Editor's Comments

Dear Authors,

Thanks for the revision. I think the paper is getting better and better. However, as you will see one referee reviewed the paper and still has several major and minor remarks that should be addressed. **1)** I checked it as well and it seems we have a problem with Fig 3 (A). The Q75% is identical to the Q(min) panel C. The reviewer, but also I, did some counting of how often some TI were used in MLR and that does not match. Please check this as it leave doubt about your analysis. **2)** Second, in the supplement material of section 5 as several symbols are lacking. Could you also make a table in the supplement on how often TI's are used (to be able to verify the numbers used in fig 3).

I look forward to the revised version in due time.

Kind regards,

Thom

Response:

1) Thank you for the comments on our manuscript. I made a mistake in presenting the relative contributions of TIs to $Q_{75\%}$ in Fig. 3(A), which caused confusion to you and reviewer. I would like to mention that the MLR models of $Q_{75\%}$ in supplementary materials are correct. However, the relative contributions of TIs to $Q_{75\%}$ in Fig. 3 was wrong. In this revision, we have corrected this mistake and updated discussion accordingly. Despite this correction, our conclusions remain the same.

2) We have provided data in tabular format in the supplementary materials (Tables S10-S13) to support the Fig. 3.

3) We have attached the new Fig. 3 as well as Tables S10-S13 as presented below for your convenience.

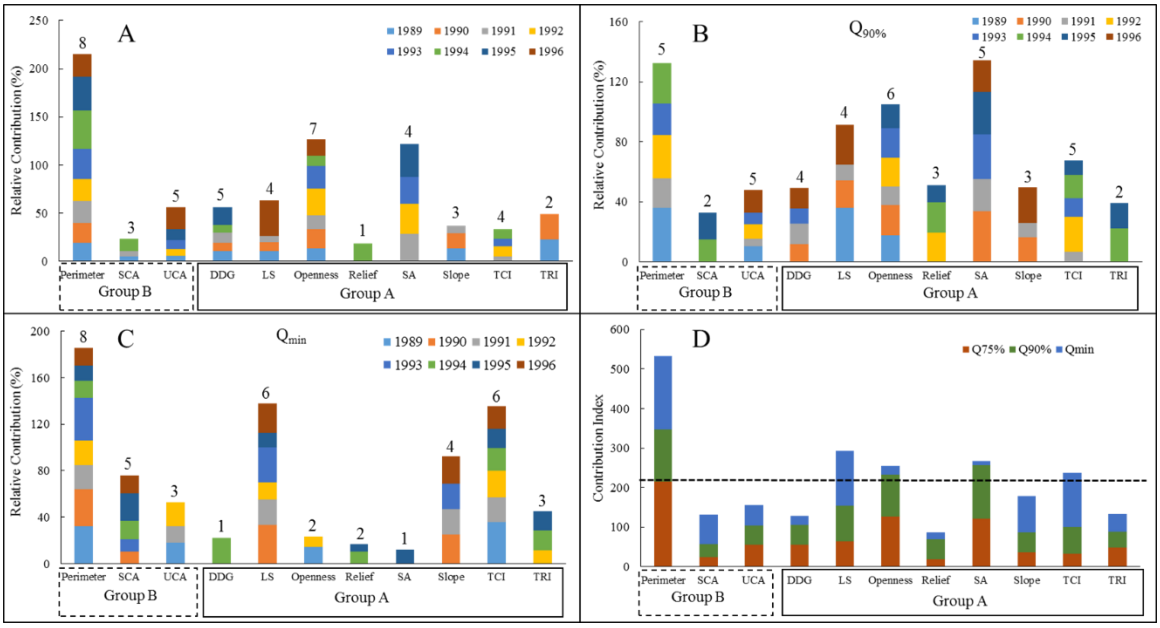

Figure 3 Relative contributions of each topographic index (TI) to $Q_{75\%}$ (Panel A), $Q_{90\%}$ (B), and Q_{min} (Panel C) from 1989 to 1996. Note that the numbers above the bars indicate the number of years when the given TIs were included in the regression models. Panel D: Contribution index (CI)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

Table S10 Summary of relative contributions of TIs to $Q_{75\%}$ from 1989 to 1996

$Q_{75\%}$	1989	1990	1991	1992	1993	1994	1995	1996	Average	Count	Contributions
Perimeter	18.7	21.3	22.6	22.6	31.3	39.7	35.3	23.2	26.9	8	214.8
SCA	4.9	-	5.3	-	-	13.4	-	-	7.9	3	23.6
UCA	5.3	-	-	7.3	9.3	-	11.6	22.4	11.2	5	55.9
DDG	10.8	8.4	10.5	-	-	8.0	18.5	-	11.2	5	56.2
LS	10.7	9.0	6.7	-	-	-	-	36.9	15.8	4	63.2
Openness	13.3	20.1	14.3	27.7	23.4	10.7	-	17.4	18.1	7	126.9
Relief	-	-	-	-	-	18.5	-	-	18.5	1	18.5
SA	-	-	28.0	31.4	27.8	-	34.6	-	30.5	4	121.8
Slope	13.4	15.3	8.0	-	-	-	-	-	12.3	3	36.8
TCI	-	-	4.5	11.0	8.2	9.8	-	-	8.4	4	33.4
TRI	23.0	26.0	-	-	-	-	-	-	24.5	2	48.9

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Table S11 Summary of relative contributions of TIs to $Q_{90\%}$ from 1989 to 1996

$Q_{90\%}$	1989	1990	1991	1992	1993	1994	1995	1996	Average	Count	Contributions
Perimeter	35.8	-	19.9	28.8	20.7	27.1	-	-	26.5	5	132.3
SCA	-	-	-	-	-	15.0	17.7	-	16.4	2	32.7
UCA	10.5	-	5.2	9.4	7.6	-	-	15.0	9.5	5	47.7
DDG	-	11.6	14.0	-	10.0	-	-	13.7	12.3	4	49.3
LS	35.8	18.5	10.5	-	-	-	-	26.6	22.9	4	91.4
Openness	17.9	19.9	12.4	19.0	19.7	-	16.0	-	17.5	6	104.9
Relief	-	-	-	19.5	-	20.0	11.6	-	17.0	3	51.1
SA	-	33.6	21.6	-	29.5	-	28.3	21.1	26.8	5	134.1
Slope	-	16.4	9.5	-	-	-	-	23.6	16.5	3	49.5
TCI	-	-	6.8	23.2	12.5	15.6	9.6	-	13.5	5	67.7
TRI	-	-	-	-	-	22.4	16.9	-	19.7	2	39.3

Table S12 Summary of relative contributions of TIs to Q_{min} from 1989 to 1996

Q_{min}	1989	1990	1991	1992	1993	1994	1995	1996	Average	Count	Contributions
Perimeter	32.2	31.6	20.9	21.1	36.8	14.8	12.6	15.9	23.2	8	185.9
SCA	-	10.2	-	-	11.0	15.5	23.9	15.5	15.2	5	76.1
UCA	17.7	-	14.2	21.0	-	-	-	-	17.6	3	52.9
DDG	-	-	-	-	-	22.2	-	-	22.2	1	22.2
LS	-	33.3	22.0	14.7	30.0	-	12.5	25.2	23.0	6	137.7
Openness	14.3	-	-	8.9	-	-	-	-	11.6	2	23.2
Relief	-	-	-	-	-	10.5	6.5	-	8.5	2	17
SA	-	-	-	-	-	-	11.9	-	11.9	1	11.9
Slope	-	24.9	21.8	-	22.3	-	-	23.3	23.1	4	92.3
TCI	35.7	-	21.1	23.1	-	19.8	16.0	20.0	22.6	6	135.7
TRI	-	-	-	11.2	-	17.1	16.6	-	15.0	3	44.9

Table S13 Summary of the lumped relative contributions of TI to $Q_{75\%}$, $Q_{90\%}$, and Q_{min}

CI	$Q_{75\%}$	$Q_{90\%}$	Q_{min}	Average
Perimeter	214.8	132.3	185.9	533.0
SCA	23.6	32.7	76.1	132.4
UCA	55.9	47.7	52.9	156.5
DDG	56.2	49.3	22.2	127.7
LS	63.2	91.4	137.7	292.3
Openness	126.9	104.9	23.2	255.0
Relief	18.5	51.1	17.0	86.6
SA	121.8	134.1	11.9	267.8
Slope	36.8	49.5	92.3	178.6
TCI	33.4	67.7	135.7	236.8
TRI	48.9	39.3	44.9	133.1
Average				218.2

Reviewer's Comments

In the manuscript by from Li et al. titled "Topography significantly influencing low flows in snow-dominated watersheds", the influence of topography on the flow regime is analysed and the main topographical features influencing the flow are identified. First, various topographical features commonly used in hydrology, geomorphology, ecology etc. were defined. Redundant features were then excluded by means of factor analysis. For the remaining features, their significance on the flow was analysed by means of multi linear regression models. Based on this analysis, low flows were found to be most sensitive to topographical features, specifically the perimeter, slope length factor, slope and topographic characteristics index.

The topic addressed is very interesting and in general well explained. However, there are some revisions necessary before publishing the paper.

Major comments:

(1) It is stated that all TIs included in the multi linear regression (MLR) model are significant (line 161). The supplementary information however does not support this: some TIs included are not significant! It was mentioned in an author response to a review that this would be corrected, yet there are this insignificant TIs included in the MLR. **(2)** In addition, Fig 3 is not supported by the MLR results given in the supplements. If I understand correctly, the number of occurrence in this figure is the number of times a TI is included in the MLR model. However, this is not always the case, for example the TI DDG for Q75%: the number of occurrences is 1 based on Fig 3 whereas it is 5 based on the supplements (1989, 1990, 1991, 1994 and 1995). This means the results are not supported by the supplements; therefore how can this figure and the conclusions drawn from it be verified?

Response: 1) We have carefully examined the statistical significance of TIs in all the MLR models. We confirm that all selected TIs are statistically significant. 2) Thanks for pointing this out. We have corrected the mistake in the last revision. In the revised manuscript, we now include Tables S10-S13 to support Fig. 3.

Minor comments:

1) Lines 75-79: It seems, the focus is on analysing the influence of the topography on various flow magnitudes instead of the flow regime in general. To avoid confusion, this could be specified more clearly, for example in the objectives.

Response: We have rephrased flow *regimes* to *magnitudes* for consistency throughout the manuscript.

2) Line 171 and 174: It is referred to a figure with the results (Fig 3) whereas this is a methodology section. A figure indeed helps explaining the methodology more clearly, yet it is too early to refer to the results in the methodology section.

Response: We have excluded this reference in methods.

3) Lines 225-230: The author states, that topography does not influence the high flows significantly as the topographical features influencing the high flows such as elevation are quite similar in this region. (a) Does this mean this study merely analyses whether a TI is variable enough to significantly influence a flow variable? Is it therefore possible that a TI significantly influences the flow, yet is not seen in this study due to low variability in the analysed catchments?

Response: Thanks for the interesting questions. The selected TIs are based on the statistical significance between TIs and hydrological variables. Our tests did not find any statistically significant relationship between TIs and high flows. This is mainly because high flows are normally associated with climate and land cover change. In addition, high flows are the hydrological variables with shorter time intervals and thus are more sensitive to any factors (e.g., climate) with quicker changes. In contrast, low flows are mainly related to accumulation of recharging and discharging processes over a much longer term, and thus are more related to the static factors (e.g., watershed property). This is why our study only found significant relationships between some TIs and low flows.

Our selection of important TIs is based on their statistical relationship to flow variables. A TI with large variation may not necessarily have significant impact on flow. Regarding your second question (Is it therefore possible that a TI significantly influences the flow, yet is not seen in this study due to low variability in the analysed catchments?), this is largely dependent on sampling. It is likely that if the number of selected watersheds is not enough, possible statistical relationship between a TI and flow variables may not be detected. In our study, we selected 28 watersheds with a large range in watershed properties for several years. We believe that this selection provides a robust inference about the relationship between TIs and flow variables.

Technical corrections:

4) Line 102: I assume Figure 1 is meant instead of Figure 2.

Response: Done.

5) Line 120: Sentence is grammatically incorrect. Suggested alternative: “They are defined as the daily flow that occurred each year at a given percentage.”

Response: Thanks for your suggestion. We have revised it.

6) Line 188: I assume Figure 2 is meant instead of Figure 3.

Response: Done.

7) Figures 1 and 3 have inconsistent captions when comparing the caption in the main text and the one below the figure.

Response: Done.

8) Line 329: spelling mistake: “in” instead of “is”

Response: Done.

9) Line 333: grammatical error: “in a study region” instead of “in the study region”

Response: Done.

10) Fig S5: inconsistent variable names: “PPT” & “P” for precipitation

Response: Done.

11) Fig S1-5: wrong units in the axes labels (mm/yr) instead of (mm)

Response: Done.

12) Section 5.1 in the supplements: spelling mistakes or inconsistencies in the naming of the TIs (for example CA instead of UCA, SCA or SA), making it rather difficult to compare the different results. If it is not a spelling mistake, then TIs are mentioned in the supplements, but not in the manuscript, for instance Table 1.

Response: Thanks for pointing this out. The CA in the supplementary material stands for the UCA. We have corrected the expression throughout the manuscript for consistency.

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 in various flow variables. In this study, 28 watersheds with snow-dominated hydrological regimes were selected with daily flow records from 1989 to 1996. These 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 daily flows occurred in any given year ~~that~~ at the percentage (x) ~~occurred in any given year~~. Factor analysis (FA) was first adopted to exclude some redundant or repetitive TIs. Then, multiple linear 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 (flow magnitudes $\leq Q_{75\%}$) than high flows. However, the effects of TIs on flow ~~variables~~ magnitudes are not consistent. Our analysis also determines ~~four~~ five significant TIs including perimeter, slope length factor, ~~slope,~~surface area, ~~openness, slope length factor,~~ openness, and terrain characterization index, which can be used to compare watersheds when low flow assessments are conducted, especially in snow-dominated regions with the watershed sizes less than several thousand square kilometres.

Keywords: Topographic indices; Flow ~~regime~~magnitudes; Snow-dominated; Relative contribution; Low flow.

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 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 ~~o~~in 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 various flow ~~regimes~~ magnitudes has been widely recognized (Price, 2011), the quantitative relationship between specific TIs and 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 required primary 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 hydrological 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 et al., 2005; McGuire and McDonnell, 2006), and hydrological connectivity (Jencso and McGlynn, 2011). These studies were often based on a short period of data (< 5 years), limiting our ability to draw general conclusions on how topography affects hydrological processes. Moreover, hydrological responses are compounded by the spatially diverse effects of climate, vegetation, soil, and topography (Li et al., 2017; Wei et al., ~~2017~~2018; Zhang et al., 2017). For example, several hydrological models have been applied to test the effects of 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 significant implications for sustainable management of aquatic ecosystems (Zhang et al., 2016). Therefore, the major objectives of this study were: 1) to examine the role of topography in various flow magnitudes~~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 topographic indices that can be used to compare variations in flow ~~regimes~~ magnitudes 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~~ hydrological 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 of selected stations are complete. In addition, we

further confirm that vegetation changes (using LAI~~,~~ as a proxy) did not significantly alter 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 a spatial resolution of 500 meters and averaged for each watershed. PET was calculated using the Hargreaves method (Liu et al., 2016; Wang 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~~ 1 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 ArcGIS 10.4.1 (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.

Figure 1. Locations and elevations of the 28 study watersheds, and their hydrometric stations (red star sign).

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

Table 1. 22 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}) (mm day^{-1}). They are defined as the daily flow that occurred each year ~~is~~ at the given percentage ~~occurred in each year~~. For example, $Q_{90\%}$ is the flow magnitude 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 introduce 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 major 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 topography, the average TIs at the watershed level are not varied dramatically between watersheds (McGuire and McDonnell, 2006; Price, 2011). Therefore, to ensure better differentiation, the standard deviations of TIs of 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 were 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 of specific TIs, 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 group of TIs with the largest KMO, Barlett's test P <0.05, and the diagonals of anti-image correlation > 0.7 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's tau correlation examined the statistical correlations between flow variables and the FA selected TIs in the 28 study watersheds. If a significant correlation is detected, it indicates high topographic control on that flow variable. Multiple linear regression (MLR) models were then built for each year between 1989 and 1996 for each flow variable (see section 5 in the SI for details). The purposes of the MLR models were: 1) to further exclude those TIs that were insignificantly related to flow variables, and 2) to quantify the relative contributions of the selected TIs to each flow variable in each year. In the MLR models, each flow variable was treated as a dependent variable, while all FA selected TIs were regarded as independent variables. To exclude insignificant TIs to flow variables, all the selected 11 TIs by the FA were initially included in the MLR model. The ANOVA test was then adopted to identify the statistical significance between TIs and each flow variable in each year. If one TI was insignificant ($P>0.05$), then it was removed from the model. The ANOVA test was then re-run for the rest TIs to ensure that all significant TIs were selected. By the trial and error process, the final models with only significant TIs to flow variables were determined. The detailed procedure can also be found in Li et al. (2014). Then, the R package "relaimpo" was used to quantify the relative contributions of the selected TIs to each flow variable (Gromping, 2006). In particular, the relative contributions of each dependent variable to R^2 were calculated for each model. In this way, the contributions of the significant TIs to flow variables were derived for each MLR 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 the selected TIs appearing in the final multiple linear regression models (the maximum number is eight because each flow variable is studied for eight years), and *C* is the average relative contribution of each TI to the specific flow variable . Therefore, a higher *CI* indicates a higher influence of that TI on a flow variable ~~(e.g., Fig. 3 A to C)~~. The lumped *CI* of each TI to each flow variable is treated as the total contribution of the TI to all flow variables. Finally, the TIs with the CI values that are higher than the average of the lumped CI of all TIs were determined as the final set of TIs ~~(e.g., Fig. 3 D)~~. As such, TIs with higher contributions were selected for the flow variables.

4. Results

4.1. Factor analysis

A subset of 11 TIs ~~were~~ was selected from the initial 22 calculated TIs using the FA procedure. The KMO test (0.853), Barlett's test (P<0.001), and the diagonals of anti-image correlation (> 0.7) on the 11 TIs further confirm that our selected TIs are adequate to represent topographical characteristics of a watershed in our study region. In the FA analysis, the first and second factors explained 80.9% and 11.7% of total variance of TIs in the selected watersheds, respectively (Fig. 2). 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 further conclude that the first factor represents watershed roughness or complexity, while the second factor describes the watershed size. Therefore, the selected 11 TIs were subsequently classified into two groups representing complexity (Group A) and area (Group B) (Fig. ~~3~~2).

Figure 1. 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's tau test revealed significant correlations between the TIs and each flow variable from 1989 to 1996 (Tables S2 to S8 in SI). The number of significant TIs in each year increased from 1 to 11 with decreasing in flow magnitudes. A larger number of the TIs were correlated to low flow variables ($Q_{75\%}$, $Q_{90\%}$, and Q_{min}), indicating that topography plays a more pronounced role in regulating lower flows. Here, flows lower than or equal to $Q_{75\%}$ are defined as the low flows. Thus, MLR models were 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 MLR models are listed in the SI. The TIs that were included in each model are shown in Fig. 3 and Tables S10-S13. The relative contributions of each TI to $Q_{75\%}$, $Q_{90\%}$, and Q_{min} showed large variations between years (Fig. 3 A to C, and Tables S10-S12). Fig. 3 revealed that each TI influences flow variables differently (e.g. SA played a prominent role in $Q_{90\%}$ but did not significantly contribute to the variation of Q_{min} ~~and $Q_{75\%}$~~, while ~~SCA~~ openness 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 was the highest in Group B as well as among all TIs (Fig. 3). In Group A, the TIs above the average of the lumped CI were LS, SA, openness, ~~slope,~~ ~~TCI~~SA, and TCI ~~and LS~~ receiving high contributions to low flows. Therefore, we conclude that the above-mentioned ~~four~~ five TIs are significant topographic indices influencing low flow variables, which can be used to assess and compare low flows in any watershed studies where there are similarities in watershed sizes and climate.

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. Dash line is the average of the lumped CI.

~~**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.~~

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 annual mean flow and 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 significantly related to elevation and climate in our study region (Winkler et al., 2005). 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 often occur in the later summer (late August) and winter (October to February) (e.g., Fig. S5), and are mainly driven by groundwater discharges and small amounts of precipitation. 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 recharge and higher low flows (Price, 2011). Our Kendall's tau correlation tests uncover a positive relationship between the selected TIs and low flow variables (Tables S6-S8), indicating that the rougher or more complex of a watershed is, and the higher yields of low flows are. Therefore, we conclude that topography plays a more important role in low flows than in high flows in the study region.

~~Four~~ Five TIs including perimeter, LS, ~~slope~~SA, openness, and 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 quantitatively assessed. 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. Through this study design, we expect that the selected ~~four~~ five TIs can effectively be 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 ~~four~~ five 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 ~~four~~ five TIs, ~~two~~ perimeter, a primary TI~~s, (perimeter and slope) are~~ is commonly used in scientific studies to describe the characteristic of watershed topography. Our study further proves that ~~they~~ it ha~~ves~~ high influences on low flow variables. However, ~~the other two~~ four secondary

TIs (LS, SA, openness, and 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). Park et al. (2001) revealed that TCI is a better TI to predict soil depth than TWI, plan curvature, and profile curvature (see definitions in Table 1). LS is one of the key inputs to the universal soil loss equation (USLE) being used to quantify soil erosion hazards (Desmet and Govers, 1996). SA was used to estimate animal species and habitat (Jenness, 2004), and map the spatial patterns of a floodplain (Scown et al., 2015). Openness was initially adopted to identify the boundary of different geological units and can be 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 ~~four~~ five TIs were initially filtered by the FA test, indicating that each selected TI has uniqueness in describing watershed topographic characteristics, and is more outperformed than the other tested TIs in describing variation in flow variables in our study region. Therefore, we expect that ~~TCI and LS~~selected five TIs can be applied to support hydrological analysis and modelling.

To our surprise, some commonly-used TIs in hydrology, such as slope, median elevation, upslope contribution area, wetland areas, etc. are not included in the FA 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 full 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). It is also worth mentioning that some secondary TIs played critical roles in determining the spatial heterogeneity of ecological and geomorphological processes, but their roles in hydrological processes in our study region were not demonstrated. These TIs were, therefore, not selected in this study. For example, ~~T~~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 played 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). ~~It is also worth mentioning that some secondary TIs played critical roles in determining the spatial heterogeneity of ecological and geomorphological processes, but their roles in hydrological processes were not demonstrated. These TIs were, therefore, not selected in this study. For instances, SA was used to estimate animal species and habitat (Jenness, 2004), map the spatial patterns of a floodplain (Scown et al., 2015). Openness was initially adopted to identify the boundary of different geological units and can be used to identify surface convexities and concavities, which is better than the commonly used profile and plan curvature (Yokoyama et al., 2002).~~ In summary, our selected ~~four~~ five 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.

In our study, FA was first introduced to exclude reductant TIs. The MLR models were further employed to exclude the insignificant TIs to various flow ~~regimes~~magnitudes. There is a concern whether the TIs excluded by FA were significantly related to flow ~~regimes~~magnitudes, but not included in the MLR models. To address this concern, we have re-run analysis by conducting the MLR models for Q_{min} in 1989, 1990, and 1991 as examples (section 6 in SI). The results showed that the MLR models would include several redundant TIs (e.g., wetland coverage, roundness, stream length) if the FA test was not conducted (Table S1~~0~~4). Kendall's tau correlation tests uncovered that they were not significantly correlated with low flows (Table S8). This further demonstrates that some redundant and nonsignificant TIs would be introduced if the FA test was not initially conducted. In addition, 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. As far as we know, there are no such studies conducted in either snow- or rain-dominated regions. Our research methodology or framework can be applied in rain-dominated regions to assess how topography controls flow in any regions where there are sufficient long-term monitoring data.

There are several uncertainties in our study. Firstly, hydrological responses are the ~~combined~~ resultant 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. In addition, climate could be a confounding factor affecting our comparisons. In this study, annual flow variables were standardized by the annual precipitation to minimize the effects of climate on flow variables. In this way, the effects of climate variability were considered to some extent but not in full detail. For examples, in extreme dry or wet years (e.g., 1994 and 1996 are the driest and wettest years in our study period, respectively) (Fig. S2-S5), hardly any of the TIs were significantly correlated to $Q_{90\%}$ (Table S7), but almost all were correlated to Q_{min} (Table S8). This is because that the flows at $Q_{90\%}$ in 1994 and 1996 in the selected watersheds occurred in the winter (October-February) (e.g., Fig. S5), while Q_{min} in the majority of watersheds were in the late summer (August and September). Our Kendall's tau correlation tests (Table S7) also confirm that topography played a minor role in $Q_{90\%}$, but a significant role in Q_{min} (Table S8). Thus, hydrological responses are mainly controlled by the combined effects of climate and topography. Secondly, LS and TCI 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 degrees by the inclusion of these TIs, but not in 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 that 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~~ in high flows is limited. A total number of ~~four~~ five topographic indices, including perimeter, LS (slope length factor), SA (surface area), ~~slope~~openness, ~~SA (surface area),~~ and TCI (topographic characteristic index), were identified with significant contributions to low flow variables. It is recommended that those above-mentioned ~~four~~ five TIs can be used to assess the magnitude of low flows in ~~the~~ a study region which is characterized by a snow-dominated hydrological regime with the watershed sizes up to several thousand square kilometres. Our research methodology can be applied to other regions for investigating how topography controls flow ~~regimes~~magnitudes.

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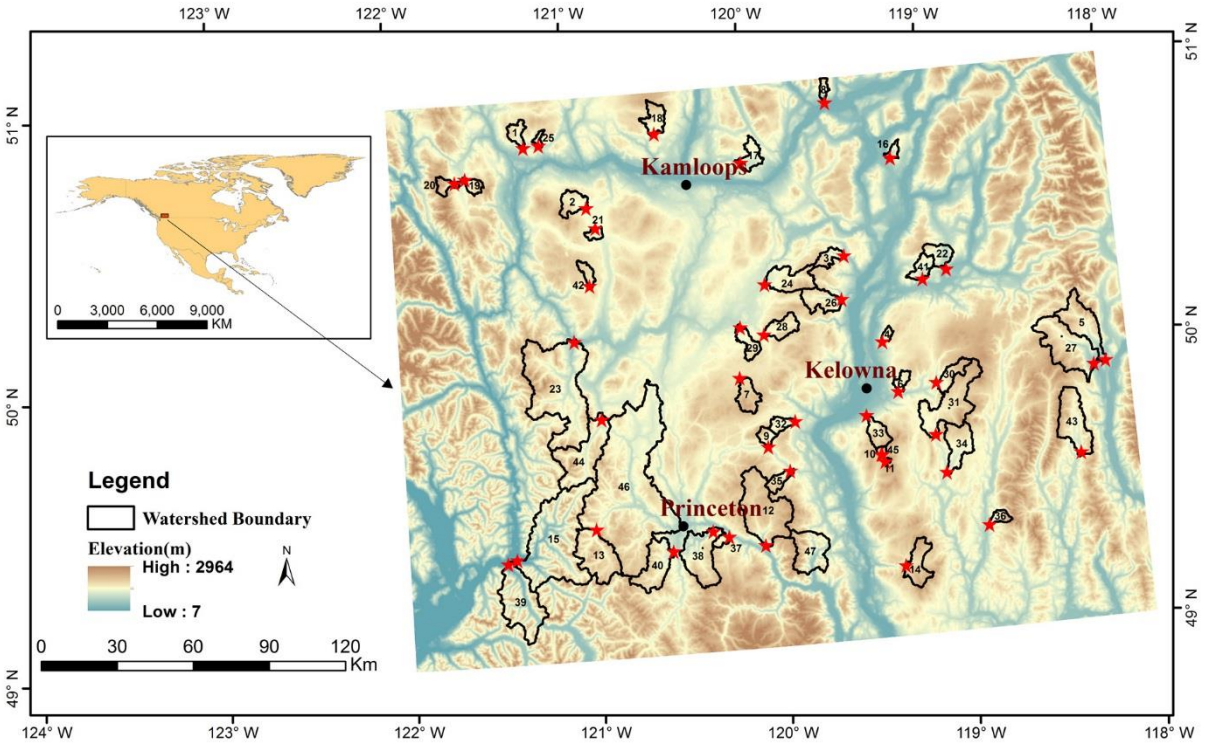


640 **Figure 1.** Locations and elevations of the 28 study watersheds, and their hydrometric stations (red star sign).

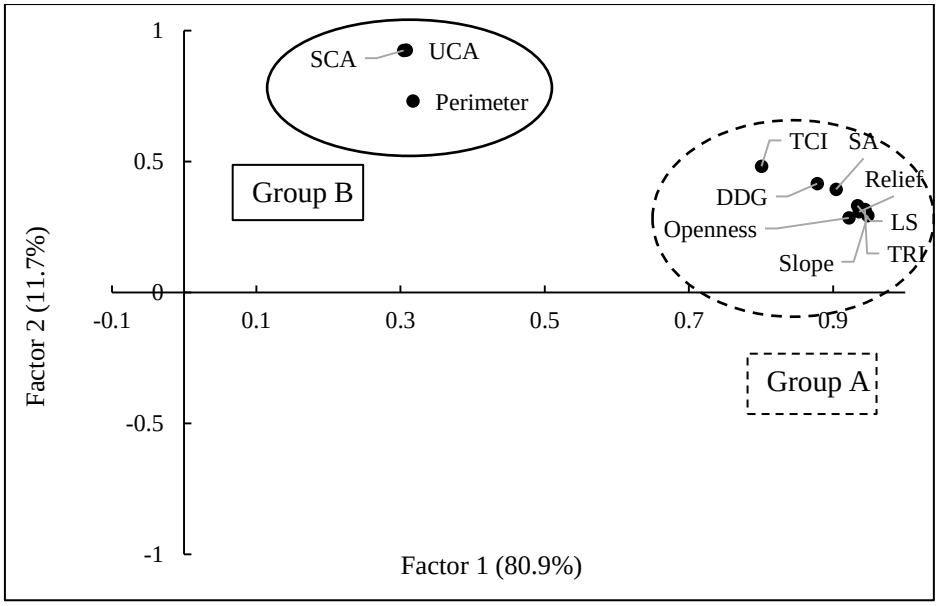
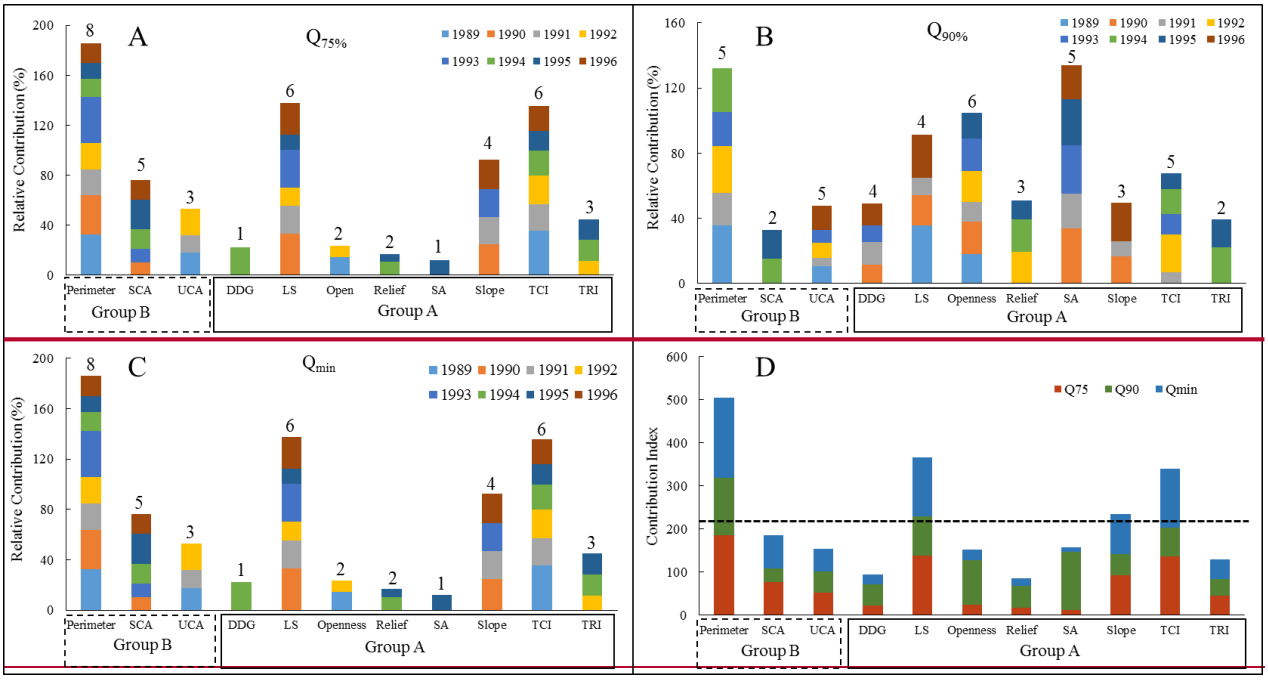


Figure 2. Factor analysis of topographic indices (TIs) among 28 watersheds. The first and second factors explained 80.9% and 11.7% of the total variance, respectively.


A
$Q_{75\%}$
B
$Q_{90\%}$
C
Q_{min}
D
1989 1990 1991 1992 1993 1994 1995 1996
Relative Contribution (%)
Contribution Index
Q75 Q90 Qmin
Perimeter SCA UCA DDG LS Openness Relief SA Slope TCI TRI
Group B
Group A

645

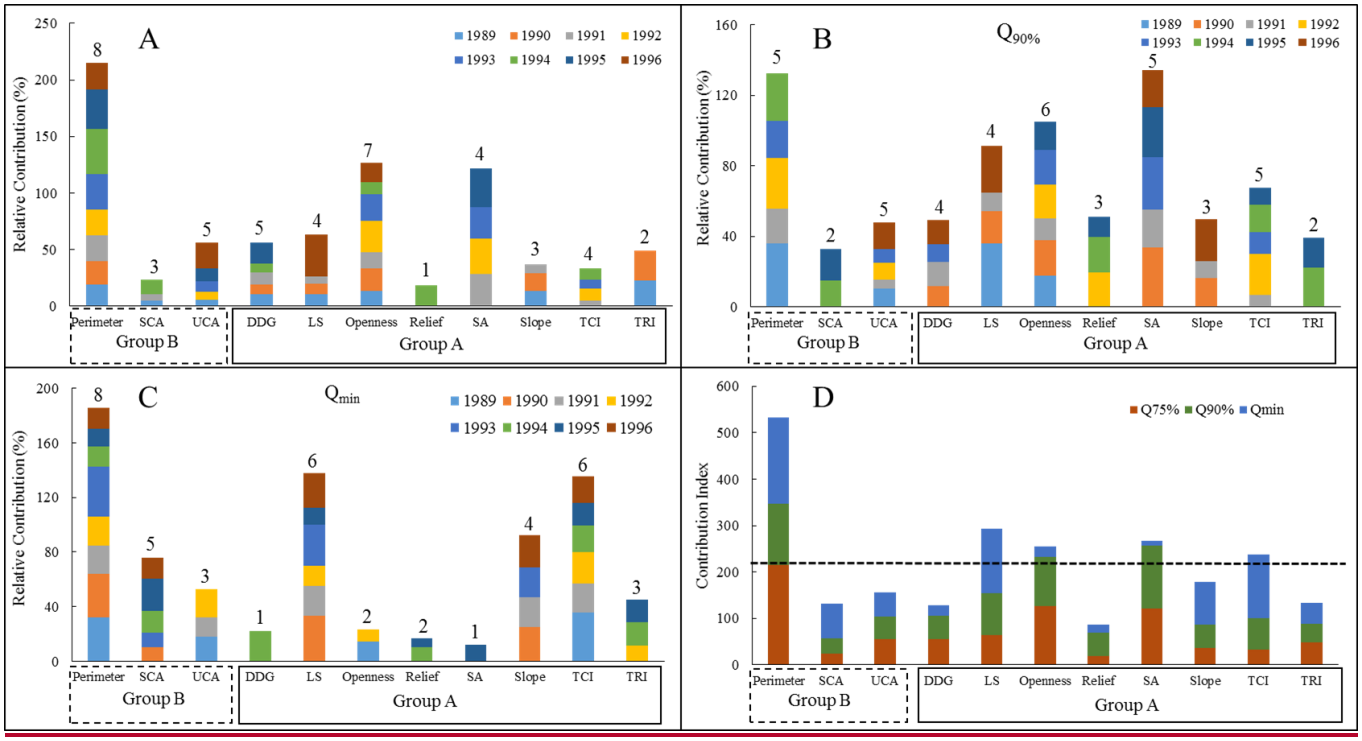


Figure 3. Relative contributions of each topographic index (TI) to $Q_{75\%}$ (Panel A), $Q_{90\%}$ (B), and Q_{min} (Panel C) from 1989 to 1996. Note that the numbers above the bars indicate the number of years when the given TIs were included in the regression models. Panel D: Contribution index (CI)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

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 low on concave slope profiles and high on convex slope profiles (Hjerdt et al., 2004).
3	DDGD	Downslope Distance Gradient Difference	The difference between DDG and local or neighbour 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 TCI values 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). It calculates the sum changes between a grid cell and its eight neighbour grid cells. Higher values indicate more ruggedness of a watershed.
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	The total length of mainstream.
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 and low for concave forms, respectively (Yokoyama et al., 2002).
20	**SA**	Surface Area	The land area of each DEM, which may provide a better estimation of the surface roughness than the planimetric area (Jenness, 2004). A lower value indicates a more gentle topography.
21	**Perimeter**	Perimeter of a watershed	The perimeter of a watershed.
22	Total	Total curvature	The standard curvature combines profile and planform curvatures (Moore et al., 1991).

Note: Bold and underlined TIs are selected by the Factor Analysis test.