Editor’s Comments

Comments to the Authors:

Dear Authors,

Thanks for the detailed responses in the discussion phase of your article. The referees indicate it is an interesting and well written article. I agree and would like to publish it. I look forward receiving a revised manuscript which should reflect/include the different aspects discussed in the open discussion phase (TI descriptions, methodology of FA and MLR including the nice discussion leading Table R1 (supplement?)

Lastly, I noticed the authors replied a few times saying that "this is something for future research". I challenge the authors to try to discuss some of that in the discussion section of the article. I support you in your wish to stay close to the results of your research, but some thoughts on transferability and use of hydrological indexes could be interesting for HESS readers.

Kind regards

Thom Bogaard

Response to Editor's comments:

Dear Dr. Thom Bogaard,

Thank you for your constructive comments on our manuscript. We have carefully addressed your and reviewers' comments. In this revision, we have provided detailed descriptions in TIs description (Table 1), FA and MLR methods, and included Table R1 in the Discussion section. As per reviewers' suggestions, we also have added some discussions to address uncertainties in our results. Please see our response letter and marked manuscript for the details.

In addition, our method of investigating the topographic control on low flow was established in snow-dominated watersheds. We suggest our research framework can be applied to rain-dominated watersheds with available long-term hydrological data. We also recommend using our selected TIs for hydrological analysis and modelling, which could be of interest to HESS readers.

I am looking forward to hearing from you further.

Sincerely,

Qiang Li

Reviewer #1 Comments by Dr. Petra Hulsman:

The manuscript "Topography significantly influencing low flows in snow-dominated watersheds" from Li et al, submitted to Hydrology and Earth System Sciences, attempts to assess the role of topography on various flow variables to identify important topographic indices (TIs). This was done by first defining a set of TIs of which redundant ones were excluded based on a factor analysis. The remaining TIs were used to estimate their relative contribution to the flow variables: each variable separately for each year. This contribution was estimated with linear regression models. This analysis indicated that the contribution of the TIs were greater for the low flows; the most significant TIs were: perimeter, surface area, openness, and terrain characterization index and slope length factor. Hence, the topography significantly influences the low flows for this study region.

The topic addressed in this manuscript is very interesting. In general, the paper is well written: there is a clear structure, complete and concise summary and a clear title indicating the conclusion of this paper. The methods are generally explained clearly with just a few missing details needed for reproducibility, for example on occurrence/contribution of TIs and on the linear regression model. Based on the results shown, it is clear how the conclusions are taken. However, it is not possible to verify everything, for example the selection of non-redundant TIs. There are just some drawbacks that should be improved.

Response: Thanks for your comments on our manuscript.

General comments:

1) The focus seems to be on having an extensive list of TIs rather than flow variables while both is necessary to thoroughly assess the influence of topography on the flow. Additional flow variables that might be interesting to include are, for example slope of flow duration curve, rising limb density, auto-correlation function or the timing (start of a season, duration of a season).

Response: Thanks for your suggestion. The main theme of this manuscript is to investigate how topography influences several key variables in association with flow regimes. We agree that the suggested additional hydrological variables (slope of flow duration curve, rising limb density, auto-correlation function or the timing, etc.) are also important. However, flow variables selected in this study focus on flow magnitudes, while the suggested variables are mainly related to the characteristic of the hydrograph. Therefore, we are concerned that inclusion of those suggested variables might dilute our key focus of this paper.

2) (a) Good idea to exclude redundant signatures, but as a result some signatures are only included indirectly (line 260-262) making it rather difficult to assess their significance on the flow variables.

(b) Also, what if a secondary TI selected for the analyses (e.g. DDG), turns out to be significant only because of the primary TI (e.g. slope) included in this secondary TI? So how conclusive are the results with the selection of these TIs?

Response: We think both questions are valid and relevant, but they are all related to the test methods themselves we used in this study. (a) The Factor Analysis (FA) is a widely used technique to reduce larger datasets that consist of several variables into fewer sets or factors (Yong and Pearce, 2013). The goal of the FA in this study is to determine the reduced number of significant variables to represent the large dataset of TIs. In our study, the number of topographic indices (TIs) was reduced from 22 to 11 by the FA. 11 TIs were further classified into two groups and named as "area" and "complexity". Some primary TIs may be indirectly included in the secondary TIs, which indicates that those primary TIs are not significant, and less representative than those secondary TIs. As such, the contributions of these primary TIs not selected by the FA test are much lower than the selected secondary TIs.

(b) Of the selected TIs, both primary and secondary TIs were determined by the FA test. The FA test can distinguish the variables according to the properties of TIs rather than the categories of the TIs (i.e. primary or secondary). In this study, we set three criteria (see the manuscript for the details) to exclude the redundant TIs. We selected the more conservative KMO and anti-image correlation values of 0.7 instead of the commonly-used 0.5. Such selection ensures our results more robust. In this way, the TIs containing redundant information were excluded, while the most representative and significant TIs were kept. Thus, it is possible that some variables (e.g., slope) might be excluded because they are not selected by the FA test, but their signatures may be included in other selected and significant TIs.

3) (a) Explain the methodology of the stepwise linear regression model detailed: include whether a fixed order for including additional TIs was used and whether this order is of significance. (b) In the linear regression, TIs were included even though their resulting estimates are very low. Aren't these TIs insignificant and shouldn't they therefore be excluded?

Response: (a) Thanks for your suggestion. We have included a more detailed explanation regarding multiple linear regression models (MLR) in the revised manuscript (See Line 155-165). Here, we brief the procedure of MLR to respond to the reviewer's comments. All the selected 11 TIs by the FA test were initially included in the MLR model. The ANOVA test was used to identify the significance between TIs and flow variables. If one TI was insignificant, 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, final models with only significant TIs to hydrological variables were determined.

(b) The reviewer noticed that some TIs in regression models were not statistical significant (P>0.05), but still included. We agree with the reviewer's assessment. In this revision, we have excluded those insignificant TIs and updated our results accordingly in our revised manuscript.

4) Suggested addition to the discussion: under what conditions are the results transferable to other watersheds? For example are results expected to be differently for even larger watersheds (e.g. 150 000 km^2) with similar climatic conditions?

Response: Thanks for your suggestion. In this study, watersheds sizes range from 2.6 to 1780 km^2 under a similar climate condition. Therefore, our results can definitely be transferred to any other watersheds with the similar watershed size range defined in this study. It is an interesting and open question if our results can be extrapolated to other very large watersheds. Therefore, our refined results can be transferable to any watershed sizes up to several thousand square kilometres under a similar climate condition.

Specific comments:

5) Line 42: The term "somehow" is not nice in a paper, it just be removed here

Response: We have excluded it in our revision.

6) Line 94: include an evaluation with ground measurements if possible

Response: ClimateBC model has been validated by climate stations across British Columbia, Canada. The validation process is presented in Wang et al. (2006), and this reference is cited in the manuscript.

7) Line 119: unclear unit of the flow variables: mm/year or mm/d?

Response: The unit is mm day^{-1}. We have corrected it in the revised manuscript.

8) Line 129/130: include in section "2.1 Study Watersheds" that the topography is similar and how that is assessed.

Response: We assumed that topography is similar if the average values of TIs at the watershed level do not vary significantly. This is because that the average values can cancel out large variations in TIs. As such, we used standard deviation to represent the variations in TIs between watersheds. Please see Line 130-134 for more details.

9) Line 134: The third criteria seems to be excluded from the analysis. It is not mentioned after this section. If that is the case, then exclude it here too.

Response: No. Excluding a TI by the FA test is a trial and error process. Therefore, we strictly followed all three criteria. Therefore, this criterion was not excluded. We made it more explicit in the revised manuscript.

10) Line 158: It is unclear what exactly is meant with the "occurrence of a TI" and how it is determined (it's actually clearer in the caption of Fig 3).

Response: Original Line 158: *O* is the number of occurrences of a TI in a flow variables model.
Revision: *O* is the number of selected TIs appearing in the final multiple linear regression models.

11) Line 160: It is unclear what exactly is meant with the "contribution of each TI" and how it is determined.

Response: The "contribution of each TI" means the contribution (%) of each selected TI to explain the R^2 of each multiple regression model.

We have provided such statement in Line 153-155. The R package "relaimpo" was used to quantify the relative contributions of the selected TIs to flow variables. Specifically, the relative contribution of each independent variable to R^2 was calculated for each model.

12) Line 167: Include results indicating that other (groups of) TIs are indeed repetitive and should be excluded for the sake of verification.

Response: We understand your comment. Although 11 TIs were excluded by the FA test, it would be useful to indicate them. Thus, we highlighted the selected TIs in Table 1 so that those unselected TIs can easily be identified.

13) Line 170: a) Variance of what? b) How is it calculated?

Response: a)
Revision: First and second factors explained 80.9% and 11.7% of <u>total variance of TIs in the selected watersheds, respectively</u>.

b) The total variance is one of the standard outputs of the FA. In this study, it is calculated by the SPSS software.

14) Line 170-175 and Fig2: SA is the surface area, yet it is not grouped in group 2 which describes the area!

Response: As described in Table 1, the SA is the land area of each DEM pixel. It represents the roughness of a DEM pixel or a watershed. The larger value of SA indicates more roughness of a watershed. Therefore, it is classified in Group 2 or Group B in the updated manuscript.

15) Line 182: Confusing formulation of "1, 1, 4, 8, 9, 10 and 11"

Response: The Kendall tau tests were conducted between flow variables and each TI for each year from 1989 to 1996. Due to the difference in climate among years, flow variables showed distinct responses to topography. Therefore, we counted the numbers of the significant TIs to represent the relationship between flow variables and TIs. Here is the revision.

Revision: The number of significant TIs in each year increased from 1 to 11 from 1989 to 1996.

16) Line 194: Sentence contradicts results in Fig 3. According to Fig 3, SA does not play a significant role in Q_{min}, but is significant in $Q_{75\%}$.

Response: Thanks for pointing this out. We have corrected this statement.

Revision: SA played a prominent role in $Q_{90\%}$, but did not significantly contribute to the variation of $Q_{75\%}$ and Q_{min}.

17) Line 221: "positive relationship between the selected TIs and low flow variables"; this is not the case for the openness which always has negative estimates in the regression model results as shown in the supplements.

Response: Thanks for pointing this out. We revised our statement accordingly in the revised manuscript.

18) Line 256: It is not surprising these commonly used TIs such as slope was not in the final list as it was excluded from the selected TIs and therefore its contribution was not even calculated in order to end up in the final list. Its contribution is only indirectly assessed through other TIs. How different would the results and conclusion be if all TIs were included?

Response: To answer this question, we have re-run models for the minimum flows for three years without conducting the FA test first. The other procedures were kept the same. The Table R1 in this response letter (below) showed that the models now included several redundant TIs (e.g., wetland coverage, roundness, stream length) if the FA test was not conducted. However, they were not significantly correlated with low flows indicated by Kendall correlation test. This further suggests that some redundant and nonsignificant TIs would be included if the FA test was not conducted initially. It further proves the benefits of adopting the FA test. We provided such discussion in the revised manuscript and included the Table R1 in the supplementary material. Please see Line 286-299 for the details.

Table R1. Topographic indices included in the multiple regression models of Q_{min} for years of 1989, 1990, and 1991 with or without the FA test.

Year	Model variables with initial FA test	Model variables without initial FA test
1989	Openness, Perimeter, TCI, UCA	DDG, DDGD, LS, Openness, Perimeter, Relief, Roundness, SA, Stream Length, Slope, TRI, TPI, Wetland
1990	LS, Perimeter, Relief, SCA, Slope,	Median Elevation, Roundness, Stream Length, Wetland, TPI, LS, Openness, SA, TCI, TRI
1991	LS, Perimeter, Slope, TCI, UCA	DDG, DDGD, LS, Openness, Perimeter, Relief, Roundness, Stream Length, SCA, SA, TRI, Wetland

19) Fig 1: hydrometric stations are plotted, yet not mentioned in the paper. It is suggested to either mention how they were included or exclude them from the figure.

Response: We have included the stations in the revised manuscript. Please also see response No. 22.

Technical corrections:

20) Line 170 and 175: Fig 3 written, yet probably referred to Fig 2

Response: Yes. The correct reference should be Fig 2.

21) Line 193: Fig 4-7 missing

Response: This is a typo. We meant Fig. 3 (A-D).

22) Fig 1: missing scale bar for the small map of the state. This small map misses the background map showing the location of neighbouring land, now it seems the state is an island which is not the case!

Response: Thanks for your suggestion. We have redrawn Figure 1.

23) Fig 2: missing description of axes (what do these numbers on the axes indicate?); confusing choice of words: factor 2 = group 2. Use the same thing in the figure and label.

Response: First and second factors are the standard expressions of the factor analysis. Based on the factor analysis, we classified the TIs into two groups. To avoid the confusion, we have named two groups to "Group A" and "Group B", respectively.

24) Supplement tables list: inconsistent font types

Response: Thanks for pointing this out. We have revised them accordingly.

25) Supplement Fig S1: inconsistent abbreviation for precipitation (PPT in figure and P in capture); do not connect the points to lines as the results for each watershed are independent from each other; line for temperature is not visible in a black/white print

Response: We have corrected them accordingly.

Reference

Yong, A. G., Pearce, S. (2013). A beginner's guide to factor analysis: Focusing on exploratory factor analysis. *Tutorials in quantitative methods for psychology*, *9*(2), 79-94.

Reviewer #2's Comments by Dr. Niclas Hjerdt:

In this paper, Li et al. present evidence that certain topographic indices are useful to describe the variability in low flows between watersheds with snow-dominated hydrological regimes in the Southern Interior of British Columbia, Canada. The authors arrive at this conclusion by analyzing 22 different topographic indices and comparing them to flow statistics in the different watersheds. Using factor analysis, half of the original number of topographic indices was found to be non-redundant and together describe more than 90% of the variance in the watersheds. By building multiple regression models of these indices to explain the variability in flow statistics, the authors identified a set of five indices which were especially useful to compare watersheds when low flow assessments are conducted. These topographic indices were perimeter, surface area, openness, terrain characterization index, and slope length factor.

The topic of this study has actually been discussed during recent years of drought where I work in Sweden. Different authorities have been looking for ways to map streams with high risk of drying out during prolonged periods of dry weather. The results of this study add nicely to the already existing knowledge on the subject, i.e., the risk of a stream drying out increases with decreasing catchment area, decreasing winter precipitation, increasing ratio between evapotranspiration and precipitation, absence of lakes and wetlands, and decreasing soil depth. Not all of Sweden has snowmelt-dominated hydrology, so the findings would have to be verified across a wider spectrum of landscapes and climatology, but this would be interesting to pursue in the near future.

The general conclusion that "topographic ruggedness/roughness acts to sustain low flows" warrants further investigation to become practically useful. Earlier studies have indicated that riparian areas play a central role in streamflow generation, and it is difficult to relate this finding directly to the work done in this study. There has also been evidence that, during dry periods, topographic controls on drainage may be surpassed by local (evaporative) controls, making much of the watershed "disconnected" from the hydrologic network. Nevertheless, the study by Li et al. brings up interesting linkages between topography and hydrology not previously explored.

Response: Thanks for your comments on our manuscript. It is commonly accepted that climate, land use or land cover, and topography are the three major drivers that affect hydrological responses. This study examines how different hydrological variables response to topography alone, which fills the knowledge gap between topography and hydrology.

General comments:

1) The ratio of annual PET/P (Figure S4 in the supplement) is useful in a broad sense, but the effect of evapotranspiration on the water balance varies greatly between winter and summer. This causes summer precipitation to be "less valuable" to water storage in the catchment compared to winter precipitation. In able to distinguish this, i.e., identifying years with more/less effective precipitation, I recommend that PET/P is analyzed monthly instead of annually.

Response: Thanks for your constructive comments. In this study, we selected 28 watersheds in the snow hydrology-dominated region, and concluded that topography plays a more dominant role in low flows. Of selected watersheds, low flows often occur in summer (June-September). Therefore, we suggest that the PET/P in summer can provide more valuable information than that from monthly data in our study area. Here is the revised Fig. S5 in the revised manuscript.

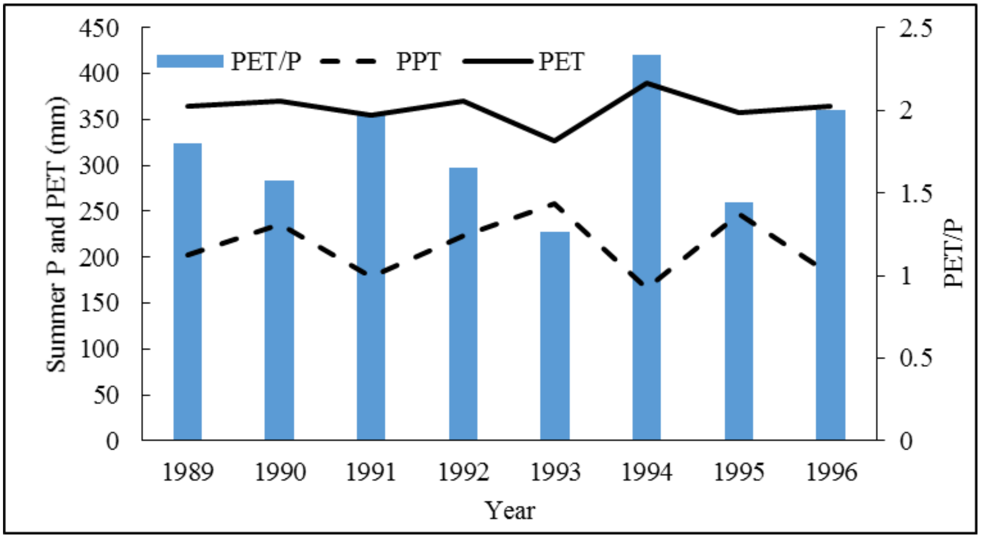

Figure S5 Temporal variations of the average summer (June-September) precipitation (P), potential evapotranspiration (PET), and dryness index (PET/P) in the study watersheds from 1989 to 1996.

2) The results of this study are somewhat difficult to translate to practical meaning as many of the topographic indices can be quite abstract to many readers. In the discussion part of the paper, the authors should consider to supplement the reasoning around the different indices with examples that illustrate what the indices measure in reality, e.g., examples of landscapes with low vs. high index values. This is not absolutely necessary but would stimulate discussions about the findings of the study.

Response: We fully understand the point. Numerous topographic indices (TIs) have been developed for various purposes, and therefore not all TIs are closely related to flow regimes. In the updated manuscript, we determined four TIs that have higher contributions to low flows than other TIs. Of the selected TIs, the perimeter and slope are the easiest ones to measure and visualize. The others derived from ArcGIS are hard to measure in the field and also abstract to readers. However, our study provides valuable information in understanding topographic control on hydrological processes, especially for low flows in a watershed. Our final goal is to provide a watershed sensitivity map based on integration of various selected TIs in our future studies, which can provide a practical guide for resource planning and management. As suggested, we have added detailed explanations of TIs in Table 1 and in the discussion section.

<u>Specific comments:</u>

3) Lines 121-122. Each annual flow variable was standardized with annual (P), but flows may be more related to (P-ET) which better describes the effective precipitation.

Response: Yes, the effective precipitation is a good indicator for hydrological variables, especially for annual runoff. In this study, we were investigating how topography controls different magnitudes of daily flows. In our study watersheds, evapotranspiration was not consistent throughout the year, but dominant in the summer. If flow variables were standardized by the effective precipitation, the standardized flows may be overestimated in the summer and underestimated in the winter. This would introduce more uncertainty into the assessment. In addition, streamflows are usually normalized by precipitation in literature. Therefore, we argue that precipitation is a relatively better indicator than effective precipitation for our study objective.

4) Lines 217-218. Please rephrase "[: : :] are mainly driven by small return periods of precipitation events of relatively short durations".

Response: Here is the revision (Underlined).

Line 217-218: Low flows occur in the later summer (late August) and winter (October to February), <u>and are mainly driven by groundwater discharges and small amounts of precipitation.</u>

5) Supplement Table S7-S8. In extreme years (1994 dry, 1996 wet) hardly any of the TIs are significantly correlated to Q_{90}, but almost all are correlated to Q_{100}. Why?

Response: Thanks for pointing this out. To answer this question, we revisited the hydrology data in the selected watersheds. We found that flow magnitudes at the Q_{90} in 1994 and 1996 in most watersheds occurred in the winter (October-February) (Please also see Figure S5 in Supplementary Material). Our correlation tests (Table S7) indicates that topography plays a minor role in $Q_{90\%}$ As such, hydrological responses are mainly controlled by the combined effects of climate and topography. In contrast, Q_{100} in the majority of watersheds occurs in the late summer (August and September). Table S8 suggests that topography is significantly related to Q_{100} indicating that the role of topography plays a more dominant role in minimum flows. We have added more discussion in the revised manuscript (Line 306-317) to clarify this issue.

6) Supplement Table S8. Consider changing Q_{100} to Q_{min} to avoid confusion with the main text.

Response: Thanks. We have revised them accordingly.

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~~ 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 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, 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 are not consistent. Our analysis also determines ~~five~~ four significant TIs including perimeter, ~~surface area~~slope, slope length factor, and ~~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 with the watershed sizes up to several thousand square kilometers.

Key words: Topographic indices; Flow regime; 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 ~~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~~ between specific TIs ~~to~~ 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 ~~major~~

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 conducted based on a short period of data (< 5 years), limiting our ability to draw general conclusions about on how topography affects flowshydrological 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; Zhang et al., 2017). For example, several hydrological models have been applied to test the effects 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 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 ~~TIs~~ topography 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~~ topographic indices 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 of selected stations are complete. In addition, we further confirm that vegetation changes (using LAI, as a proxy) did not significantly ~~change~~ 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 ~~500 x 500 m points~~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 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 hydrometric stations.

Table 2. 22 Ttopographic 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~~mm day^{-1}). 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~~ 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 ~~may~~ are not ~~vary~~ varied greatly between watersheds (McGuire and McDonnell, 2006; Price, 2011). Therefore, to ensure better differentiation, the standard deviations of TIs ~~in~~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 ~~are~~ 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~~s~~ of TIs with the largest KMO, ~~and~~ 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 correlation between ~~the~~ flow variables and the FA selected TIs in the 28 study watersheds. If a significant correlation is detected, it indicates a high topographic control on that flow variable. ~~Stepwise~~ Multiple linear regression (MLR) models were then built for each year between 1989 and 1996 for each flow variable (see section ~~6~~ 5 ~~of~~ in the SI for details). ~~Each flow variable was treated as the dependent variable, while each~~ all ~~TI was the independent variables.~~ 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 an 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, ~~T~~the R package "relaimpo" was used to quantify the relative contributions of the selected TIs to each flow variable (Gromping, 2006). ~~Specifically,~~ In particularthe 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 ~~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 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). ~~Finally, t~~ The lumped *CI* of each TI to each flow variable is ~~presented~~ 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 ~~selected~~ 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 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), and the diagonals of anti-image correlation (> 0.7) on the 11

TIs further confirm that our selected TIs are adequate to represent topographical~~y~~ characteristic 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. ~~3~~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 ~~TIs~~ represents watershed roughness or complexity, while the second factor ~~TIs~~ describes the watershed size. Therefore, the selected 11 TIs were subsequently classified into two groups representing complexity (Group ~~1~~A) and area (Group ~~2~~B) (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'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 ~~from 1989 to 1996~~ with decreasing ~~of the~~in flow magnitudes. ~~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~~MLR models w~~as~~ere 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~~ MLR 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. 3 A to C ~~4-7~~). Fig. 3 revealed that each TI influences flow variables differently (e.g. SA played a prominent role in $Q_{90\%}$~~Q_{min}~~ but did not significantly contribute to the variation of ~~-~~Q_{min} and $Q_{75\%}$, while ~~DDG~~ SCA 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 B~~2~~ as well as among all TIs (Fig. 3). In Group ~~1~~A, the TIs above the average of the lumped CI were ~~SA~~slope, ~~, openness,~~ TCI, and LS receiving high contributions to low flows. Therefore, we conclude that the above-mentioned ~~5~~ four TIs are significant topographic indices influencing low flow variables, which can be used to assess and compare low flows in ~~watershed~~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.

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~~ annual mean flow ~~to~~ 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 (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. ~~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 recharg~~e~~~~ing~~ 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 that a watershed is, the higher the yields of low flows. Therefore, we conclude that topography plays a more important role in low flows than in high flows in the study region.

Four TIs including perimeter, ~~SA~~slope, ~~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 quantitatively assessed ~~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~~ four TIs can effectively 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~~four 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~~5~~ TIs, ~~one~~ two primary TIs (perimeter and slope) ~~is~~ are commonly used in scientific studies to describe the characteristic of watershed topography. Our study further proves that ~~it has~~they have high influences on low flow variables. However, the other two 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). 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). In this study, the selected four TIs were initially filtered by the FA test, indicating that ~~this sub-set of TIs~~ each selected TI has uniqueness in describing watershed topographic characteristics, and is more ~~and~~ outperformed than the other tested TIs in describing variation in flow variables in our study region. Therefore, we expect that TCI and LS can be applied to support hydrological analysis and modelling.

To our surprise, some commonly-used TIs in hydrology, such as median elevation, upslope contribution area, wetland areas, ~~TWI,~~ etc. are not included in the ~~final~~ 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 ~~a~~ full~~er~~ 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~~ 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 flood plain (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 ~~5~~ selected four 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 flow regimes. There is a concern whether the TIs excluded by FA were significantly related to flow regimes, 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 S10). 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. ~~As far as we know, there are no such studies conducted in either snow- or rain-dominated regions.~~ In addition, o~~O~~ur 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 Our research methodology or framework can be applied in rain-dominated regions to assess how topography controls flow ~~regimes in rain-dominated regions, we recommend applying our framework~~ in any regions where there are sufficient ~~an area with large numbers of~~ long-term monitoring data~~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. 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 a 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~~-~~ 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 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 high flows is limited. A total number of four ~~5~~ topographic indices, including perimeter, LS (slope length factor), ~~SA (surface area)~~slope, and TCI (topographic characteristic index)~~, and openness~~, were identified with significant contributions to low flow variables. It is recommended that those above-mentioned four~~5~~ four TIs can be used to assess the magnitude of low flows in the study region which is characterized by a snow-dominated hydrological regime with the watershed sizes up to several thousands square kilometers. Our research methodology can be applied to other regions for ~~1780 km^2~~~~. The application of our research framework to rain-dominated regions is recommended to~~ investigate~~e~~ing how topography controls flow regimes~~ in these areas~~.

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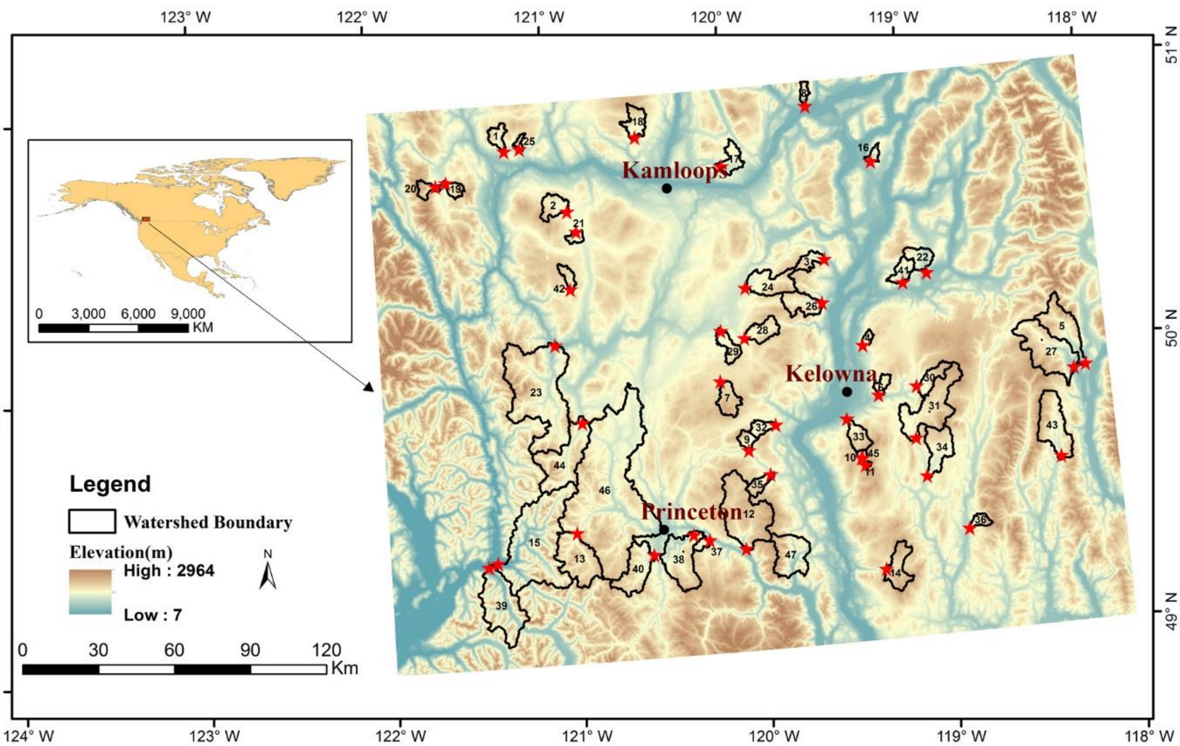

Figure 1. Locations and, elevations of the 28 study watersheds, and their hydrometric stations (red star sign).

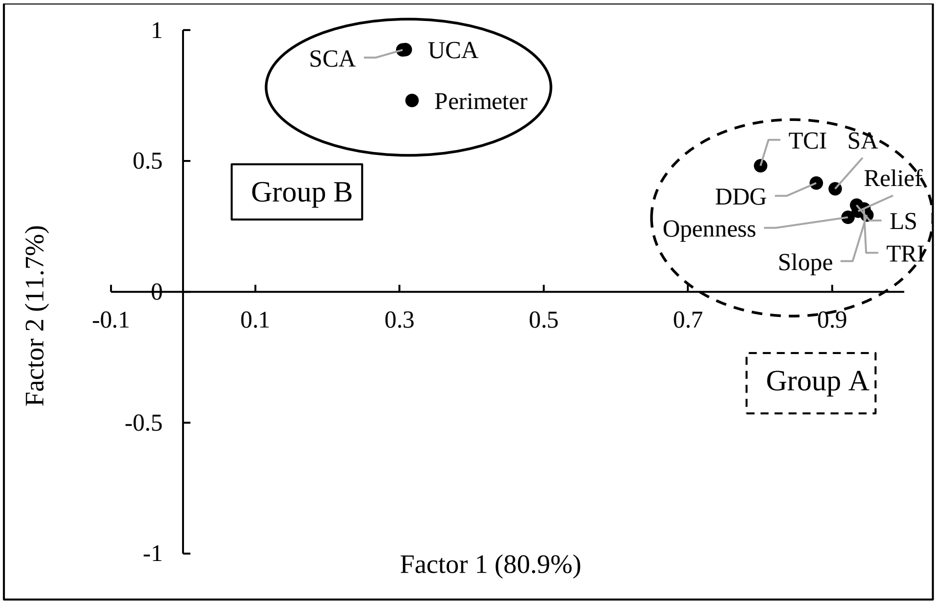

Figure 2. Factor analysis of topographic indices (TIs) among 28 watersheds. The first and second factors explained 80.9% and 11.7% of the total variance, respectively.

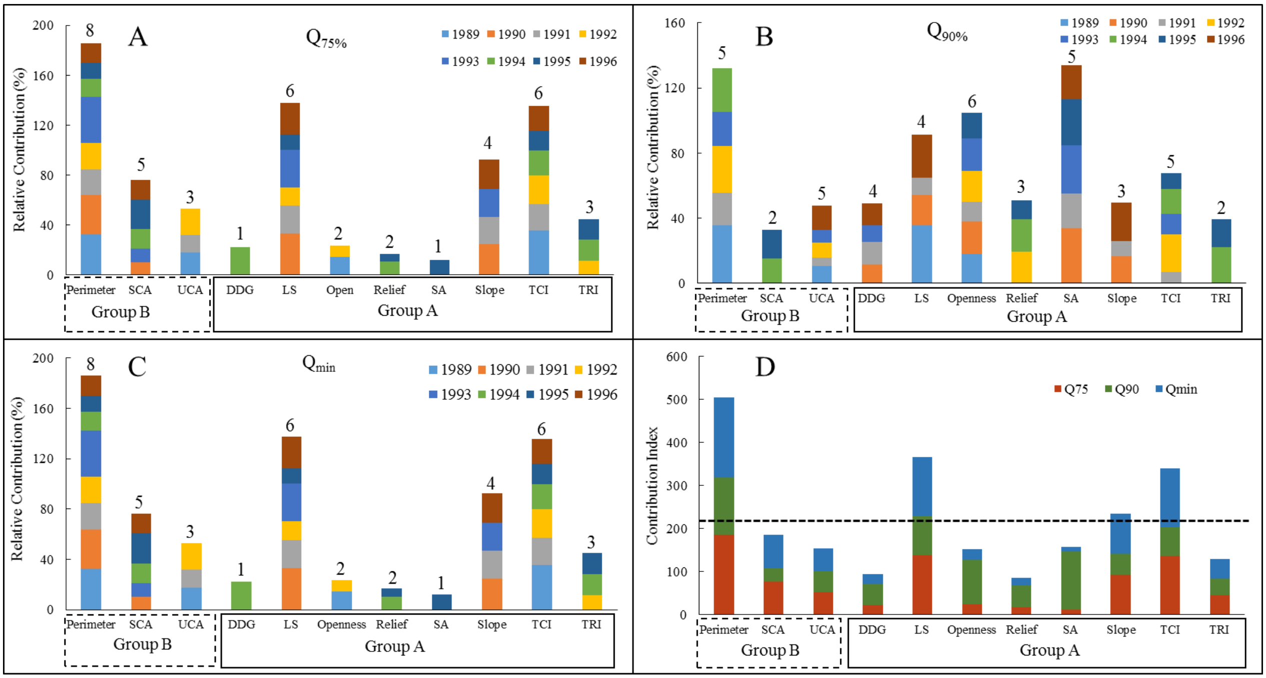

Figure 3. Relative contributions of each topographic index (TI) to $Q_{75\%}$ (Panel A), $Q_{90\%}$ (B), and Q_{min} (Panel C) from 1989 to 1996. Note that the numbers above the bars indicate the number of years when the given TIs were included in the regression models. Panel D: Contribution index (CI)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

Table 1. Topographic indices and descriptions

No.	Abbreviation	TI	Description and references
1	**<u>UCA</u>**	Upslope contributing area	UCA is the area that can potentially produce runoff to a given location (Erskine et al., 2006).
2	**<u>DDG</u>**	Downslope Distance Gradient	DDG is a hydrologic measure of the impact of the local slope characteristics on a hydraulic gradient. Values are low~~er~~ on concave slope profiles and high~~er~~ 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	**<u>Relief</u>**	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	**<u>Slope</u>**	Slope Degree	Slope degree of each DEM pixel (Burrough et al., 2015).
9	**<u>LS</u>**	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	**<u>SCA</u>, 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	**<u>TCI</u>**	Terrain Characterization Index	TCI = Cs *$\log_{10}$ (SCA), where Cs is the surface curvature index; The higher positive TCI <u>values</u>~~s~~ reflect higher aggradation of soil materials at a certain point along the hillslope (Park and van de Giesen, 2004).
13	**<u>TRI</u>**	Terrain Ruggedness Index	TRI expresses the degrees of difference in elevation among adjacent cells (Riley, 1999). <u>It calculates the sum changes between a grid cell and its eight neighbor grid cells. Higher values indicate more ruggedness of a watershed.</u>
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 ~~T~~total length of main stream~~,~~.
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~~ and low for concave forms, respectively (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). Lower value indicates a more gentle topography.
21	**Perimeter**	Perimeter of a watershed	The ~~P~~perimeter of a watershed.
22	Total	Total curvature	The ~~S~~standard curvature combines profile and planform curvatures (Moore et al., 1991).

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