Chapter 4
Digital Terrain Analysis Approaches for Tracking Hydrological and Biogeochemical Pathways and Processes in Forested Landscapes

Irena F. Creed and Gabor Z. Sass

We would argue that any mapping or characterization of landscape heterogeneity and process complexity must be driven by a desire to generalize and extrapolate observations from one place to another, or across multiple scales, and must not be allowed to perpetuate the notion of characterization or mapping for its own sake.

(McDonnell et al. 2007)

4.1 Introduction

Digital terrain analysis (DTA) comprises a set of tools that use digital elevation models (DEMs) to model earth surface processes at a range of scales. DEM and its derivatives are part of a larger set of digital terrain models (DTMs) used in various fields to model the flow of energy and materials across surfaces. The ubiquity of DTMs in the hydrologist's toolkit has led to the widespread use of terrain attributes such as slope and upslope contributing area to characterize the way water and associated nutrients move across landscapes. Algorithms to compute terrain attributes are now programmed into all commercial Geographic Information System (GIS) software (e.g., ArcGIS, Idrisi) and with a push of the button users can map patterns of potential surface hydrological flows. While the derived layers always look visually stimulating, field hydrologists have often raised the question: are DTMs often merely interesting spatial patterns with not much relevance to predicting actual hydrological behavior? This synthesis critically answers this question by discussing the relevance of DTA for practicing forest hydrologists in the twenty-first century.

Topographic information has been exploited to better understand the hydrological functions of catchments since early theories on catchment rainfall-runoff were proposed (Horton 1945; Hewlett and Hibbert 1967). However, prior to desktop computing, catchment scale attributes, such as a catchment's area, length, perimeter and relief ratio (maximum relief divided by longest flow path length), were used to investigate hydrological behavior, because only these attributes could be easily derived from contour maps (Schumm 1956). Although these metrics helped explain differences in water and sediment yields between basins (Garcia-Martinó et al. 1996),

D.F. Levia et al. (eds.), *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*, Ecological Studies 216,
DOI 10.1007/978-94-007-1363-5_4, © Springer Science+Business Media B.V. 2011

they did little to predict the flow of water within basins. With the advent of the digital age in the 1980s, terrain analysis entered a new era and is now one of the cornerstones of the new computer-enabled toolkit for hydrologists. In many hydrological investigations, it is the first (and sometimes only) step to understanding the way water moves through the landscape since it requires the least data input. New DEM sources, such as laser altimetry, are making it possible to map surface water flow and surface water storage at very fine spatial resolutions and even under dense canopies.

Before pushing any buttons in a terrain analysis system, the hydrologist must consider the physical basis for using topography as the main driver of hydrological flows. Topography controls water flow by directing water from high elevations to low elevations due to the force of gravity and by forcing water to converge or diverge due to the shape of the surface. However, other factors such as climate, geology, soils, and vegetation will also impart some control on the flow of water.

In general, in humid landscapes with shallow soils where the bedrock is impermeable and mimics the surface topography, topography has a strong control on water flow. In these catchments, runoff is first produced in topographically low areas around streams, wetlands and lakes, where the dominant runoff generating mechanism is saturation excess overland flow (Fig. 4.1a). The runoff generating saturated areas vary in size as a function of water input, which results in hydrological behavior that is formally described as variable source area (VSA) dynamics (Hewlett and Hibbert 1967). VSA theory has received considerable experimental support (Dunne et al. 1975) and still lies at the heart of most hydrological models (e.g., Beven and Kirkby 1979; Tague and Band 2004). While providing a good explanation of hydrological behavior in many instances, the list of "exceptions to the rule" has started to increase and many have advocated for a post-VSA hydrological theory (McDonnell et al. 2007). For example, in both subarctic and humid catchments, detailed trenching and tracer work has revealed that flow along the soil–bedrock interface can introduce drainage patterns not well predicted by surface topography (Spence and Woo 2003; Tromp-van Meerveld and McDonnell 2006) (Fig. 4.1b). Interestingly, DTA of bedrock topography has been shown to be useful in explaining the spatial pattern of subsurface flow (Freer et al. 2002). In fact, this type of bedrock driven runoff was also envisaged as part of VSA behavior (Hewlett and Nutter 1970). On the other end of the wetness spectrum, research in subhumid environments with deep surficial deposits has identified runoff to be governed by subsurface high conductivity materials and evapotranspiration by pond side vegetation (Devito et al. 2005) (Fig. 4.1c).

Given these geographic differences in runoff generating mechanisms, users of DTA must carefully decide the physical basis of using DTMs to explain hydrological behavior. Clearly, in geographies where VSA hydrology is dominant, DTA will have a strong conceptual basis. However, hydrologists working in non-VSA dominated terrain might still ask whether analysis of surface topography has some role to play in understanding hydrological behavior. The answer to this question is dependent on spatial and temporal scales. For example, at longer timescales (capturing the full climatic spectrum) and at broader spatial extents (watershed-scale), topography may still be important in predicting the steady-state location of water bodies such as streams and wet areas. Therefore, conceptualization of

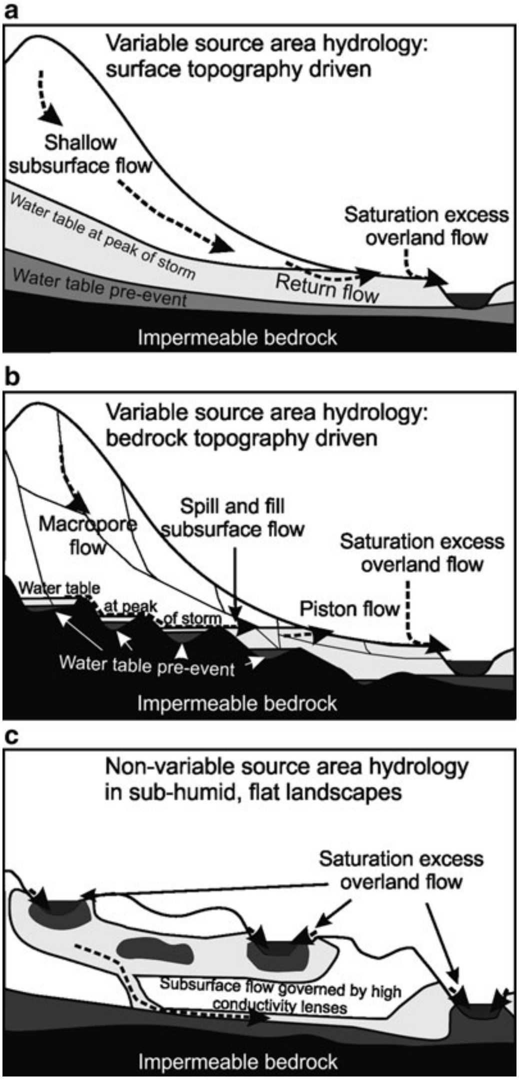

Fig. 4.1 Conceptual model of runoff generating mechanisms in three different terrains: (**a**) terrain where water-table mirrors surface topography and runoff may be described by variable source area (VSA) concepts; (**b**) terrain where runoff mechanisms are governed by macropore flow and/or spill and fill subsurface flow along bedrock–soil interface (may be described as a particular case of VSA concept); and (**c**) terrain where subsurface differences in substrate control runoff

hydrological processes must also consider the scale of analysis when considering the appropriateness of DTA for hydrological investigations.

This chapter is a synthesis of recent advances in DTA techniques and their application to track hydrological and biogeochemical pathways and processes through forested catchments. The discussion is structured to follow the logical evolution of the most relevant and widely used terrain attributes and terrain features that form the basis of analysis in the study of stream initiation, water storage (location and time), and water release (discharge), as well as land-to-atmosphere and land-to-aquatic biogeochemical linkages within different forested landscapes.

Prior to addressing how DTMs have been used in advancing hydrological research, we provide an introduction to the sources of digital elevation data and the basic DTA processing steps required to extract useful hydrological information.

4.2 Digital Terrain Analysis for Forest Hydrologists

4.2.1 Digital Elevation Models

Since DEMs are the ultimate source of all DTMs, their acquisition is the foundation of DTA. DEMs may be derived using three different remote sensing approaches: stereo photogrammetry, radar interferometry, and laser altimetry. Traditionally, stereo pairs of aerial photographs were used to derive DEMs at spatial resolutions of 15–100 m. Canada, USA, and other countries have freely available DEMs, generated using photogrammetry, covering much of their landmass (e.g., http://www.geobase.ca/). The vertical error of these DEMs is in the range of 1–5 m (Natural Resources Canada 2007), with much larger errors over vegetation since the wavelengths used to take the photographs cannot penetrate the vegetation canopy. However, remote areas and poorer jurisdictions have little to no coverage due to the costs associated with flying photogrammetry missions.

Radar interferometric techniques using satellite platforms have been able to provide global coverage of DEMs at 25–100 m spatial resolution, although there is still considerable error in vegetated and mountainous regions (vertical error of 10–20 m) (Bourgine and Baghdadi 2005). Radar interferometry uses two or more radar images to compute the differences in the phase of the waves returning to the satellite. The shuttle radar topography mission (SRTM) provided the first global dataset at sub 100 m resolution for use in DEM development (Farr et al. 2007).

Of the three DEM sources, it is laser altimetry, also known as light detection and ranging (LiDAR) sensors, that has revolutionized the collection of elevation data. LiDAR sensors collect submeter spatial resolution datasets at much higher vertical accuracy (15–30 cm) even in dense vegetation (Reutebuch et al. 2003). The only limitation to LiDAR-derived DEMs is that they are very expensive to acquire from airborne platforms. Future satellite-based LiDAR sensors are needed to allow for imaging of the entire globe at fine spatial resolutions. From the raw elevation points, three main tessellations can be chosen: square grid, triangulated irregular network, and contour-based network (Moore et al. 1991). Of these, the square grid is by far the most common type and this chapter focuses solely on DTMs of this type of tessellation.

4.2.2 Modeling Hydrological Flowpaths

Hydrological flowpaths are modeled using DEMs based on the assumption that water flows along surface or shallow subsurface pathways parallel to the surface. Prior to modeling, the digital surface must be hydrologically conditioned. The first step of hydrologically conditioning is to "burn" water bodies (streams and lakes) into the DEM to ensure higher order streams and lakes coincide with the digital hydrography derived from aerial photographs whose locations are well accepted by the hydrological community (Hutchinson 1989). It is noteworthy that first- and second-order streams are often not represented in the digital hydrography and are therefore not represented in the DEM. The next step is to ensure that water can "flow" unimpeded from each grid cell to the outlet. In every DEM, there are depressions that terminate the flow of water, usually due to data error, interpolation, and limited horizontal and vertical resolution (Martz and Garbrecht 1998). For this reason, depressions need to be removed and drainage must be enforced across all ambiguous areas including topographic flats and depressions (Martz and Garbrecht 1998). Depressions may be filled by raising the elevation of all depression grid cells or breached by lowering grid cell elevations along a breach channel (Planchon and Darboux 2001). The difference between methods may be substantial; therefore, selective use of either approach is suggested to reduce the overall impact on the DEM modification (Lindsay and Creed 2005). Not all depressions are artifacts and their identification is critical especially in the delineation of biogeochemical source areas to streams. Lindsay and Creed (2006) introduced an innovative probabilistic method of identifying true depressions on the digital landscape.

Once the DEM has been hydrologically conditioned, flow direction can be determined, which is critical for tasks such as delineation of catchment boundaries, stream networks, upslope contributing area, and anything else where flow direction needs to be modeled. Hydrological flow routing is based on the question: which way does a drop of water flow over a surface (Table 4.1)? Given the gridded discretization, there are only eight potential cells water may flow to. The easiest option is directing the flow along the steepest neighboring cells (referred to as the D8 approach) (O'Callaghan and Mark 1984), creating very distinct but often unrealistic linear flow patterns on hillslopes. Paik (2008) improved the realism of flow direction of D8 by allowing for variable neighborhood searches used to determine slopes (GD8). However, more realistic flow dispersal can only be achieved with multiple flow direction algorithms that override the limitation of D8 and GD8 by apportioning flow to more than one downhill cell either by (1) random weighting (Rho8) (Fairfield and Leymarie 1991), (2) weighting by slope gradient and slope length (FD8) (Quinn et al. 1991), (3) fitting a triangular facet (Tarboton 1997), or (4) by a combination of facet fitting and assigning weights by slope (MDinfinity) (Seibert and McGlynn 2007). Perhaps a more accurate approach of multiple flow direction routing, but also more complex and case-specific, is based on flow lines [Digital Elevation Model Networks (DEMON)] (Costa-Cabral and Burges 1994). Recent research in flow routing has advocated the use of "smart routers," where flow on hillslopes is routed using dispersive algorithms and flow focusing routing below channels heads (Lindsay 2003). Investigators comparing these common flow routing algorithms found most algorithms to be efficient in finding channels; however, choice of algorithm strongly affected flow path distributions on hillslopes (e.g., Wolock and McCabe 1995; Desmet and Govers 1996). In summary, differences in flow routing algorithms are least important for finding channels and predicting drainage divides and most important for predicting hillslope distribution of soil moisture.

Table 4.1 Evolution of hydrological flow routing algorithms

Name	Summary	Details	References
D8	Directs flow from each cell to one of the eight nearest neighbors based on slope gradient	Computationally simple, but does not allow for multiple flow directions; bias toward eight cardinal and diagonal directions produces artificial straight lines	O'Callaghan and Mark (1984)
GD8	Directs flow from cells to one of the eight nearest neighbors based on local slope gradient and corrects using higher-order neighborhood searches (up to global search)	Removes accumulated directional error associated with single flowpath algorithms, but does not allow for multiple flow directions	Paik (2008)
Rho8	Random numbers weighted by slope (i.e., flowpaths with steepest gradients have greatest probability) used to direct flow from cells	Removes bias toward eight neighboring directions; degree of randomness breaks up parallel straight flowpaths that D8 tends to produce on flat surfaces, resulting in more realistic-looking networks, but a different network can be produced with each iteration	Fairfield and Leymarie (1991)
FD8	Directs flow to downslope cells weighted by slope gradient, slope length, and directional weights	May produce artificial flow dispersion because flow goes to all downslope grid cells. Multiple flowpaths produce artificial flow dispersion and path crossing on convergent slopes	Quinn et al. (1991)
DEMON	Directs flow from cells using local aspect angle vector calculated from two-dimensional flow strips defined by convergence/ divergence	Produces more realistic flows, but may produce inconsistent results and is computationally complex and may produce inconsistent flowpaths. Computationally complex; two-dimensional planes fit to some elevation combinations leading to inconsistent flow directions	Costa-Cabral and Burges (1994)
ADRA	Directs flow according to slope gradient and prediction of cell's position relative to channel head	Simulates divergence on slopes and convergence in channels	Lindsay (2003)
D∞	Directs flow from cells following path of steepest descent calculated in planar triangular facets between centroids of neighboring cells (infinite angles)	Produces more realistic flows, but may produce unrealistic results in flat areas	Tarboton (1997)
MD∞	Directs multiple flows from cells following path of steepest descent calculated in planar triangular facets between neighboring cell centers (infinite angles) and weighted by slope gradient	Removes dispersion on planar or concave slopes; allows multiple directions on convex slopes	Seibert and McGlynn (2007)

4.2.3 Hydrologically Relevant Terrain Attributes and Terrain Features

At the heart of all DTAs is a set of terrain attributes and terrain features that are used to model hydrological pathways and associated processes. Terrain attributes, on the one hand, are derived from DEMs either by computing surface derivatives or various physical characteristics of flow lines including length, contributing area, and elevation differences. Terrain features, on the other hand, are landform features that share unique physical characteristics defined by various terrain attributes. Terrain attributes can be thought of as continuous grids, whereas terrain features are discontinuous (or discrete) objects.

Although there is a long list of terrain attributes that can be computed from DEMs (e.g., Moore et al. 1991; Wilson and Gallant 2000), only a handful are useful in hydrological or biogeochemical modeling. One of the most important of these attributes is slope, because it is used to approximate the hydraulic gradient, the variable that determines the rate at which water can move through a point (Fig. 4.2). Areas with low slope have a low propensity to transmit water laterally and therefore favor the accumulation of water and the formation of saturated and inundated zones. Upslope contributing area is as important to consider as slope because it provides an approximation of the potential runoff volume that may pass through a point. Valley-bottoms have much larger upslope contributing areas than ridges and are the reason why most saturated or inundated areas are located at the bottom of hillslopes. Combining the concept of hydraulic gradient with potential runoff volume is essential in determining the potential for water accumulation because areas of low slope on higher plateaus or flat ridgelines will not be classified as saturated due to much smaller upslope contributing areas. While slope and upslope contributing area are the two most important terrain attributes for hydrologically or biogeochemically relevant terrain analyses, measures of profile and plan curvature

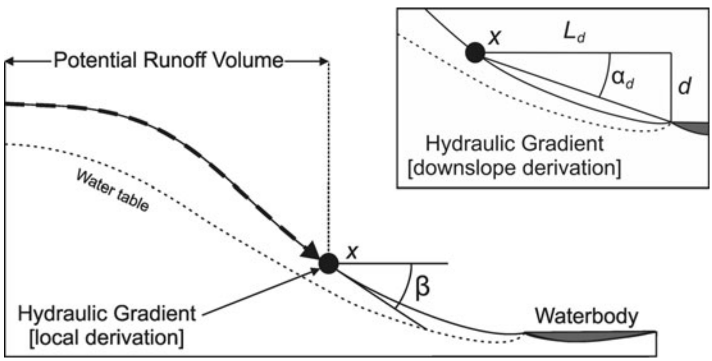

Fig. 4.2 Hydrologically important terrain attributes used in the modeling of water, nutrient, and sediment redistribution along a hillslope

as well as elevational differences between grid cell of interest and local or global elevation minima and maxima are also important for classifying terrain features. Curvature gives an indication of flow divergence or convergence, whereas elevation differences give an indication of hydraulic pressure.

Another way to model spatial variability in the relative importance of hydrological and biogeochemical processes is by classifying catchments into different terrain features, where each unique object class is assumed to behave in a similar fashion with respect to the process being modeled. Such object-oriented analysis overcomes the limitations of looking at individual terrain attributes and instead factors in additional spatial, textural, and contextual information from multiple terrain attributes. Perhaps, the simplest way of classifying landscapes is by differentiating between hillslopes and riparian areas, which has been found to be useful in explaining hillslope coupling to streams (McGlynn and Seibert 2003). More elaborate landscape classification approaches are based on the concept of the catena (Conacher and Dalrymple 1977). These approaches identify terrain features from the top of hillslopes to the bottom, including crest, shoulder, backslope, footslope, toeslope and valley-bottoms, each corresponding to zones of different hydrological, pedological, and biogeochemical processes (Fig. 4.3). From a longitudinal perspective, it is common (and important from a forest management perspective) to differentiate between colluvial and fluvial channel segments, especially in mountainous regions of western North America (Montgomery and Buffington 1997).

The challenge of landscape classification is to find the combinations of terrain attributes that can differentiate between the required terrain features (e.g., riparian zone vs. hillslopes). This is not a trivial process. The most fruitful approaches have involved the application of fuzzy boundaries given the inexact definition of the transition zones (MacMillan et al. 2000). The terrain attributes and heuristic

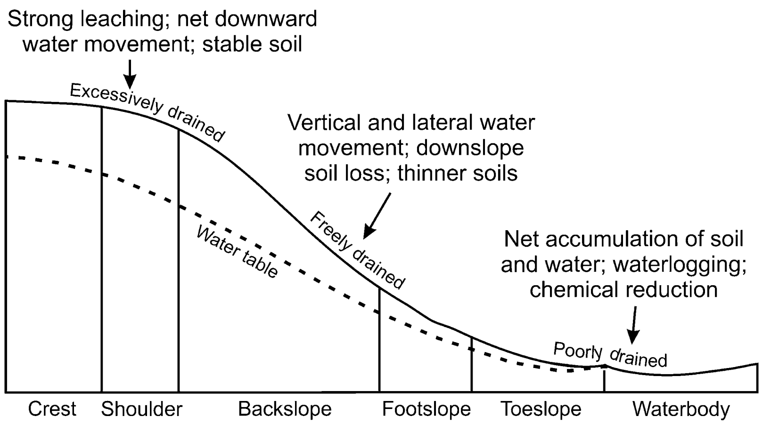

Fig. 4.3 Hydrologically important terrain features used in the modeling of water, nutrient (dissolved and gaseous), and sediment redistribution along a hillslope

classification rules have to be determined for each landscape and often need expert guidance. An alternative classification system fits a mathematical function to the cumulative distribution function of a modified upslope contributing area index (Roberts et al. 1997). It uses derivatives of this function to find breakpoints that are used to create four categories: the combination of ridge tops and upper slopes, midslopes, lower slopes, and in-filled valley/alluvial deposits (Summerell et al. 2005). This approach has successfully delineated major landforms across six catchments with different geologies in Australia but needs to be evaluated on other forested landscapes.

Successful applications of terrain attributes or terrain features in the analysis of hydrological or biogeochemical processes are predicated on the careful consideration of process conceptualization in the selection of proper DTA tools.

4.2.4 Scale Issues

Another important consideration when selecting the most appropriate DTA tools for the process being modeled is scale. One of the central features of DTA is that it is scale dependent (Band and Moore 1995). Although there are different components of scale, such as extent, support and spacing (Blöschl and Sivapalan 1995), the main concern for DTA has been the effect of support or spatial resolution on hydrological modeling. Numerous studies have investigated the effects of DEM spatial resolution on the derivation of terrain attributes and hydrological objects such as stream networks (McMaster 2002; Deng et al. 2007; Sorensen and Seibert 2007). These studies have found that most terrain attributes and features are very sensitive to the spatial resolution at which they are derived (Zhang and Montgomery 1994), and therefore, the hydrological features modeled must be properly matched to the spatial resolution of the DTM.

Beven (1997) suggests that to avoid significant error, terrain attributes should be derived at spatial resolutions well below the average slope lengths of a landscape. However, the reverse is also true where the spatial resolution is too fine to model the hydrological process properly. For instance, due to submeter spatial resolution, laser altimetry derived DEMs may contain too much detail to have hydrological usefulness. This fine spatial resolution may negatively affect the derivation of terrain attributes or require too much computational power because of the large DEM size (Creed et al. 2003). While the optimal grid size needs to be determined for each hydrological process (Zhang and Montgomery 1994), a general rule of thumb is that hillslope-scale features should be modeled with DEM resolutions of 1–5 m, whereas catchment-scale features can be modeled at 5–10 m resolution (e.g., Thompson and Moore 1996).

In the following sections, the potential of some traditional but mostly novel approaches to identify hydrological (Sect. 4.3) and biogeochemical (Sect. 4.4) pathways and associated processes in forested landscapes described in Table 4.2 are illustrated.

Table 4.2 Digital terrain indices used to infer different hydrological and biogeochemical patterns and processes in forested landscapes

Hydrological index	Calculation	Description	References
Drainage network			
Stream initiation	$A_s > C$; where A_s is specific contributing area, and C represents a critical threshold to define the stream channel	Delineates stream network by assuming upslope area controls channelized flow	O'Callaghan and Mark (1984)
Stream initiation	$A_s \tan \beta^{\alpha} > C$; where A_s is specific contributing area, $\tan \beta$ is local slope, α is modifier representing geological differences, and C represents a critical threshold to define the stream channel	Delineates stream network by assuming upslope area is modified by local slope controls channelized flow	Montgomery and Dietrich (1992)
Wet areas			
Local slope index	$\tan \beta < C$; where $\tan \beta$ is computed using finite differences in four cardinal directions, and C represents a critical threshold to define a wet area	Describes wet areas by assuming water accumulation in flat areas is due to local topography	Creed et al. (2003)
Topographic wetness index (TWI)	$\ln(A_s/\tan \beta) > C$; where A_s is specific contributing area, $\tan \beta$ is local slope, and C represents a critical threshold to define a wet area ($\tan \beta$ may be replaced by $\tan \alpha_d$ to consider downslope gradient)	Describes wet areas by assuming water accumulation in float areas is due to upslope and local topography	Beven and Kirkby (1979)
Downslope distance or downslope gradient index	$L_d > C$; where L_d is the downslope distance index defined as the horizontal distance to the point with an elevation d meters below the elevation of the starting cell following the steepest-direction flowpath, and C represents a critical threshold to define a wet area. A modification of this index is $\tan \alpha_d = d/L_d$, where $\tan \alpha_d$ is the downslope gradient index. The d is catchment dependent and needs to be defined for each new locale	Describes wet areas by assuming water accumulation in flat areas is due to upslope, local and downslope topography	Hjerdt et al. (2004)
Hydrogeomorphic terrain feature detection and classification	Terrain features delineated from an edge-enhanced downslope gradient index ($\ln(\tan \alpha_d)$) map	Describes wet areas by hydro-geomorphic features using object-based classification	Richardson et al. (2009)

(continued)

Table 4.2 (continued)

Hydrological index	Calculation	Description	References
Depth-to-water table index	Depth-to-water table is computed in an iterative fashion: (1) cumulate slope values along each flowpath, (2) select least cumulative slope path from source cell to surface water cell, (3) assign cumulated slope value of surface water cell to source cell, (4) take difference of local slope and cumulated slope, and (5) threshold the depth-to-water table index	Describes wet areas by factoring in both the distance from a surface water source and the slope of the land surface between the cell of interest and the surface water source cell	Murphy et al. (2007)
Probability of depression index	$p_{\mathrm{dep}} < C$; where p_{dep} is probability of a cell belonging to a topographic flat or depression and C represents critical thresholds to define a wet area. The probability layer is computed Monte Carlo style: (1) add random error term to DEM, (2) extract flats and depressions, and (3) average across all binary realizations	Describes wet areas by assuming all flats and depressions identified by algorithm are areas of water accumulation	Creed et al. (2008)
Hydrological flushing potential			
Variable source area (VSA)	Recursive accumulation of catchment area with normalized TWI (TWI_n) < max catchment TWI_n at stream	Describes hydrologically responsive part of catchments	Creed and Beall (2009)
Effective VSA (*eff*VSA)	Upper quartile of frequency distribution of TWI_n within VSA	Describes hydrological flushing areas, where water table rises to soil surface	Creed and Beall (2009)
Rate of change in flow gradient of VSA	Second derivative of a polynomial equation derived from the frequency distribution of TWI_n within *eff*VSA	Describes potential rate of expansion or contraction of hydrological flushing areas	Creed and Beall (2009)
Hydrologic filtering potential			
Riparian area	Ratio of riparian area to upslope contributing area	Describes riparian buffering capacity of catchments	McGlynn and Seibert (2003)
Riparian curvature	Profile curvature of cells surrounding stream or lake	Describes riparian buffering capacity (via surface vs. subsurface flowpaths) of catchments	Devito et al. (2000)

(continued)

Table 4.2 (continued)

Hydrological index	Calculation	Description	References
Hydrological connectivity of wet areas to drainage network			
Wet areas connected to surface drainage network or shoreline	Connectivity is defined by the % wet area within upslope contributing area connected to surface waters	Describes hydrological connectivity of wet areas to surface water	Devito et al. (2000) and Sass et al. (2008)
Network index	Connectivity is defined by an analysis of TWI along flowpaths; wet areas contribute to stream discharge only when TWI indicates continuous wetness through the length of a flowpath to the point where the path becomes a stream	Describes hydrological connectivity within drainage network	Lane et al. (2004)
Hydrological residence time			
Median subcatchment area	Median of the subcatchment areas of all stream cells upstream the catchment outlet	Describes catchment-scale differences in drainage structure and residence time	McGlynn et al. (2003)
L/*G* index	*L*/*G*; where *L* is flowpath distance and *G* is flowpath gradient	Describes catchment-scale mean water residence time	McGuire et al. (2005)
Compound indices for geographies where topography is not the only dominant control on water flow			
Combined soil-TWI	$\ln(A_s/T \tan \beta)$; where T is lateral transmissivity at saturation of surface soils in the catchment	Modifies TWI by including soil transmissivity as a function of runoff generation (requires knowledge of pattern of hydraulic conductivity and soil depth)	Beven (1986)
Combined climate-soil-TWI	Modifies the size of each cell in the TWI calculation as a function of mean annual water balance relative to catchment average	Modifies TWI to capture the effect of climatic forcing	Güntner et al. (2004)
Hydrogeological index	Index is computed as a function of three factors (Strahler stream order, relative elevation of lake to surrounding landscape, and position of lake within local to regional groundwater flow system), which are combined into an empirical model with weighting of factors calibrated with an independent measure of hydrogeological setting	Describes potential groundwater-lake interactions as recharge vs. discharge areas	Devito et al. (2000)

4.3 Tracking Hydrological Pathways Using Digital Terrain Analysis

4.3.1 Where Do Streams Begin?

Streams begin in the generally uncharted headwaters either within cryptic rivulets and/or wetlands (Creed et al. 2003; Bishop et al. 2008). These hidden source areas of water are not captured on traditional topographic maps; therefore, novel approaches have been sought for their mapping. DTA, especially based on LiDAR-derived DEMs, has significantly improved our ability to map headwater streams in forested environments (Remmel et al. 2008). The difficulty in determining the exact position of stream heads from topographic data alone is that there are additional climatic and geological factors that play a role in stream initiation. Stream networks may be mapped in one of the two ways: (1) analyzing surface morphology and looking for specific patterns such as "v" shapes (Peucker and Douglas 1975), or (2) calculating upslope contributing areas and delineating stream cells based on critical thresholds (O'Callaghan and Mark 1984). Practitioners favor the flow-based method because the morphology-based approaches do not result in a continuous network, something that is critical for topological analysis (Lindsay 2006). The simplest flow-based method classifies stream cells based on specific contributing area alone (O'Callaghan and Mark 1984). The pioneering work of Montgomery and Dietrich (1992) determined that the product of specific catchment area and the square of the local slope can be used to predict the initiation of channelized flow, although with considerable uncertainty (Table 4.2). However, channel initiation thresholds need to be validated in each new locale.

Although the choice for stream initiation thresholds is variable between catchments, the choice of flow routing algorithm is not as critical for stream network delineation because upslope contributing areas derived by different flow algorithms start identifying very similar stream networks in valley bottoms. In fact, single flow algorithms are usually preferred because they identify areas of convergence well, although they may still tend to generate parallel channels in valley bottoms (McGlynn and Seibert 2003). Once the stream network has been extracted, it may serve as the foundation for segmenting the catchment into hillslopes based on stream reaches, defining riparian areas, or extracting physical characteristics of the stream network such as stream order and drainage density. A critical component in many forested landscapes is the presence of wetlands and lakes; however, the incorporation of these open water features is not yet a commonplace feature of most DTA software.

4.3.2 Where is Water Stored?

Water in catchments is held in both surface and subsurface storages. Although subsurface storage of water can be substantially greater than surface storage, surface water storage is particularly important in terms of hydrological response (rapid water delivery to stream or lake) as well as biogeochemical behavior (e.g., export of nutrients). DTA is particularly well suited to estimate the location and amount of surface water storage. Surface water is stored in depressions or flat areas that inhibit the downhill movement of water. These wet areas may be ephemeral (e.g., small depressions collecting water) or permanent (e.g., bottomland swamps). Wet areas not only store water and therefore retard runoff (if the depression is not at capacity) or enhance runoff (if at capacity), but they may also form critical spots for biogeochemical activity (Agnew et al. 2006).

In many landscapes, topography influences the development of saturated and inundated areas through its effect on the hydraulic gradient. The last three decades have seen many different DTA techniques developed in order to automate the derivation of wet areas (Fig. 4.4). Slope has been a very effective terrain attribute to delineate wet areas (Creed et al. 2003). The shortcoming of using slope

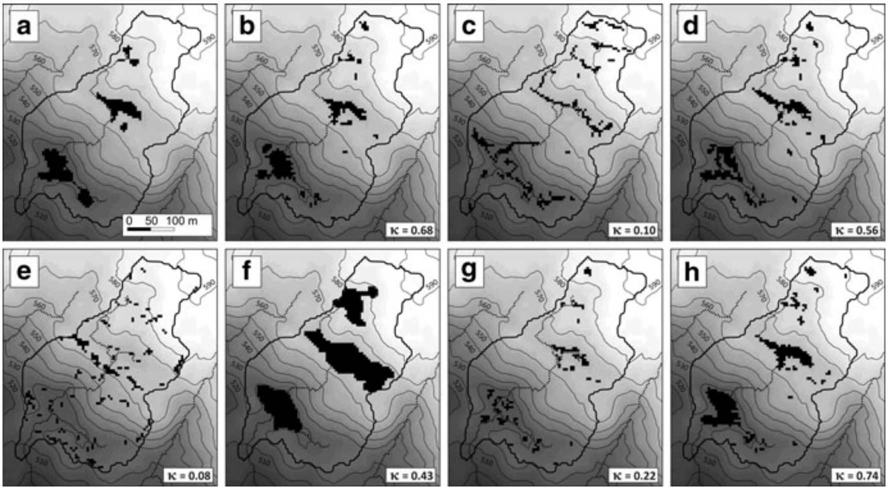

Fig. 4.4 Comparison of digital terrain analysis (DTA) techniques for wet area mapping. Base map is a 5 m LiDAR-derived DEM of catchment (c50) in the Turkey Lakes Watershed in Ontario, Canada. Wet areas were defined by (**a**) ground surveys using a differential global position system to collect geographic coordinates of the boundaries of wet areas; (**b**) local slope, β, $\leq$ critical threshold of 2.7° (Creed et al. 2003); (**c**) topographic wetness index, $\ln(A_s/\tan\beta)$, $\geq$ critical threshold of 6.9 (Beven and Kirkby 1979); (**d**) downslope gradient index, $\tan\alpha = d/L_d$, with $d = 2$ m and $\alpha \leq$ critical threshold of 1.7° (Hjerdt et al. 2004); (**e**) TWI modified by use of downslope gradient instead of local gradient, $\ln(A_s/\tan\alpha)$, $\leq$ critical threshold of 2.9 (Hjerdt et al. 2004); (**f**) objects classified using downslope gradient index and L/G (Richardson et al. 2009); (**g**) depth-to-water index, where index $\leq$ critical threshold of 1 m (Murphy et al. 2007); and (**h**) probability of depression index, where index $\leq$ critical threshold of 0.3 (Creed et al. 2008). Critical thresholds selected to optimize area to ground-surveyed wet areas. For each map, κ is kappa coefficient showing level of agreement in terms of location and area between DTA-derived map and ground-surveyed map, where 0 is agreement due entirely to chance and 1 is 100% agreement

alone to map wet areas is that there may be low slope areas close to ridgelines (e.g., plateaus) with no water storage observed. The solution to this problem was introduced by the seminal work of Beven and Kirkby (1979), who integrated the concept of runoff volume (using upslope contributing area as a proxy) with hydraulic gradient into a compound index. This topographic wetness index (TWI) has been successfully used around the world to delineate wet areas (Quinn et al. 1995; Güntner et al. 2004), albeit only in humid conditions when surface topography is a reasonable replica of the water table (Western et al. 2001).

One of the limitations of the TWI is that it only takes into account the upslope properties of the hillslope. To incorporate the influence of downslope effects on drainage, Hjerdt et al. (2004) introduced the downslope index, which considers the horizontal distance water would have to travel along a flowpath to drop a given vertical distance (Fig. 4.2). This index is very versatile and has been used in three main ways in identifying wet areas: (1) as a downslope hydraulic gradient; (2) as a new TWI to replace TWI and (3) as a replacement of the local slope term in a modified TWI (Güntner et al. 2004; Hjerdt et al. 2004; Inamder and Mitchell 2006; Sorensen et al. 2006). In terms of approximating the water table gradient, the downslope index greatly improves approximations based on local slope, because local slope is highly sensitive to DEM resolution.

The past decade has seen a number of novel approaches introduced in mapping wet areas that go beyond the traditional approach of identifying a threshold in a terrain attribute (Table 4.2; Fig. 4.1). A recent study used object-based classification to define hydrologically meaningful terrain features using the spatial distribution of downslope gradient as an input (Richardson et al. 2009). The depth-to-water index uses least cost analysis based on a cumulative slope layer from the point of interest to a source cell (stream, lake, or depression) (Murphy et al. 2007). It has been validated in humid catchments on the east coast of Canada and used in forest operations planning (Murphy et al. 2007). Lindsay et al. (2004) identified wet areas based on a probabilistic scheme using Monte Carlo simulation, where a random error term, based on the vertical accuracy of the DEM, was added to the DEM and depressions flagged after each of 1,000 iterations. A layer depicting probability of belonging to a depression was calculated by averaging the individual depression maps, and grid cells above a certain depression probability threshold were identified as a true depression with the potential to saturate or inundate. This method has been very accurate in identifying even cryptic wetlands below dense canopies in forests across eastern Canada (Creed et al. 2003).

It needs to be noted that the source of the input data is critical for each of these techniques. Although there has been some success in DTA modeling of wet areas below canopies using generally available DEMs from provincial or state government agencies (Creed et al. 2008), the best success comes if the DEM is derived from a source that penetrates the canopy (Creed and Beall 2009). Currently, only laser altimetry-based DEMs provide information from below the canopy, emphasizing the need to provide global coverage using this technology.

4.3.3 How Are Water Source Areas Connected to Surface Waters?

Hydrological response to rainfall at the outlet of catchments is highly dependent on the ability of water source areas to connect to surface waters such as streams and lakes. The basic premise is that saturated areas are prone to the generation of lateral flow leading to quick runoff at the catchment outlet only if they are connected to the stream network of the catchment. Although substantial foundational work on hydrological connectivity has been done, the incorporation of the concept of connectivity into a coherent hydrological framework is only now being undertaken (Bracken and Croke 2007).

A simple measure of connectivity that has been applied in a broad range of forested landscapes is the percent cover of all wet areas that are contiguous and connected to the stream network (e.g., Devito et al. 2000; Creed et al. 2003; Creed and Beall 2009). Another measure of connectivity is based on TWI values along a flowpath; if all upslope cell values are above a given TWI threshold, then all upslope cells are assumed to contribute to stream flow. Using this approach, a large proportion of saturated sources areas were found to be disconnected from the streams, which otherwise would have been assumed to be connected and contribute to stream flow (Lane et al. 2004).

Jencso et al. (2009) strengthened the case for the need to consider both topography and topology (the spatial relationship between terrain attributes) as first-order controls on stream flow response in steep and humid catchments. They found that upslope contributing area explained 91% of the variability in the longevity of the water table connection among hillslope, riparian zone, and stream sequences. The analysis of hydrological connectivity has greatly benefited from ideas infused by geostatistics (Western et al. 2001) and percolation theory (Lehmann et al. 2007). Although much ground-breaking work has been done in exploring hydrological connectivity with DTA, fully integrating this concept into the analysis of catchment hydrology has been slow. As a result, there is great potential for new discoveries and understanding, especially related to the nonlinear behavior of stream flow response.

4.3.4 How Long is Water Stored?

Knowing the length of time a water droplet resides in a catchment is important because the longer a water droplet is in contact with the substrate of a catchment, the greater chance it has to undergo and facilitate biogeochemical reactions (Burns et al. 2003). The residence time of all of the droplets is a fundamental catchment descriptor called the mean residence time (MRT), which can reveal important information on storage, flowpaths, and sources of water (McGuire and McDonnell 2006). MRT can be modeled using a residence time model with stable isotopes of oxygen and hydrogen as inputs (McGuire et al. 2005). However, given the usefulness of this catchment-wide descriptor, recent studies have focused on investigating the relationship between MRT and catchment characteristics, in order to facilitate automated computation for ungauged catchments.

Contrary to the expectation that catchment size would explain variation in MRT among catchments, MRT was instead correlated to catchment terrain attributes such as median subcatchment area (McGlynn et al. 2003) as well as median flowpath distance and flowpath gradient to the stream network in humid catchments (McGuire et al. 2005). MRT was negatively related to flowpath gradient (shorter MRT with steeper flowpath gradient) and positively related to median flowpath length and median subcatchment areas (longer MRT with longer flowpath length), reflecting the expected relation between hydraulic gradients and water flow. It is interesting to note that although hillslope-scale runoff production in these humid catchments is influenced by subsurface macropore and bedrock flowpaths, surface topographic properties explain the majority of the variation in MRT, which is strongly influenced by the substrate. Perhaps, this provides evidence for the fact that topography is a reflection of climatic forcing on geological substrates. The ratio of flowpath length to flowpath gradient was a weaker predictor in Scottish catchments but still able to explain 44% of the variation in MRT (Tetzlaff et al. 2009).

4.3.5 How Does Topography Influence Flow Response at the Catchment Outlet?

DTA's strength has been at explaining inter-catchment variability in discharge. In general, DTA provides metrics on capturing spatial differences in storage of water and the efficiency of water transfer through a catchment (Table 4.2). Although more traditional attributes such as catchment area, slope, and drainage density are still useful today, especially in studies where only coarser resolution DEMs are available (Garcia-Martinó et al. 1996), newer techniques in combination with newer DEM sources provide the next generation of tools.

For example, the importance of delineating cryptic wetlands under a forest canopy in order to understand stream response was highlighted by Lindsay et al. (2004), who were able to predict both runoff timing and runoff magnitude using wetland metrics from a LiDAR-derived DEM. The performance of the different wetland metrics (e.g., total area of bottomland wetlands, depression volume of wetlands) depended on hydroclimatic conditions. During dry and mesic conditions, wetland metrics explained a higher proportion of the variation of runoff *timing*, whereas during wet conditions, wetland metrics explained a higher proportion of variation of runoff *magnitude* (Lindsay et al. 2004). Along similar lines, Laudon et al. (2007) were able to explain a significant proportion of the variation in event and pre-event partitioning using median subcatchment area, which is another measure of stream network organization. Interestingly, median subcatchment area was useful to predict the pre-event/event ratio at peak flood and on the hydrograph's falling limb, but on the rising limb percent wetland area was the significant factor (Laudon et al. 2007). There is also evidence that the effectiveness of terrain attributes to explain hydrological response depends not only on hydroclimatic conditions but also on catchment size. Sanford et al. (2007) reported on the existence of a catchment area threshold for low flow conditions, where low flow hydrograph metrics were successfully predicted by the proportion of near stream riparian area within catchments less than 600 ha in size. These examples point to the ability of DTA to capture hydrological source areas, storages, and connectivity with the ability to predict flow response related to catchment size and hydroclimatic conditions.

4.3.6 Digital Terrain Analysis Beyond Topography

Clearly, topography is not a first-order control in every catchment. Consequently, the future of DTA lies in its ability to fuse data and approaches that incorporate other dominant controls on hydrological processes including climate, geology, and soils (Table 4.2). For example, Güntner et al. (2004) proposed factoring in climate patterns in the TWI. Studying catchment-scale differences in hydrological and biogeochemical response, Devito et al. (2000) proposed a hydrogeologic index that incorporated the concepts of stream ordering, relative relief, and recharge vs. discharge nature of lakes, all estimated by proxies derived from topography. In another study, Baker et al. (2003) developed a DTA technique that approximated the regional hydraulic gradient and integrated this information with hydraulic conductivity estimated from surficial geologic maps. Beven (1986) introduced soil transmissivity in the calculation of TWI to account for changes in soil hydraulic conductivity within catchments. In landscapes where depressions on the bedrock surface control fill-and-spill flow (Spence and Woo 2003; Tromp-van Meerveld and McDonnell 2006), it is not so much the DTA techniques that need to be modified but that a DEM is needed of the bedrock surface (Freer et al. 2002; Lehmann et al. 2007). Unfortunately, wide-scale application of these integrative approaches is hindered by the lack of bedrock DEMs as well as other spatially distributed information on climate, geology, and soils.

4.4 Tracking Biogeochemical Pathways Using Digital Terrain Analysis

Hydrology influences biogeochemical cycling through its control on the conditions of chemical reactions (e.g., temperature, moisture, dissolved oxygen) and by facilitating the transport of key reactants. Because water and reactants are not uniformly distributed across landscapes, the rate of biogeochemical activity is also very heterogeneous. Disproportionately high reaction rates are observed in hot spots that occur, where hydrological flowpaths converge with substrates or other flowpaths containing complementary or missing reactants creating the ideal environmental conditions for biogeochemical processing. Similarly, high reaction rates are observed during hot moments that occur when episodic hydrological flowpaths activate processes and/or mobilize accumulated reactants (McClain et al. 2003). In general, biogeochemical hot spots and hot moments often occur at hydrological transition zones (between terrestrial and aquatic interfaces) along ephemeral and permanent streams, wetlands and lakes (Yarrow and Marin 2007). Below we explore how DTA can be used to identify hydrological controls on the formation of biogeochemical pools and then explore how and where the transfer of water and nutrients creates biogeochemical hot spots and hot moments with respect to land–atmosphere and land–water linkages in forested landscapes.

4.4.1 Soil Biogeochemical Pools

The pioneering work of Geoffrey Milne identified topography as the master variable with which to determine soil properties along a hillslope. Milne (1935) used the concept of the *catena* (Latin for chain) as the fundamental soil-topography land unit that repeats sequentially across the landscape, therefore allowing the systematic mapping of soils across landscapes (Milne 1935).

Catenas form due to the interplay of static and dynamic factors resulting in soils of different properties. Static factors are controlled by terrain attributes such as slope, aspect, and elevation that influence the moisture, temperature, and solar radiation at a site. Dynamic factors are controlled by the relative position of the site within the catena, which influences the transport of particulate and dissolved materials downslope (Young 1972, 1976). Soils formed in a single material (geology) differ because of hydrological processes that result in differential drainage, leaching, translocation, and redeposition of soluble materials (Hall and Olson 1991). Therefore, in general we can expect drier, nutrient-poor conditions at the top and moister, nutrient-rich conditions at the bottom of a slope (Fig. 4.3). The essence of DTA is to take advantage of this predictable heterogeneity of physical and chemical properties of soils, including the precursors (reactants) and products of the transformation of biologically important nutrients, and use it to model biogeochemical activity over entire catchments.

Previous studies that report topographic controls on distribution of soil nutrient pools span over 50 years and cover forested landscapes ranging from gentle to steep relief in forests across major biomes (cf., Creed et al. 2008). The degree of heterogeneity that exists within soils places limits on the ability to predict the distribution of soil nutrient pools. We compared DTA approaches to general purpose soil surveys, where <10% of the heterogeneity in nutrients can be explained (Webster 1977), hence predictions >10% would be an improvement. Creed et al. (2002) found that slope, aspect, and elevation explained 38% of the variation in carbon and nitrogen in the forest floor but none of the variation within the soil profile. Soil sampling schemes based on random or equal spacing such as those used by Creed et al. (2002) capture the most common topographic features on a landscape but underestimate the rare features. Rare features, although occupying a small proportion of the landscape, may be hot spots with disproportionately higher rates of biogeochemical cycling than other areas.

To detect these small but potentially important features, Webster et al. (2011) combined expert knowledge and a probabilistic classification approach to design a topographic template *sensu* Conacher and Dalrymple (1977) (Fig. 4.3) for the same sugar maple forest studied by Creed et al. (2002). While the carbon in canopy foliage was homogeneous, there was significant heterogeneity in soil carbon pools among the terrain objects, reflecting the importance of topographic templates for detecting, sampling, and mapping carbon pools on the landscape.

It is likely that topographic templates would be applicable to most low-order catchments with minor adjustments, however, estimating topographic controls on the distribution of soil nutrients at larger scales requires nested sampling (and modeling) strategies that incorporate the multiple scales of factors that influence soil development. For example, dominant topographic factors at the hillslope or catchment scale are those that affect dynamic factors of soil development. These include drainage conditions, transport and deposition of suspended materials and/or leaching, translocation and redeposition of soluble materials (modeled by wetness index, planar and profile curvature). However, at a regional scale, the dominant topographic factors are those that affect the static factors of soil development. These are topographic factors, modeled by slope, aspect, and elevation that influence external inputs such as solar radiation, temperature, moisture, and nutrient loadings. Scalable methods that consider heterogeneity and uncertainty in carbon pools will become increasingly important as national and international policies for reporting changes in carbon pools that accompany changes in land cover and land-use are implemented.

4.4.2 Land–Atmosphere Biogeochemical Linkages

Forest soils are significant terrestrial reservoirs of carbon and nitrogen and have a crucial role in the global budgets of the main greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). As countries implement strategies to reduce GHG emissions, detailed information to inform policy making and guide mitigation measures is required on the fluxes of all GHGs from forested areas as well as the accompanying tools that can be used to predict GHG fluxes across landscapes and under different climates (Watson et al. 2000). Many forests are found in complex landscapes with intricate assemblages of substrates and environmental controls of GHG fluxes. Predominant among the controllers of GHG fluxes are those related to hydrology (e.g., the spatial and temporal distribution of soil properties, soil environment, and movement of the substrates for GHG production). We need to develop methods for accurate accounting of GHG fluxes in forests with complex terrain.

The use of DTA to understand land–atmosphere interactions in forests has revealed that topography is an important control on soil CO_2 efflux in both relatively arid and humid forests. In *softwood* forests, such as lodgepole pine in semiarid subalpine ecosystems, upslope contributing area (a proxy for lateral redistribution of water) was positively correlated with seasonal soil CO_2 efflux, where the highest soil CO_2 efflux rates were observed in areas with persistently high soil moisture in riparian lowlands (Riveros-Iregui and McGlynn 2009). In *hardwood forests*, such as sugar maple in humid ecosystems, Webster et al. (2008a) used topographic features to estimate soil CO_2 efflux (Fig. 4.3). The study revealed that transiently wet areas adjacent to wetlands (i.e., footslopes and toeslopes) yield significantly larger CO_2 efflux than the adjacent upland or wetland portions of the catchment. The follow-up study by Webster et al. (2008b) explored sensitivity of catchment-aggregated soil CO_2 efflux to different spatial partitioning schemes and found a minimum of three features (upland, critical transition zone, and wetland) was needed for accurate catchment-averaged estimates, especially under climate scenarios that became warmer and drier. Even in forests with heterogeneous cover, where species composition and site history impart important controls on soil processes, spatial variation of soil CO_2 efflux was attributed to topographically induced hydrological patterns on soil properties, root production, and soil CO_2 efflux (Martin et al. 2009).

These results underscore the importance of considering the relationships between topography and land–atmosphere GHG exchanges. We clearly need much more work especially in understanding efflux of trace gases, such as CH_4 and N_2O, which have much higher global warming potential than CO_2. Furthermore, static DTAs will need to be combined with dynamic approaches such as remote sensing and distributed simulation modeling to capture the roaming nature of hot spots and hot moments across the landscape.

4.4.3 Land–Water Biogeochemical Linkages

Forest soils are also sources of nutrients to surface waters, with important downstream water quality implications for different biota including human uses. DTA can be used to track the movement of nutrients from terrestrial source areas to streams and lakes in both fluvial and lacustrine forested landscapes. Given the interrelated nature of water and nutrient movement, most of the approaches to tracking water pathways noted earlier (Sect. 4.3) are also applicable to tracking nutrients (Table 4.2).

In *VSA-controlled landscapes* (Fig. 4.1a), as the groundwater table rises toward the surface after a drier period and intersects surface soils that have accumulated nutrients in the intervening dry period, nutrients are mobilized and flushed to receiving waters resulting in the export of carbon (Hornberger et al. 1994); nitrogen (Creed et al. 1996), or phosphorus (Evans et al. 2000). Topography influences the hydrological flushing of nutrients in various ways. It affects (a) the generation of nutrient supply (e.g., nutrient-poor areas develop if soil conditions are too dry or too wet);

(b) potential expansion vs. contraction rates of the VSAs (e.g., catchments with a greater potential for lateral expansion of source areas will have longer flushing times and higher rates of nutrients export, while catchments with less potential for lateral expansion of source areas will have shorter flushing times and lower rates of nutrient export); and (c) the transport of flushable nutrients to surface waters, which is a function of both the size and spatial organization of the VSA (e.g., catchments with larger, hydrologically connected VSAs will have larger nutrient export, whereas catchments with smaller or hydrologically disconnected VSAs will have lower nutrient export or more leaching to groundwater).

To date, most studies have assumed that the simple metric of proportion of near-saturated and saturated area within a catchment provides a good assessment of the magnitude of its VSA. This simple approach has been very successful in predicting the export of nutrients, including dissolved organic carbon (Creed et al. 2003; Richardson et al. 2009), dissolved organic nitrogen (Creed and Beall 2009), and total dissolved phosphorus (Creed unpublished data) to streams, explaining up to 90% of the variation in nutrient export. A true test of the strength of this empirical modeling approach is that using DTA on generally available data provided from government agencies across a large geographic area covering diverse climates, forest types, and forest soils explained almost 70% of the variation in DOC export (Creed et al. 2008). Not only is wetland cover highly correlated with nutrient exports to streams, but it is also highly correlated with the nutrient status of lakes (D'Arcy and Carignan 1997; Gergel et al. 1999; O'Connor et al. 2009; Winn et al. 2009). A key finding of many of these studies is that the source of the DEM used to delineate wetlands is very important and consideration of both open canopy and closed canopy wetlands is critical in estimating nutrient export from forested catchments (Creed et al. 2003).

The proportion of wetlands within a catchment has been an effective way to characterize the size of the VSA in relatively humid catchments with shallow soils, where topography is a good approximation for the water table. However, even in VSA-type landscapes (Fig. 4.1a), it is worth investigating whether all of the wetlands are contributing to runoff and whether the potential dynamics (expansion and contraction) of wetlands may be captured by DTA techniques. These were the objectives of Creed and Beall (2009), who used DTA techniques to derive indices of hydrological flushing potential and tested them against stream nutrient export.

Creed and Beall (2009) found that catchments with small nitrate-N export (but considerable DON export) were characterized by catchments with small contiguous source areas connected to the stream (*effective* VSA [*eff*VSA]) that had a small potential for expansion as the catchment wets up and/or a large proportion of wetlands. In contrast, catchments with large nitrate-N export were characterized by large source areas, with greater potential for expansion as the catchment wets up and/or few-to-no wetlands (Table 4.2). These indices explained 85% of the variance in nitrate-N export from topographically varying catchments in a sugar maple forest, which improved the traditional "wetland proportion" index by 18% (Creed and Beall 2009). These results demonstrate that hydrological connectivity is important to assess even in humid catchments. They also show that DTA techniques

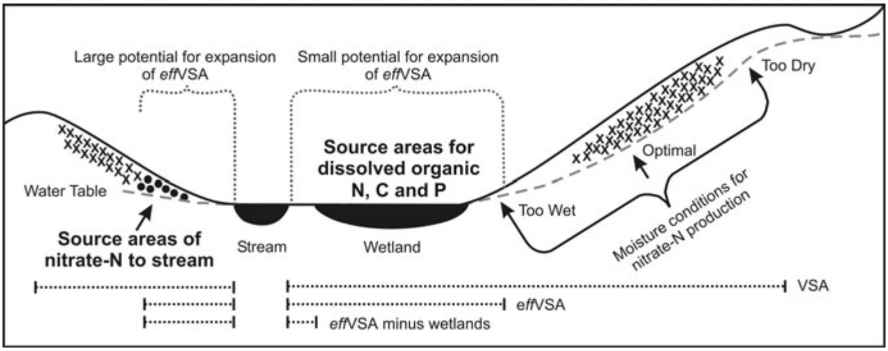

Fig. 4.5 Conceptual model of water and nutrient source areas in VSA-dominated landscapes (adapted from Creed and Beall 2009)

may capture the dynamic concept of hydrological flushing by estimating the potential for expansion of the VSA (Fig. 4.5).

Future work needs to focus on the effectiveness of these topographic indicators in scaling nutrient export from first- to higher-order catchments within a specific forest type and across forested regions with different forest types, forest disturbance histories, and environmental conditions. As VSAs expand and contract with changing climatic conditions, it is also important to consider the changes in magnitude and ratio of C:N:P as it may have consequences for the productivity of downstream aquatic ecosystems.

In *non-VSA-dominated landscapes* (Fig. 4.1c), DTA techniques using surface topography will not suffice in predicting hydrological or biogeochemical pathways. In subhumid catchments, where the characteristics of the deep substrate regulate water and nutrient transfer from land to aquatic systems, terrain indices that capture the spatial pattern of subsurface pathways are needed. A great example of this is a hydrogeological index (Table 4.2) developed using DTA techniques in order to predict total phosphorus (TP) concentration for lakes on the Boreal Plain in Alberta (Devito et al. 2000). The hydrogeology index captured the degree of interaction of lakes with regional, intermediate, and/or local groundwater flow systems by characterizing (a) lake order; (b) elevation of the lake relative to the surrounding landscape; and (c) position of the lake within the local to regional groundwater flow system. Lake order was determined using the ordering method of Mark and Goodchild (1982). The relative elevation of a lake was defined as the ratio of the change in elevation from the lake's surface to the regional low to the change in elevation from the relational low to the regional high. The position of the lake within the potential groundwater flow system was based on a steady-state groundwater model, which predicted whether a lake was in a groundwater recharge or discharge system. The index of hydrogeology was confirmed using an independent chemical measure of groundwater influence (combined concentrations of calcium and magnesium). Devito et al. (2000) combined the hydrogeology index with a hydrological connectivity index (proportion of wetlands connected to the lake) to predict the potential for TP loading to the lakes. They were able to predict almost 60% of the variation in changes in TP in lakes from a dry to a wet year, reflecting surface and subsurface hydrological controls on TP. In a similar setting, Sass et al. (2008) explained over 70% of the steady-state concentration of chlorophyll *a* in 40 lakes using an index of hydrogeological setting, a proxy for dominant runoff mechanisms (size and organization of wetlands), and lake-to-lake connectivity (presence or absence of contributing lakes).

These studies underscore the value of spatially extensive datasets for developing and testing our understanding of hydrological controls on biogeochemical export to surface waters on forested landscapes and also illustrate that DTA is important in a broad range of hydrogeological contexts (VSA as well as non-VSA dominated) and forest regions. It is noteworthy that comparable amounts of variation in lake nutrient concentrations were explained in both VSA and non-VSA geographies. However, given the different approaches taken, there is a clear need to repeat these studies with standard methods and data to allow for direct intercomparison.

4.5 From Science to Practice

Forest managers aim to minimize adverse impacts of forest operations on water, sediment and nutrient loading to surfaces waters. Although well intended, the management practices used to minimize effects are often borrowed from other jurisdictions, and while based on the best available science may not be wholly applicable to the management locale. Practitioners must recognize the importance of understanding the processes responsible for the movement of water and nutrients across landscapes to predict the effects of forest management strategies on the hydrological and biogeochemical response of surface waters. Echoing the quotation at the beginning of the chapter, we do not need mapping for its own sake but we need process-informed characterization of landscapes to lead to useful generalizations that can be applied in practical contexts.

This chapter has demonstrated that DTA can be used to predict origin, age, pathway, and fate of water and nutrients within a forest. Although our theoretical treatment of DTA techniques has focused on hydrological and biogeochemical studies, there is an increasing body of literature detailing the use of DTA in water-related geomorphic and ecological applications. For example, the susceptibility of landscapes to landslides has been modeled using DTA based on the observation that landslides are partly triggered when soil pore water pressures reach a critical point (Montgomery et al. 2000; Dhakal and Sidle 2004). Depending on the landscape, different terrain attributes have been found to be useful in prediction of areas, where pore water pressures reach critical levels (Montgomery et al. 2000; Gritzner et al. 2001; Borga et al. 2002). An interesting ecological application of the topographic index is the prediction of critical brook trout spawning sites along the margins of forest lakes which in some landscapes occur in topographically convergent zones, where there is discharging groundwater (Borwick et al. 2005).

The transfer of scientific knowledge to practice has been facilitated by different governmental and nongovernmental organizations such as the Sustainable Forest Management Network in Canada. There are now numerous examples of how forest managers have been incorporating the scientific results in best management practices. Forest managers and operators are using DTA to map hydrologically sensitive areas (areas where the water table intersects with the forest floor, such as wetlands and low-order streams), in order to assist in the placement of roads (especially considering water crossings), culverts, as well as cut blocks (Murphy et al. 2007). There is substantial improvement in mapping accuracy when LiDAR-derived DEMs are used to delineate these hydrologically sensitive areas, many of which are often hidden beneath the canopy or are not represented by coarse resolution DEM pixels in traditional aerial photo-derived DEMs (cf., Remmel et al. 2008). In more mountainous terrain, roads are critical conduits of water and the sediments it carries so that the planning of roads is especially important to reduce these impacts (Megahan and King 2001). Roads and cut-blocks also lead to increased susceptibility to landslides (especially for small and moderate size precipitation events), so that forest management in these mountainous regions also considers landslide susceptibility in their planning (Dhakal and Sidle 2003).

DTA-based characterization together with an enhanced understanding of hydrological processes will assist the conservation of hydrologically sensitive areas and minimize adverse impacts through more effective harvest design and location of roads and riparian buffers. DTA can be a powerful tool for forest managers, especially when combined with remote sensing and distributed simulation modeling, which can be used to predict both the spatial heterogeneity and the temporal variability in hydrological features and land–atmosphere and land–water exchanges of water, nutrients, and pollutants.

4.6 Towards an Operational Digital Terrain Analysis Approach

DTA is poised to become an integral tool in many earth science and ecological fields. It has evolved to the point where it has a strong theoretical basis that captures both hydrological and biogeochemical processes and patterns. To develop an operational approach to DTA for forest hydrologists, the following four recommendations should be implemented.

4.6.1 Improved Characterization of Surface and Subsurface

The next generation of DEMs must achieve <15 cm vertical and <5 m horizontal accuracy across all forest cover types. Ideally, this will be achieved with satellite-based LiDAR systems to provide complete global coverage from taiga to tropical forests. A much greater achievement will be the characterization of bedrock topography, also at a global scale. Geotechnical techniques offer some hope in mapping subsurface features but the type of precision and accuracy needed is currently still out of reach. These achievements would lead to an integrated terrain analysis framework, where water would be able to be routed along surface and/or subsurface pathways. Until we attain the required integrated flow-path characterization, there is a need for continued ground-based surveys of soils and surficial geology so that in combination with geotechnical methods we will be able to predict bedrock topography in unsurveyed areas. Unfortunately, it is all too tempting in the light of budget constraints to chop ground-surveys in the mistaken belief that DEMs of the surface can model everything.

4.6.2 Classification of Process-Based Terrain Attributes and Features

DEMs and the terrain attributes and terrain features derived from them contain a wealth of information and opportunities, many of which have already between translated from science to practice. However, an operational DTA would benefit enormously from a classification of terrain attributes and terrain features based on process-understanding. This could lead to a common DTA toolkit that would help practitioners match the right tool to the right process at the right place. This toolkit could be customized for each hydrological region, so as to reflect climatic, geological, and soil conditions. A common toolkit would also enable direct comparisons between different hydrological regions. The foundation of such classification would have to be based on ground surveys, providing yet another strong reason for their retention.

4.6.3 Global Benchmark Datasets

We have yet to test the true potential of DTA, as the research community has so far used ad hoc, piecemeal approaches. We need a coordinated comprehensive benchmarking of different procedures and products. Global benchmark datasets consisting of DEMs as well as ground-truthing data would allow the authors of new and improved metrics to weigh in against existing ones using the same datasets. Such comparisons would also aid the classification of the metrics based on hydrological regions.

4.6.4 Integration with Other Digital Data, Tools and Techniques

The future of DTA lies in its integration with field data, remote sensing, and distributed hydrological modeling. These integrated systems could use the static maps of DTA as a basis for dynamic modeling of processes and patterns that are calibrated by local, ground-based monitoring networks. These catchment-scale analysis systems should be freeware with transparent codes such as the Terrain Analysis System and its successor Whitebox (Lindsay 2005).

4.7 Conclusions

DTA is becoming a ubiquitous tool in the hydrologist's toolbox and can be used to predict hydrological and biogeochemical processes and patterns in different hydrological landscapes. Given the general availability of DEMs and how readily DTMs can be derived, there is a strong temptation to uncritically apply topographic analysis as a first (and sometimes only) step in understanding the hydrological and biogeochemical dynamics of an area. The literature is now replete with examples, especially at headwater catchment scales, where runoff is controlled by nonlinear mechanisms, such as bedrock-controlled subsurface flow and macropore flow. In such regions, DTA will be of limited use, especially in understanding rainfall-runoff mechanisms. However, set in a proper physical context, DTA can be an indispensable tool in modeling flowpaths, surface storages, nutrient source areas, and characterizing landforms. The future of DTA lies in the use of LiDAR-derived DEMs at an optimum spatial resolution and the integration of terrain analysis with remote sensing and hydrological distributed modeling to breathe life into the static patterns created by DTMs. The fusion of modern digital tools with forest managers' innate understanding of their landbase will provide a powerful new approach for implementing sustainable forest management.

Acknowledgments This work was supported by an NSERC Discovery grant to IFC and an NSERC Postdoctoral fellowship to GZS.

References

Agnew LJ, Lyona S, Gerard-Marchantet P et al (2006) Identifying hydrologically sensitive areas: bridging the gap between science and application. J Environ Manag 78:63–76

Baker ME, Wiley MJ, Carlson MI et al (2003) A GIS model of subsurface water potential for aquatic resource inventory, assessment, and environmental management. Environ Manag 32:706–719

Band LE, Moore ID (1995) Scale: landscape attributes and geographical information systems. Hydrol Process 9:401–422

Beven KJ (1986) Runoff production and flood frequency in catchments of order n: an alternative approach. In: Gupta VK, Rodriguez-Iturbe I, Wood EF (eds) Scale problems in hydrology. D. Reidel, Dordrecht, pp 107–131

Beven KJ (1997) Topmodel: a critique. Hydrol Process 11:1069–1085

Beven KJ, Kirkby MJ (1979) A physically based, variable contributing area model of basin hydrology. Hydrol Sci 24:43–69

Bishop K, Buffam I, Erlandsson M et al (2008) Aqua Incognita: the unknown headwaters. Hydrol Process 22:1239–1242
Blöschl G, Sivapalan M (1995) Scale issues in hydrological modeling: a review. Hydrol Process 9:251–290
Borga M, Fontana GD, Cazorzi F (2002) Analysis of topographic and climatic control on rainfall-triggered shallow landsliding using a quasi-dynamic wetness index. J Hydrol 268:56–71
Borwick J, Buttle J, Ridgway MS (2005) A topographic index approach for identifying groundwater habitat of young-of-year brook trout (*Salvelinus fontinalis*) in the land–lake ecotone. Can J Fish Aquat Sci 63:239–253
Bourgine B, Baghdadi N (2005) Assessment of C-band SRTM DEM in a dense equatorial forest zone. Comptes Rendus Geosci 337:1225–1234
Bracken LJ, Croke J (2007) The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol Process 21:1749–1763
Burns DA, Plummer NL, McDonnell JJ et al (2003) The geochemical evolution of riparian ground water in a forested piedmont catchment. Ground Water 41:913–925
Conacher AJ, Dalrymple JB (1977) The nine unit landsurface model: an approach to pedogeomorphic research. Geoderma 18:1–154
Costa-Cabral MC, Burges SJ (1994) Digital elevation model networks (DEMON): a model of flow over hillslopes for computation of contributing and dispersal areas. Water Resour Res 30:1681–1692
Creed IF, Beall FD (2009) Distributed topographic indicators for predicting nitrogen export from headwater catchments. Water Resour Res 45:W10407
Creed IF, Band LE, Foster NW et al (1996) Regulation of nitrate-N release from temperate forests: a test of the N flushing hypothesis. Water Resour Res 32:3337–3354
Creed IF, Trick CG, Band LE et al (2002) Characterizing the spatial pattern of soil carbon and nitrogen pools in the Turkey Lakes Watershed: a comparison of regression techniques. Water Air Soil Poll Focus 2:81–102
Creed IF, Sanford SE, Beall FD et al (2003) Cryptic wetlands: integrating hidden wetlands in regression models of the export of dissolved organic carbon from forested landscapes. Hydrol Process 17:3629–3648
Creed IF, Beall FD, Clair TA et al (2008) Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils. Glob Biogeochem Cycles 22: GB4024
D'Arcy P, Carignan R (1997) Influence of catchment topography on water chemistry in southeastern Québec Shield lakes. Can J Fish Aquat Sci 54:2215–2227
Deng Y, Wilson JP, Bauer BO (2007) DEM resolution dependencies of terrain attributes across a landscape. Int J Geog Inf Sci 21:187–213
Desmet PJJ, Govers G (1996) Comparison of routing algorithms for digital elevation models and their implications for predicting ephemeral gullies. Int J Geog Inf Syst 10:311–331
Devito KJ, Creed IF, Rothwell RL et al (2000) Landscape controls on phosphorus loading to boreal lakes: implications for the potential impacts of forest harvesting. Can J Fish Aquat Sci 57:1977–1984
Devito KJ, Creed IF, Gan T et al (2005) A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? Hydrol Process 19:1705–1714
Dhakal AS, Sidle RC (2003) Long-term modeling of landslides for different forest management practices. Earth Surf Proc Land 28:853–868
Dhakal AS, Sidle RC (2004) Pore water pressure assessment in a forest watershed: simulations and distributed field measurements related to forest practices. Water Resour Res 40:W02405
Dunne T, Moore TR, Taylor CH (1975) Recognition and prediction of runoff-producing zones in humid regions. Hydrol Sci 20:305–327
Evans JE, Prepas EE, Devito KJ et al (2000) Phosphorus dynamics in shallow subsurface waters in an uncut and cut subscatchment of a lake on the Boreal Plain. Can J Fish Aquat Sci 57:60–72

Fairfield J, Leymarie P (1991) Drainage networks from grid digital elevation models. Water Resour Res 27:709–717
Farr TG, Rosen P, Caro E et al (2007) The shuttle radar topography mission. Rev Geophys 45: RG2004
Freer J, McDonnell JJ, Beven KJ, Peters NE, Burns DA, Hooper RP, Aulenbach B, Kendall C (2002) The role of bedrock topography on subsurface storm flow. Water Resour Res 38: WR000872
Garcia-Martinó AR, Scatena FN, Warner GS et al (1996) Statistical low flow estimation using GIS analysis in humid montane regions in Puerto Rico. Water Resour Bull 32:1259–1271
Gergel SE, Turner MG, Kratz TK (1999) Dissolved organic carbon as an indicator of the scale of watershed influence on lakes and rivers. Ecol Appl 9:1377–1390
Gritzner ML, Marcus WA, Aspinall R, Custer SG (2001) Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology 37:149–165
Güntner A, Seibert J, Uhlenbrook S (2004) Modeling spatial patterns of saturated areas: an evaluation of different terrain indices. Water Resour Res 40:W05114
Hall GF, Olson CG (1991) Predicting variability of soils from landscape models. In: Manusbach MJ, Wilding LP (eds) Spatial variabilities of soils and landforms, Soil Science Society of America Special Publication, No. 28, Madison, pp 9–24
Hewlett JD, Hibbert AR (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In: Sopper WE, Lull HW (eds) Forest Hydrology. Pergamon Press, New York, pp 275–290
Hewlett JD, Nutter WL (1970) The varying source area of streamflow from upland basins. In: Proceedings of the symposium on interdisciplinary aspects of watershed management. Montana State University, Bozeman, 3–6 Aug 1970, pp 65–83
Hjerdt KN, McDonnell JJ, Seibert J et al (2004) A new topographic index to quantify downslope controls on local drainage. Water Resour Res 40:W05602
Hornberger GM, Bencala KE, McKnight DM (1994) Hydrological controls on dissolved organic carbon during snowmelt in the Snake River near Montezuma, Colorado. Biogeochemistry 25:147–165
Horton RE (1945) Erosional development of streams and their drainage basins. Bull Geo Soc Am 56:275–370
Hutchinson MF (1989) A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. J Hydrol 106:211–232
Inamder SP, Mitchell MJ (2006) Hydrologic and topographic controls on storm-event exports of dissolved organic carbon (DOC) and nitrate across catchment scales. Water Resour Res 42: W03421
Jencso KG, McGlynn BL, Gooseff MN et al (2009) Hydrologic connectivity between landscapes and streams: transferring reach- and plot-scale understanding to the catchment scale. Water Resour Res 45:W04438
Lane SN, Brookes CJ, Kirby MJ et al (2004) A network-index-based version of TOPMODEL for use with high-resolution digital topographic data. Hydrol Process 18:191–201
Laudon H, Sjoblom V, Buffam I et al (2007) The role of catchment scale and landscape characteristics for runoff generation of boreal streams. J Hydrol 344:198–209
Lehmann P, Hinz C, McGrath G et al (2007) Rainfall threshold for hillslope outflow: an emergent property of flowpathway connectivity. Hydrol Earth Syst Sci 11:1047–1063
Lindsay JB (2003) A physically based model for calculating contributing area on hillslopes and along valley bottoms. Water Resour Res 39:1332
Lindsay JB (2005) A terrain analysis system: a tool for hydro-geomorphic applications. Hydrol Process 19:1123–1130
Lindsay JB (2006) Sensitivity of channel mapping techniques to uncertainty in digital elevation data. Int J Geog Inf Sci 20:669–692

Lindsay JB, Creed IF (2005) Removal of article depressions from DEMs: towards a minimum impact approach. Hydrol Process 19:3113–3126
Lindsay JB, Creed IF (2006) Distinguishing actual and artefact depressions in digital elevation data: approaches and Issues. Comput Geosci 32:1192–1204
Lindsay JB, Creed IF, Beall FD (2004) Drainage basin morphometrics for depressional landscapes. Water Resour Res 40:W09307
MacMillan RA, Pettapiece WW, Nolan SC et al (2000) A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic. Fuzzy Set Syst 113:81–109
Mark DM, Goodchild MF (1982) Topologic model for drainage networks with lakes. Water Resour Res 18:275–280
Martin JG, Bolstad PV, Ryu SR et al (2009) Modeling soil respiration based on carbon, nitrogen, and root mass across diverse Great Lake forests. Agric For Meteorol 149:1722–1729
Martz LW, Garbrecht J (1998) The treatment of flat areas and depressions in automated drainage analysis of raster digital elevation models. Hydrol Process 12:843–855
McClain ME, Boyer EW, Dent CL et al (2003) Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301–312
McDonnell JJ, Sivapalan M, Vache K et al (2007) Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology. Water Resour Res 43:W07301
McGlynn BL, Seibert J (2003) Distributed assessment of contributing area and riparian buffering along stream networks. Water Resour Res 39:1082
McGlynn BL, McDonnell JJ, Stewart M et al (2003) On the relationships between catchment scale and streamwater mean residence time. Hydrol Process 17:175–181
McGuire KJ, McDonnell JJ (2006) A review and evaluation of catchment transit time modeling. J Hydrol 330:543–563
McGuire KJ, McDonnell JJ, Weiler M et al (2005) The role of topography on catchment-scale water residence time. Water Resour Res 41:W04002
McMaster KJ (2002) Effects of digital elevation model resolution on derived stream network positions. Water Resour Res 28:1042
Megahan WF, King JG (2001) Erosion, sedimentation, and cumulative effects in the northern Rocky Mountains, In: Proceedings of the society of American foresters, Washington, 16–20 Nov 2000, pp 58–63
Milne G (1935) Some suggested units of classification and mapping, particularly for East African soils. Soil Res 3:183–198
Montgomery DR, Buffington JM (1997) Channel-reach morphology in mountain drainage basins. Geol Soc Am Bull 109:596–611
Montgomery DR, Dietrich WE (1992) Channel initiation and the problem of landscape scale. Science 255:826–830
Montgomery DR, Schmidt KM, Greenberg HM et al (2000) Forest clearing and regional landsliding. Geology 28:311–314
Moore ID, Grayson RB, Ladson AR (1991) Digital terrain modeling: a review of hydrological, geomorphological, and biological applications. Hydrol Process 5:3–30
Murphy PNC, Ogilvie J, Connor K et al (2007) Mapping wetlands: a comparison of two different approaches for New Brunswick, Canada. Wetlands 27:846–854
Natural Resources Canada (2007) Canadian digital elevation data, level 1, Product Specifications, Government of Canada, Natural Resources Canada, Centre for Topographic Information
O'Callaghan JF, Mark DM (1984) The extraction of drainage networks from digital elevation data. Comput Vision Graph Image Process 28:323–344
O'Connor EM, Dillon PJ, Molot LA et al (2009) Modeling dissolved organic carbon mass balances for lakes of the Muskoka River Watershed. Hydrol Res 40:273–290
Paik K (2008) Global search algorithm for nondispersive flowpath extraction. J Geophys Res 113: F04001

Peucker TK, Douglas DH (1975) Detection of surface-specific points by local parallel processing of discrete terrain elevation data. Comp Graph Image Proc 4:375–387
Planchon O, Darboux F (2001) A fast, simple and versatile algorithm to fill depressions of digital elevation models. Catena 46:159–176
Quinn P, Beven K, Chevallier P et al (1991) The prediction of hillslope flowpaths for distributed hydrological modeling using digital terrain models. Hydrol Process 5:59–79
Quinn PF, Beven KJ, Lamb R (1995) The ln(a/tanB) index: how to calculate it and how to use it within the TOPMODEL framework. Hydrol Process 9:161–182
Remmel TK, Todd KW, Buttle J (2008) A comparison of existing surficial hydrological data layers in a low-relief forested Ontario landscape with those derived from a LiDAR DEM. Forest Chron 84:850–865
Reutebuch SE, McGaughey RJ, Andersen HE et al (2003) Accuracy of a high-resolution lidar terrain model under a conifer forest canopy. Can J Remote Sens 29:527–535
Richardson MC, Fortin MJ, Branfireun BA (2009) Hydrogeomorphic edge detection and delineation of landscape functional units from lidar digital elevation models. Water Resour Res 45: W10441
Riveros-Iregui DA, McGlynn BL (2009) Landscape structure control on soil CO_2 efflux variability in complex terrain: scaling from point observations to watershed scale fluxes. J Geophys Res Biogeosci 114:G02010
Roberts DW, Dowling TI, Walker J (1997) FLAG: a fuzzy landscape analysis GIS method for dryland salinity assessment, Technical Report 8/97, CSIRO Land and Water, Canberra
Sanford SE, Creed IF, Tague CL et al (2007) Scale-dependence of natural variability of flow regimes in a forested landscape. Water Resour Res 43:W08414
Sass GZ, Creed IF, Devito KJ (2008) Spatial heterogeneity in trophic status of shallow lakes on the Boreal Plain: influence of hydrologic setting. Water Resour Res 44:W08444
Schumm SA (1956) The role of creep and rainwash on the retreat of badland slopes. Am J Sci 254:693–706
Seibert J, McGlynn BL (2007) A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. Water Resour Res 43:W04501
Sorensen R, Seibert J (2007) Effects of DEM resolution on the calculation of topographical indices: TWI and its components. J Hydrol 347:79–89
Sorensen R, Zinko U, Seibert J (2006) On the calculation of the topographic wetness index: evaluation of different methods based on field observations. Hydrol Earth Syst Sci 10:101–112
Spence C, Woo M-K (2003) Hydrology of subarctic Canadian shield: soil-filled valleys. J Hydrol 279:151–166
Summerell GK, Vaze J, Tuteja NK et al (2005) Delineating the major landforms of catchments using an objective hydrological terrain analysis method. Water Resour Res 41:W12416
Tague CL, Band LE (2004) RHESSys: regional hydro-ecologic simulation system – an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. Earth Interact 8:1–19
Tarboton DG (1997) A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour Res 33:309–319
Tetzlaff D, Seibert J, McGuire KJ et al (2009) How does landscape structure influence catchment transit time across different geomorphic provinces? Hydrol Process 23:945–953
Thompson JC, Moore RD (1996) Relations between topography and water table depth in a shallow forest soil. Hydrol Process 10:1513–1525
Tromp-van Meerveld HJ, McDonnell JJ (2006) Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. Water Resour Res 42:W02411
Watson R, Noble I, Bolin B et al (2000) Summary for policymakers: land-use, land-Use change, and forestry. IPCC Special Report 92-9169-114-3, Geneva
Webster R (1977) Quantitative and numerical methods in soil classification and survey. Clarendon Press, Oxford, p 269

Webster KL, Creed IF, Bourbonniere RA et al (2008a) Controls on the heterogeneity of soil respiration in a tolerant hardwood forest. J Geophys Res Biogeosci 113:G03018

Webster KL, Creed IF, Beall FD et al (2008b) Sensitivity of catchment-aggregated estimates of soil carbon dioxide efflux to topography under different climatic conditions. J Geophys Res Biogeosci 113:G03040

Webster KL, Creed IF, Beall FD et al (2010) A topographic template for estimating soil carbon pools in forested catchments, Geoderma 160:457–467

Western AW, Blöschl GRB (2001) Toward capturing hydrologically significant connectivity in spatial patterns. Water Resour Res 37:2000WR900241

Wilson JP, Gallant JC (2000) Terrain analysis: principles and applications. Wiley, New York

Winn N, Williamson CE, Abbitt R et al (2009) Modeling dissolved organic carbon in subalpine and alpine lakes with GIS and remote sensing. Landscape Ecol 24:807–816

Wolock DM, McCabe GJ (1995) Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL. Water Resour Res 31:1315–1324

Yarrow MM, Marin VH (2007) Toward conceptual cohesiveness: a historical analysis of the theory and utility of ecological boundaries and transition zones. Ecosystems 10:462–476

Young A (1972) The soil catena: a systematic approach. In: Adams WP, Helleiner FM (eds) International geography, Vol. 1. International geography congress. University of Toronto Press, Toronto, pp 287–289

Young A (1976) Tropical soils and soil survey. Cambridge University Press, Cambridge

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