HYDROLOGICAL CHARACTERIZATION OF WATERSHEDS IN THE BLUE NILE BASIN

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ABSTRACT

Thirty-two watersheds (31–4350 km^2), in the Blue Nile Basin, Ethiopia, were hydrologically characterized with data from a study of water and land resources by the US Department of Interior, Bureau of Reclamation (USBR) published in 1964. The USBR document contains data on flow, climate, topography, geology, soil type, and land use for the period 1959 to 1963. The aim of the study was to identify watershed variables best explaining the variation in the hydrological regime, with a special focus on low flows. Moreover, this study aimed to identify variables that may be susceptible to management policies for developing and securing water resources in the dry periods. Principal Component Analysis (PCA) and Partial Least Square (PLS) were used to analyze the relationship between hydrologic variables (total flow, maximum flow, minimum flow, runoff coefficient, low flow index) and 30 potential watershed variables. The watershed variables were classified into three groups: land use; climate and topography; and, geology and soil type. Each of the three groups had almost equal influence on the variation in hydrologic variables (R^2 values ranging from 0.3 to 0.4). Specific variables from within each of the three groups of explanatory variables were better in explaining the variation. Land use, geology and soil type were powerful discriminants of low and high flow. Low flow and low flow index were positively correlated to land use types woodland, dense wet forest and savannah grassland; whereas, grazing land and bush land were negatively correlated. The results indicated extra care should be taken on tuffs/basalts, which comprise 52% of the Blue Nile Basin, for preserving low flow. Land management promoting woodland, dense wet forest and, grassland can promote higher low flows and increased areas of grazing land diminish low flows.

Key words: Blue Nile, Ethiopia, low flow, US Bureau of Reclamation (USBR), variables

1. Introduction

Due to the complexity of hydrology, the response of watersheds to rainfall cannot be predicted with certainty (Sivapalan, 2005). General classes of watershed characteristics attributed to the differences in hydrological response to rainfall are soil properties, geology, anthropogenic activities, relief, size, local climate and, vegetation cover (Black, 1997; Uhlenbrook, 2003; Sivapalan, 2005). Some watershed characteristics are more important in ways that are specific to different watersheds and scales. One way to advance the predictive power of watershed hydrology is to characterize watersheds based on the most influential factors (McDonnell et al., 2007), as this provides a basis for planning of land management issues for developing and securing water resources (Saxena et al., 2000). Moreover, characterization of watersheds with reference to spatial differences in hydrological response complements modeling (Yadav et al., 2007), as the difficulty in parameterization of differences in watershed characteristics is one of the major obstacles to the progress of hydrological modeling (Hauhs and Lange, 2008).

The characterization of hydrological response of watersheds is crucial in areas such as the Blue Nile where the well-being of the majority of the population depends on the ability to manage water scarcity. Although 60% of Nile flow at Aswan comes from the Blue Nile, the local population can still suffer from water shortages during the dry season. Therefore, landscape management may be necessary for reducing seasonal water shortages. However, other factors influence water availability besides those that can be "managed", such as topography, geology and local climate. Management plans, and expectations for success need to be based on understanding of the full range of factors controlling watershed response to rainfall, in addition to those that management can influence.

The watersheds in the Blue Nile Basin were characterized and, hydrological homogenous units were delineated for the purpose of flood frequency analysis using Hoskin L-moments (Abebe, 2007). Abebe (2007) found five generalized regional flood frequency curves for the Basin. In addition, Adane and Foerch (2006) discuss the characterization of watersheds for predicting the base flow index in *Wabi Shebele*, a 1.2×10^5 km^2 Basin in Ethiopia that adjoins the Blue Nile Basin to the Southeast and flows to the East of the country. Catchment size, stream density, climate index, hypsometric integral, Normalized Difference Vegetation Index (NDVI) and, geological parameters were evaluated for their usefulness in predicting the base flow index for this Basin. Adane and Foerch (2006) conclude the strongest correlation was between lower dry season flows and higher NDVI. Given the importance of the Blue Nile, which is less arid than the *Wabi Shebele*, there is scope for a more complete characterization of watersheds of the Blue Nile Basin, especially the critical low flow period.

However, the spatial characterization of the differences in the hydrological regime of the watersheds in the Blue Nile requires data. Systematic and spatially extensive flow data were collected on the Blue Nile from 1959 to 1963 at the time of the building of the Aswan Dam on the Nile. The investigation of land and water resources was initiated by the Ethiopian government in cooperation with the US Department of Interior, Bureau of Reclamation (USBR). Hydrological data were collected from 59 gauge stations during the period 1959 to 1963 and monthly flow data along with descriptions of soil, geology, land use and, topography were published for 35 stations covering the four year period (US Department of Interior, 1964). This paper attempts to apply multivariate methods to these published data in order to characterize the hydrological response of the region (high flows, annual flows and dry season flows) in terms of catchment geology, topography, land use, soil and, climate.

The aim of this study was to determine the watershed variables that best described the variability in hydrological regime, in particular the low flow, for different watersheds in the Blue Nile Basin. Moreover, this study aimed to identify variables that may be susceptible to management policies for developing and securing water resources in the dry periods. Data from 1959-1963 is valid for determining the hydrological response to different natural land use types, such as forest and grassland cover, that are now uncommon (Bekele, 2003).

2. Materials and Methods

2.1 Site description of the Blue Nile Basin

The 2×10^5 km^2 Blue Nile Basin contributes about 60% of the Nile’s flow at Aswan, Egypt, even though the Blue Nile comprises only about 8% of the Nile’s catchment area. In the period 1960-1964, rainfall in the Blue Nile ranged from 880 to 2070 mm per annum. The watersheds of the Basin have a range of sizes, slopes, climatic patterns, topography, drainage patterns, geological formations, soils, vegetation cover and, anthropogenic activities. There are three broad topographical divisions: the highland plateau, steep slopes adjoining the plateau that tilt to the west and, the western low lands with gentler topography comprising the remainder of the Basin. The steep slopes and the plateaus extend from 1500 m to ca 4000 m above sea level and combined cover about 65% of the Basin area. In addition, the Basin is characterized by three different geological formations: the crystalline basement exposed over 32% of the area; sedimentary formations covering about 11% and visible in the deep valleys of major southern tributaries; and, volcanic formations covering about 52% of the area in the North, Central and Eastern part of the Basin (Ministry of Water Resources, 1998). The dominant soil texture of the Basin is clay with the special type of shrinking and expanding clay, *Vertisol*, covering about 15% of the Basin.

2.2 The study watersheds

Between 1958 and 1963, USBR and the Ethiopian Government studied the land and water resources of the Blue Nile Basin. In 1964, USBR published "Land and Water Resources of the Blue Nile" in seven volumes, comprising one main report and six appendixes: Plans and estimates, Hydrology, Geology, Land classification, Power, and Agriculture and Economics (US Department of Interior, 1964).

The USBR document contains monthly discharge data from 35 watersheds for the period 1959 to 1963. All 35 of these watersheds were included in the study from the beginning; however, three watersheds were excluded, two because they were comprised of other watersheds in the data set, and one because of insufficient flow data. The characteristics of the watersheds selected are presented in Figure 1 and Table 1. The terminology in Table 1 is used in subsequent figures and tables.

"Place Figure 1 here"

Data for 6 different hydrological variables and 30 different watershed characteristics were extracted from the main report and appendices for Hydrology, Geology, and Land classification; from the four volumes out of the seven.

Discharge was based on continuous stage measurements on control reaches that were made using automatic chart recorders backed up by manual staff gauge readings made daily at 0600 and 1800. The rating curve for each control reach constructed from repeated flow measurements during the four-year study period using current meters deployed either from bridges or aerial cableways.

The hydrologic variables used in the study were average annual flow (Qt [mm/yr]), minimum monthly flow (Ql [mm/yr]), maximum month flow (Qh [mm/yr]) and low flow index (LFI), which is the ratio of minimum flow (during the driest month) to the total flow for the year.

Flow data were transformed from the SI units (monthly cubic meters) to mm, based on watershed areas. Maximum and minimum flow, low flow index, and runoff coefficient (C) which is the ratio of total flow to rainfall, were computed from the monthly flow data for the four years published in the USBR report.

The climatic data, i.e. rainfall (P [mm/yr]) and temperature (T [$^{\circ}$C/day]) were collected by the National Meteorological Service Agency of Ethiopia. from. Thirty-nine meteorological stations were considered, which are being closest to each watershed. Potential evaporation (ET [mm/day]) extracted from the USBR documentation. The geographical information taken from the main report of the USBR document includes latitude (Lat) and longitude (Long) (both in degree-decimal) of the centre of each watershed, area of the watersheds (Area [km^2]), average elevation (El [m]) and, average slope class (Slope [%]). All variables were summarized from text and map information in the USBR document.

The hydrologic, climatic, relief, and, geographical data were all continuous variables, so-called numerical descriptors. The geology, soil and, land use types were discontinuous, so-called categorical descriptors. The different classes within the groups of these variables were dependent on each other, as the sum of the coverage of the different classes within a group is 100%. Fuzzy coding, a means of assigning dummy variables (Upton and Cook, 2006) was used to quantitate the nominal descriptors. For example, four different geological classes were identified: alluvials (Allu), sandstones/limestones (S/L stones), tuffs/basalts (Tu/Ba) and, metamorphic rocks (Meta). The four fractions of the geological classes equal one (100%) for each watershed. The same procedure was used for soil and land use types.

Nine different soil types were considered. These included: shallow leptosols (Lepto), soils with a very high content of coarse materials; cambisols (Cambi) characterized by a cambic B horizon or an umbric A horizon; arenosols (Areno) with albic, argillic, cambic or oxic horizon; luvisols (Luvi) highly basic and with an argillic horizon; alisols (Ali), acidic and infertile soils; eutric-vertisols (EutV), clay rich soils; regosols (Rego), soils formed on unconsolidated material except for recent alluvial deposits; acrisols (Acri), soils with an argillic B horizon and less basic; and, wetlands (Wet), soils having voids filled with water.

Nine different land use classes were selected. These included: cultivated land (CU), arable land for seasonal crop production; dense wet forest (DWF), a humid highland forest where annual rainfall exceeds 1500 mm; dense dry forest (DDF), a montane forest where annual rainfall ranges from 500-1500 mm; open woodland (OWL), sparsely distributed trees and shrubs with dominant grassland; woodland (WL), a drought resistant vegetation type dominated by trees and shrubs; savannah grassland (SGL), lowland grasslands up to 1.3 m in height and undisturbed by humans; grazing land (GL), land designated for open grazing under human management; riverine forest (RF), continuous forest cover along river banks where the height of trees could be greater than 10 m; and, bush land (BL), vegetation includes shrubs, succulents and grasses with shallow degraded soil. Any temporal changes in soil and land use properties due to natural and human activities within the watersheds were assumed insignificant due to the short period (1959-1963) being examined for spatial differences in hydrology.

"Place Table 1 here"

2.3 Statistical analysis

Principal Component Analysis (PCA) and Partial Least Square (PLS) were used to explore multivariate relationships between the watershed variables and hydrologic variables. PCA and PLS find new and independent latent variables (principal components) that maximize the explained variance among all variables (PCA) or the y-variables (PLS). In PCA, the two types of variables, hydrologic and watershed, are treated together. In PLS, the hydrologic variables are assigned as response variables, and the watershed variables are explanatory: in this case, the y-variables are the hydrologic variables. Both PCA and PLS were run with SIMCA 12.0.1 (UMETRICS, 2009).

Multivariate analysis is capable of handling both categorical and continuous types of data in the same analysis (Eriksson et al., 2001; Gärdenas, 1998; and Eriksson et al., 1995). However, two specific steps were taken to render the data suitable for PCA and PLS analyses. The first step was transforming the categorical data, which sums to one with a special log- transformation recommended by Wang et al. (2010), called log-ratio transformation. The log-ratio transformation is defined as:

$$t = \log \frac{x_i}{\sqrt[p]{\prod_j^p x_j}};$$

Where t is transformed value, x_i is the original value, x_j is the number of parts (portions) in the unit one, and the total number parts are p.

This transformation linearized the data and resolves the problem of proportions adding to unit one. The second step was centering and scaling of the variances to control variability caused by the different data types with different units. Centering and scaling is used to generate unit variance and control the differences in scales (Eriksson et al., 2001) given to each variable in the geology, soil and land use groups.

The PCA and PLS runs were done in two steps. In the first step, all explanatory variables were included to identify the most significant variables. Then, based on the result from the first step significant variables were used for the second step PCA and PLS run. A variable said to be insignificant if failed to be significant at the 90% confidence-interval by Jack-Knifing in at least one of four model components. Significance, based on a 95% confidence interval was also determined. The PLS, with significant variables, was run in two steps. First, it was conducted for all response variables; then, PLS models were run for two grouped response variables: total/high flow (total flow, maximum flow and runoff coefficient) and low flow (minimum flow and low flow index) regimes. The explanatory variables were grouped into three conceptual groups: climate and topography, geology and soil and, land use. The PLS, with significant variables, was conducted for each conceptual explanatory group to assess whether the different groups of explanatory variables differed in their ability to explain the hydrologic variables. These groups were compared on the percent of variation of hydrologic variables explained by the different models, and R^2 was used as the measure of fit of the data to the model in SIMCA.

3. RESULTS

In both PCA and PLS runs, significant and non-significant variables were distinguished at the 90% confidence interval. Significant variables from each of the four components were recruited (the non-significant variables are listed in Table 2) and only the significant variables were used in the final PCA and PLS plots (Figure 2 and Figure 3).

3.1 Principal component analysis (PCA)

Approximately 60% of all the variables were significant in explaining the variation between the watersheds with respect to the hydrological regime. The total variation explained by the first two components was R^2=0.4 (Figure 2): the total variation explained by four components was R^2=0.6. Dry season flows increased with increased rainfall, dense wet forest, riverine forest and, alisols but, decreased with more dense dry forest, bush land, alluvials, regosols, eutric-vertisols and, cultivated land. The LFI, which normalizes the low flow to annual flow, was positively correlated to wetland and woodland, but was negatively correlated to average slope, grazing land and, tuffs/basalts. Total flow, high flow and, runoff coefficient increased with increment of tuffs/basalts and average slope but, decreased with the increment of wetland and woodland.

There were clear relationships between different land use variables. There were negative correlations between grazing land and woodland or wetland and, between dense wet forest or riverine forest and dense dry forest or bush land.

"Place Figure 2 here"

3.2 Partial Least Square (PLS)

The variables explaining the variation and potential predictors of the total/high flow regime were grazing land, tuffs/basalts, rainfall, dense wet forest and leptosols (Figure 3). The cumulative variation explained by the first two components was R^2=0.5 and the cumulative variation explained by four components was R^2=0.6.

Alluvials, luvisols, rainfall, savannah grassland, dense wet forest, tuffs/basalts, longitude and, eutric-vertisols were significant for explaining the variation in the low flow regime (Ql and LFI) (Figure 3). The variability explained by the first two components was R^2=0.4 and the variability explained by four components was R^2=0.6.

In the PLS analysis (Table 2), the hydrological variables (both total/ high flow and low flow regimes) were positively correlated to rainfall. However, tuffs/basalts had contrasting relationships to the total/high and low flow regimes: this geological group was positively correlated to the total/high flow group and negatively correlated to the low flow group. A comparison of the groups of explanatory variables indicated the geology and soil group explained 10% more variation and gave better predictions for the total/high flow group than the climate and topography or land use groups (Table 2). All three groups of variables (climate and topography, land use, geology and soils) had an equal influence on variation and prediction of low flow regime (Table 2).

"Place Figure 3 here"

"Place Table 2 here"

4. DISCUSSION

Different watersheds have different properties that influence the flow regime and knowledge of different properties can help in planning action on variables susceptible to management measures. Thus, it is useful to classify watersheds within a region on the similarity and differences in hydrologic regimes. Hydrological science seeks to find a way of understanding the interconnection of hydrological processes at the watershed scale by characterizing watershed variables (Sivapalan, 2005). As part of this process, this study characterized the relationship of catchment variables to hydrologic variables through multivariate analysis in order to identify predictors of the hydrological regime in the Blue Nile Basin.

The PCA analysis explained 60% of the variation within the significant watershed variables and hydrologic variables, of which 80% was explained in the first two axes. Each of the variables had plausible causal explanations for being either positively or negatively correlated to the total/high flow regime. Wetland and woodland were the main factors for reducing total/high flow regime. For variables positively correlated to the total/high flow regime (average slope, tuffs/basalts and grazing land), flow would increase and infiltration would decrease, thus, groundwater storage would decrease. With variables negatively correlated to total/high flow (wetland and woodland), water would flow slowly and the infiltration rate into soils would be higher, thus, increasing the ability to store water. Therefore, management for promoting water infiltration, such as woodland, could result in lower high flows. This result was in accordance with other studies, as summarized by Bruijnzeel (2004). However, other factors, such as tuffs/basalts and average slope, that are not influenced by management need to be considered in water planning.

The major variables positively correlated with dry season flow (Ql and LFI) were wetland, woodland, dense wet forest, rainfall, riverine forest and, alisols. Grazing land, tuffs/basalts, average slope, bush land, regosols, eutric-vertisols, dense dry forest, cultivated land and, alluvials negatively correlated to the low flow regime. These relationships are plausible in terms of catchment processes. Grazing and bush land are features of land degradation in the region (Demel and Tesfaye, 2002), which promotes rapid runoff so less of the rainy season precipitation is held in the soil. The reduction of low flow with the increment of slope and eutric-vertisols is probably related to rapid runoff in steep terrain and accentuated by vertisols being prone to cracking and rapid bypass flows (Dekker and Ritsema, 1996).

The summarized PLS results from different groups of explanatory variables indicated how much each group explained the hydrologic variables and the relative importance of specific explanatory variables within each group. From the climate and topography group, rainfall was the single factor positively correlated with both total/high flow and low flow regimes. Longitude was negatively correlated with low flow regime, which indicated more low flow in the western watersheds than the eastern watersheds. The three groups of explanatory variables (climate and topography, geology and soil, and, land use) have almost equal strength in influencing the variability of flow regimes and in predicting flow regimes. The three groups separately explained less variation than selected variables from the whole explanatory variables, based on the level of significance, with almost twice the variation being explained by the significant variables, as R^2 increased from 0.3 to 0.6 (Table 2 and Figure 3).

Dense wet forest, woodland and, savannah grasslands were the three dominant land use features positively correlated to low flow regime. An improvement of low flow regime through woodland and grasslands is hypothesized for tropical areas by Bruijnzeel (2004) and Malmer et al. (2009). Such land use features in tropical areas increase the water retention of the soils. Land use such as grazing land and bush land are features indicating degradation of land resources (forests and soils) (Gete, 2000; Demel and Tesfaye, 2002). There was a negative correlation between grazing land and wetland or woodland and between riverine forest and dense wet forest (Figure 2). This correlation should be considered in land management for improving dry season flows, especially if a ‘tradeoff’ in land use management between woodland, savannah grassland, and wetland at one hand, and, bush land and grazing land on the other hand is required. Woodland, savannah grassland and wetland ecosystems should be conserved for development and sustenance of low flow in the landscape, as low flows are a risk for current and future water availability (Smakhtin, 2001).

Low flow was positively correlated to rainfall (Figures 2 and Figure 3). Although rainfall is the source of water for every flow regime, some watershed variables have better ability to retain rainfall through soil infiltration rather than others that lose the rain to rapid runoff. Woodland, savannah grassland and, wetland accompanied by deep soil and/or large catchment size were positively correlated to a catchment’s ability to intercept and retain rainfall for later dry season flow. However, while we believe the general relations are valid even 50 years later, the precise values of specific relationship may have been changed. That is because land use properties have been changed and soils have been degraded (Gete and Hurni, 2001). Although the data used in the study was older data, there was extensive spatial coverage and comparability of the sites, as they were all studied with similar methods within a single project. The fact that there was more extensive natural forest and grassland cover than at present (Bekele, 2003) is also of interest for conclusions on land use management can be made. Although land use has changed and soil degradation is suspected, the results are considered generally applicable to water management practices that consider the influences of significant watershed variables. One potential problem with this study could be the non-stationarity of the climate, which particularly influences seasonal flow regimes. However, as the distinct wet/dry season regimes remains in the region, the focus on low flows and high flows was still valid for current climatic conditions, as peak and low flows remain the dominant seasonal aspect of the flow regime.

5. Conclusions

A major goal of landscape management in the Blue Nile Basin is reduction of seasonal water shortages. Hydrological characterization provides a foundation for regionalization of watershed management in the Basin and can be especially useful for the management of un-gauged watersheds. We used multivariate analysis to make a hydrological characterization, and this method proved useful in ways that may be applicable to other basins and/or time periods. .

The analysis of spatially comprehensive data from the Blue Nile Basin collected between 1959 and 1963 provides empirical evidence of relevance for ongoing debates about whether some land use types, such as dense wet forest, woodland, wetland and, savannah grassland, can promote higher low flow. We conclude that for sustaining water availability in dry periods, conservation of woodland, savannah grassland and wetland is important, whereas, grazing land and bush land could exacerbate water shortages during the dry season.

Factors influenced by land management, such as extent of dense forest or woodland or grassland, can enhance the low flow regime and GIS and map information, such as relief and soil type are useful in identifying where low flow will be a problem for local communities. Although this may be obvious, it is undocumented, and this documentation could serve as the basis for aiding calibration of hydrological models for management purposes.

However, other factors influence water availability besides those that can be “managed”, such as topography, geology and, local climate. This study highlighted how dry season flows can be generally lower in areas with volcanic soils, such as tuffs/basalts, which cover half of the

Basin. Management plans and, expectations for success in these plans need to be based on an understanding of the full range of factors controlling watershed response to rainfall, in addition to the factors management can influence. When attempting to identify human impacts on land use/land cover, factors such as geology and local climate need to be separated, as management plans cannot influence these.

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Table 1. Watersheds and their respective variables, as extracted from the USBR document (US Department of Interior, 1964)[a].

Watershed		***Qt***	***Ql***	***Qh***	***LFI***	***C***	***P***	***T***	***ET***	***El***	***Slope***	***Allu***	***S/L stone***	***Tu/Ba***	***Meta***	***GL***	***CU***	***OWL***	***DWF***
name	***code***																		
Gilgel Abbay	GA	981.5	3.2	355.5	0.0032	0.63	1562	17.0	3.4	2250	12.5	0	0	1	0	0.2	0.5	0.1	0
Koga	Ko	578.7	5.0	224.3	0.0086	0.37	1562	17.0	3.4	2250	7.5	0.1	0	0.9	0	0.2	0.6	0	0
Gummera	Gu	747.6	4.1	380.3	0.0055	0.51	1460	17.0	3.4	2900	7.5	0.1	0	0.9	0	0.1	0.5	0.2	0
Megetch	Me	240.9	0.5	99.1	0.0020	0.21	1170	20.4	3.8	2250	22.5	0.05	0	0.95	0	0.1	0.8	0.1	0
Angereb	An	374.8	2.9	168.0	0.0078	0.30	1264	17.0	3.4	2000	12.5	0.1	0	0.9	0	0.1	0.7	0.05	0
Ribb	Ri	235.9	0.2	228.4	0.0010	0.16	1460	17.0	3.4	2500	10	0.15	0.05	0.8	0	0.1	0.5	0.2	0
Wizer	Wi	711.7	0.2	355.8	0.0002	0.80	887	14.2	3.3	2800	5	0	0	1	0	0.2	0.5	0	0
Beressa	Be	509.4	1.2	240.0	0.0024	0.57	887	14.2	3.3	2800	15	0	0	1	0	0.2	0.5	0	0
Muger_chancho	Mc	289.2	0.9	137.9	0.0030	0.24	1192	13.3	3.1	2800	5	0.2	0	0.8	0	0.3	0.3	0	0
Guder_Jibat	Gj	648.4	2.5	170.3	0.0039	0.48	1352	13.3	3.1	2800	7.5	0.2	0	0.8	0	0.1	0.4	0	0
Guder_Guder	Gg	792.5	1.8	318.4	0.0023	0.59	1352	13.3	3.1	2800	7.5	0.2	0	0.8	0	0.15	0.45	0	0
Guder_Melke	Gm	510.0	2.4	167.3	0.0047	0.38	1352	13.3	3.1	2800	5	0.2	0	0.8	0	0.15	0.45	0	0
Guder_Fato	Gf	613.2	1.8	218.1	0.0030	0.45	1352	13.3	3.1	2800	5	0.2	0	0.8	0	0.05	0.45	0	0
Guder_Idris	Gi	866.7	6.6	370.3	0.0076	0.64	1352	13.3	3.1	2800	5	0.2	0	0.8	0	0.2	0.5	0	0
Guder_Bello	Gb	819.1	1.8	294.3	0.0022	0.61	1352	13.3	3.1	2800	12.5	0.2	0	0.8	0	0.2	0.5	0	0
Fincha	Fi	330.3	3.1	89.1	0.0095	0.32	1025	22.5	3.9	1750	22.5	0.45	0.05	0.5	0	0.1	0.3	0	0
Beles	Bs	313.4	0.7	139.8	0.0023	0.32	971	23.9	4.0	750	5	0	0	0.75	0.25	0	0.2	0.2	0
Birr_Jiga	Bj	668.3	0.2	364.0	0.0004	0.49	1355	19.2	3.5	2750	22.5	0	0	1	0	0.2	0.4	0.1	0
Birr_Temcha	Bt	1291.0	2.5	537.2	0.0019	0.79	1644	19.2	3.5	2750	18.5	0	0	1	0	0.3	0.45	0	0
Temim	Te	827.4	0.3	396.7	0.0003	0.61	1355	19.2	3.5	2750	18.5	0	0	1	0	0.15	0.45	0	0
Arera	Ar	477.9	2.9	223.9	0.0061	0.35	1355	19.2	3.5	2750	7.5	0	0	1	0	0.15	0.45	0	0
Leza	Le	415.2	2.1	252.8	0.0052	0.31	1355	19.2	3.5	2750	18.5	0	0	1	0	0.1	0.4	0.2	0
Ketchem	Kt	1107.3	0.9	455.6	0.0008	0.82	1355	19.2	3.5	2750	18.5	0	0	1	0	0.2	0.4	0.1	0
Dabana	Da	590.6	2.6	213.4	0.0044	0.29	2071	22.6	3.8	1000	5	0	0	1	0	0	0.3	0.2	0.2
Angar	Ag	611.0	3.0	191.6	0.0049	0.30	2071	22.6	3.8	1000	7.5	0	0.25	0.25	0.5	0.1	0.3	0.2	0.1
Chemoga	Ch	716.7	1.7	294.8	0.0023	0.53	1355	15.7	3.4	2750	18.5	0.15	0	0.85	0	0.2	0.4	0	0
Djilil	Dj	480.5	1.9	217.4	0.0039	0.35	1355	15.7	3.4	2750	18.5	0.15	0	0.85	0	0.1	0.6	0	0
Kulch	Ku	1157.8	4.4	574.8	0.0038	0.70	1655	15.7	3.4	2750	18.5	0.15	0	0.85	0	0.2	0.5	0	0
Jedeb	Je	1100.2	3.8	517.8	0.0035	0.35	1355	15.7	3.4	2750	18.5	0.15	0	0.85	0	0.2	0.4	0	0
Fettaru	Fe	1725.6	7.0	676.1	0.0041	0.70	2071	17.9	3.3	1750	10	0	0	1	0	0.1	0.4	0.1	0.2
Sifa	Si	754.1	3.6	177.9	0.0047	0.81	2071	17.9	3.3	1750	12.5	0	0	1	0	0.2	0.3	0.1	0.3
Wama	Wa	604.1	2.9	194.9	0.0048	0.83	2071	17.9	3.3	1750	12.5	0	0	1	0	0.2	0.3	0.1	0.3

Table 1. *continued…*

Watershed		***DDF***	***SGL***	***WL***	***RF***	***BL***	***Lepto***	***Cambi***	***Areno***	***Luvi***	***Ali***	***EutV***	***Rego***	***Acri***	***Wet***	***Area***	***Long***	***Lat***
name	***code***																	
Gilgel Abbay	GA	0.1	0	0.05	0.05	0	0	0	0	0.8	0	0	0.2	0	0	1660	37.1	11.5
Koga	Ko	0	0	0.2	0	0	0	0	0	0.9	0	0	0	0	0.1	266	37.1	11.5
Gummera	Gu	0.2	0	0	0	0	0	0	0	1	0	0	0	0	0	1239	37.6	11.8
Megetch	Me	0	0	0	0	0	1	0	0	0	0	0	0	0	0	519	37.5	12.7
Angereb	An	0	0.1	0	0.05	0	0.9	0	0	0.1	0	0	0	0	0	660	37.6	11.5
Ribb	Ri	0.2	0	0	0	0	0	0	0	0.2	0	0.8	0	0	0	1497	37.7	12.0
Wizer	Wi	0	0	0	0	0.3	0	0	0	0	0.8	0.2	0	0	0	60	38.8	10.3
Beressa	Be	0	0	0	0	0.3	0	0	0	0	0	0.8	0.2	0	0	220	38.7	9.6
Muger_chancho	Mc	0.3	0.1	0	0	0	0.1	0	0	0	0	0.8	0.1	0	0	606	38.7	9.3
Guder_Jibat	Gj	0.3	0.1	0	0	0.1	0	0	0	0.3	0.5	0.2	0	0	0	143	37.9	9.0
Guder_Guder	Gg	0.3	0	0	0	0.1	0	0	0	0.3	0.45	0.25	0	0	0	499	37.9	9.0
Guder_Melke	Gm	0.3	0	0	0	0.1	0	0	0	0.35	0.5	0.15	0	0	0	80	37.9	8.9
Guder_Fato	Gf	0.3	0	0	0	0.2	0	0	0	0.3	0.5	0.2	0	0	0	98	37.8	8.9
Guder_Idris	Gi	0.25	0	0	0	0.05	0	0	0	0.3	0.45	0.25	0	0	0	76	37.9	9.0
Guder_Bello	Gb	0.25	0	0	0	0.05	0	0	0	0.3	0.45	0.25	0	0	0	244	37.8	8.9
Fincha	Fi	0.2	0.2	0.1	0.1	0	0	0.2	0.2	0	0.2	0.2	0	0	0.2	1390	37.5	9.5
Beles	Bs	0.1	0.2	0	0	0.3	0.2	0.5	0	0	0	0.3	0	0	0	3520	36.5	11.2
Birr_Jiga	Bj	0.2	0	0	0.1	0	0.1	0	0	0.2	0.45	0.2	0	0	0.05	813	37.5	10.6
Birr_Temcha	Bt	0.1	0	0	0.15	0	0.05	0	0	0.1	0.6	0.15	0	0	0.1	350	37.6	10.2
Temim	Te	0.2	0.1	0	0.1	0	0.1	0	0	0.2	0.4	0.2	0.1	0	0	108	37.4	10.7
Arera	Ar	0.2	0.1	0	0.1	0	0.1	0.2	0	0.2	0	0.2	0.3	0	0	31	37.3	10.7
Leza	Le	0.2	0	0	0.1	0	0.1	0	0	0.2	0.4	0.2	0.1	0	0	159	37.4	10.7
Ketchem	Kt	0.1	0.1	0	0.1	0	0.1	0	0	0.2	0.7	0	0	0	0	183	37.6	10.6
Dabana	Da	0.2	0	0	0.1	0	0.1	0	0	0	0.8	0	0	0.1	0	3080	36.3	8.4
Angar	Ag	0.2	0	0	0.1	0	0	0	0	0	0.7	0	0	0.3	0	4350	36.4	9.4
Chemoga	Ch	0.1	0	0.1	0.1	0.1	0	0.1	0	0	0.8	0.1	0	0	0	320	37.8	10.3
Djilil	Dj	0.05	0.1	0	0.1	0.05	0	0	0	0	0.7	0.2	0.05	0	0.05	70	37.5	10.8
Kulch	Ku	0.1	0.1	0	0.1	0	0.05	0	0	0	0.55	0.3	0.05	0	0.05	50	37.3	11.0
Jedeb	Je	0.1	0	0	0.1	0.2	0	0.1	0	0	0.8	0.1	0	0	0	250	37.7	10.5
Fettaru	Fe	0	0.2	0	0	0	0	0	0	0	0.7	0.3	0	0	0	200	36.7	9.1
Sifa	Si	0	0.1	0	0	0	0	0	0	0	0.8	0.2	0	0	0	978	36.8	8.9
Wama	Wa	0	0.1	0	0	0	0	0.1	0	0	0.8	0.1	0	0	0	764	36.6	8.9

[a]Codes of the variables represent; Qt total flow (mm/yr), Qh maximum flow (mm/yr), Ql minimum flow (mm/yr), LFI low flow index, C runoff coefficient, P rainfall (mm/yr), T temperature (^{0}C/day), ET evapotranspiration (mm/day), El elevation (m), slope average watershed slope (%), Tu/Ba tuffs and basalts, S/L stone sand/lime stone, Meta metamorphic rock, Allu Alluvial, GL grazing land, CU cultivated land, OWL open woodland, DWF dense wet forest, DDF dense dry forest, SGL savannah grassland, WL woodland, BL (degraded) bush land, RF riverine forest, Lepto leptosols, Cambi cambisols, Rego regosols, Areno arenosols, Acri acrisols, Ali alisols, EutV Eutric Vertisols, Luvi luvisols, Wet Wetland, Area watershed area (km^2), Long Longitude (degree-decimal), Lat Latitude (degree-decimal).

Table 2. Non-significant variables column shows variables identified from four components for both PCA and PLS. Group of variables column shows the relation of groups of explanatory variables for explaining response variables (flow parameters), as summarized from PLS analysis.[a]

Non-significant variables			**Group of variables**					
PCA	**PLS_total/high flow**	**PLS_low flow**	**Total/high flow regime**			**Low flow regime**		
			Climate and topography	Geology & soil	Land use	Climate and topography	Geology & soil	Land use
S/L stone	T	El	+P	+Ali	+GL	+P	+S/L stone	+SGL
SGL	Slope	Slope	+El	+Tu/Ba	+DWF	-ET	+Luvi	+DWF
Lepto	Allu	GL	-ET	-Meta	-BL	-T	+Allu	-OWL
Cambi	S/L stone	CU	-Area	-Lepto		-Area	-Tu/Ba	
Acri	CU	DDF				-Long	-Meta	
Areno	OWL	WL					-Ali	
Luvi	WL	RF					-Tu/Ba	
Lat	DDF	BL					-EutV	
	SGL	Areno						
	RF	Lepto						
	Acri	Cambi						
	Areno	Rego						
	Luvi	Lat						
	Cambi	Wet						
	EutV							
	Rego							
	Wet							
	Long							
	Lat							
R^2			0.3	0.4	0.3	0.3	0.3	0.3

[a]"+"sign indicates positive relationship between hydrologic and watershed variables; "–" indicates an inverse relationship.

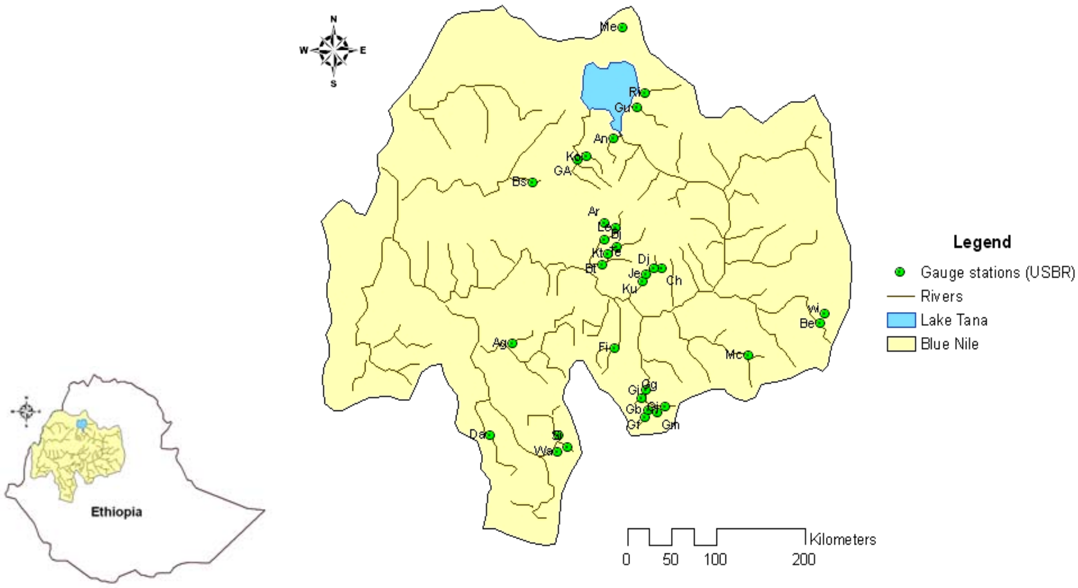

Figure 1. Location of USBR hydrological stations in the Blue Nile Basin, included in this study (32 watersheds).

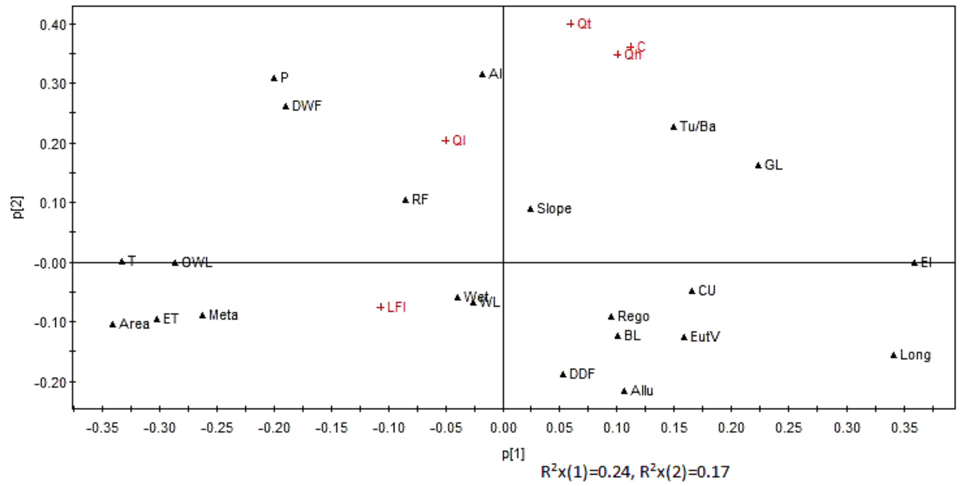

Figure 2. PCA plot with a selection of major watershed variables.

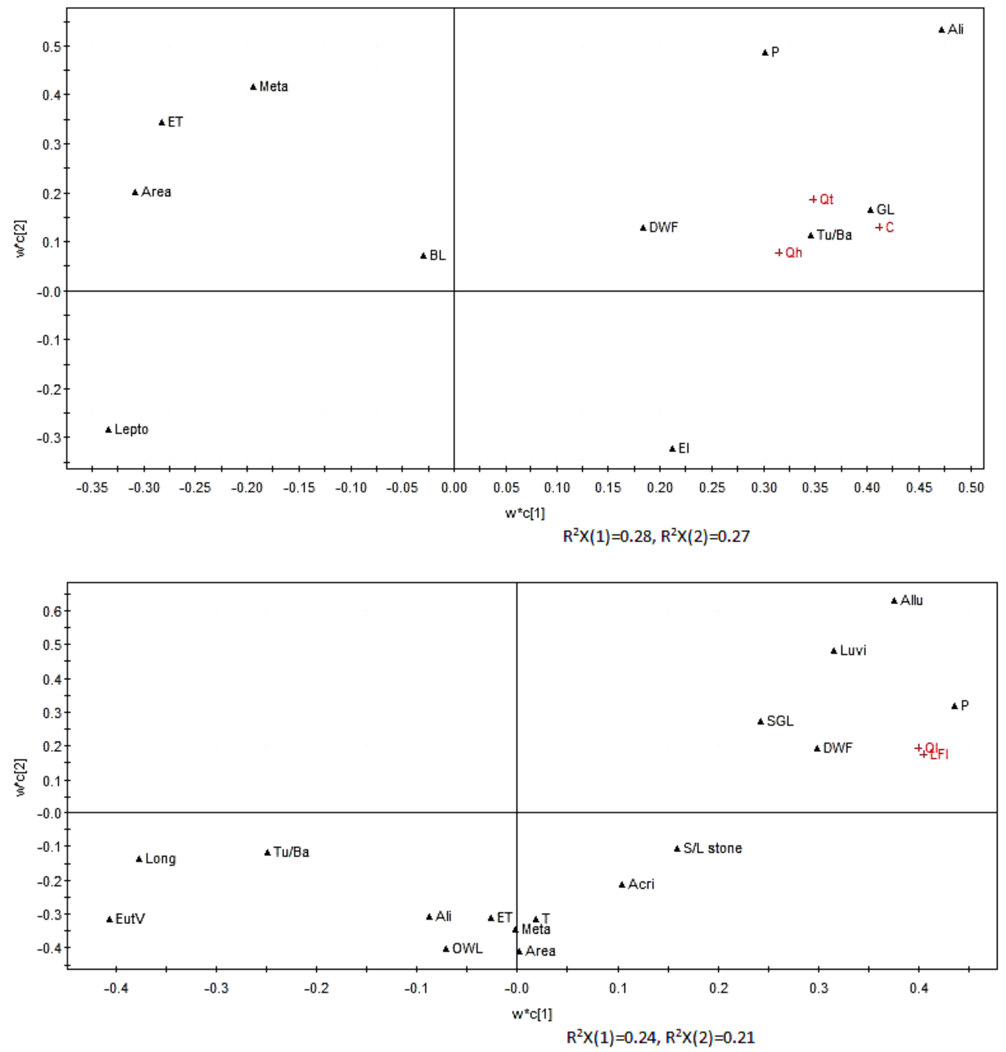

Figure 3. PLS loading plots for total/high flow group (the first pane) and low flow group (second pane) with significant watershed variables.