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Topography significantly influencing low flows in snow-dominated watersheds

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Abstract. Watershed topography plays an important role in determining the spatial heterogeneity of ecological, geomorphological, and hydrological processes. Few studies have quantified the role of topography on various flow variables. In this study, 28 watersheds with snow-dominated hydrological regimes were selected with daily flow records from 1989 to 1996. The watersheds are located in the Southern Interior of British Columbia, Canada and range in size from 2.6 to 1,780 km^2. For each watershed, 22 topographic indices (TIs) were derived, including those commonly used in hydrology and other environmental fields. Flow variables include annual mean flow (Q_{mean}), $Q_{10\%}$, $Q_{25\%}$, $Q_{50\%}$, $Q_{75\%}$, $Q_{90\%}$, and annual minimum flow (Q_{min}), where $Q_{x\%}$ is defined as flows that at the percentage (x) occurred in any given year. Factor analysis (FA) was first adopted to exclude some redundant or repetitive TIs. Then, stepwise regression models were employed to quantify the relative contributions of TIs to each flow variable in each year. Our results show that topography plays a more important role in low flows than high flows. However, the effects of TIs on flow variables are not consistent. Our analysis also determines five significant TIs including perimeter, surface area, openness, terrain characterization index, and slope length factor, which can be used to compare watersheds when low flow assessments are conducted, especially in snow-dominated regions.

Key words: Topographic indices; Flow regime; Snow-dominated; Relative contribution; Low flow.

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1. Introduction

Topography plays a critical role in geomorphological, biological, and hydrological processes (Moore et al., 1991; Quinn et al., 1995). Many topographic indices (TIs) have been derived to describe the spatial patterns of a landscape (Yokoyama et al., 2002), locate spatial patterns of species (Jenness, 2004), and simulate spatial soil moisture (Park et al., 2001). In hydrology, hydrological responses are forced by climatic inputs (e.g. precipitation) but are somehow controlled by topography and other factors such as land use and land cover (Beven and Kirkby, 1979; Hewlett and Hibbert, 1967). In describing the role of topography on hydrology, numerous TIs have been developed and applied to help understand hydrological processes and to explain the variation between watersheds (Moore et al., 1991). Although the importance of topography in controlling flow regimes has been widely recognized (Price, 2011), the quantitative relationship of specific TIs to various flow variables is not well understood.

TIs can be categorized into two groups, namely, primary and secondary (or compounded) indices (Moore et al., 1988). Primary indices (e.g. slope, elevation, and aspect) are normally directly calculated from a digital elevation model (DEM), while secondary indices are the combination of primary indices that are used to explain the role of topography in geomorphology, biology, and hydrological processes. For instance, the topographic wetness index (TWI) is defined as: ln (α/tanβ), where α is the upslope contributing area per unit contour length and β is the slope. TWI is a major input for TOPMODEL and other hydrological applications (Beven, 1995; Beven and Kirkby, 1979; Quinn et al., 1995). Hydrological studies mainly focus on primary TIs and a few secondary TIs with limited explanatory powers as they largely fail to explain the variation in hydrological processes. Several TIs (e.g., terrain characterization index, topographic openness) have been widely adopted in geomorphology and biology, but they are seldom used in hydrologic studies. A thorough examination of existing TIs is needed to identify those best accounting for hydrological variations between watersheds.

Studies of watershed topography on hydrological processes often include topics such as specific discharge (Karlsen et al., 2016), spatial baseflow distribution (Shope, 2016), transit time (McGuire and McDonnell, 2006; McGuire et al., 2005), and hydrological connectivity (Jencso and McGlynn, 2011). These studies were often conducted based on a short period of data (< 5 years), limiting our ability to draw general conclusions about how topography affects flows. Moreover, hydrological responses are compounded by the spatially diverse effects of climate, vegetation, soil, and topography (Li et al., 2017; Zhang et al., 2017). For example, several hydrological models have been applied to test the effect of the spatial distribution of a hydrological variable (e.g. specific discharge, soil moisture, or groundwater recharge) (Erickson et al., 2005; Gómez-Plaza et al., 2001; Li et al., 2014). However, the effects of topography alone on hydrology are not usually addressed in those studies. Finally, understanding how topography influences hydrology has important implications for sustainable management of aquatic ecosystems (Zhang et al., 2015). Therefore, the major objectives of this study were: 1) to examine the

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role of TIs in various flow variables in 28 selected watersheds with snow-dominated hydrological regimes in the Southern Interior of British Columbia, Canada; and 2) to identify the most important TIs that can be used to compare variations in flow regimes between watersheds under similar climatic conditions.

2. Data

2.1. Study watersheds

In this study, 28 watersheds were selected ranging in sizes ranging from 2.6 to 1,780 km^2 (Fig. 1 and Table S1 in the Supplementary Information (SI)). The watersheds are located between 51ºN 122ºW and 49ºN 118ºW in the Southern Interior of British Columbia, Canada where hydrological regimes are snow-dominated. In this region, the Pacific Decadal Oscillation shifted from a cool to a warm phase around 1977 (Fleming et al., 2007; Wei and Zhang, 2010), resulting in more precipitation and lower temperatures, and consequently affecting flow regimes. In addition, an extensive mountain pine beetle infestation caused large scale forest cover change from 2003 onwards. To avoid the uncertainties associated with these perturbations and maximize the sample size, the period of 1989-1996 was selected during which daily flow records are complete. In addition, we further confirm that vegetation changes (using LAI, as a proxy) did not significantly change annual mean flow during this period (see the SI, section 2).

Annual mean temperature (T) and precipitation (P) of the study watersheds were calculated from the ClimateBC dataset (Wang et al., 2006). ClimateBC is a standalone program that extracts and downscales PRISM (Daly et al., 2008) monthly climate normal data and calculates seasonal and annual climate variables for specific locations based on latitude, longitude, and elevation. Annual P, T, and potential evapotranspiration (PET) were determined at 500 x 500 m points and averaged for each watershed. PET was calculated using the Hargreaves method (Liu et al., 2016; Zhang and Wei, 2014). The average mean annual P and PET of all 28 watersheds were 813 ± 205 mm and 586 ± 58 mm for 1989-1996, respectively (Fig. 2 and Figs. S1-S4).

2.2. Topographic indices

Based on availability and representation of TIs in literature, 22 topographic indices (TIs) were derived using a gridded DEM at a spatial resolution of 25 m (Table 1). The DEM, geospatial streamflow networks, lakes and wetland coverage were obtained from GeoBC (Government of British Columbia, http://www2.gov.bc.ca/gov/content/data/about-data-management/geobc/geobc-products). All data were transformed to the same projected coordinate system prior to the calculations of TIs. Calculation of the TIs was made in ArcGIS10.4.1 (ERSI®) and SAGA GIS 2.1.2. Detailed information on the calculation and interpretation of TIs can be found in the references listed in Table 1.

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Figure 1. Locations of the 28 study watersheds and hydrometric stations.

Table 1. Topographic indices and descriptions

3. Methods

3.1. Definitions of the selected flow variables

Annual mean flow (Q_{mean}) and other flow variables generated by annual flow duration curve (FDC) were used in this study. The selected flow variables include: $Q_{10\%}$, $Q_{25\%}$, $Q_{50\%}$, $Q_{75\%}$, $Q_{90\%}$, and annual minimum flow (Q_{min}) (in millimeters). They are defined as the daily flow that is at the given percentage occurred in each year. For example, $Q_{90\%}$ is the flow at 90% of the time in a year (Cheng et al., 2012). To account for the confounding effects of climate, each annual flow variable was standardized with annual (P) and expressed as Q_X/P.

3.2. Factor analysis

Because some initially selected TIs may be highly related, the first step was to use factor analysis (FA) to reduce the number of TIs while still retaining important topographic information. FA can be interpreted in a similar manner as principal component analysis (PCA). The difference between the two approaches is that FA not only considers the total variance but also makes the distinction between common and unique variances (Lyon et al., 2012). As TIs were calculated in a region with similar

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topography, the average TIs may not vary greatly between watersheds (McGuire and McDonnell, 2006; Price, 2011). Therefore, to ensure better differentiation, the standard deviations of TIs in a watershed were used for the FA test. It should be noted that the flow variables were not included in the FA test.

Three criteria are used in the FA procedure to exclude redundant TIs: Kaiser-Meyer-Olkin (KMO), Bartlett's test, and anti-image correlation. KMO is a measure of sampling adequacy, which tests that partial correlations among variables are small enough to ensure the validity of the FA test. Bartlett's test of sphericity assesses the level of correlation between the variables in the FA to determine if the combination of variables is suitable for such analysis (Lyon et al., 2012). The diagonals of anti-image correlation matrix are a measure of sampling adequacy, which ensures that TIs are adequate for the FA. If a TI makes the FA indefinite, namely KMO < 0.7, Bartlett' test P > 0.05, and the diagonals of anti-image correlation < 0.7, then this TI is excluded from further consideration. With this iterative approach, the groups of TIs with largest KMO and Barlett's test P $<0.05$are determined as the final group of TIs. In this study, FA tests were conducted in the IBM® SPSS® Statistics Version 22.

3.3. Relative contributions of each TI to flow variables

The nonparametric Kendall tau correlation examines the flow variables and FA selected TIs in the 28 study watersheds. If a significant correlation is detected, it indicates a high topographic control on that

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flow variable. Stepwise regression models were then built for each year between 1989 and 1996 for each flow variable (see section 6 of the SI for details). Each flow variable was treated as the dependent variable, while each TI was the independent variable. The purposes of the stepwise regression models were: 1) to further exclude those TIs that were insignificantly related to flow variables; and 2) to quantify the relative contributions of selected TIs to each flow variable in each year. The detailed procedure can be found in Li et al. (2014). The R package "relaimpo" was used to quantify the relative contributions of the selected TIs to each flow variable (Gromping, 2006). Specifically, the relative contributions of each dependent variable to R^2 were calculated for each model.

To quantify the role of each TI in regulating each flow variable, we defined a contribution index (*CI*), which can be expressed as: $CI = O \times C$, where, O is the number of occurrences of a TI in a flow variable model (the maximum number is eight because each flow variable is studied for eight years), and C is the average relative contribution of each TI. Therefore, a higher *CI* indicates a higher influence of that TI on a flow variable. Finally, the lumped *CI* of each TI is presented as the total contribution of the TI to all flow variables. The TIs with the CI values that are higher than the average of lumped CI of all TIs were selected as the final set of TIs.

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4. Results

4.1. Factor analysis

A sub-set of 11 TIs were selected from the initial 22 calculated TIs using the FA procedure. The KMO test (0.853) and Barlett's test ($P<0.001$) on the 11 TIs further confirm that our selected TIs are adequate to represent topography in our study region. In the FA analysis, the first and second factors explained 80.9% and 11.7% of total variance, respectively (Fig. 3). TIs included in the first factor are: DDG, LS, openness, relief, slope, SA, TCI, and TRI, while those in the second factor include SCA, perimeter, and UCA. Based on the definition of each TI, we conclude that the first factor TIs represent watershed roughness or complexity, while the second factor TIs is about watershed size. Therefore, the selected 11 TIs were subsequently classified into two groups representing complexity (Group 1) and area (Group 2) (Fig. 3).

Figure 2. Factor analysis of topographic indices (TIs) among 28 watersheds. The first and second factors explained 80.9% and 11.7% of the total variance, respectively.

4.2. Relative contributions of TIs to flow variables

The nonparametric Kendall tau test revealed significant correlations between the TIs and each flow variable from 1989 to 1996 (Tables S2 to S8 in SI). Of the selected 11 TIs by FA, a total of 1, 1, 4, 8, 9, 10, and 11 TIs were significantly related to Q_{mean}, $Q_{10\%}$, $Q_{25\%}$, $Q_{50\%}$, $Q_{75\%}$, $Q_{90\%}$, and Q_{min}, respectively, in at least one year during the study period. A larger number of the TIs were correlated to low flow variables ($Q_{50\%}$, $Q_{75\%}$, $Q_{90\%}$, and Q_{min}), indicating that topography plays a more pronounced role in regulating lower flows. Here, flows lower than $Q_{75\%}$ are defined as the low flows. Thus, stepwise regression modeling was only carried out for $Q_{75\%}$, $Q_{90\%}$, and Q_{min}.

The regression models between flow variables and the selected TIs were all significant (P<0.01) with R^2 values > 0.5, indicating that selected TIs can be used to explain the variations of flow variables (Table S9). The details of regression models are listed in the SI. The TIs that were included in each model are shown in Fig. 3. The relative contributions of each TI to $Q_{75\%}$, $Q_{90\%}$, and Q_{min} showed large variations between years (Fig. 4-7). Fig. 3 revealed that each TI influences flow variables differently (e.g. SA played a prominent role in Q_{min} but did not significantly contribute to the variation of $Q_{75\%}$, while DDG had the opposite role). This means that each TI cannot be used to explain variation in the same way for each flow variable. Based on the lumped CI values, the relative contribution of the perimeter TI was the highest in Group 2 as well as among all TIs (Fig. 3). In Group 1, the TIs above the average of lumped CI were SA, openness, TCI, and LS receiving high contributions to low flows. Therefore, we conclude that the above-mentioned 5 TIs are significant topographic indices influencing low flow variables, which can be used to assess and compare low flows in watershed studies.

Figure 3. Relative contributions of each topographic index (TI) to $Q_{75\%}$ (Panel A), $Q_{90\%}$ (B), and Q_{min} (Panel C) from 1989 to 1996. Note that the numbers above the bars indicate the number of years

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when the given TIs were included in the regression models. Panel D: Contribution index (CI) of the 11 topographic indices (TIs) selected by factor analysis (FA) to $Q_{75\%}$, $Q_{90\%}$, and Q_{min}, respectively.

5. Discussion

In this study, our results show that a limited number of TIs are significantly related to the Q_{mean}, $Q_{10\%}$, and $Q_{25\%}$, suggesting that topography plays a limited role in the variations of average to high flows. This study area is characterized by snow-dominated hydrological regimes, with high flows (e.g., $Q_{25\%}$ or greater) coming predominantly from the snow-melt process in early March to late May (e.g. Fig. S5). Snow-melting processes are normally related to elevation and climate. As the study watersheds in the Southern Interior of BC, Canada have similar elevation ranges and climate variability, it is not surprising that only a limited TIs were significantly related to high or mean flows. In contrast, more TIs were significantly associated with low flows, suggesting that topography plays a more important role in low flows than high flows in the study region. Low flows occur in the later summer (late August) and winter (October to February) (e.g. Fig. S5) and are mainly driven by small return periods of precipitation events of relatively short durations, soil water storage, and groundwater discharge or baseflow. A watershed with more complexities of topography would likely have higher water retention ability due to longer flow paths and residence time, and consequently promote more groundwater recharging and higher low flows (Price, 2011). Our correlation tests uncover a positive relationship between the selected TIs and low flow variables, indicating that the rougher or more complex that a

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watershed is, the higher the yields of low flows. Therefore, topography plays more important role in low flows than in high flows in the study region.

Five TIs including perimeter, SA, openness, TCI, and LS were identified as the major contributors to flow variables in this study. As far as we know, no studies have quantified topographic controls on various flow magnitudes. Nevertheless, the relationship between topography and the mean transit time (McGuire and McDonnell, 2006), temporal specific discharge (Karlsen et al., 2016), and hydrological connectivity (Jencso and McGlynn, 2011) have been investigated. It is no doubt that topography is one of the major contributors to hydrological variations (Price, 2011; Smakhtin, 2001). Although these studies pinpointed specific TIs and their interactions with hydrological responses, only a limited number of TIs were included. In contrast, a total number of 22 TIs were calculated for 28 watersheds in this study. The much higher number of TIs included, along with our filtering methods applied allows us to select more suitable and significant TIs in this study. Through this study design, we expect that the selected five TIs can be effectively used to support assessment or comparisons of low flows between watersheds in the study region. It should also be noted that we only selected the first 5 TIs that had substantially higher contributions than the other calculated TIs. The rest of the hydrological-related TIs had a minor ability for explaining flow variations.

Among the selected 5 TIs, one primary TI (perimeter) is commonly used in scientific studies. Our study further proves that it has high influence on flow variables. However, the 4 secondary TIs (SA, openness, TCI, and LS) are mainly used in geomorphology to characterize ruggedness or roughness of landscapes and to identify topographic functioning of ecosystems. For examples, TCI has been used to map soil organic matter concentration (Zeng et al., 2016), while SA was used to estimate animal species and habitat (Jenness, 2004), map the spatial patterns of a flood plain (Scown et al., 2015). Openness was initially adopted to identify the boundary of different geological units (Yokoyama et al., 2002) and calderas (Yoshida et al., 1999). LS is one of the key inputs to the universal soil loss equation (USLE) used to quantify soil erosion hazards (Desmet and Govers, 1996). Park et al. (2001) indicated that TCI is a better TI to predict soil depth than TWI, plan curvature, and profile curvature (see definitions in Table 1). Openness is considered a robust index that is used to identify surface convexities and concavities, which is better than the commonly used profile and plan curvature (Yokoyama et al., 2002). In this study, the selected 5 TIs were initially filtered by the FA test, indicating that this sub-set of TIs each has uniqueness in describing watershed topographic characteristics, and outperformed the other tested TIs in describing variation in flow variables.

To our surprise, some commonly used TIs in hydrology, such as slope, median elevation, upslope contribution area, wetland areas, TWI, etc. are not included in the final list as the topographic information contained in those primary TIs also exists in some secondary TIs. Secondary TIs have the advantage of describing the hydrology-related landscapes in a fuller detail. For example, slope is directly included in calculations of the TWI (secondary) and DDG (secondary). UCA (primary TI) is included in TWI and TCI (secondary). The TWI has long been used as a key input variable for TOPMODEL, and is an indicator of soil moisture (Beven, 1995). Our study identified that TWI and wetland area were not significantly related to flow variables, indicating that these factors had a limited role in the selected flow variables in our region. This may be because the watersheds in this area need to overcome a soil moisture storage threshold prior to releasing water (Karlsen et al., 2016). In summary, our 5 selected TIs significantly represent low flow characteristics of the watersheds in the southern interior of British Columbia, Canada, which is characterized by a snow-dominated hydrological regime. As far as we know, there are no such studies conducted in either snow- or rain-dominated regions. Our research framework was developed based on a large number of watersheds with long-term hydrological data all in a similar climatic region that snow-dominated. To explore how topography controls flow regimes in rain-dominated regions, we recommend applying our framework in an area with large numbers of long-term monitoring stations.

There are several uncertainties in our study. Firstly, hydrological responses are the combined effects of climate, soil, vegetation, topography, and geology (Price, 2011; Smakhtin, 2001). In this study, LAI representing the variations of vegetation cover in different watersheds was included in our analysis in order to minimize the effects of different vegetation coverages in the studied watersheds. However, it was excluded by the FA test, confirming that the differences in vegetation cover and their effects were minor so that our selected watersheds are comparable in terms of forest coverage. Secondly, LS, TCI, and SA are commonly-used indicators of soil erodibility, and were included in this study to capture the influence of soil conditions. For example, Park et al. (2001) showed that the areas with high values of TCI have high rates of soil erosion. Therefore, the variation of soil properties was considered to some degree by the inclusion of these TIs, but not in a full detail. In fact, it is impossible to derive accurate soil properties over a large area. Thirdly, potential impacts of the DEM resolution on the calculation of TIs were not considered. However, Panagos et al., (2015) indicated that the resolution of 25 meters is adequate for calculation of slope factor at the European scale. Similarly, DEM resolutions were not found to significantly affect the calculation of DDG (Hjerdt et al., 2004). Thus, considering the same DEM data with the resolution of 25-meter, we assume the error caused by the DEM resolution would also be minor.

6. Conclusion

This study concludes that topography plays a significant role in low flows, while its role is high flows is limited. A total number of 5 topographic indices, including perimeter, LS (slope length factor), SA (surface area), TCI (topographic characteristic index), and openness, were identified with significant contributions to low flow variables. It is recommended that those above-mentioned 5 TIs can be used to assess the magnitude of low flows in the study region which is characterized by a snow-dominated hydrological regime. The application of our research framework to rain-dominated regions is recommended to investigate how topography controls flow regimes in these areas.

References

Ambroise, B., Beven, K., and Freer, J.: Toward a generalization of the TOPMODEL concepts: Topographic indices of hydrological similarity, Water Resour Res, 32, 2135-2145, 1996.

Beven, K., and Kirkby, M. J.: A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant, Hydrological Sciences Journal, 24, 43-69, 1979.

Beven, K.: Linking Parameters across Scales - Subgrid Parameterizations and Scale-Dependent Hydrological Models, Hydrol Process, 9, 507-525, doi: 10.1002/hyp.3360090504, 1995.

Burrough, P. A., McDonnell, R., McDonnell, R. A., and Lloyd, C. D.: Principles of geographical information systems, Oxford University Press, 2015.

Cheng, L., Yaeger, M., Viglione, A., Coopersmith, E., Ye, S., and Sivapalan, M.: Exploring the physical controls of regional patterns of flow duration curves - Part 1: Insights from statistical analyses, Hydrol Earth Syst Sc, 16, 4435-4446, 10.5194/hess-16-4435-2012, 2012.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., and Pasteris, P. P.: Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, Int J Climatol, 28, 2031-2064, 10.1002/joc.1688, 2008.

Desmet, P. J. J., and Govers, G.: A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units, J Soil Water Conserv, 51, 427-433, 1996.

Erickson, T. A., Williams, M. W., and Winstral, A.: Persistence of topographic controls on the spatial distribution of snow in rugged mountain terrain, Colorado, United States, Water Resour Res, 41, Artn W04014, doi:10.1029/2003wr002973, 2005.

Erskine, R. H., Green, T. R., Ramirez, J. A., and MacDonald, L. H.: Comparison of grid-based algorithms for computing upslope contributing area, Water Resour Res, 42, 2006.

Fleming, S. W., Whitfield, P. H., Moore, R. D., and Quilty, E. J.: Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia-Puget transboundary ecoregion, Hydrol Process, 21, 3264-3287, doi:10.1002/hyp.6544, 2007.

Gómez-Plaza, A., Martınez-Mena, M., Albaladejo, J., and Castillo, V.: Factors regulating spatial distribution of soil water content in small semiarid catchments, J Hydrol, 253, 211-226, 2001.

Greenlee, D. D.: Raster and vector processing for scanned linework, Photogramm Eng Rem S, 53, 1383-1387, 1987.

Gromping, U.: Relative importance for linear regression in R: The package relaimpo, J Stat Softw, 17, 2006.

Hewlett, J. D., and Hibbert, A. R.: Factors affecting the response of small watersheds to precipitation in humid areas, Forest hydrology, 1, 275-290, 1967.

Hjerdt, K. N., McDonnell, J. J., Seibert, J., and Rodhe, A.: A new topographic index to quantify downslope controls on local drainage, Water Resour Res, 40, Artn W0560, doi: 10.1029/2004wr003130, 2004.

Jencso, K. G., and McGlynn, B. L.: Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation, Water Resour Res, 47, Artn W11527 doi:.10.1029/2011wr010666, 2011.

Jenness, J.: Topographic Position Index (tpi_jen. avx) extension for ArcView 3. x, v. 1.3 a. Jenness Enterprises, URL: http://www. jennessent. com/arcview/tpi. htm, 2006.

Jenness, J. S.: Calculating landscape surface area from digital elevation models, Wildlife Soc B, 32, 829-839, Doi 10.2193/0091-7648(2004)032[0829:Clsafd]2.0.Co;2, 2004.

Karlsen, R. H., Grabs, T., Bishop, K., Buffam, I., Laudon, H., and Seibert, J.: Landscape controls on spatiotemporal discharge variability in a boreal catchment, Water Resour Res, 52, 6541-6556, 10.1002/2016WR019186, 2016.

Li, Q., Qi, J. Y., Xing, Z. S., Li, S., Jiang, Y. F., Danielescu, S., Zhu, H. Y., Wei, X. H., and Meng, F. R.: An approach for assessing impact of land use and biophysical conditions across landscape on recharge rate and nitrogen loading of groundwater, Agr Ecosyst Environ, 196, 114-124, 10.1016/j.agee.2014.06.028, 2014.

Liu, W., Wei, X., Li, Q., Fan, H., Duan, H., Wu, J., Giles-Hansen, K., and Zhang, H.: Hydrological recovery in two large forested watersheds of southeastern China: the importance of watershed properties in determining hydrological responses to reforestation, Hydrol Earth Syst Sc, 20, 4747, 2016.

Lyon, S. W., Nathanson, M., Spans, A., Grabs, T., Laudon, H., Temnerud, J., Bishop, K. H., and Seibert, J.: Specific discharge variability in a boreal landscape, Water Resour Res, 48, Artn W08506, doi: 10.1029/2011wr011073, 2012.

McGuire, K. J., McDonnell, J. J., Weiler, M., Kendall, C., McGlynn, B. L., Welker, J. M., and Seibert, J.: The role of topography on catchment-scale water residence time, Water Resour Res, 41, Artn W05002, doi: 10.1029/2004wr003657, 2005.

McGuire, K. J., and McDonnell, J. J.: A review and evaluation of catchment transit time modeling, J Hydrol, 330, 543-563, 10.1016/j.jhydrol.2006.04.020, 2006.

Moore, I., Burch, G., and Mackenzie, D.: Topographic effects on the distribution of surface soil water and the location of ephemeral gullies, Trans. ASAE, 31, 1098-1107, 1988.

Moore, I. D., Grayson, R. B., and Ladson, A. R.: Digital Terrain Modeling - a Review of Hydrological, Geomorphological, and Biological Applications, Hydrol Process, 5, 3-30, DOI 10.1002/hyp.3360050103, 1991.

Panagos, P., Borrelli, P., and Meusburger, K.: A new European slope length and steepness factor (LS-Factor) for modeling soil erosion by water, Geosciences, 5, 117-126, 2015.

Park, S. J., McSweeney, K., and Lowery, B.: Identification of the spatial distribution of soils using a process-based terrain characterization, Geoderma, 103, 249-272, doi: 10.1016/S0016-7061(01)00042-8, 2001.

Park, S. J., and van de Giesen, N.: Soil-landscape delineation to define spatial sampling domains for hillslope hydrology, J Hydrol, 295, 28-46, 10.1016/j.jhydrol.2004.02.022, 2004.

Price, K.: Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review, Prog Phys Geog, 35, 465-492, 2011.

Quinn, P., Beven, K., Chevallier, P., and Planchon, O.: The Prediction of Hillslope Flow Paths for Distributed Hydrological Modeling Using Digital Terrain Models, Hydrol Process, 5, 59-79, DOI 10.1002/hyp.3360050106, 1991.

Quinn, P. F., Beven, K. J., and Lamb, R.: The Ln(a/Tan-Beta) Index - How to Calculate It and How to Use It within the Topmodel Framework, Hydrol Process, 9, 161-182, doi: 10.1002/hyp.3360090204, 1995.

Riley, S. J.: Index That Quantifies Topographic Heterogeneity, intermountain Journal of sciences, 5, 23-27, 1999.

Scown, M. W., Thoms, M. C., and De Jager, N. R.: Measuring floodplain spatial patterns using continuous surface metrics at multiple scales, Geomorphology, 245, 87-101, 10.1016/j.geomorph.2015.05.026, 2015.

Shope, C. L.: Disentangling event-scale hydrologic flow partitioning in mountains of the Korean Peninsula under extreme precipitation, J Hydrol, 538, 399-415, 10.1016/j.jhydrol.2016.04.050, 2016.

Smakhtin, V. U.: Low flow hydrology: a review, J Hydrol, 240, 147-186, doi: 10.1016/S0022-1694(00)00340-1, 2001.

Wang, T., Hamann, A., Spittlehouse, D. L., and Aitken, S. N.: Development of scale-free climate data for western Canada for use in resource management, Int J Climatol, 26, 383-397, doi: 10.1002/Joc.1247, 2006.

Wei, X. H., and Zhang, M. F.: Quantifying streamflow change caused by forest disturbance at a large spatial scale: A single watershed study, Water Resour Res, 46, doi: 10.1029/2010wr009250, 2010.

Yokoyama, R., Shirasawa, M., and Pike, R. J.: Visualizing topography by openness: a new application of image processing to digital elevation models, Photogramm Eng Rem S, 68, 257-266, 2002.

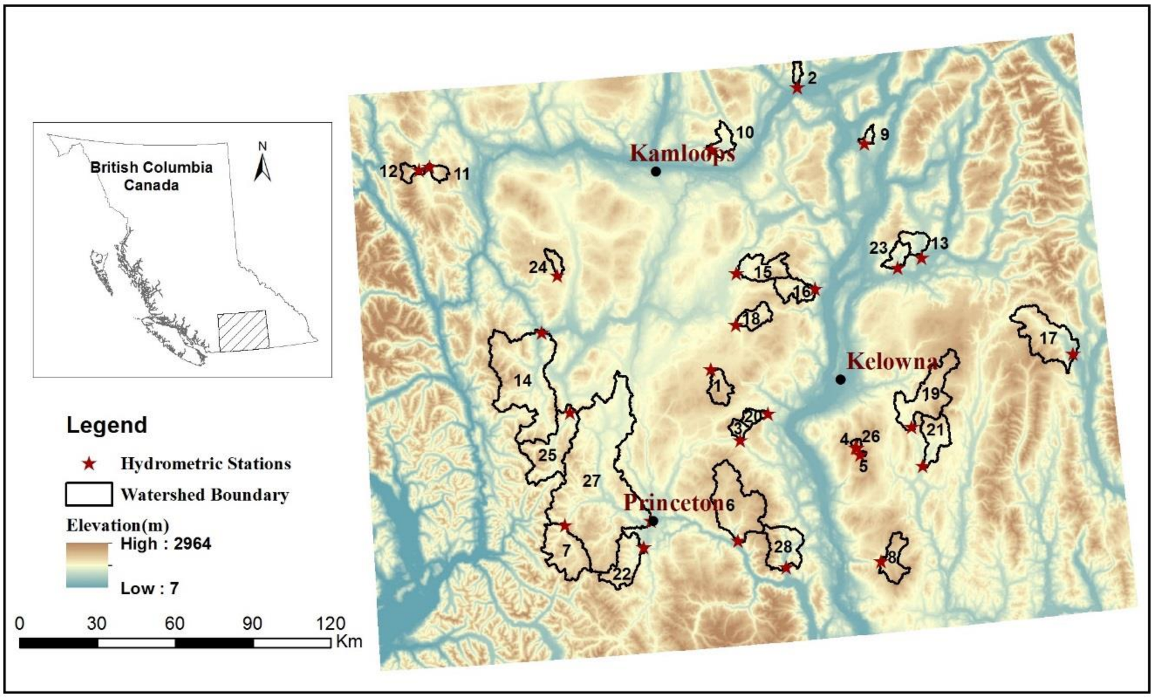
Yoshida, T., Kanisawa, S., Yokoyama, R., Shirasawa, M., and Ohguchi, T.: Refinement of geological map by referring to high-resolution DEM and the derived digital maps—application to the study of Late Cenozoic caldera swarm in the NE Honshu arc, Japan, EOS Transactions on American Geophysical Union, 80, F1088, 1999.

Zeng, C. Y., Yang, L., Zhu, A. X., Rossiter, D. G., Liu, J., Liu, J. Z., Qin, C. Z., and Wang, D. S.: Mapping soil organic matter concentration at different scales using a mixed geographically weighted regression method, Geoderma, 281, 69-82, doi:10.1016/j.geoderma.2016.06.033, 2016.

Zhang, M., and Wei, X.: Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: implications for forest management and future forest hydrology studies, Hydrol Process, 28, 6183-6195, doi: 10.1002/hyp.10107, 2014.

Zhang, M., Wei, X., and Li, Q.: A quantitative assessment on the response of flow regimes to cumulative forest disturbances in large snow-dominated watersheds in the interior of British Columbia, Canada, Ecohydrology, 2015.

Zhang, M. F., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X. H., Ning, D. Y., Hou, Y. P., and Liu, S. R.: A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime, J Hydrol, 546, 44-59, doi:10.1016/j.jhydrol.2016.12.040, 2017.



425 **Figure 1.** Locations of the 28 study watersheds and hydrometric stations.

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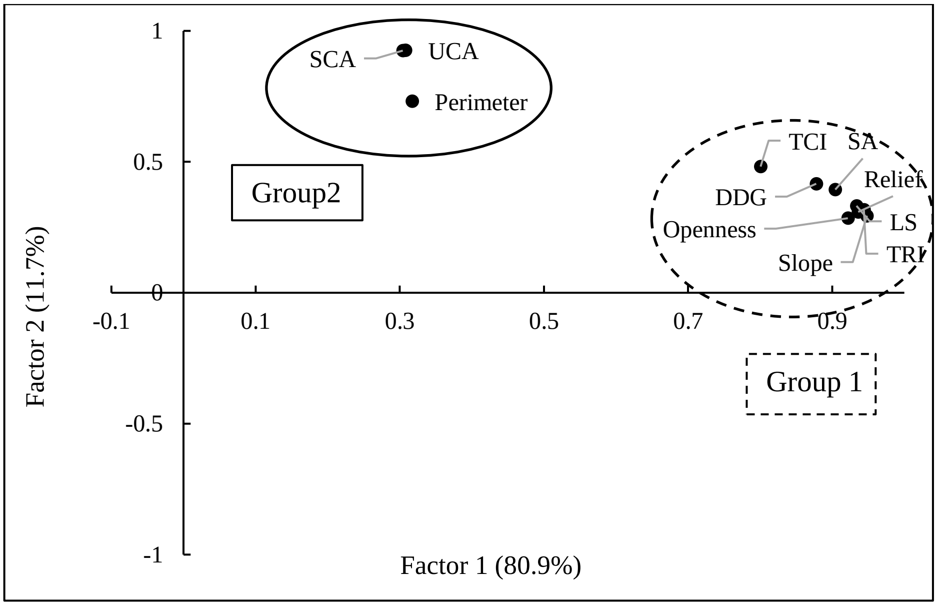

Figure 2. Factor analysis of topographic indices (TIs) among 28 watersheds. The first and second factors explained 80.9% and 11.7% of the total variance, respectively.

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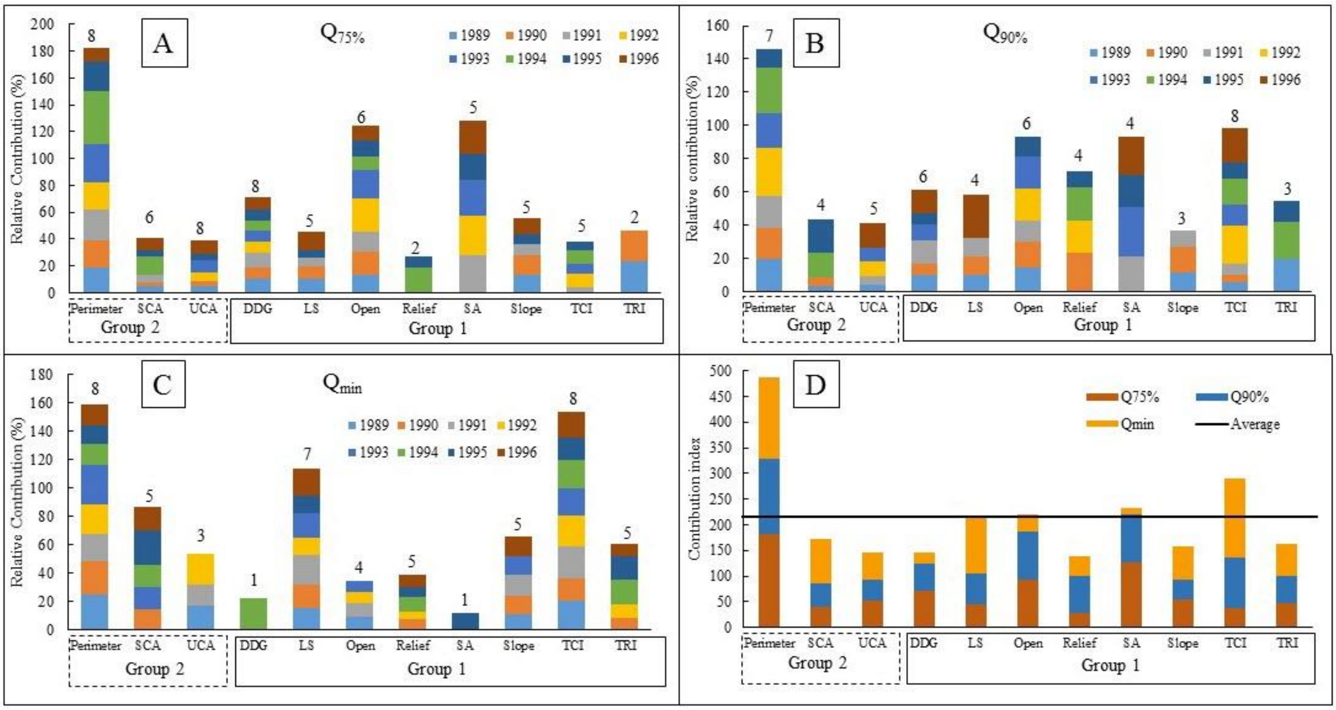

Figure 3. Relative contributions of each topographic index (TI) to $Q_{75\%}$ (Panel A), $Q_{90\%}$ (B), and Q_{min} (Panel C) from 1989 to 1996. Note that the numbers above the bars indicate the number of years when the given TIs were included in the regression models. Panel D: Contribution index (CI) of the 11 topographic indices (TIs) selected by factor analysis (FA) to $Q_{75\%}$, $Q_{90\%}$, and Q_{min}, respectively.

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Table 1. Topographic indices and descriptions

No.	Abbreviation	TI	Description and references
1	UCA	Upslope contributing area	UCA is the area that can potentially produce runoff to a given location (Erskine et al., 2006).
2	DDG	Downslope Distance Gradient	DDG is a hydrologic measure of the impact of the local slope characteristics on a hydraulic gradient. Values are lower on concave slope profiles and higher on convex slope profiles (Hjerdt et al., 2004).
3	DDGD	Downslope Distance Gradient Difference	The difference between DDG and local or neighbor gradients (Hjerdt et al., 2004).
4	FLD	Downstream flow length	The downslope distance of a pixel along the flow path to the outlet of a watershed (Greenlee, 1987).
5	ME	Median Elevation	Median elevation among all DEM pixels in a watershed.
6	Relief	Relief	The difference between the highest and lowest elevations within a local analysis window. 11×11 grid cell window is used in this paper.
7	Roughness	Roughness	Roughness is calculated as 1/cos(slope) of each DEM pixel.
8	Slope	Slope Degree	Slope degree of each DEM pixel (Burrough et al., 2015).
9	LS	Slope Length Factor	LS is a combined factor of slope length and slope gradient. It represents the ratio of soil loss per unit area on a site to the corresponding loss from a 22.1 m long experimental plot with a 9% slope (Desmet and Govers, 1996).
10	SCA, also known as A_s	Specific Contributing area	Upslope contributing area per unit length of contour (Quinn et al., 1991).
11	STD	Stream Density	Ratio of the sum of all stream length to watershed area.
12	TCI	Terrain Characterization Index	TCI = Cs *$\log_{10}$ (SCA), where Cs is the surface curvature index; The higher positive TCIs reflect higher aggradation of soil materials at a certain point along the hillslope (Park and van de Giesen, 2004).
13	TRI	Terrain Ruggedness Index	TRI expresses the degrees of difference in elevation among adjacent cells (Riley, 1999).
14	TPI	Topographic Position Index	TPI ≈ 0 indicates flat area. TPI>0 tends towards ridge tops and hilltops. TPI< 0 tends towards the valley and canyon bottoms (Jenness, 2006). A 9×9 grid cell window is used in this paper.
15	TWI	Topographic Wetness Index	TWI = ln (SCA/Tan(slope)), it shows the spatial distribution of zones of surface saturation and soil water content (Ambroise et al., 1996; Quinn et al., 1995).
16	Wetland	Wetland coverage	Percentage wetland area to total watershed area.
17	Length	Length of Main River	Total length of main stream,

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18	Roundness	Roundness coefficient	The ratio of watershed area to the area of a circle with the same perimeter. A lower value indicates a longer and narrow watershed.
19	Openness	Positive topographic openness	Describe the degree of dominance or enclosure of a location on an irregular surface. Values are high for convex forms (Yokoyama et al., 2002).
20	SA	Surface Area	Land area of each DEM, which may provide a better estimation of the surface roughness than planimetric area (Jenness, 2004).
21	Perimeter	Perimeter of a watershed	Perimeter of a watershed.
22	Total	Total curvature	Standard curvature combines profile and planform curvatures (Moore et al., 1991).