 1994; Nelson et al. 1999). Curve simplification or generalization is typically required to remove raster effects in the channel network (Fig. 1). Nevertheless, the resulting streams are statistically equivalent to the original hydrography (Douglas and Peucker 1973).

Incorporating basin boundaries permits hydrographic TINs to accurately capture the watershed area [Fig. 3(a)]. Watershed delineation is based on creating a depressionless DEM, deriving the overland flow direction along the steepest path and computing the upslope area at each outlet (e.g., O'Callaghan and Mark 1984; Jenson and Domingue 1988). As in the stream network, simplification or generalization of the rasterized watershed boundary is typically required (Fig. 1). The basin boundary is preserved by enforcing triangulation to soft breaklines that sample the DEM for elevation values. In addition, using an inner ring of interpolated elevations as a buffer for the boundary maximizes the basin area captured (not shown). This overcomes problems that arise when the TIN terrain model is represented as its dual Voronoi diagram (Rybarczyk 2000), a convenient computational scheme for distributed hydrologic and geomorphic models (Braun and Sambridge 1997; Tucker et al. 2001b; Ivanov et al. 2003a). Fig. 3(b) illustrates the stream network and basin boundary as they are represented in the hydrographic TIN model.

Floodplains and Riparian Zones

In addition to stream and basin boundary representations, hydrographic TINs can resolve floodplains or riparian zones found along high-order reaches. If a detailed floodplain model consisting of surveyed transects is available (e.g., Tate et al. 2002), it can be integrated directly within a coarser resolution model of the entire watershed. Given that river and floodplain cross sections infrequently exist, a simple method is required to appropriately delineate a floodplain from a raster DEM and represent it within a TIN model. For such cases, we have implemented an elevation-threshold algorithm developed by Williams et al. (2000) to extract a floodplain boundary from a DEM and subsequently retain the floodplain topography at high resolution. The algorithm extracts a floodplain DEM from the points that lie within a specified difference in elevation of the basin outlet. This floodplain DEM is subsequently sampled at high resolution and incorporated into the hydrographic TIN along with points representing the watershed

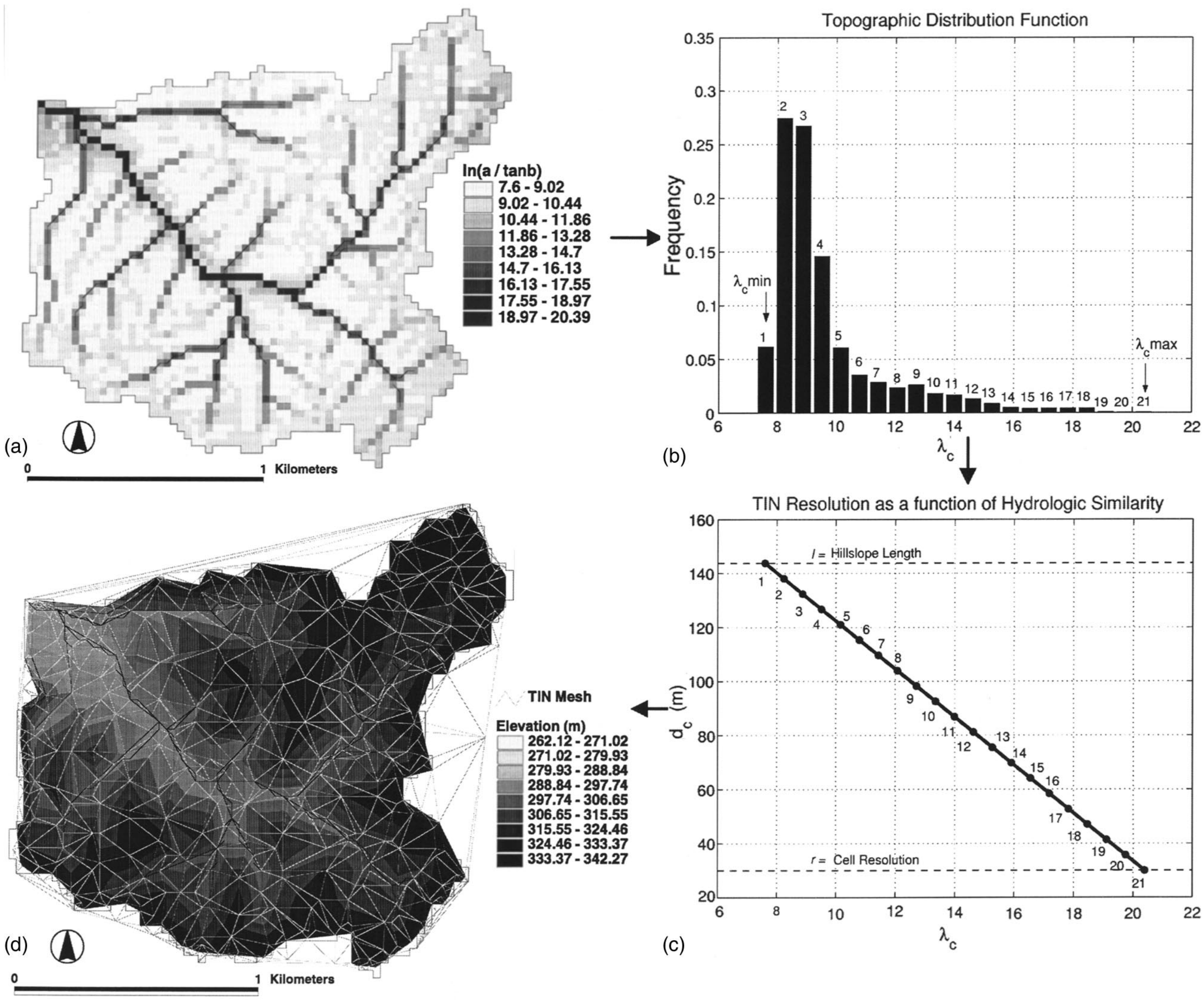

Fig. 4. Example of procedure for generating hydrological similarity triangulated irregular networks (TINs) from a high-resolution digital elevation model (DEM) [see Fig. 3(a)]. (a) Spatial distribution of topographic or wetness index, $\lambda = \ln(a/\tan\beta)$, ranging from 7.6 to 20.4; (b) frequency distribution of λ arranged into 21 classes characterized by the mean index value (λ_c); (c) functional relationship between the proximal distance (d_c) and the mean index value (λ_c), shown here as a linear function with an upper limit on d_c of the mean hill slope length (l) and lower limit of the DEM cell size (r) (horizontal dashed lines); (d) facet and elevation of the resulting hydrological similarity TIN model based on the topographic index distribution, stream network and buffered watershed boundary.

topography, channels and boundaries (Fig. 1). Ultimately, the floodplain is retained in the watershed terrain model as *nested* triangulation [Fig. 3(c)]. For the tRIBS model, a high-resolution floodplain or riparian zone is a key hydrographic feature since convergent valley bottoms tend to saturate frequently and produce runoff via the variable source area mechanism (Ivanov et al. 2003a,b; Vivoni et al. 2003a).

Landscape Features

Hydrographic TINs can also resolve regional landscape features such as soils, vegetation and geological units used in distributed hydrologic models to parameterize land surface processes. Landscape descriptors, typically available as polygon features, can be directly incorporated into a TIN terrain model, ensuring that surface properties do not vary at the subelement scale [Fig. 3(d)]. In addition, combinations of land surface descriptors can be used to represent areas of similar hydrologic response (see, for example, Kouwen et al. 1993). These hydrologic response units (HRUs) can be directly included into the TIN model, thus ensuring the triangulation conforms to the unit boundaries. The polygons that represent the hydrologic response units, or soils, vegetation and geologic features, are typically generalized and incorporated as soft breaklines in the hydrographic TIN (Fig. 1). Alternatively, HRUs can be used to constrain the triangulation by varying the TIN resolution for each unit according to a measure of hydrologic significance [Fig. 3(c)]. This approach combines the simplicity of a HRU classification with a triangulated terrain model but depends on the availability of ancillary surface data (vegetation, soils).

Embedding Steady-State Hydrologic Response: Hydrological Similarity Triangulated Irregular Networks

Hydrographic TIN methods represent essential physiographic features within a watershed without explicitly considering internal hydrologic dynamics. In principle, a hydrologically significant terrain model should preferentially resolve areas within a catchment that dominate the hydrologic response to rainfall. For example, regions that saturate (unsaturate) frequently due to a rising (falling) water table typically lead to an expanding (contracting) variable source area that alters the partitioning of rainfall into infiltration or runoff (e.g., de Vries 1995). Increased domain resolution is required in variable source regions in order to accurately capture the frequent variations in saturation pattern. In the tRIBS model, for example, the coarsening of model resolution within flat, convergent regions has been shown to have a detrimental effect on the simulated surface and groundwater interactions and storm runoff production (Vivoni et al. 2003a,b).

Methods to appropriately capture hydrologic dynamics within triangulated terrain models do not currently exist. In this study, we introduce a new approach for tailoring the terrain resolution to a measure of hydrologic significance. *Hydrological similarity* TINs utilize a hydrologic criterion for selecting elevation nodes from a high-resolution DEM and combine this information with a representation of the watershed stream network and boundary in a constrained Delaunay triangulation (Fig. 1). Instead of relying on a slope-preserving method (e.g., Latticetin, VIP), DEM points are selected according to the degree of saturation or wetness within a catchment location. Terrain analysis is used to determine the steady-state hydrologic response in a basin through the topographic index proposed by Beven and Kirkby (1979) and O'Loughlin (1986):

$$\lambda_i = \ln(a_i / \tan \beta_i) \tag{1}$$

where λ_i=topographic index at the *i*th pixel; a_i=pixel contributing area per unit width; and $\tan \beta_i$=local pixel slope. Commonly referred to as the Topmodel index, Eq. (1), provides a quantifiable measure of hydrological similarity for catchments dominated by a saturation excess runoff mechanism [see Beven et al. (1995) for a review of the underlying assumptions]. The index distinguishes between convergent areas that saturate frequently (large λ) and hillslope or upslope regions that lack runoff production (small λ). A topographic distribution function constructed from the values of λ at each catchment location serves as an index of hydrological similarity, thereby combining DEM pixels of similar hydrologic behavior into a few, distinct classes. Based on this wetness classification, a higher triangulated resolution can be retained in regions that preferentially saturate.

Fig. 4 illustrates the steps for embedding the catchment steady-state hydrologic response into a triangulated domain. A terrain model such as the raster DEM in Fig. 3(a) is analyzed to derive the topographic index (λ) for each DEM cell, as illustrated in Fig. 4(a). Notice that the wetness index [Eq. (1)] resembles the stream network pattern, with high values of λ concentrated along areas of flow convergence and low values found in upslope regions. Given the spatial pattern of the topographic index, a frequency distribution is constructed by selecting an appropriate histogram bin size, which leads to a series of classes characterized by mean index value λ_c [Fig. 4(b)]. In our experience, we typically select more than 10 classes to appropriately resolve differences in λ over catchment locations. For each topographic distribution class, the method samples the DEM at a different resolution [Fig. 4(c)], thus it can retain more points in frequently saturated areas (high λ). Although the Topmodel formulation (1) is utilized, the methodology is amenable to other measures of hydrological similarity (e.g., those reported by Ambroise et al. 1996; Woods et al. 1997).

To objectively select DEM points based on the wetness index distribution, a functional relationship [Fig. 4(c)] is established between the mean index value of each class (λ_c) and the mean distance between the selected DEM points (d_c in meters):

$$d_c = f(\lambda_c) \quad r \leq d_c \leq l \tag{2}$$

where f=a functional relation; r=DEM cell resolution (in meters); and l=mean hillslope length (in meters). The mean distance between any two nodes is used as a proximity criterion to filter the DEM and is constrained based on the resolution of the topographic data (r) and a measure of the overland distance to a stream (l). The proximity filter operates on a subset of the DEM field that is disaggregated based on the index value. Data thinning is applied with a circular filter of radius $0.5d_c$ for the points within a DEM for each index class [see Vivoni et al. (2003b) for details of the algorithm]. For simplicity, the relationship is illustrated here as linearly decreasing over λ_c, which implies that regions with low values of λ are represented at low resolution (large d_c), whereas large λ values are retained at a progressively higher point density (smaller d_c).

For the linear relationship [Fig. 4(c)], the method for selecting DEM nodes using a hydrological similarity criterion depends only on r and l, computed directly from the DEM, without the need to specify an accuracy parameter (such as v or z_r). The minimum (r) and maximum (l) values selected for d_c are natural length scales for constraining the mean point spacing. In particular, the mean hillslope length (l) is a measure of hydrologic distance computed from the total stream network length (L_T) and catchment area (A):

$$l = \frac{1}{2D_d} = \frac{A}{2L_T} \tag{3}$$

where D_d=drainage density. Terrain analysis is utilized to compute A and L_T from the DEM with the selection of the constant-area stream threshold having an important effect on the value of the hillslope length (see Vivoni et al. 2003b). Both the drainage density and the mean hillslope length are key descriptors closely related to the basin topographic form and long-term hydrologic response (e.g., Tucker et al. 2001a).

Vivoni et al. (2003b) discussed in greater detail a general method for selecting the functional relation (2) using the statistical properties of the topographic index distribution (e.g., mean, variance, skewness) as well as the constraints provided by the DEM cell size and mean hillslope length. Rather than using a linear decrease in point spacing, a step-wise function is constructed that effectively depicts saturated regions (high λ) beyond the distribution peak at high resolution, while drier upslope areas (low λ) are retained at lower resolution. Relating the functional relation to the basin wetness distribution provides an objective means by which to preferentially resolve saturated areas in a TIN model.

In summary, hydrological similarity TINs sample a raster DEM with a variable resolution filter conditioned on the topographic index value. The proximity filter (d_c) is applied to a subset of hydrologically similar nodes, ensuring that point spacing reflects a relationship with the mean index value (λ_c). The selection of this functional relation is based on the wetness index distribution, although for, simplicity, we have illustrated it for the case of a linear function. Physical limits on the filter size ensure that upslope and convergent areas are sampled at low (l) or high resolution (r), respectively. After point selection, constrained Delaunay triangulation is used to create a TIN that resembles the spatial distribution of the wetness index [Fig. 4(d)]. The physical link between the TIN terrain model and the basin properties provides a consistent means by which to develop hydrological similarity TINs. Further details on the GIS algorithms for index-based

Table 1. Characteristics of Selected Watersheds Extracted from U.S. Geological Survey (USGS) and Shuttle Radar Topography Mission (STRM) Digital Elevation Model (DEM) data

Watershed	Longitude of watershed outlet, x_0 (dd)	Latitude of watershed outlet, y_0 (dd)	Basin area, A (km^2)	Grid cell resolution, r (m)	Number of DEM cells, n_g	Mean elevation, μ (m)	Elevation std dev, σ (m)	Elevation range, Δz (m)
Baron Fork, Okla.[a]	−94.84	35.92	808.15	30	897,944	346.54	59.02	367.88
Blue River, Okla.[a]	−96.24	34.00	1,236.38	30	1,373,755	259.48	66.49	245.23
Cheat River, W.Va.[a]	−79.68	39.12	1857.22	30	2,063,578	1,000.56	185.07	1002
Flint River, G.[a]	−84.43	33.24	697.71	30	775,233	264.79	19.71	105
Illinois River, Okla.[a]	−94.57	36.13	1627.60	30	1,808,444	378.06	41.34	324.21
Squannacook River, Mass.[a]	−71.65	42.63	172.03	30	191,144	194.42	80.71	387.40
Smith Canyon, Colo.[a]	−103.43	37.76	732.96	27.697	955,461	1,557.51	133.30	634.10
Abo Arroyo, N.M.[b]	−106.77	34.52	1,000.51	84.473	140,212	1,846.86	236.35	1,593
Cow Creek, Or.[b]	−123.44	42.92	992.75	26.835	1,378,595	666.43	184.09	1,353
Gun River, Mich.[b]	−85.64	42.47	268.35	26.839	372,537	217.36	21.69	118
Little Lost Creek, Mo.[b]	−91.32	38.71	110.37	27.528	145,647	208.22	31.28	152
Lost Creek, Utah[b]	−111.54	41.06	576.92	27.012	790,682	2,158.26	195.50	1,018
Picacho Wash, Ariz.[b]	−114.62	32.80	96.83	28.462	119,531	183.34	56.98	538
Rapidan River, Va.[b]	−78.03	38.32	1,182.79	27.538	1,559,706	226.68	222.68	1,135
Smith Canyon, Colo.[b]	−103.43	37.76	734.67	27.691	958,109	1,536.68	134.11	634

Note: dd=Decimal degrees.

[a]USGS (Gesch et al. 2002).

[b]SRTM data (Farr and Kobrick 2000).

point selection and proximal distance triangulation are presented in work by Vivoni et al. (2003b).

Elevation Data Products

The three methods for generating hydrologically significant TIN models are tested by utilizing U.S. Geological Survey (USGS) and Shuttle Radar Topography Mission (SRTM) DEMs. In the following, a brief description of each is presented.

U.S. Geological Survey Digital Elevation Models

The USGS has developed national topographic coverage that contains the best available DEM products at various levels of accuracy (Gesch et al. 2002). Comparisons of DEM accuracy to higher resolution data from photogrammetry and land surveying suggest that the products are reasonable approximations, although localized errors are possible (e.g., Kenward et al. 2000). For level-2 DEMs, the vertical accuracy is one-half the contour interval with discretization to the nearest unit (USGS 1998). Despite potential artifacts, the USGS DEMs provide extensive data for testing the TIN algorithms. A series of seven USGS watersheds are utilized in this study (Table 1).

Shuttle Radar Topography Mission Digital Elevation Models

SRTM DEMs are an emerging source of high-resolution topography data obtained using radar interferometry onboard the Endeavor Shuttle (Farr and Kobrick 2000). The sampling technique consisted of two radar instrument pairs separated by a 60-m mast. Processing of the *C*-band data provides a nominal 30-m product over 80% of the Earth's landmass. A preliminary distribution of 1- and 3-arcsec. (SRTM-1 and SRTM-3) products was made for evaluation purposes. Vertical accuracy is estimated at 15 m with discretization to the nearest meter (Farr and Kobrick 2000). In this study, a series of eight SRTM watersheds were chosen to test the TIN algorithms (Table 1).

Applications of Hygrographic and Hodrological Similarity Triangulated Irregular Networks

To generate the traditional, hydrographic and hydrological similarity TINs described earlier, we developed a set of terrain analysis programs in ArcInfo GIS. Elevation data from the USGS and SRTM were used to construct TIN models for a series of basins. In the following, several case studies are presented to demonstrate the GIS methods and evaluate the performance of the hydrographic and hydrological similarity TINs relative to the original and aggregate DEM products. In particular, we address five related issues in the case studies. (1) Can TIN terrain models better capture topographic variability as compared to equivalent DEM aggregation products? (2) Can triangulated terrain models reveal differences between DEM products of varying accuracy? (3) How does terrain variability and catchment form affect the aggregation and accuracy of TIN terrain models? (4) How does incorporating a measure of hydrological similarity into a TIN model improve upon hydrographic or traditional methods? (5) Is it possible to construct TIN models of continental basins that capture hydrologic behavior?

Comparisons between the different DEM and TIN terrain models are quantitatively assessed using the frequency distribution of primary and secondary terrain descriptors (Moore et al. 1991). The TIN surfaces are linearly interpolated onto a raster grid of the original DEM dimensions prior to deriving the elevation, slope, curvature and topographic index distributions. The slope and curvature fields are computed from the elevation data using algorithms described by Moore et al. (1991), while the topographic index distribution is based on the single-flow algorithm in work by Wolock and McCabe (1995). Finally, a qualitative

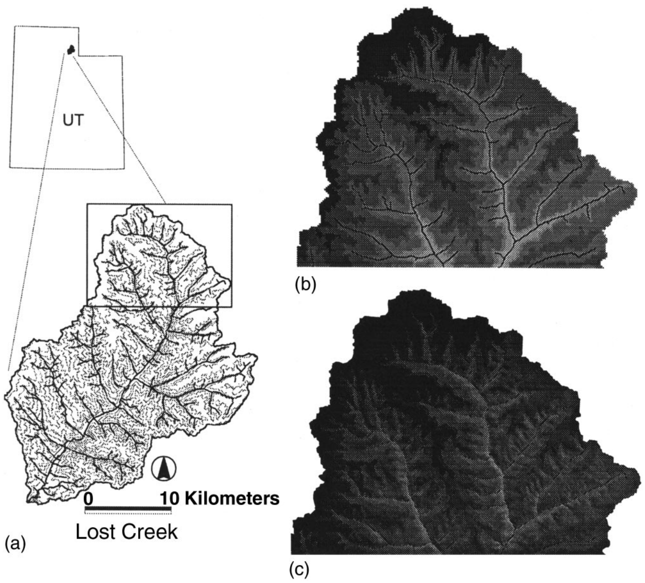

Fig. 5. Comparison of the digital elevation model (DEM) aggregation and hydrographic triangulated irrgular network (TIN) terrain products for Lost Creek basin, Utah (577 km^2). (a) Contour map of the shuttle radar topography mission (SRTM)-1 watershed elevation and stream network with basin location (contours at 100-m intervals); (b) aggregate DEM at 81-m resolution with 94,880 nodes or 12% of the original SRTM-1 DEM (Table 1); (c) hydrographic TIN model developed at an identical data reduction factor ($d=n_g/n_t=0.12$) using the Latticetin sampling method ($z_r=4$ m).

comparison between the DEM products and the hydrographic and hydrological similarity TINs is obtained by visualizing the different terrain models.

Comparison of Digital Elevation Model Aggregation and Triangulated Irregular Networks

DEM aggregation or resampling leads to the smoothing of critical slopes and shortening of flow paths which directly impact flow predictions in distributed hydrologic models (e.g., Vieux 1993; Walker and Willgoose 1999). The effect of DEM aggregation is illustrated using the SRTM DEM for the Lost Creek basin in Utah (Fig. 5). Due to its high terrain variability ($\sigma=195.5$ m), this basin exemplifies potential errors that occur during grid aggregation. SRTM-1 data were transformed from their native 27-m resolution to 81 m using bilinear interpolation, a resolution equivalent to the SRTM-3 product (Farr and Kobrick 2000). Comparisons are made to a *hydrographic* TIN derived using a slope-preserving criterion that includes the stream network and basin boundary. The elevation tolerance ($z_r=4$ m) was chosen so the data reduction factor ($d=0.12$) matched the aggregation in the 81-m DEM. Despite the low aggregation level, from 27- to 81-m resolution, the distribution of the slope, curvature and topographic index varies considerably for the aggregated DEM, but the elevation remains unaffected (Fig. 6). This illustrates the strong impact that DEM aggregation can have on distributed hydrologic model response since the slope and curvature fields determine flow paths and gradients over the complex terrain. The hydrographic TIN model, on the other hand, preserves the terrain attributes very well, in particular the slope and curvature, considering that only

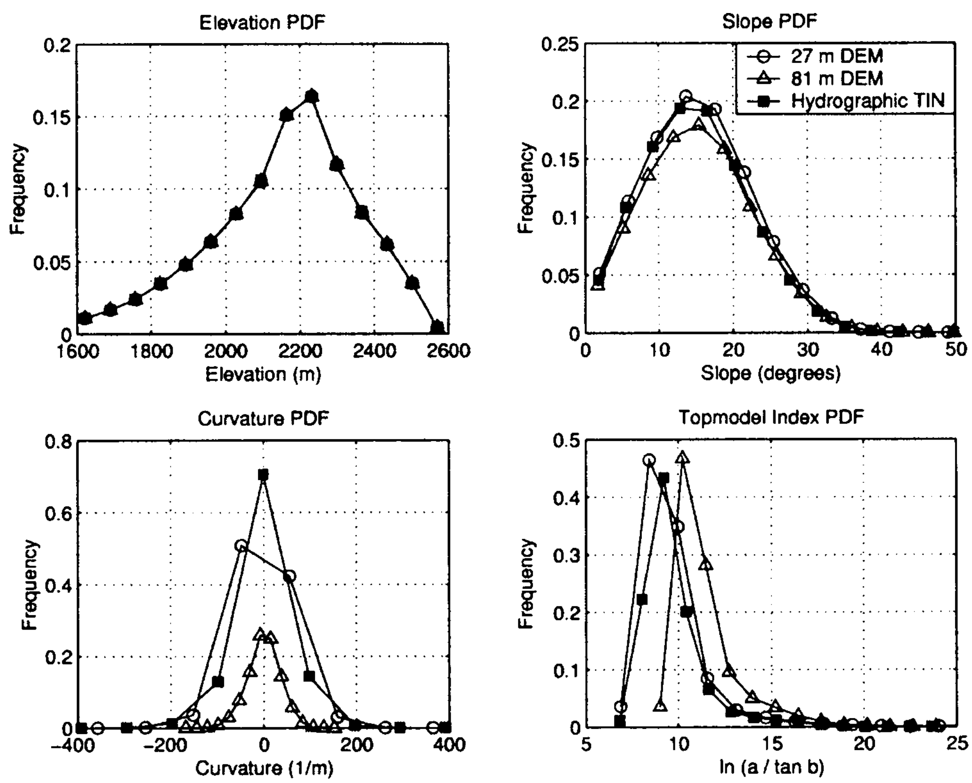

Fig. 6. Comparison of the digital elevation model (DEM) aggregation and hydrographic triangulated irregular network (TIN) products for Lost Creek basin, Utah, illustrating the effects of domain coarsening on the primary and secondary topographic attributes. Frequency distribution of the elevation (top left), slope (top right), curvature (bottom left) and topographic index (bottom right) for the original shuttle radar topography mission-1 DEM (27-m), the aggregate DEM (81-m) and the hydrographic TIN models. Both the aggregate DEM and hydrographic TIN have an equivalent number of nodes ($d=0.12$).

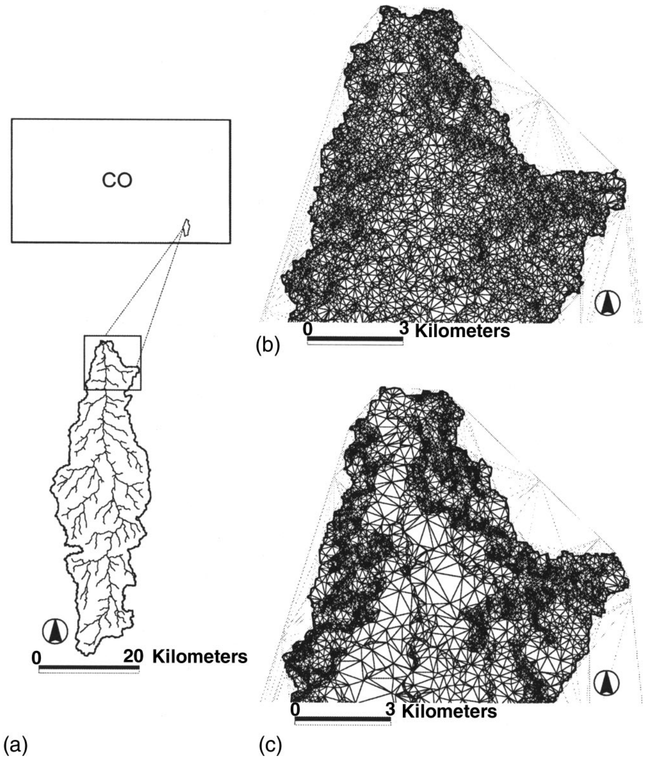

Fig. 7. Comparison of U. S. Geological Survey (USGS) and shuttle radar topography mission (SRTM) digital elevation models (DEMs) using hydrographic triangulated irregular network (TIN) terrain models for the Smith Canyon, Colo. (735 km^2). (a) Location of study watershed with representation of the watershed boundary and stream network from USGS DEM; (b) hydrographic TIN model using SRTM-1 DEM (75,025 nodes; $d=0.08$); (c) USGS DEM-derived hydrographic TIN model (99,958 nodes, $d=0.1$). Both the SRTM-1 and USGS TINs were derived using the Latticetin method at the same level of vertical tolerance ($z_r=4$ m). Notice the marked differences in TIN resolution over the flat canyon bottom (SRTM TIN denser than USGS TIN) and along the steep canyon walls (USGS TIN denser than SRTM TIN). The overall effect is that higher resolution is required in the USGS TIN to meet the specified vertical tolerance.

12% of the nodes is retained in the TIN. This result confirms that hydrographic TIN models are capable of capturing topographic variability that cannot be achieved via raster aggregation due to the adaptive, irregular domain. Additional tests within this basin indicate that as the level of aggregation increases (d decreases), TINs progressively capture more terrain information than a DEM of equivalent resolution (not shown).

Comparison of U.S. Geological Survey and Shuttle Radar Topography Mission Digital Elevation Models Using Triangulated Irregular Networks

Topographic data quality varies with the methods employed for capturing and processing elevation data (e.g., photogrammetry, synthetic aperture radar, LIDAR). To illustrate the differences between the USGS and SRTM DEMs obtained using distinct techniques, we compare the two derived *hydrographic* TIN models for Smith Canyon in Colorado (Fig. 7). The topographic data is sampled using the Latticetin method at the same level of vertical tolerance ($z_r=4$ m) for both data sources. As shown in Figs. 7(b and c), DEM differences propagate to variations in the stream network, watershed boundary and the TIN terrain model resolution. Despite identical procedures, the SRTM TIN [Fig. 7(b)] contains 75,025 nodes compared to 99,958 in the USGS TIN [Fig. 7(c)]. In flat regions, the SRTM TIN captures more variability in elevation compared to the smoother USGS TIN, whereas over rugged terrain the USGS TIN has proportionally higher resolution due to larger variations in slope with respect to the SRTM TIN. Even visual comparison of the two triangulated models suggests that TINs can discern differences in elevation data quality, particularly for situations where noise or speckling may be present in the terrain model (e.g., Falorni et al. 2004). This is corroborated by comparing the terrain attribute distributions of the two DEMs in Fig. 8. A higher proportion of low slopes is present in the USGS DEM, which agrees well with the observation of larger, flatter triangles in the canyon bottom for the USGS TIN. Results from comparisons in seven other USGS-SRTM basin pairs (not shown) further suggest that TINs concisely capture differences in DEM products. While this may be achieved via direct comparison of DEM terrain attributes, the use of TIN characterization as a visualization tool for assessing DEM data quality is promising.

Comparison of Hydrographic Triangulated Irregular Networks over Varying Terrain

In generating watershed terrain models for distributed hydrologic simulations, the TIN methodology should be generally applicable to any geographic location. To evaluate the performance of the *hydrographic* TIN models over a range of basin physiographies, we investigate the dependence of TIN accuracy and data reduction on the catchment terrain roughness. Vertical accuracy is measured by the RMSE between the original DEM and the hydrographic TIN model, while terrain roughness is represented by the standard deviation (σ) in elevation. A series of basins was selected from both the USGS and SRTM data to ensure topographic heterogeneity between the catchments, with σ ranging from 20 to 220 m (Table 1). Hydrographic TINs were generated for each basin using an identical elevation tolerance ($z_r=4$ m) and included the stream network and basin boundary. Fig. 9 (top) illustrates how an increase in terrain variability (σ) leads to a higher RMSE between the original DEM surface and the hydrographic TIN model. Notice that for $z_r=4$ m, the RMSE varies narrowly between 1.2 and 2 m despite the large variations in catchment form. Terrain roughness (σ) also impacts the data reduction or coarsening (d) achieved with a TIN model (Fig. 9, bottom). A larger range of TIN aggregation (2–20% of the original nodes) is observed for the same elevation tolerance in basins of different topographic form. In general, Fig. 9 indicates that flat or gently sloping catchments with low variability in terrain can be represented with fewer TIN nodes (low d) and improved accuracy (low RMSE) for a given level of tolerance (z_r) compared to high relief, mountainous basins. Vivoni et al. (2003a) have further illustrated the effect of elevation tolerance on the data reduction achieved in a hydrographic TIN model and its subsequent impact on the vertical terrain accuracy and hydrologic model response.

Comparison of Hydrologically Significant Triangulated Irregular Networks at Two Scales

Hydrographic and hydrological similarity TINs select DEM nodes using either a slope-preserving or a wetness index criterion which leads to dramatically different terrain representations within the same basin. In order to assess the relative performance of the two methods, we compare a 30-m USGS DEM and an aggregate

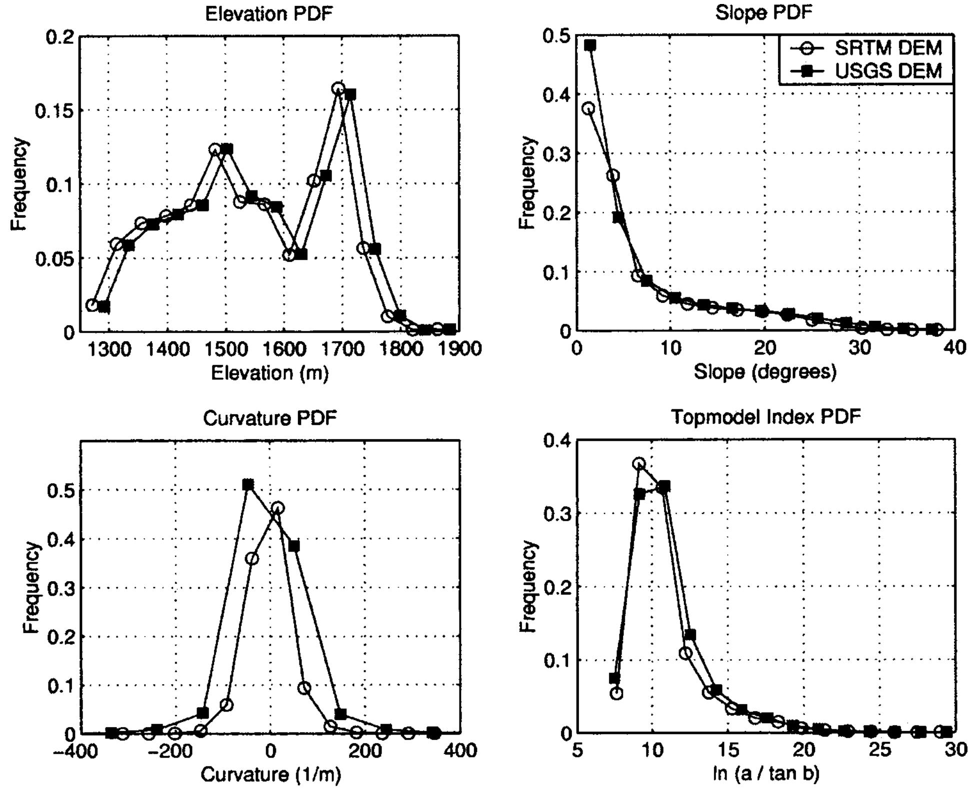

Fig. 8. Comparison of the terrain attribute frequency distribution for the shuttle radar topography mission (SRTM)-1 and U.S. Geological Survey (USGS) digital elevation models (DEMs) in Smith Canyon; elevation (top left), slope (top right), curvature (bottom left) and topographic index (bottom right). Note that the elevation bias (~20 m) between the USGS and SRTM DEMs is potentially due to systematic geodetic error in preliminary SRTM data. Differences in the slope and curvature distribution between the two data sources indicate that the USGS DEM has a higher frequency of low slope cells and high curvature regions.

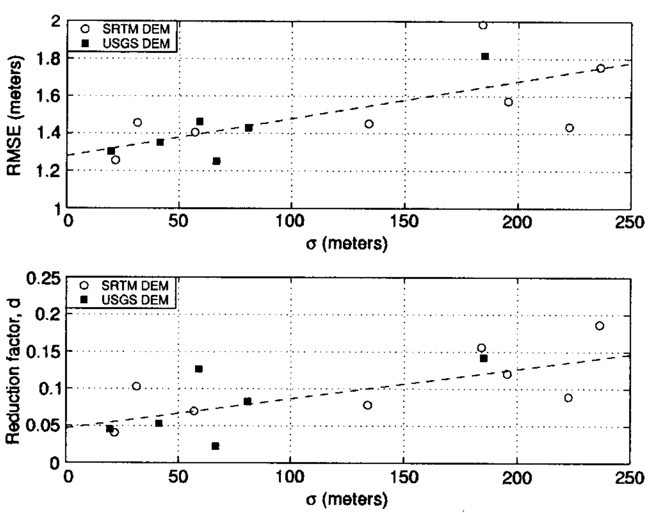

Fig. 9. Performance of hydrographic triangulated irregular network (TIN) method for a series of U.S. Geological Survey and shuttle radar topography mission digital elevation models (DEMs) of varying terrain characteristics (see Table 1); (top) root mean square error between TIN and DEM models increases with terrain variability (σ); (bottom) the data reduction factor or coarsening achieved in the TIN model ($d=n_t/n_g$) increases with σ. The dashed lines represent linear regression in each relationship. R^2 for linear regression is 0.524 and 0.518 in the top and bottom panels, respectively.

DEM with the two TIN models for the Baron Fork basin in Oklahoma (Fig. 10). The same data reduction factor ($d=0.07$; $n_t=64{,}000$ nodes) is used for the *hydrographic* TIN [$z_r=6.8$ m, Fig. 10(b)], *hydrological similarity* TIN [Fig. 10(c)], and the DEM aggregation product ($r=112$ m). A comparison of the TINs derived from the USGS DEM reveals the differences in resolved features and domain resolution. Notice that the hydrographic TIN has an imposed high resolution in the floodplain area due to nested triangulation, while other flat regions are poorly resolved. The hydrological similarity TIN, on the other hand, automatically retains high resolution within regions that saturate frequently (high λ). Along rugged hillslopes, the hydrographic TIN has higher resolution since the terrain variability is high, while the hydrological similarity TIN samples the domain evenly as the propensity for saturation and runoff is reduced (low λ).

A quantitative comparison between the hydrographic and hydrological similarity TINs is presented for the Baron Fork (808 km^2) and the nested Peacheater Creek subbasin (64 km^2) in Figs. 11 and 12, respectively, relative to the original and aggregate DEMs. In terms of terrain attributes (slope, curvature, topographic index), the performance of the two TINs is superior to DEM aggregation, as shown previously for Lost Creek (Fig. 6). Each TIN method preserves the attribute distribution that best reflects the criterion used to select the DEM nodes (slope-preserving or wetness index) relative to the original DEM. The slope distribution is preserved best in the hydrographic TIN, while the hydrological similarity TIN retains a more accurate wetness index distribution, especially for frequently saturated areas. Similar results are obtained in both watersheds, suggesting that

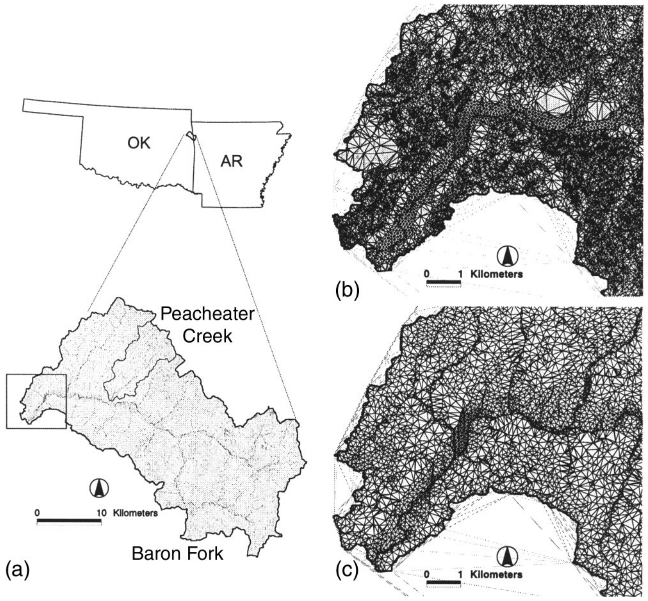

Fig. 10. Comparison of triangulated irregular network (TIN) terrain models for the Baron Fork (808 km^2) and Peacheater Creek (64 km^2) basins from a 30-m U.S. Geological Survey digital elevation model. (a) Location of the two watersheds and highlighted region overlaid on the spatial distribution of the topographic index; (b) hydrographic TIN generated using the Latticetin method ($z_r = 6.8$ m), stream network, basin boundary and nested floodplain triangulation ($n_t = 64{,}000$ nodes); (c) hydrological similarity TIN with the proximity criterion (d_c) varying from $r = 30$ m to $l = 579$ m, along with representation of a stream network and watershed boundary ($n_t = 64{,}000$ nodes). Notice the variations in model resolution between the two TIN methods.

the TIN methods performed equally well at the subbasin scale (Fig. 12) compared to the larger domain (Fig. 11). In both basins, the hydrological similarity TIN was better than the hydrographic TIN at capturing the wetness index distribution but worse for the slope distribution. Since the terrain models for the subbasins were directly extracted from the larger watershed, the performance of the nested TIN models seems to have low susceptibility to scale variations, a promising result for hydrologic applications with the tRIBS distributed model (e.g., Vivoni et al. 2003a,b).

Continental-Scale Hydrological Similarity Triangulated Irregular Networks

The multiple resolutions afforded by TIN terrain models can capture the topographic or hydrologic detail in large regional or continental basins with a reduced set of elevation points. Here, we demonstrate the performance of the *hydrological similarity* TIN method for the Mississippi River basin, approximately 3,196,675 km^2 in area [Fig. 13(a)]. Digital terrain data for the basin are obtained from the North American HYDRO1K database (1-km resolution), derived from USGS 3-arcsec DEMs (Verdin and Greenlee 1996). A low-resolution TIN commensurate with current computational capabilities of the tRIBS hydrology model is shown in Fig. 13(b) (Ivanov et al. 2003a,b). The TIN model ($n_t = 101{,}756$, $d = 0.03$) is compared with an aggregate DEM (5.65-km cell resolution) that has a comparable data reduction factor. Comparisons of the terrain frequency distributions demonstrate the superiority of the TIN model in capturing the hydrologic signature of the high-resolution data despite having only 3% of the nodes (Fig. 14).

Discussion

The case studies previously presented illustrate the construction of multiple resolution TIN models that capture the hydrographic and hydrologic features essential for distributed hydrologic simulations. We first demonstrated how hydrographic TIN models are superior to equivalent DEM aggregation products in terms of retaining critical topographic information with a minimal set of elevation nodes. This capability allows TIN-based hydrologic models to simulate larger domains than raster-based models without the loss of topographic detail. Subsequently, we illustrated the effects of DEM data quality on the generation of hydrographic TINs with the interesting result that triangulated terrain models can aid in interpretation of topographic features or errors in DEMs. Along a similar vein, an analysis of a series of catchments of different topographic form revealed that the vertical accuracy and degree of coarsening in hydrographic TINs are sensitive to the variability in watershed terrain.

A comparison of hydrographic and hydrological similarity TINs was then presented for a set of nested basins to illustrate the advantages and disadvantages of the new method for embedding the hydrologic response into the terrain model. Quantitative and qualitative comparisons of the TIN models suggest that hydrological similarity TINs are a promising method by which to capture hydrologic variability in terrain models. Finally, for a continental watershed, we showed the feasibility of generating hydrological similarity TINs in large domains while capturing the hydrologic signature in topography with a reduced set of elevation nodes. In the following, we discuss several key issues regarding the use of hydrographic and hydrological similarity TINs for distributed watershed simulations in light of our recent applications of the tRIBS model.

Aggregation and Hydrologic Predictions

Minimizing the trade-off between model errors and execution time is desirable when selecting the hydrologic model resolution. In raster-based models, simulations of large basins may require significant DEM aggregation to account for the simulation time and computational effort (e.g., Wigmosta et al. 1994; Vázquez et al. 2002). Topographic models based on triangulated irregular networks provide a way forward in this regard, since they retain the statistical signature of the best available terrain data with at least an order of magnitude fewer elevation points. This degree of coarsening permits model application in large basins without significant loss of information on the terrain. For example, Ivanov et al. (2003b) presented simulations using the tRIBS model over a 7-year period in three basins in Oklahoma: Baron Fork (808 km^2), Illinois River (1,640 km^2) and Blue River (1,230 km^2) (Table 1). Hydrographic TINs that preserve the hillslope variability, stream network, watershed boundary and floodplain domain were constructed for each basin using 7.22% (Baron Fork), 3.98% (Illinois River) and 3.32% (Blue River) of the original 30-m DEM nodes. At this level of aggregation, continuous tRIBS simulations were computationally feasible while preserving topographic information within each basin.

Nevertheless, the selection of a triangulated irregular network for a particular basin topography may also introduce aggregation errors that propagate to the predictions of a hydrologic model.

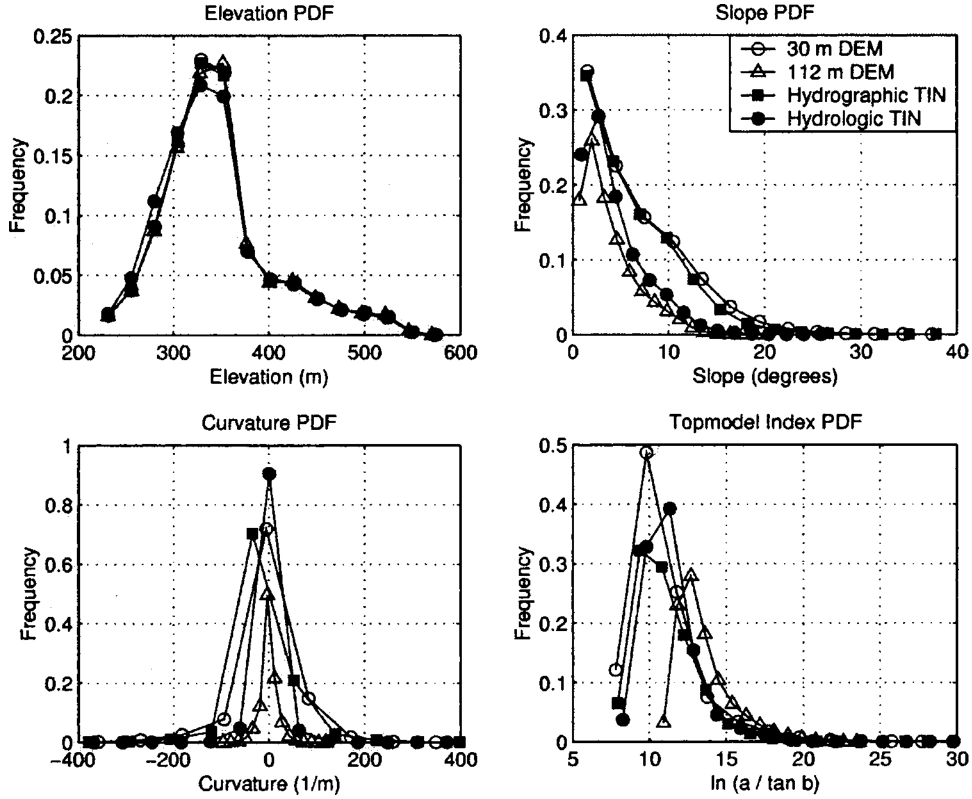

Fig. 11. Comparison of frequency distributions of elevation (top left), slope (top right), curvature (bottom left) and topographic index (bottom right) of the digital elevation model (DEM) and triangulated irregular network (TIN) terrain models for the Baron Fork watershed. Included are the original U.S. Geological Survey 30-m DEM, a DEM aggregation at 112-m resolution, a hydrographic TIN model and a hydrological similarity TIN model (labeled hydrologic TIN).

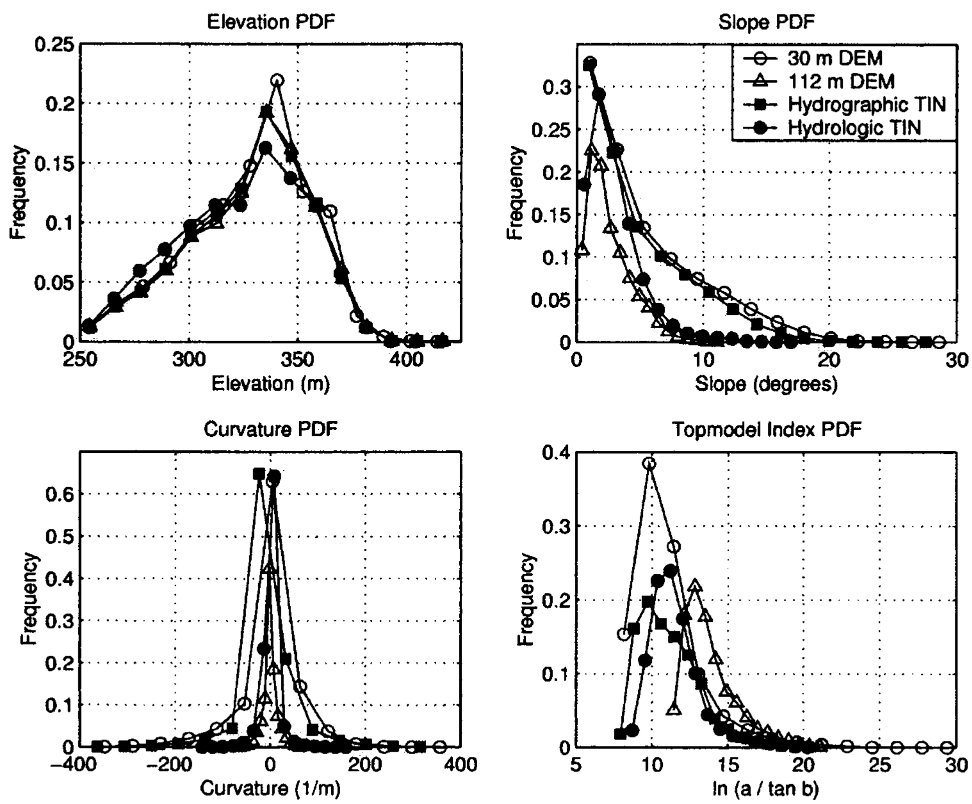

Fig. 12. Comparison of frequency distributions of terrain attributes for Peacheater Creek watershed sampled directly from the Baron Fork models. Included are the original U.S. Geological Survey 30-m digital elevation model (DEM), a DEM aggregation at 112-m resolution, a hydrographic triangulated irregular network (TIN) and a hydrological similarity TIN (labeled hydrologic TIN).

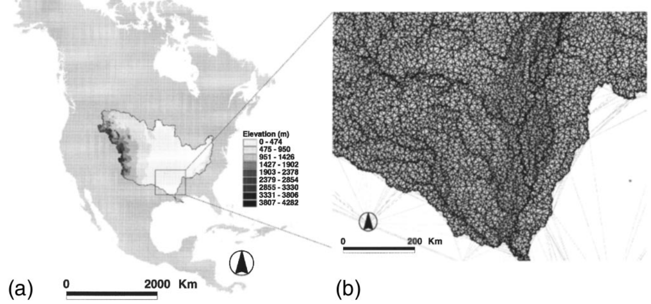

Fig. 13. Development of a hydrological similarity triangulated irregular network (TIN) for the continental-scale Mississippi River basin (3,196,675 km^2). (a) Basin boundary and topographic data obtained from the HYDRO1K database at 1-km cell resolution. (b) Facet view of the hydrological similarity TIN model extracted at low overall resolution ($n_t = 101{,}756$ nodes or $d = 0.03$) for a small region near the mouth of the Mississippi River. Notice that the TIN resolution follows the spatial pattern of the wetness index with higher resolution retained in the flat river floodplain and delta regions (darker area).

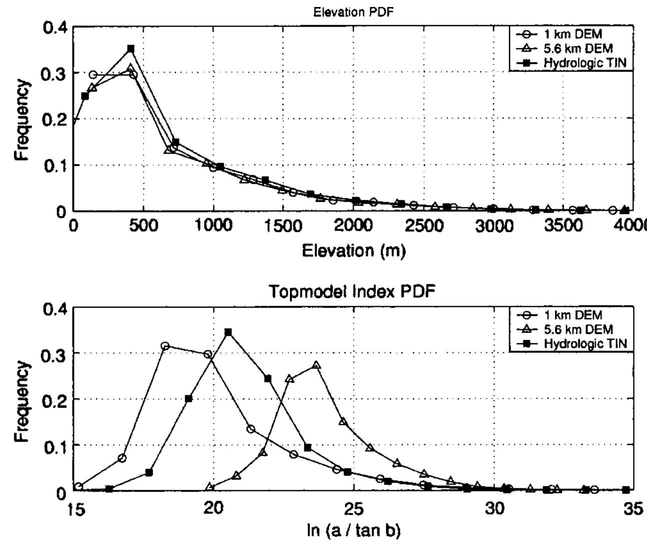

Fig. 14. Comparison of elevation (top) and topographic index (bottom) frequency distributions for the Mississippi River basin using the original HYDRO1K digital elevation model (DEM) (1-km cell resolution), a DEM aggregation product (5.65-km cell resolution, $d = 0.03$) and the hydrological similarity triangulated irregular network (TIN) model ($d = 0.03$, labeled hydrologic TIN). Notice that the hydrological similarity TIN preserves the topographic index distribution well, particularly for saturated regions (see floodplain area in Fig. 13).

Both the methodology chosen (e.g., traditional, hydrographic or hydrological similarity TINs) and the acceptable level of error in the TIN (e.g., v, z_r, RMSE) can potentially impact hydrological simulations. Given the potential uses of TINs for hydrological modeling, the propagation of TIN resolution error into model predictions is an important question. Vivoni et al. (2003a) described the construction of hydrographic TINs at multiple levels of aggregation and subsequently analyzed the impact of varying TIN data reduction on tRIBS model response in the Peacheater Creek basin (64 km^2). The impact of TIN aggregation on the distributed model response (e.g., water balance, runoff mechanisms, surface saturation and groundwater dynamics) was shown to be small over a broad range of aggregation levels. However, important effects on the hydrologic response were observed when the TIN model was coarsened beyond a point where the floodplain region was not represented accurately, because the dynamics of the variable source area were not properly captured (Vivoni et al. 2003a).

Hydrologic Modeling Using Triangulated Irregular Networks

Compared to raster grid and distribution function approaches, TIN-based hydrologic models have received little attention. Notable exceptions include the work of Goodrich et al. (1991), Palacios-Vélez and Cuevas-Renaud (1992), Tachikawa et al. (1994), Mita et al. (2001), Tucker et al. (2001b) and Ivanov et al. (2003b). Despite the advantages in representing terrain by triangulated irregular networks, the proliferation of TIN hydrologic models has been hindered by the relative complexity of the data structures and algorithms on the irregular mesh as compared to raster methods (Tucker et al. 2001b). The additional complexity in the TIN structure is perceived to outweigh the potential gains made by reducing the number of model nodes through adaptive gridding. Our experience with the tRIBS model over various watershed scales has revealed that computational effort is reasonable due precisely to the significant reduction of model nodes (Ivanov et al. 2003b). In addition, the level of detail retained in the terrain model is superior to the equivalent aggregation required for carrying out raster-based distributed simulations in large watersheds (Garrote and Bras 1995).

The accurate representation of watershed features necessary in the tRIBS model motivated the development of the hydrographic and hydrological similarity TIN methods. The hydrologically significant TINs address the deficiencies identified in previous work, such as conforming to basin boundaries and stream networks (e.g., Mita et al. 2001), resolving both the topographic field and basin hydrography (e.g. Nelson et al. 1999) and incorporating features such as floodplains, soil units or land cover. Comparisons of the two TIN methods have revealed the accuracy retained in the distribution of the criteria selected (e.g., slope or wetness index) despite the high level of terrain aggregation. An important question is whether incorporating the steady-state wetness index into a TIN model is an improvement over the hydrographic method. Vivoni et al. (2003b) addressed this issue by performing paired model simulations of the Baron Fork basin that explicitly compared the TIN methods in terms of hydrologic response. The results showed that hydrological similarity TINs capture the dynamics of the variable source area whereas hydrographic TINs can introduce errors associated with a poorly resolved floodplain. Further details on tRIBS model evaluations are discussed in work by Vivoni et al. (2003a).

Multiple Resolutions, Scale and Nesting

The capability of resolving terrain at multiple resolutions using a topographic or hydrologic criterion creates various opportunities to enhance the formulation of distributed hydrologic models. As shown for the Mississippi River basin, the use of a topographic or wetness index to constrain resolution of TIN models is a promising development for large-scale climate, weather or hydrology model applications where the domain should preferentially resolve regions of intense hydrologic activity. In addition, a low resolution, continental basin-scale TIN model can be embedded with a set of subwatersheds at different resolutions. Triangulated irregular networks permit a smooth transition between the continental basin and its multiple nested watersheds. The level of detail used to represent each basin can vary according to the hydrologic process representation or the resolution of available topographic data. Furthermore, the hydrologic signature at each scale can be preserved through a physical link to the characteristics (drainage density and topographic index) of the nested basins. As a result, hydrological similarity TINs that properly resolve both the large and small scale domains provide a means by which to enhance distributed hydrologic models.

Conclusions

In this study, we presented three approaches for developing watershed TIN models for distributed hydrologic simulations. The methodology accounts for the topographic, hydrographic and hydrologic features in real-world basins. We focused on the generation of triangulated terrain models using the concept of hydrological similarity provided through a wetness index. This new method embeds an estimate of the steady-state runoff response within the TIN mesh. By incorporating hydrologic features, the spatial representation utilized in a distributed hydrologic model can be closely tied to the underlying hydrologic processes. The new method also bridges two existing modeling approaches: Topographic distribution functions and finite-element meshes. Through a series of case studies, we illustrated and quantified the performance of hydrologically significant TINs in relation to the original DEM. The hydrological similarity TINs, in particular, capture the hydrologic signature in terrain while minimizing the significant negative effects introduced by DEM aggregation.

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