A new topographic index to quantify downslope controls on local drainage

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[1] Topography is an important control on hydrological processes. One approach to quantify this control is the topographic ln(a/tanβ) index. This index has become widely used in hydrology, but it utilizes a relatively small portion of the information contained in a digital elevation model (DEM). One potentially important feature not considered in the implementation of the ln(a/tanβ) index is the enhancement or impedance of local drainage by downslope topography. This effect could be important in some terrain for controlling hydraulic gradients. We propose a new way of estimating the hydraulic gradient by calculating how far downhill (L_d, [m]) a parcel of water must move in order to lose a certain amount of potential energy (d, [m]). Expressed as a gradient, $\tan\alpha_d = d/L_d$, values tend to be lower on concave slope profiles and higher on convex slope profiles compared with the local gradient, tanβ. We argue that the parameter d controls the deviation of hydraulic gradient from surface slope. While we determine this subjectively, landscape relief, DEM resolution, and soil transmissivity should be considered at the selection of d. We found the downslope index values to be less affected by changes in DEM resolution than local slope. Three applications are presented where the new index is shown to be useful for hydrological, geomorphological, and biogeochemical applications. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1866 Hydrology: Soil moisture; 1860 Hydrology: Runoff and streamflow; 1890 Hydrology: Wetlands; *KEYWORDS:* topographic index, drainage efficiency, hydraulic gradient, terrain analysis

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1. Introduction

[2] Topography has been a central focus in hydrologic research ever since the introduction of the variable source area concept for stormflow generation [*Hewlett and Hibbert*, 1967]. In areas with moderate to steep topography, where elevation potential dominates total hydraulic potential, landform is a key variable in the distribution and redistribution of water [*Anderson and Kneale*, 1982], as well as for determining the catchment response to precipitation inputs [*Rodriguez-Iturbe and Valdes*, 1979; *Beven and Kirkby*, 1979; *O'Loughlin*, 1986]. How one parameterizes topography into a mathematical representation of a landscape, and how one uses this to determine the dominant topographic controls on the hydrological response of a watershed, remains an important research question. Arguably, the most successful approach to date is the topographic ln(a/tanβ) index, which has been applied in numerous hydrologic studies and applications for water flow path estimation and moisture redistribution [*Beven et al.*, 1995]. The index is formulated as I = ln(a/tanβ), where a is the upslope contributing area per unit contour length and tanβ is the local topographic gradient, and is calculated from a gridded digital elevation model (DEM) of a watershed. One reason the ln(a/tanβ) index has been so successful is that it represents an objective way to parameterize first-order controls on water movement from topographic information. Over the last decade, research has tended to focus on ways to improve existing algorithms for calculating the ln(a/tanβ) index [*Quinn et al.*, 1995; *Tarboton*, 1997; *Woods et al.*, 1997] and to relax some of the underlying theoretical assumptions that form the physical foundation of models that employ the index [*Barling et al.*, 1994; *Saulnier et al.*, 1997; *Ambroise et al.*, 1996].

[3] Few attempts have been made thus far to utilize other types of topographic information for modeling purposes. Consequently, although the use of topography and DEMs in hydrologic research has become increasingly popular, most research has focused exclusively on the ln(a/tanβ) index, often overlooking other potentially useful information contained in a DEM.

[4] While the ln(a/tanβ) index is and has been a tremendously useful tool for hydrological modelers since its inception, it has become clear that many hydrologic processes that drive the wetness distribution may be controlled by other factors not captured by the index [see, e.g., *Grayson and Western*, 2001]. Several studies have reported weak correlations between index values and distributed point observations of soil moisture or groundwater levels [*Burt and Butcher*, 1986; *Jordan*, 1994; *Iorgulescu and

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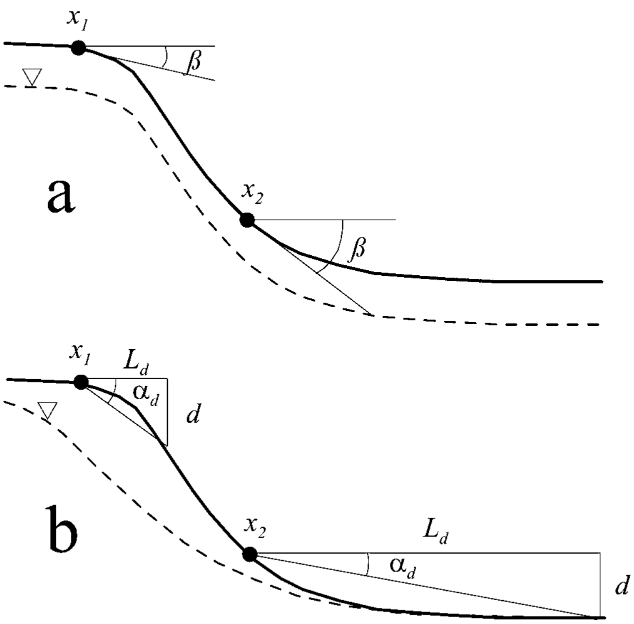

Figure 1. A drawing of a hillslope flow path in profile that illustrates the differences between (a) the local gradient ($\tan\beta$) and (b) the downslope index (d/L_d or $\tan\alpha_d$) for points x_1 and x_2. The groundwater table in each plot is assumed to reflect the calculated gradients.

Jordan, 1994; *Moore and Thompson*, 1996; *Seibert et al.*, 1997]. It has been argued that such findings should be expected because any direct attempt to compare point data to spatially distributed processes is fundamentally flawed since we do not fully understand how to scale up point measurements [*Bloschl*, 2001]. Recognizing this problem, *Rodhe and Seibert* [1999] used land use information from commercially available maps as "ground truth" in their study of the ability of the $\ln(a/\tan\beta)$ index to distinguish "wet areas" from other areas. They found that local topographic slope alone was a better predictor of wet areas than the $\ln(a/\tan\beta)$ index. Similarly, *Merot et al.* [1995] compared the $\ln(a/\tan\beta)$ index distribution with the distribution of different soil types in two catchments in Brittany, France, and concluded that the relationship between index and soil type was strongest in the wettest areas of the catchments. *Roberts et al.* [1997] used different measures such as plan and profile curvature, together with a smoothened elevation model, to predict groundwater discharge areas and soil salinization in two Australian catchments.

[5] Theoretically, the $\ln(a/\tan\beta)$ index makes the assumption that local drainage is not affected by downslope conditions. However, *Speight* [1980] argued that it is the balance between the specific catchment area (upslope contributing area per unit length of contour) and the specific dispersal area (downslope area per unit length of contour) that controls the drainage of water from any location. Later, *Crave and Gascuel-Odoux* [1997] reported that soil characteristics in a small catchment in Normandie, France, were strongly linked to dispersal (or downslope) controls. They calculated the head difference between a point on the hillslope and its point of exit into a stream, following the (surface) flow path in the steepest direction, and found it to be a strong predictor of soil class. These findings suggest that downslope topography may be an important factor to consider. The purpose of this paper is to present an alternative method for estimating hydraulic gradients using downslope topography. We present an algorithm that estimates the hydraulic gradient for an arbitrary point in a DEM by stepping down the flow path in the steepest descent until a user-specified vertical drop has been achieved. The result is reported as a gradient, $\tan\alpha_d$, which is the ratio between the vertical drop and the horizontal distance necessary to achieve this drop. We use elevation data from a synthetic hillslope profile to illustrate the most important features of this new index. Effects of changing DEM resolution on gradient calculations are examined, and the new index is compared with other indices. Finally, we report results from three applications of the downslope index and demonstrate how it was used in (1) a hydrological application where we simulate the distribution of soil moisture in the Kassjöån basin, central Sweden, (2) a geomorphological application where we used the new index to explain a significant amount of the variance of soil depth distribution at Panola Mountain Research Watershed, Georgia, and (3) a biogeochemical application where we explain the spatial extent of subsurface nitrate (NO_3^-) source areas at the Neversink Watershed in New York.

2. Theory

[6] Many common hydrologic models use land surface slope as a substitute for the slope of the groundwater table and hydraulic gradients. In strongly convex or concave terrain, however, hydraulic gradients may also be influenced by drainage conditions downslope of the immediate area around the point of consideration. For instance, downhill damming could cause the slope of the groundwater table to be less than ground surface slope in concave toe slope positions. We propose a new method to simulate the effects of downslope topography on local hydraulic gradient (Figure 1b). This method extends ideas introduced by *Crave and Gascuel-Odoux* [1997], who used elevation differences along flow paths to quantify and map drainage efficiency. They calculated the head difference between a point on the hillslope and its point of exit into a stream, following the (surface) flow path in the steepest direction, and found it to be a strong predictor of soil class. Our method builds on the same principle, that is, calculating head differences along flow paths, but it does not use the exit point at the stream as reference; instead, the algorithm looks at how far a parcel of water has to travel along its flow path to lose a given head potential, d [m]. In other words, how far downslope does one have to go to descend d meters?

[7] The downslope index value can be reported either as a distance, L_d [m], or as a gradient, $\tan\alpha_d$,

$$\tan\alpha_d = \frac{d}{L_d}, \qquad (1)$$

where L_d is the horizontal distance to the point with an elevation d meters below the elevation of the starting cell, following the steepest-direction flow path (see Figure 1b). When this point is located in between two elevation points, local linear interpolation is used to calculate the value of L_d. The slope angle, α_d, is the angle between the starting point and this target point. As the elevation difference, d,

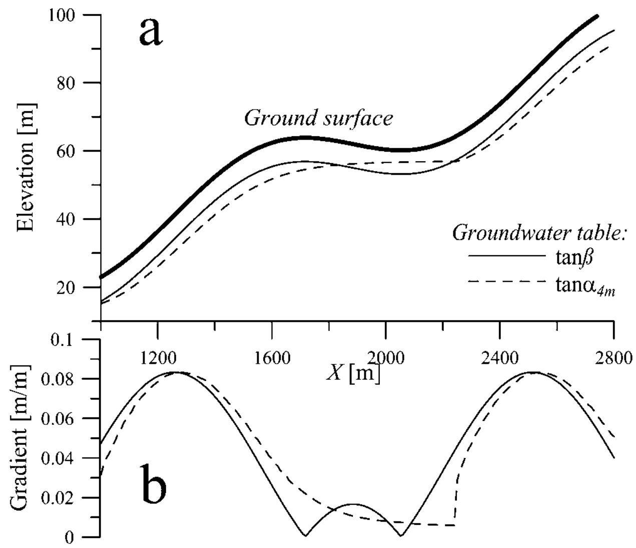

Figure 2. Local gradient, $\tan\beta$, and the downslope index, $\tan\alpha_{4m}$, calculated for a computer-generated hillslope profile. (a) Approximate groundwater table elevations were calculated from (b) the gradient data to better illustrate the differences. A groundwater table depth of 6 m at $X = 2250$ m was assumed as the starting point for this integration.

approaches zero, the value of $\tan\alpha_d$ approaches the local gradient of the ground surface, $\tan\beta$:

$$\lim_{d \to 0} \tan\alpha_d = \tan\beta. \tag{2}$$

On the other hand, as d becomes larger, topography farther downslope from the starting point will be integrated, and values are likely to deviate more from the local ground surface slope. Reasonable values of d are assessed on the basis of topographic relief, resolution of the DEM used, and local soil transmissivity. We illustrate the effects of varying the d value for a given DEM in section 3.

[8] In order to highlight differences between the local slope and downslope indices, we generated a synthetic hillslope profile from a modified sine function and used it as a basis for comparison. Both the local slope ($\tan\beta$) and the downslope index ($\tan\alpha_d$) were calculated for the hillslope (Figures 2a–2b). The downslope index reaches a minimum at the foot of the slope, whereas the local gradient reaches zero both in the sink and on the crest. Corresponding groundwater table profiles (Figure 2a) were computed, starting with a fixed value at one point and subsequently integrating the estimated gradients (Figure 2b). They illustrate how the proposed index captures our perception of groundwater ‘‘backing up’’ [*McDonnell*, 1990] in the convergent regions of the hillslope (foot slope areas) and also the increasing drainage of groundwater in the convex regions (shoulder areas), thus, in a sense, integrating the effects of downslope topography on local drainage. The hydraulic gradients computed from the downslope index appear intuitively more reasonable than those based on local slope, which mimic the surface topography in the immediate region of the grid cell.

3. Initial Tests

[9] We used a DEM of the 40.5 ha, forested headwater W-9 catchment at Sleepers River Research Watershed in Danville, Vermont, to demonstrate some important properties of the downslope index. Sleepers River has been well described in the literature [*Wolock and Price*, 1994; *Shanley and Chalmers*, 1999], and the DEM we used has a resolution of 5 m.

[10] First, we calculated and compared the downslope index for a set of different d values (Figures 3a–3c). A small d will produce a groundwater table that mimics surface topography closely. As we increase d, the groundwater table becomes increasingly smooth compared with surface topography, and mainly larger-scale topographic features will affect its shape. Statistical analysis of the downslope index distributions revealed that values generally decrease (mean and median) and show less variation (standard deviation and quartile range) with increasing d (Table 1a). As a result the index values between downslope index coverages decreased with increasing differences in d (Table 1b).

[11] In the next test we resampled the 5 m DEM at coarser resolutions (10, 25, and 50 m) and calculated slope and

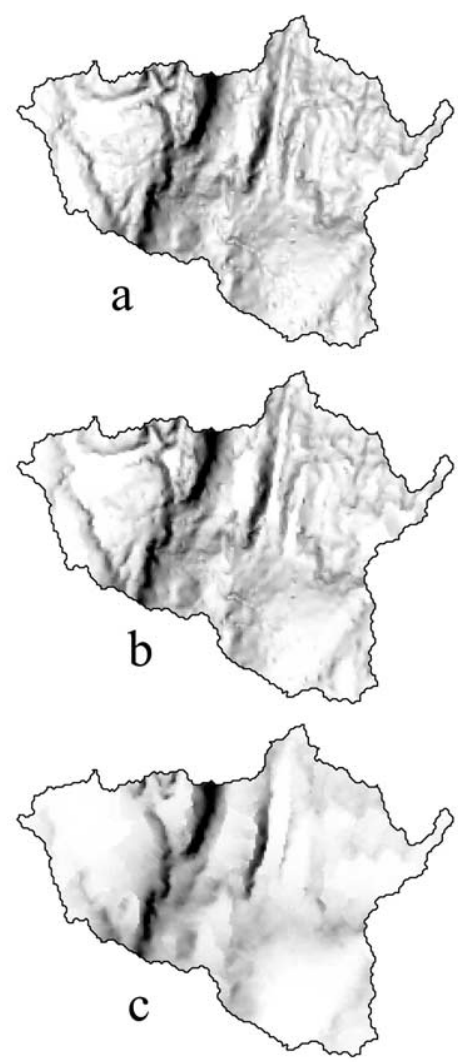

Figure 3. Raster coverages of (a) $\tan\beta$, (b) $\tan\alpha_{2m}$, and (c) $\tan\alpha_{10m}$ for the 41 ha W-9 catchment at Sleepers River, Vermont. Steep gradients are dark in the figures.

Table 1a. Basic Statistics of Index Distributions[a]

	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Quartile Range	Standard Deviation
$\tan\beta$	0.251	0.196	0.000	1.660	0.109	0.325	0.216	0.213
$\tan\alpha_{1m}$	0.244	0.191	0.009	1.574	0.103	0.318	0.215	0.207
$\tan\alpha_{2m}$	0.240	0.183	0.015	1.574	0.097	0.313	0.215	0.208
$\tan\alpha_{5m}$	0.228	0.161	0.022	1.574	0.092	0.290	0.198	0.204
$\tan\alpha_{10m}$	0.209	0.140	0.031	1.515	0.089	0.257	0.168	0.194
$\tan\alpha_{20m}$	0.194	0.134	0.050	1.406	0.089	0.226	0.137	0.171
$\tan\alpha_{40m}$	0.188	0.143	0.074	0.949	0.105	0.213	0.108	0.129

[a]N = 12,521.

downslope index for each of the new DEMs. In this exercise we used a d value of 5 m. Our results confirmed what earlier studies have found: Increasing grid cell size decreases the mean slope of a DEM [*Zhang and Montgomery*, 1994]. Distributions of both $\tan\beta$ and $\tan\alpha_{5m}$ were affected by a change in resolution, but the $\tan\alpha_{5m}$ index was affected much less so (Table 2a). The Kolmogorov-Smirnov (K-S) D value, which is equal to the maximum absolute difference between two cumulative distributions [see, e.g., *Haan*, 1977] was considerably smaller for the downslope index than for $\tan\beta$, except when comparing 5 and 10 m resolution (Table 2b). This confirmed that the downslope index was less affected by a change in DEM resolution. This is because the downslope index is integrating over a number of cells, depending on the value of L_d, and L_d is hardly affected by different DEM resolutions if grid sizes are smaller than L_d.

4. Applications

4.1. Simulating the Spatial Distribution of Wetlands in Kassjöån, Sweden

[12] We used the spatial extent of mires depicted on a 1:50,000 topographic map to test hydrological assumptions about the downslope index. A number of topographic indices were calculated from a 50 m digital elevation model for the 165 km^2 Kassjöån watershed in central Sweden, including the $\ln(a/\tan\beta)$ index, local slope ($\tan\beta$), and the downslope index ($\tan\alpha_d$). We assumed mires to represent the wettest areas of the landscape and thus used mire coverage from land use maps as our ground truth. On the basis of the total mire area in the catchment we defined a threshold value for each index that would reproduce the same total area of wet cells. The percentage of correctly classified area of each index was calculated from the overlap between the predicted wet area and mire coverage. The different topographic index maps were then queried using a binary land use map (mires/nonmires), and the index distributions for the two classes were compared using basic statistics and the K-S D value. Results showed that the downslope index with a d value of 2 m gave the best agreement between the simulated and actual wetness patterns. As an additional test we assessed the ability of each index to locate the wettest areas in the catchment. *Hjerdt* [1997] and *Rodhe and Seibert* [1999] provide more thorough descriptions of the study; only results relating to the performance of the new downslope index are highlighted here.

[13] Median values of the $\ln(a/\tan\beta)$ index for mire cells were different from nonmire cells, but there was a large overlap between the frequency distributions of the indices for the two classes. The mire map based on predictions by the index gave poor results in terms of correspondence between predicted and observed mire cells (38% were correctly classified using an index threshold value of $\ln(a/\tan\beta)$ = 10.7). In fact, using slope ($\tan\beta$) alone as a wetness predictor resulted in a slightly higher fraction of correctly classified cells (42%, using a slope threshold value of $\tan\beta$ = 0.026). This indicates that either the gradient is more important for the development of mires than the size of the upslope drainage area or the infilling of mires in the landscape leads to smaller gradients or both. The $\tan\alpha_{2m}$ index was more successful in reproducing the spatial distribution of mires (47%, using an index threshold value of $\tan\alpha_{2m}$ = 0.022), suggesting that downslope topography may be important to local drainage conditions and mire development. When the $\ln(a/\tan\beta)$ index was modified to include $\tan\alpha_{2m}$ instead of $\tan\beta$, the results did not change significantly. We found that mire distributions simulated by the $\ln(a/\tan\beta)$ index as well as the alternative $\ln(a/\tan\alpha_{2m})$ index were primarily controlled by the contributing area factor, a. Thus mires in

Table 1b. Linear Correlation Matrix[a]

	$\tan\beta$	$\tan\alpha_{1m}$	$\tan\alpha_{2m}$	$\tan\alpha_{5m}$	$\tan\alpha_{10m}$	$\tan\alpha_{20m}$	$\tan\alpha_{40m}$
$\tan\beta$	1						
$\tan\alpha_{1m}$	1	1					
$\tan\alpha_{2m}$	0.98	0.99	1				
$\tan\alpha_{5m}$	0.92	0.92	0.94	1			
$\tan\alpha_{10m}$	0.81	0.82	0.84	0.92	1		
$\tan\alpha_{20m}$	0.66	0.66	0.68	0.76	0.88	1	
$\tan\alpha_{40m}$	0.47	0.47	0.48	0.55	0.67	0.84	1

[a]Correlations are significant at $p < 0.05000$. N = 12,521.

Table 2a. Basic Statistical Properties of $\tan\beta$ and $\tan\alpha_{5m}$ Calculated From DEMs of Varying Resolutions

	DEM Resolution			
	5 m	10 m	25 m	50 m
	tanβ			
Mean	0.2342	0.2272	0.2115	0.2001
Median	0.1863	0.1810	0.1665	0.1663
Standard Deviation	0.1947	0.1880	0.1729	0.1540
	tanα5m			
Mean	0.2119	0.2139	0.2110	0.2000
Median	0.1545	0.1600	0.1636	0.1630
Standard Deviation	0.1866	0.1819	0.1673	0.1506

Table 2b. Kolmogorov-Smirnov D Values for Pairs of Index Distributions With Different DEM Resolutions

	DEM Resolutions					
Index	5 m Versus 10 m	5 m Versus 25 m	5 m Versus 50 m	10 m Versus 25 m	10 m Versus 50 m	25 m Versus 50 m
$\tan\beta$	0.0194	0.0777	0.1284	0.0629	0.1156	0.1156
$\tan\alpha_{5m}$	0.0252	0.0473	0.0683	0.0264	0.0731	0.0685

the lower parts of the landscape were often correctly simulated, whereas mires situated on higher ground were not. In these upslope locations, mire formation seems to be primarily controlled by hydraulic gradients.

4.2. Mapping Soil Depth at Panola Mountain, Georgia

[14] The downslope index (in this case, formulated as L_d) was tested by *Zumbuhl* [1998] at the Panola Mountain Research Watershed, Georgia, along with a number of other topographic and geomorphic indices, for their ability to explain the distribution of measured soil depth at the 10 ha so-called "100 catchment." These indices included plan/profile curvatures and local slope at different map scales, upslope drainage area, and the $\ln(a/\tan\beta)$ topographic index. The ground truth consisted of a 20 m resolution gridded physical soil depth survey. The results of the study revealed a surprisingly strong relationship between soil depth and the downslope index, L_{10m} (r = 0.77) (A. Zumbuhl, personal communication, 1998). The L_{10m} explained more of the variance of soil depth distribution than any of the other indices. This suggests that the downslope index may capture some of the physical linkage between drainage rates, mass wasting, and landscape processes.

4.3. Identifying Nitrate Source Areas at Neversink Catchment, New York

[15] A final example of the usefulness of the downslope index was reported by *Welsch* [1999] in a study of the linkages between topography and the chemical composition of soil water and shallow groundwater at a 24 ha Dry Creek headwater catchment, Neversink Watershed, Catskill Mountains, New York. The primary aim of the study was to test the topographically driven flushing hypothesis for nitrate (NO_3^-) and dissolved organic carbon, since little data exist on how the variability of shallow subsurface storm flow (SSSF) chemistry relates to topographic position [*Welsch et al.*, 2001].

[16] The landscape at Dry Creek is highly affected by layering of sedimentary bedrock, which has contributed to the formation of a terrace-like topography on a roughly 15 m scale. Steep hillslopes are sharply interrupted by comparatively flat plateau regions, and groundwater seeps are commonly found at the base of each hillslope where the slope profile is highly concave. As these seeps dominate streamwater chemistry most of the time, their identification in the landscape is crucial for understanding and modeling the controls on SSSF chemistry. The catchment was clear-cut in the winter of 1996–1997, resulting in elevated NO_3^- concentrations in soil water, groundwater, and streamflow. A spatially distributed network of piezometers was used to investigate the relationship between topography and SSSF chemistry. Several indices of topography were computed from a DEM with a resolution of 10 m, including the $\ln(a/\tan\beta)$ topographic index and the downslope index described in section 2.

[17] Correlations between the $\ln(a/\tan\beta)$ index values and SSSF chemistry improved when the local slope term ($\tan\beta$) was exchanged for the downslope index ($\tan\alpha_{2m}$). When NO_3^- concentrations from piezometers from Dry Creek were correlated with topography as represented by $\ln(a/\tan\beta)$, a mean Pearson correlation coefficient of 0.50 was obtained. However, when topography was represented as $\ln(a/\tan\alpha_{2m})$, the mean Pearson correlation coefficient between NO_3^- concentrations and topography improved to 0.61 (D. Welsch, personal communication, 1999). Correlation between sulfate (SO_4^{2-}) concentrations and the $\ln(a/\tan\beta)$ index values also improved but to a lesser extent (from $r = -0.38$ to $r = -0.41$). The fact that the inclusion of the downslope index term, in this case, $\tan\alpha_{2m}$, improved correlations between simulated and observed biogeochemical patterns suggests that it captures some additional information about first-order controls on subsurface drainage. Thus we have improved our predictive capability by using a terrain index as surrogate of the biogeochemical environment, as argued by *Creed et al.* [1996] in the context of the traditional $\ln(a/\tan\beta)$ index.

5. Concluding Remarks

[18] We have presented the downslope index, $\tan\alpha_d$, as a new index to quantify the topographic controls on hydrology. We suggest that the new index is a better estimation of groundwater gradients than the traditionally used local slope because it allows quantification of downslope influences on local drainage. The downslope index might be a useful tool across a broad range of research fields. The three catchment studies presented in this paper demonstrated the usefulness of the new index to simulate the spatial distributions of hydrological, geomorphological, and biogeochemical characteristics. Results indicate that the proposed index can be useful in certain terrain to capture dominant controls on local drainage regimes, especially in cases where profile curvature exerts a strong control on the drainage pattern. It is encouraging that the information contained in this index to some degree advances our ability to discretize a complex landscape into homogeneous units, which remains an important goal of geoscientific research.

[19] The new index seems to be less sensitive than local surface slope ($\tan\beta$) to changes in DEM resolution. This result was expected since resolution in a sense becomes decoupled from the calculation of the $\tan\alpha_d$ index, in which the d parameter (and not grid cell size) determines the area used in the gradient calculation. This would suggest that models that utilize the new index would be more readily transferable between topographic data of different resolution and scale; that is, modeling results will not be as dependent on data resolution. In addition, data noise and error in a DEM are less likely to affect the distribution of the new index than the distribution of the local gradient because of the areal integration. However, many problems related to

DEM resolution still remain, such as determining the critical resolution needed to capture the landform that controls the modeled processes or how to regionalize process descriptions within a model when data resolution crosses this critical boundary.

[20] A drawback with the proposed index, as compared with $\tan\beta$, is that it is not objective in the sense that its value depends on the choice of d. Both computational and hydrological aspects should be considered in the choice of this parameter value. Computationally, the relief (i.e., typical range in elevation between adjacent grid cells) can give some indication of a proper value for d. In general, a high relief requires a relatively large value of d in order to produce values of L_d that are larger than the grid cell size, that is, to integrate more of the slope than only the next cell downslope. Hydrologically, the surface of the groundwater table is generally smoother than the ground surface, and the value of d controls how much of the microtopographic features are to be filtered out. Increasing d will produce a smoother groundwater surface relative to the ground surface.

[21] We suggest that the downslope index may be a suitable replacement for local gradient in the TOPMODEL index. A more reasonable groundwater profile was computed for the synthetic hillslope based on the drainage efficiency index rather than the local gradient. Reasoning in the other direction, the downslope index should, in many cases, be assumed to provide a better estimate of hydraulic gradients than the local gradient of the surface. The proposed index could also be a helpful tool for predicting the spatial pattern of recharge and discharge areas in watersheds.

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