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Topographic Effects on Stormflow Acidity

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Abstract

This paper describes the theoretical and observed effects of topography on stormflow acidity in upland, forested watersheds. The theoretical effects were determined by a sensitivity analysis using the hydrologic model TOPMODEL. The observed effects were determined by an analysis of topographic and stormflow acidity data collected from eight watersheds in Wales, Great Britain. Results of the analyses indicated that the observed effects of topography were consistent with the theoretical expectations; that is, topography has an important effect on flow path, and that flow path, in turn, has an effect on stormflow acidity.

Introduction

Stormflow acidity is affected by the flow path that water follows in traversing a watershed. It has been observed in streams of some upland, forested watersheds that acidity (hydrogen-ion concentration) increases during stormflow periods (streamflow during intense precipitation) (Lynch et al., 1986). In watersheds that show this response, evidence suggests that the proportions of shallow subsurface flow (water moving 0 to 0.5 m below the land surface) and surface flow in total streamflow increase as the magnitude of flow increases (Lynch et al., 1986). The increase in streamflow acidity during storms occurs on such watersheds because surface and shallow subsurface flow are often acidic. The acidity of surface flow is a result of high rainfall acidity. The acidity of shallow subsurface flow is a result of the abundance of organic acids in near-surface soil horizons and the low buffering capacity of shallow, weathered soils (DeWalle et al., 1985).

One watershed characteristic thought to affect the volume of surface and shallow subsurface flow in stormflow is topography (Dunne et

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al., 1975). Watersheds with substantially different topographic characteristics are expected to produce different volumes of surface and shallow subsurface flow; therefore they are expected also to have different levels of stormflow acidity (Wolock et al., 1989).

The objective of the research described in this paper was to determine the theoretical and observed effects of topography on stormflow acidity. The theoretical effects of topography on the likelihood of a watershed to produce surface and shallow subsurface flow and hence have high stormflow acidity were determined by a sensitivity analysis using the hydrologic model TOPMODEL. The observed relations between topography and stormflow acidity were assessed by a statistical analysis of topography and stormflow-acidity data for eight watersheds in Wales, Great Britain. The consistency between the theoretical and observed effects was also evaluated.

Description of TOPMODEL

TOPMODEL (Beven and Kirkby, 1979) is a mathematical representation of the variable-source-area concept. This concept states that stormflow originates from surface and shallow subsurface flow paths produced by saturated 'source' areas located near stream channels. The location and extent of source areas in a watershed are controlled primarily by basin topography and the state-of-wetness of the watershed. Source areas are found where large quantities of subsurface water collect; these are areas into which large upslope areas drain and where there is a limited capacity for subsurface water to drain farther downhill. In TOPMODEL, the effects of topography are quantified by the spatial distribution of upslope area drained per unit contour (α) and local slope ($\tan B$) (Beven and Kirkby, 1979). The critical topographic characteristics for a watershed as a whole are the first three moments (mean, variance, and skew) of the spatially aggregated distribution function of $\ln(\alpha/\tan B)$ (Wolock et al., 1989).

In addition to the $\ln(\alpha/\tan B)$ moments, use of TOPMODEL requires the specification of soils characteristics (saturated hydraulic conductivity, soil depth, and field capacity), latitude, and time series of precipitation and temperature. Watershed latitude is used to generate a time series of day length, which, together with the time series of temperature, is used to calculate potential evapotranspiration (Hamon, 1961). The model predictions include streamflow and estimates of surface and shallow subsurface flow.

Description of the Data

Data from eight upland, forested watersheds in Wales, collected by the Institute of Hydrology during its Llyn Brianne Study (Whitehead et al., 1988), were used in this analysis. Average watershed area is 0.9 km^2 (ranging from 0.34 to 2.52 km^2), and average total relief is 148 m (ranging from 112 to 201 m). Stream stage and pH have been monitored more or less continuously since 1984 in all eight watersheds at 15-min intervals.

To characterize stormflow acidity, data from August 1985 were used. Seven storms occurred during this period, providing a good sample of stormflow acidity (Table 1).

Topographic data were derived from 1:10,000-scale contour maps. The contour maps were digitized, and 25-m square grids of elevations were generated by interpolation. The grid of elevations was used to calculate α and tanB for each sloping point in the watershed (Wolock et al. 1989). Statistical moments of the ln(α/tanB) distribution then were computed for each watershed (Table 1).

Table 1. Mean hydrogen-ion (H^+) concentration for seven storms during August 1985 and ln(α/tanB) distribution moments for eight watersheds in Wales, Great Britain.

		ln(α/tanB) distribution moments		
Watershed	Mean H^+ Concentration (μeq/L)	Mean	Variance	Skew
LI1	21.1	7.24	1.73	2.69
LI2	48.1	7.52	1.61	0.93
LI3	9.3	7.08	2.90	6.28
LI6	0.2	6.74	1.91	4.68
CI3	9.7	7.00	2.00	5.09
CI4	8.7	7.23	2.51	3.97
CI5	4.7	7.14	1.74	2.60
CI6	4.8	6.95	2.28	3.75

Theoretical Effects of Topography on Stormflow Acidity

The theoretical effects of topography on stormflow acidity were determined by a sensitivity analysis using TOPMODEL. Monte Carlo simulations were performed to assess the effects of the ln(α/tanB) distribution moments on predicted surface and shallow subsurface flow. Single values of field capacity and soil depth and a single time series of climatic variables were used as input to the model. Each model simulation, however, had a different set of ln(α/tanB) distribution moments selected from the observed ranges. By specifying different values for the moments of the distribution, different theoretical watersheds, which varied in their topographic characteristics, were created for each model simulation.

A rank regression analysis (Wolock et al., 1989) was used to determine the effects of the ln(α/tanB) moments on predicted surface and shallow subsurface flow. The magnitudes and signs of the regression statistics indicate the theoretical effects of topography on surface and shallow subsurface flow (Table 2). The magnitudes of the partial F-values show that the mean of the ln(α/tanB) distribution has the most important effect on the likelihood of a watershed to produce surface and shallow subsurface flow. The sign of the partial regression coefficients indicates that as the mean ln(α/tanB) value increases, the predicted volumes of surface and shallow subsurface flow increase as well. These results illustrate that theoretically, watersheds with large mean ln(α/tanB) values are likely to produce large volumes of surface and shallow subsurface flow. A large mean ln(α/tanB) value indicates that a watershed has extensive convergent areas and gentle slopes. This propensity of large mean ln(α/tanB) watersheds to generate acidic surface and shallow subsurface flow makes such watersheds likely to have high stormflow acidity. Thus, given the model results and the assumption that surface and shallow subsurface flow are acidic, large mean ln(α/tanB) watersheds are expected to have acidic stormflow.

Table 2 . Rank regression analysis of the effects of the ln(α/tanB) distribution moments on predicted shallow subsurface flow and surface flow.

	Shallow subsurface flow		Surface flow	
ln(α/tanB) moment	Sign of partial regression coefficient	Partial F-value	Sign of partial regression coefficient	Partial F-value
Mean	+	56.8	+	28.5
Variance	-	8.9	+	25.6
Skew	+	3.9	-	2.1

Observed Relations between Topography and Stormflow Acidity

The mean concentration of streamflow acidity during August 1985 (Table 1) was used as an indicator of stormflow acidity. Among the watersheds, the mean of the ln(α/tanB) distribution was significantly correlated (r=0.85) with the mean hydrogen-ion concentration (Figure 1).

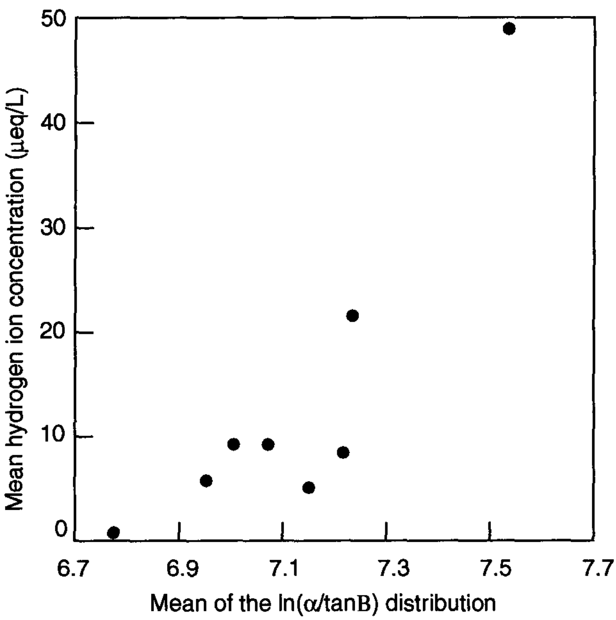

Figure 1. Mean ln(α/tanB) Value as a Function of August 1985 Mean Hydrogen-Ion Concentration for Eight Watersheds in, Wales, Great Britain.

Watersheds with larger ln(α/tanB) mean values (the ones expected from the TOPMODEL simulations to produce more surface and shallow subsurface flow) had higher acidity. These results are consistent with those of other researchers who have shown a relation between flow path and stormflow acidity (e.g., Lynch et al., 1986). Stormflow acidity appears to be substantially affected by topographic and inferred hydrologic differences.

Conclusions and Implications

This research has demonstrated that topographic characteristics are significantly correlated with stormflow acidity. This result is consistent with the hypothesis that topography has an important effect on flow path, and that flow path, in turn, has an effect on stormflow acidity.

The relation between topography and stormflow acidity has an important implication. Government regulatory agencies are interested in the regional assessment of watershed sensitivity to surface-water acidification. The research presented here shows that sensitivity is in part a result of watershed topographic characteristics that can be readily derived from topographic maps.

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