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Article

Flow Regime Classification and Hydrological Characterization: A Case Study of Ethiopian Rivers

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Abstract: The spatiotemporal variability of a stream flow due to the complex interaction of catchment attributes and rainfall induce complexity in hydrology. Researchers have been trying to address this complexity with a number of approaches; river flow regime is one of them. The flow regime can be quantified by means of hydrological indices characterizing five components: magnitude, frequency, duration, timing, and rate of change of flow. Similarly, this study aimed to understand the flow variability of Ethiopian Rivers using the observed daily flow data from 208 gauging stations in the country. With this process, the Hierarchical Ward Clustering method was implemented to group the streams into three flow regimes (1) ephemeral, (2) intermittent, and (3) perennial. Principal component analysis (PCA) is also applied as the second multivariate analysis tool to identify dominant hydrological indices that cause the variability in the streams. The mean flow per unit catchment area (QmAR) and Base flow index (BFI) show an incremental trend with ephemeral, intermittent and perennial streams. Whereas the number of mean zero flow days ratio (ZFI) and coefficient of variation (CV) show a decreasing trend with ephemeral to perennial flow regimes. Finally, the streams in the three flow regimes were characterized with the mean and standard deviation of the hydrological variables and the shape, slope, and scale of the flow duration curve. Results of this study are the basis for further understanding of the ecohydrological processes of the river basins in Ethiopia.

Keywords: Ethiopia; flow regime; ephemeral; intermittent; perennial; hydrological indices; flow duration curve

1. Introduction

The stream flow response to rainfall depends on the catchment attributes [1] that include the physiographic, underlying geology, vegetation cover and rainfall amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and induce complexity which cannot yet be predicted in hydrology [2]. River flow regime is one of the means that addresses the complexity of stream flow response through the process of systematically organizing streams, rivers or catchments into groups that are most similar with respect to their flow characteristics [3].

Historically, flow regimes have played a vital role in the ecological sciences in understanding river flow variability [4–7], planning conservation efforts for freshwater ecosystems [8,9], exploring the influence of stream flow on living communities and ecological processes [10–14], providing an inventory of hydrologic types for water resource management [15,16], and hydrologic regionalization analyses [17]. Recently, grouping of gauging stations into flow regime classes based on time series data and selected hydrological variables has shown some significance in large-scale river management and research [7,18] for environmental monitoring, simplifying water allocation decisions and environmental flow setting [1,18,19], and also used as a tool for comparative hydrology to understand the physical representations of the flow duration curves [20–24].

Flow regime classification is achieved commonly on the basis of stream flow characteristics using hydrologic indices with five stream flow components; magnitude, frequency, duration, timing, and rate of changes of flows [25,26]. In most of the studies, the hydrological indices of the rivers are calculated from a time series data recorded at gauging stations [27]. Statistical similarities in hydrological indices are then used to group gauging stations with similar flow regimes [18]. The use of a flow regime classification is maximized when class membership is extrapolated to ungauged locations. In several recent studies, temporal flow data have been combined with spatial environmental and physical data of watersheds in statistical classifications that were used to predict river flow regimes for ungauged watersheds [1,19].

To our knowledge, there have been no comparable studies that focused specifically on flow regimes of rivers at gauge stations in Ethiopia. Thus the objectives of the study were to (1) classify the rivers of the country based on hydrological indices into three flow regimes as ephemeral, intermittent, and perennial, and (2) develop relationships among flow regimes, hydrological variables, and catchment descriptors to characterize flows for ungauged rivers.

2. Study Area and Dataset

2.1. Study Area Description

Ethiopia is a country that has a high plateau with a central mountain range divided by the Great Rift Valley. The altitudinal variation of the country ranges between two extremes, from 125 m below sea level at Denakil Depression to 4543 m above sea level at RasDejen (Dashen) peak. Broadly, the country can be divided into two areas: the highlands and the lowlands, by the dividing contour line at an altitude of 1500 m above sea level. The high lands, covering nearly 44% of the country's landmass, accommodate 88% of the total human and 70% of the livestock populations [28,29]. Rivers that originate from the central and western highlands on the west side of the Great-Rift Valley flow to the west into the Nile River basin system, and cover about 39% of the land mass and 70% of the surface water of the country. The rivers originating from the eastern highlands of the country mainly flow to the east. These rivers together with the two Rift Valley river basins cover the largest land mass of the country (61%) but generate only 30% of the surface water [30]. Those rivers flowing to the west are mono-modal in nature with distinct single peak flow in July–August, whereas the rivers flowing to the east and south are generally bi-modal in nature with different seasonal flow peaks in March–April, and September–October.

2.2. Data Set

The daily flow data and stream flow gauging stations were collected from the Hydrology Directorate of the Ministry of Water and Energy of Ethiopia. River flow data from 208 flow gauging stations with more than 15 years daily flow data were collected and processed (Figure 1). A 30 m digital elevation model (DEM) data was used to delineate the catchments and compute different catchment features upstream of the gauging stations.

3. Methodology

3.1. Data Analysis

Daily time series flow data of the selected stations were analyzed using REXCEL, a software application which combines the computational capability of R with excel data. The hydrological indices and statistical analysis were computed using the RExcel version 3.2.12. The statistical methods were programmed in open access R software. The Archydro extension of ArcGIS was also used to delineate catchment area and to compute the catchment attributes.

3.2. Flow Regime Classification

Flow regime classification provides the basis for hydrological and ecological studies [31]. Stream flow is a useful measure for classification purposes, because it integrates the influences of most landscape features into a single measurable "characteristic". Likens [32], Richter [33], and Poff [25] suggested five stream flow categories; magnitude, frequency, duration, predictability, and rate of change that include a number of flow characteristics and represent the flow regimes as ephemeral, intermittent, and perennial.

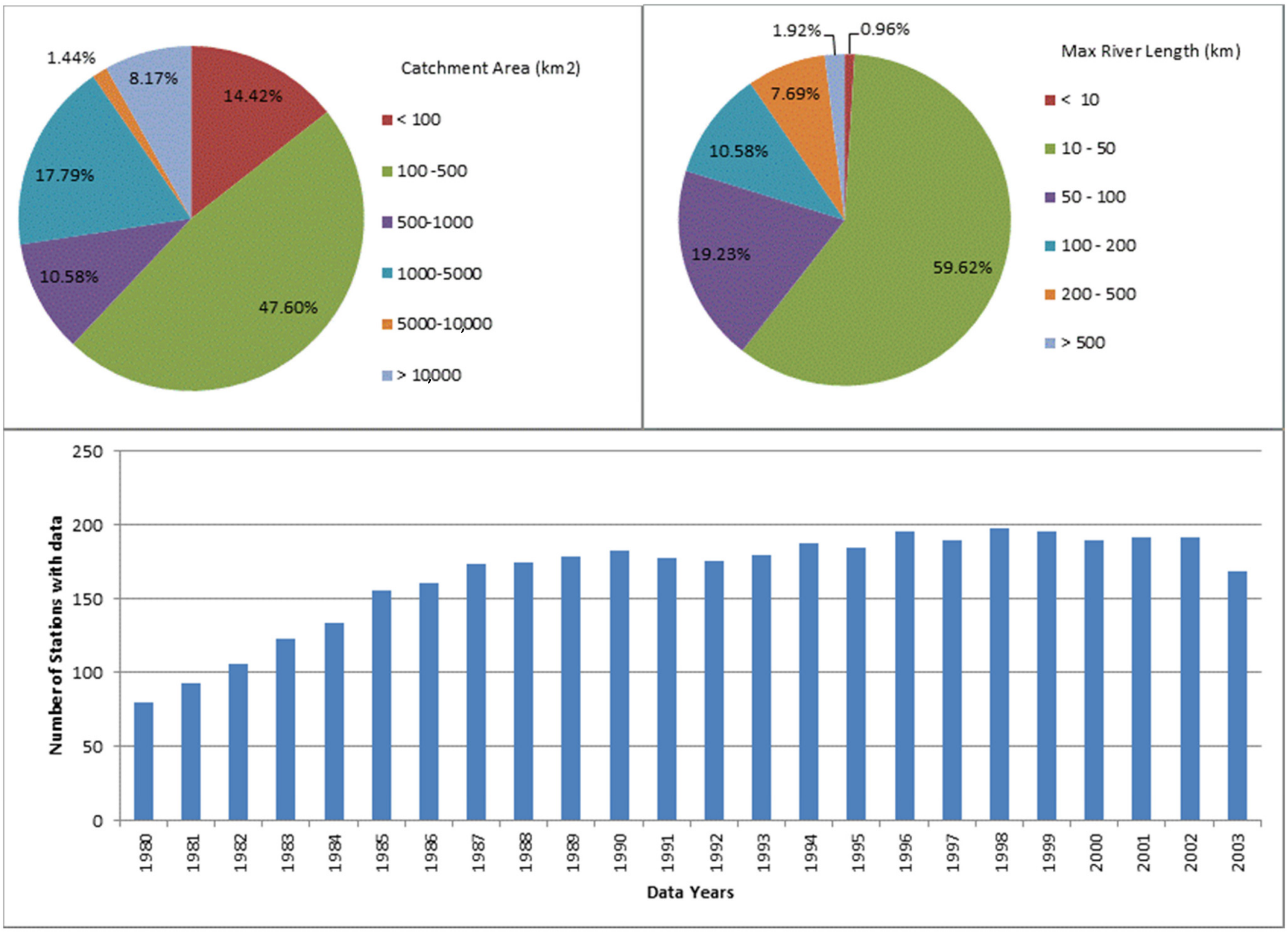

Figure 1. Summary statistics of catchment area, river length, and gauging stations used in this study.

The flow regimes classification for Ethiopian gauged streams used a supervised approach. First, the three flow types were identified from the sample selected rivers in the country as ***Ephemeral*****:** a stream or portion of a stream which flows briefly in direct response to precipitation in the immediate vicinity, and whose channel is at all times above the groundwater reservoir. ***Intermittent*****:** a stream where portions flow continuously only at certain times of the year (*i.e.*, seasonal). At low flow there may be dry segments alternating with flowing segments. The stream bed has at sometime of the year to be above the groundwater table. ***Perennial:*** a stream or portion of a stream that flows year-round is considered a permanent stream, and for which base flow is maintained by groundwater discharge to the stream bed due to the groundwater elevation adjacent to the stream typically being higher than the elevation of the streambed [34]. The flow regime of the sampled rivers is used to define the flow regimes of the 208 gauged streams in the country.

Cluster analysis is the method most often used to make classifications of objects [35]. It is used to portion the dataset into groups (clusters) using the statistical proximity according to some defined distance measure. We grouped 208 gauged rivers into three clusters using the agglomerative hierarchical clustering. Poff and Ward [3] employed a conceptual stream classification model, which was based on a hierarchical ranking of four components of flow regime (intermittency, flood frequency, flood predictability, and overall flow predictability). Moliere [36] also followed the previous work and arrived at a broad streams classification as perennial, seasonal, dry seasonal, and seasonal intermittent using the hierarchical ranking. A study in the Mediterranean basin also adopted the same clustering approach with the introduction of a new variable called flashiness index [37]. Thus, in this study, the hierarchical agglomerative clustering was used to define the flow regime of the gauged streams using six hydrological indices, which were grouped into three flow regime descriptors (Table 1).

Table 1. Definitions of the hydrological variables derived for each station.

Variable	Symbol	Definition
Catchment descriptors		
Flow per catchment unit area	QmAR	Mean daily discharge divided by the catchment Area ($m^3/s/km^2$)
Base flow Index	BFI	The ratio of mean daily discharge by the mean daily base flow
Flow variability		
Coefficient of Variation	CV	Coefficient of variation of daily flows
flashiness index	RBI	Flashiness reflects the frequency and rapidity of short term changes in stream flow
Extent of Intermittency		
Mean Peak flow day	PFday	The mean day of the year for the peak flow occurred
Zero flow DAY index	ZFI	Mean annual number of zero flow days is divided by 365

3.2.1. Catchment Descriptor

Two hydrological variables; the mean flow per unit catchment area (QmAR), and the base flow index (BFI) are used as the catchment descriptors in the multivariate clustering analysis [36,37]. The BFI indicates the nature of the water dynamics in the river and is related to the groundwater aquifer. In northeastern USA, 1575 stream flow stations were classified into different regional properties based on base flow [38].

In our study, the base flows for 208 stream gauged stations were computed based on Digital Filter Approach. It uses a numerical algorithm (a digital filter) to partition the stream flow hydrograph into “high frequency” (direct runoff) and “low frequency” (base flow) components. The following single parameter algorithm is used for the computation of the base flow.

$$R_{t+1} = \alpha R_t + \frac{1+\alpha}{2}\left(Q_{t+1} - Q_t\right) \quad (1)$$

Check: If $R_{t+1} < 0$; then $R_{t+1} = 0$ and If $R_{t+1} > Q_{t+1}$; then $R_{t+1} = Q_{t+1}$

Compute base flow: $B_{t+1} = Q_{t+1} - R_{t+1}$

The single parameter α is taken as 0.98 as default value.

3.2.2. Flow Variability

Two measures of flow variability were used in this category. The first is the annual daily flow coefficient of variation, which is calculated as the standard deviation of all the daily flow values divided by the mean annual daily flow. The second is the flashiness index, which indicates the frequency and rapidity of short term changes in the stream flow [39]. Streams that rise and fall quickly are considered as flasher than those that maintain a steady flow [40]. The quantifying approach of this flashiness was proposed by Baker [39] as flashiness index (RB Index) as

$$RB_{Index} = \frac{\sum_{i=1}^{n} |q_{i-1} - q_i|}{\sum_{i=1}^{n} q_i} \quad (2)$$

where, i is the time step and q is the daily flow.

3.2.3. Extent of Intermittency

The mean annual number of days with zero flow ratio (ZFRatio) is computed by dividing the mean annual number of days with zero flow by 365 [36,41]. This index has been widely used in river classification taxonomy [42].The mean day of the peak flow (PFday) is also the other variable that measures the time of the occurrence of the flood for the given station. Then values of the six hydrological variables (QmAR, BFI, CV, RBI, PFday, and ZFI) for 208 gauging stations were used as input to group the streams into three flow regimes. With the Agglomerative Hierarchical Ward Clustering method, the streams are broadly grouped into three classes. Then the three groups are assigned as (1) Ephemeral, (2) Intermittent, and (3) Perennial streams, based on their representative sampled rivers at the time of supervision.

3.2.4. Principal Component Analysis of Hydrologic Variables

Principal component analysis (PCA) is used as a secondary multivariate analysis in this study. This analysis was performed for each homogeneous group of streams and for all the streams combined. For every set of streams, PCA was extracted from the correlation matrix of the hydrological indices and employed to examine dominant patterns of inter-correlation among the hydrological variables and to identify the major sources of variation. PCA was selected in this analysis since it puts a unit on the diagonal and all of the variances (variance unique to each variable, variance common among variables and error variance) in the matrix are considered [43]. Its contributions are scale-independent [44] and less sensitive to extreme values [45].

3.3. Flow Regime Characterization

Once the flow regimes were developed with the clustering procedure, they were characterized and described using the hydrological variables and the flow duration curve (FDC). The hydrological variables describe the magnitude and rate of change of the flows. The flow duration curve also characterizes the flow regime using the magnitude, frequency, and duration of the flow. The graphical display power of FDC also helps to visualize the variability of the stream flows in different flow regimes.

3.4. Relationships of Flow Duration Curve (FDC) and Catchment Descriptors

The computations of FDC quantiles for ungauged basins can be done through different methods. In this research, the multiple regression model, which is widely applied for such a purpose was used to relate the catchment descriptors, catchment area (A, km^2) and longest flow length of the catchment (L, km), with different regime characteristics to estimate values for ungauged basins.

4. Results

4.1. Clustering

Since the Spearman rank correlation coefficient among the variables was insignificant, all the six variables (QmAR, BFI, CV, RBI, ZFI, and Pfday) were used for flow regime clustering. The 208 gauged streams of the country were grouped into three clusters (ephemeral, intermittent and perennial streams) based on a supervised classification (Figure 2).

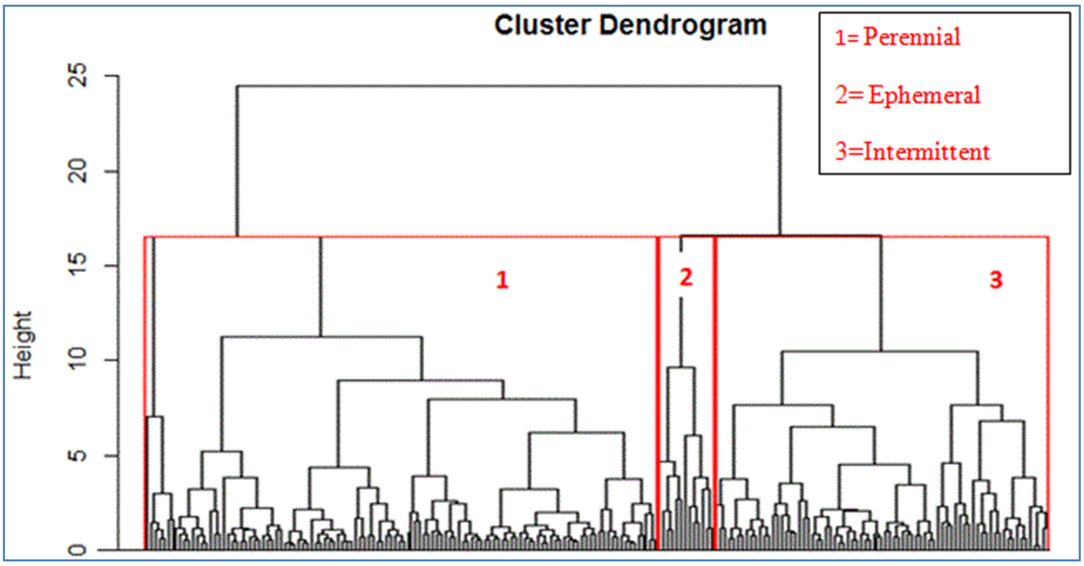

Figure 2. Cluster dendrogram of flow regime classification.

4.2. Principal Component Analysis of Hydrologic Indices

The RBI has significant correlation with BFI and CV, which makes RBI a redundancy for PCA factor analysis. Similarly, the mean annual day number for peak flow (PFday) showed no variation among the clusters and it did not add value in the interpretation of the PCA. The two variables (RBI and Pfday) were then removed from the PCA and factorial analysis.

The PCA variable factor map [46] also showed the significant variations among the variables to describe the variability in the river types of the country (Figure 3). The mean coefficient of variation (CV), the mean zero flow days ratio (ZFI), and the base flow index (BFI) had strong correlation with the first principal component (Table 2), which had 45.33% contribution for the variability of streams in the country. On the other hand, flow per catchment unit area (QmAR) had very strong correlation with the second principal component (Table 2) that contributes 24.76% of the variability of the streams.

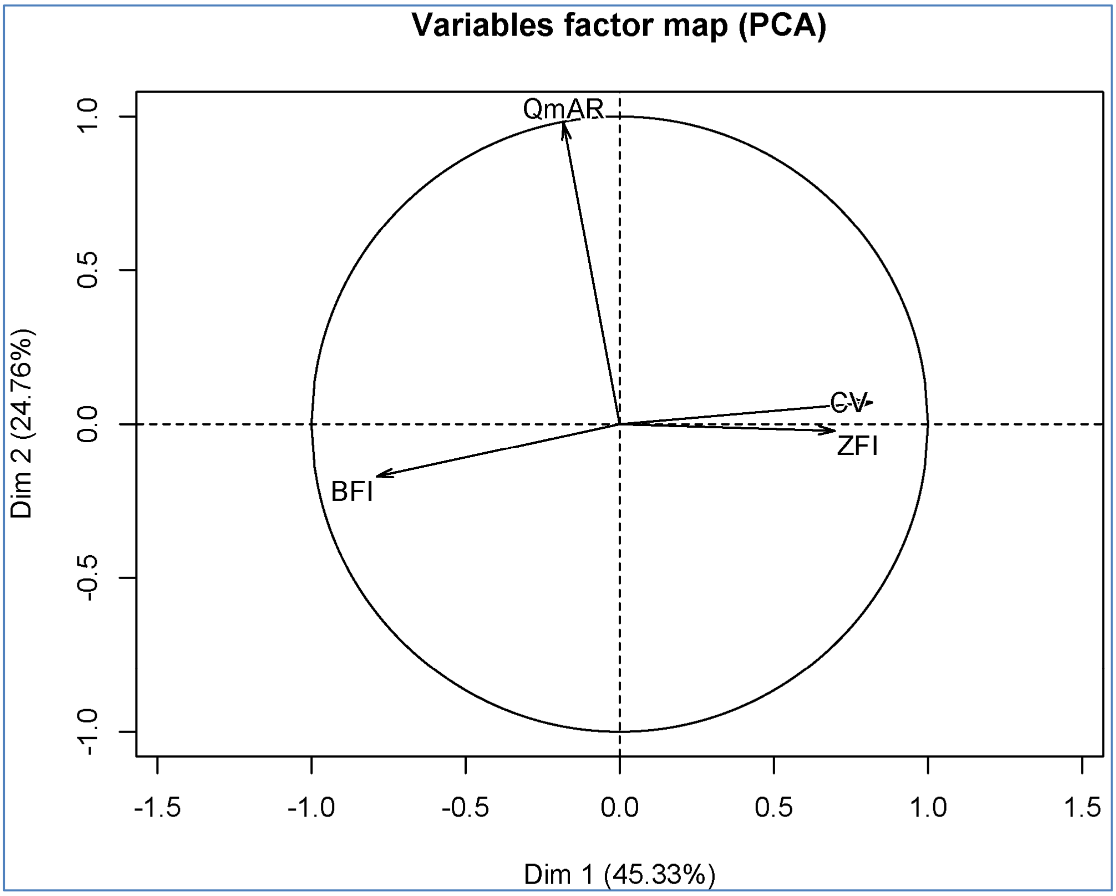

Figure 3. Variable factor and individual factor map of Principal Component Analysis (PCA).

Table 2. Correlation and *p*-values of variables with the two dimensions of PCA.

PCA Dimension	Variables	Correlation	*p*-Value
Dimension 1 (45.33%)	CV	0.82	0.00000
	ZFI	0.70	0.00000
	QmAR	−0.18	0.00838
	BFI	−0.79	0.00000
Dimension 2 (24.76%)	QmAR	0.98	0.00000
	BFI	−0.17	0.01354

The four hydrological variables that were identified with the PCA showed different trends with the different flow regimes. The QmAR and BFI showed an incremental trend with ephemeral, intermittent and perennial streams, whereas the number of mean ZFI and CV of daily flows showed a decreasing trend with ephemeral to perennial flow regimes (Table 3).

Table 3. The mean, standard deviation (SD) and coefficient of variation (CV) of variables of flow regimes.

Flow Regimes	Mean Flow Per Catchment Area (QmAR)			Base Flow Index (BFI)			Number of Mean Zero Flow Days Ratio (ZFI)			Coefficient of Variation of Daily Flow (CV)		
	Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Ephemeral	0.013	0.012	0.918	0.189	0.080	0.420	0.242	0.224	0.924	4.386	1.622	0.370
Intermittent	0.015	0.015	0.985	0.294	0.097	0.329	0.104	0.109	1.048	1.230	0.598	0.486
Perennial	0.022	0.033	1.475	0.451	0.118	0.262	0.044	0.075	1.695	0.507	0.226	0.446

4.3. Flow Duration Curve

The identified flow regimes are further described with the help of the flow duration curve, which is a graphical representation of cumulative frequency that shows the percent of time specified discharges were equaled or exceeded during a given period [47,48]. It represents the relationship between the magnitude and frequency of stream flow for a particular river basin [49]. It is effectively an alternative representation of the cumulative distribution function of daily (or hourly) stream flow [50]. It gives a holistic understanding of overall historical variability associated with stream flow in a river basin [49]. The shape of the flow duration curves describes the flow characteristics of the flow regimes. As Peters [51] stated, the shape of the flow duration curve shows the hydrological characteristics of the drainage area.

The streams in the ephemeral flow regime had FDC with a sharp curved shape at the fast flow region of FDC (Figure 4A). It indicates the flashiness characteristics of the streams, whereas the streams in the perennial flow regime had a less steep curve (Figure 4C), which is the behavior of non-flashy streams. The FDC curve of the intermittent regimes shows a curved nature in between the two extremes (Figures 4B). Likewise, the slope of the flow duration curves shows the variability of flows in the stream. The steeper slopes have higher variability than the flatter slopes. The streams in the ephemeral flow regime show more variability than the streams in the perennial flow regimes (Figure 4D).

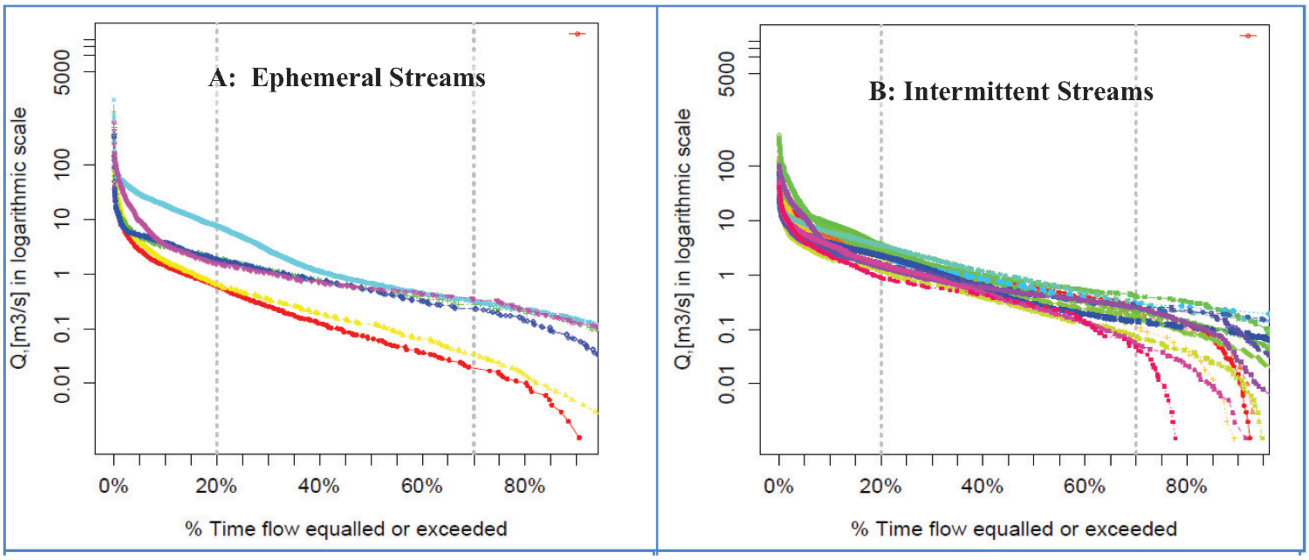

Figure 4. *Cont.*

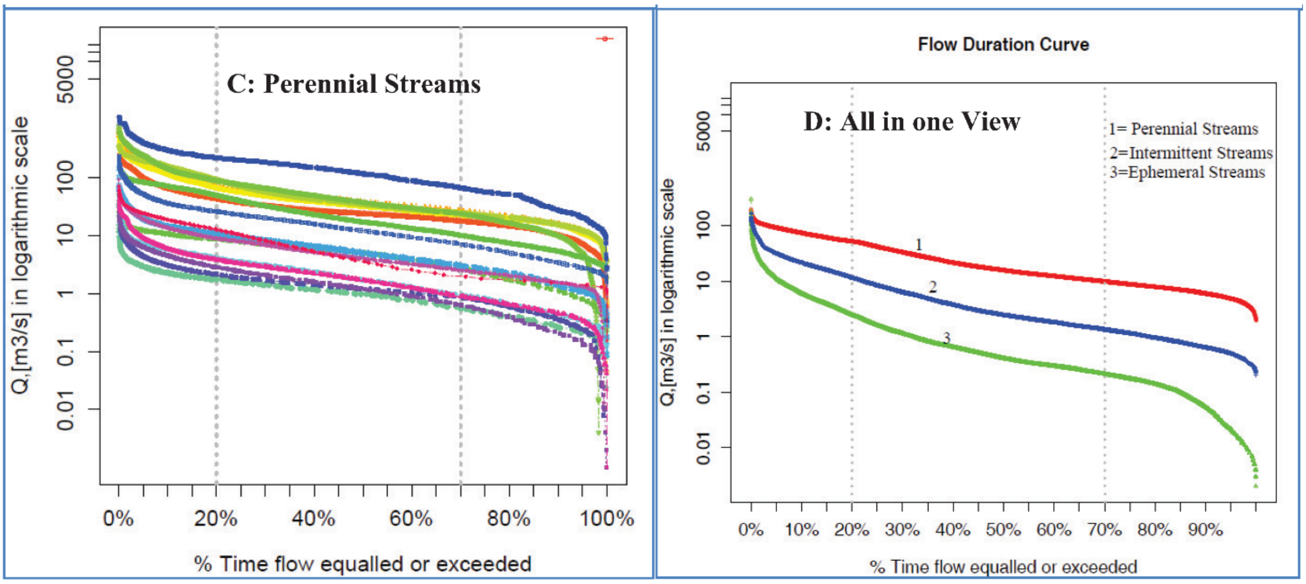

Figure 4. Flow duration curve (FDC) of streams for different flow regimes in Ethiopia. (**A**) Ephemeral streams; (**B**) Intermittent streams; (**C**) Perennial stream; (**D**) All in one view.

4.4. Catchment Descriptors and Flow Duration Relations

A multiple regression analysis was applied to develop the relationships of catchment descriptors, longest flow length, L (km) and catchment area A (km^2) (Table 4). The catchment descriptors L and A showed strong relationship with the flow quantiles shown in the FDC for perennial, intermittent and ephemeral streams with ranges of R^2 values (0.86–0.98), (0.67–0.91) and (0.53–0.64), respectively. These linear relationships have a significant contribution in estimating the quantiles and plotting the FDC for ungauged catchments. The poor correlation between the flow quantiles and catchment descriptors in ephemeral streams is an indicator of a flashy nature of the stream flow and shows the flow is not very dependent on the area and length of the drainage area.

Table 4. Linear relationship of catchment descriptors with flow duration curve for each flow regimes.

Flow Regime	Linear Relationship	R-Square
L = Length of the longest river in the catchment (km); A = Catchment area of the basin (km^2)		
Ephemeral streams	Q10 = −3.7621 + 0.3614 × L − 0.0077 × A	0.642
	Q20 = −1.4761 + 0.1540 × L − 0.0042 × A	0.533
	Q33 = −0.3934 + 0.0500 × L − 0.0014 × A	0.640
	Q66 = −0.0988 + 0.0122 × L − 0.0003 × A	0.624
	Q80 = −0.0833 + 0.0084 × L − 0.0002 × A	0.605
	Q90 = −0.0465 + 0.0049 × L − 0.0002 × A	0.570
Intermittent streams	Q10 = 10.0137 − 0.0870 × L + 0.0138 × A	0.913
	Q20 = 3.0111 + 0.0294 × L + 0.0045 × A	0.805
	Q33 = 1.2064 + 0.0114 × L + 0.0017 × A	0.738
	Q66 = 0.5749 − 0.0061 × L + 0.0005 × A	0.864
	Q80 = 0.3164 − 0.0033 × L + 0.0002 × A	0.836
	Q90 = 0.1823 − 0.0007 × L + 0.0001 × A	0.665

Table 4. *Cont.*

Flow Regime	Linear Relationship	R-Square
Perennial streams	Q10 = 13.7561 − 0.2223 × L + 0.0274 × A	0.976
	Q20 = 6.7423 + 0.0916 × L + 0.0111 × A	0.915
	Q33 = 5.5108 + 0.0552 × L + 0.0053 × A	0.858
	Q66 = 1.2939 − 0.0036 × L + 0.0018 × A	0.959
	Q80 = 0.6057 + 0.0062 × L + 0.0009 × A	0.952
	Q90 = 0.4870 − 0.0021 × L + 0.0006 × A	0.959

5. Discussions

5.1. Flow Regime Classification

The three flow regimes (ephemeral, intermittent and perennial) of the streams of the country were identified and classified using the flow indices derived from flow data collected at the gauging stations. The spatial distribution of the stream types in the river basins along with the topographical variability of the country is presented in Figure 5.

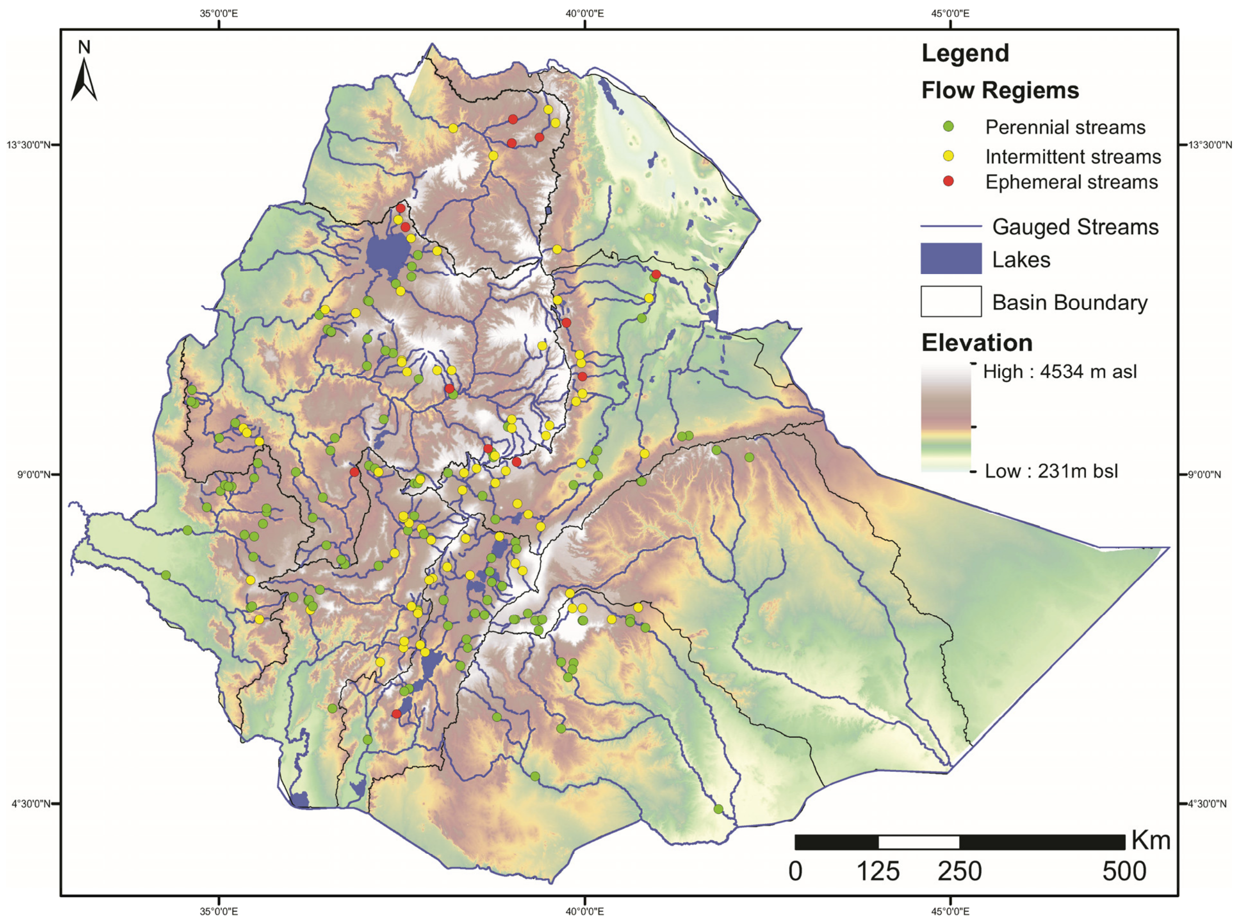

Figure 5. Flow regimes of Ethiopian streams along with elevation variability.

As depicted in Figure 5, most of the stream gauging stations in the country fall under perennial followed by the seasonal (intermittent) category. The ephemeral streams, which have significant variability on the flood occurrence, were not well represented by the existing gauging stations. Therefore, the results of this research indicate the need for a better stream monitoring network. Ephemeral streams are found on the head water catchments, whereas the perennial and intermittent streams were identified in the lower and intermediate section of the river basins. The result is also useful to predict flow regime of ungauged streams based on their catchment area and river length as shown in Table 4.

5.2. Flow Regime Characterization

The PCA differentiates the hydrological variables that have a contribution for the variability of stream regimes in the country. The singularity and no variance conditions make the PCA senseless and its verification is essential to identify the hydrological variables that contribute more for flow regime variations [37]. As stated in the results section, RBI has strong correlation with the other two variables (CV and BFI), and PFday has no variability among the flow regimes, Using them in the PCA is a redundancy. Although the two variables (PFday and RBI) are removed from the PCA analysis, they have a significant importance in describing the characteristics of rivers in Ethiopia. The mean annual values of PFday range from 157–271 days. It means that the peak flows of the rivers in the country are recorded in the months of June to September, which is referred to as the main rainy season of the country [30]. Similarly, the mean flashiness index (RBI) of the streams of the different clusters ranges from 0.011–1.113, which is the smallest value among mean flashiness indices computed in similar studies in tropical and Mediterranean regions [37,39,40].This is a good indicator that Ethiopian rivers are non-flashy.

The values of selected hydrological variables (QmAR, BFI, ZFI, and CV) characterize the different flow regimes and potentially can be used to characterize streams of ungauged watersheds. Ephemeral streams can be characterized with small QmAR and BFI values and high ZFI and CV values. It shows that ephemeral streams are relatively small streams with a large dry period and high variability of flow. Perennial streams are large streams with significant contribution of the base flows and relatively less variability throughout the year. This finding is in line with similar studies in France [47] and other tropical regions [36].

Furthermore, the different flow regimes were characterized by their shape, scale, and slope of the flow duration curve. A flow duration curve (FDC) with a steep slope results from a streamflow that is highly influenced by direct runoff, which is a marked characteristic of ephemeral streams. Whereas a curve with a relatively lower slope results from streamflow that is well sustained by surface releases or groundwater discharges and also identified as a perennial stream. The shape of the FDC is determined by the hydrologic and geologic characteristics of the drainage area and the FDC can be used to study the hydrologic response of basins to various types and distributions of hydro-meteorological inputs.

Finally, linear relationships among catchment descriptors and the FDC were developed for flow regimes characterization of ungauged catchments. A number of studies presented different relationships of catchment descriptors with regional models of FDCs for various geographical areas of the world [21,52–59]. Similarly, the linear relationships of catchment descriptors and FDC presented in Table 4 can serve as the basis for the estimation of FDC for ungauged catchments and also to characterize the flow regimes of ungauged catchments of the country. Selection of the flow regimes for ungauged catchments can be initiated based on the size of the catchment as described above in the hydrological variables characterization section. Then, the selection can be verified using the scale, shape, and slope of the FDC drawn after the computation of the FDC quantiles using the relationships in Table 4.

6. Conclusion

Multivariate cluster analysis was applied in this study in order to classify rivers based on flow data from 208 gauging stations in Ethiopia. Six hydrological variables (daily mean flow area ratio, base flow index, coefficient of variation, flashiness index, mean peak flow day, and the ratio of mean zero flow days) that were grouped into three categories as catchment descriptor, flow variability, and extent of intermittency were used for the flow regime classification. The study result shows Ethiopian Rivers are grouped into three flow regimes: (1) Ephemeral streams, (2) Intermittent streams and (3) Perennial streams.

The three flow regimes are characterized using the hydrological variables and the shape, slope, and scale of the flow duration curve. The flow duration curve is selected for the characterization of the flow regimes because of its ability to describe the magnitude, frequency, duration, timing, and rate of change of flows. Thus, rivers that have lower mean daily flows and a high proportion of zero flow days are ephemeral streams whereas large mean daily flows and a lower proportion of zero flow days become perennial streams. Similarly, sharp curved, very steep, and lower scale flow duration curves described the ephemeral flow regimes as the lower boundary, and a straight curve with flatter slope and high scale flow duration curves describe the upper boundary of the flow regime classification as perennial flow regimes.

The linear relationships among the catchment descriptors and FDC also help to classify and characterize the flow regimes of ungauged catchments. These flow regimes of the country can further be refined with additional hydrological signatures and by integrating them with other similar hydrological regimes, like rainfall regimes and soil hydrological classification, to assist in the understanding of the spatiotemporal variability of the hydrological and ecological processes.

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Author Contributions

This research article is the part of the PhD thesis of the first author, Belete Berhanu. Therefore he is responsible for research design, analysis, and write-up. The other three co-authors, Yilma Seleshi, Solomon S. Demisse and Assefa M. Melesse are the supervisors of this Ph.D work, particularly Assefa Melesse who contributed more on editing, organizing, and submission of this research article.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Snelder, T.H.; Lamouroux, N.; Leathwick, J.R.; Pella, H.; Sauquet, E.; Shankar, U. Predictive mapping of the natural flow regimes of France. *J. Hydrol.* **2009**, *373*, 56–67.
2. Sivapalan, M. Pattern, process and function: Elements of a unified theory of hydrology at the catchment scale. In *Encyclopedia of Hydrological Sciences*; Anderson, M.G., Ed.; John Wiley & Sons, Ltd.: Chichester, UK, 2005.
3. Poff, N.L; Ward, J.V. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. *Can. J. Fish. Aquat. Sci.* **1989**, *46*, 1805–1818.
4. Mosley, M.P. Delimitation of New Zealand hydrologic regions. *J. Hydrol.* **1981**, *49*, 179–192.
5. Haines, D.A. A lower atmospheric severity index for wildland fire. *Natl. Weather Dig.* **1988**, *13*, 23–27
6. Poff, N.L. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshw. Biol.* **1996**, *36*, 71–91.
7. Poff, N.L.; Olden, J.D.; Pepin, D.M.; Bledsoe, B.P. Placing global stream flow variability in geographic and geomorphic contexts. *River Res. Appl.* **2006**, *22*, 149–166.
8. Nel, J.L.; Roux, D.J.; Maree, G.; Kleynhans, C.J.; Moolman, J.; Reyers, B.; Rouget, M.; Cowling, R.M. Rivers in peril inside and outside protected areas: A systematic approach to conservation assessment of river ecosystems. *Divers. Distrib.* **2007**, *13*, 341–352.
9. Snelder, T.H.; Dey, K.; Leathwick, J.R. A procedure for making optimal selection of input variables for multivariate environmental classifications. *Conserv. Biol.* **2007**, *21*, 365–375.
10. Jowett, I.G.; Duncan, M.J. Flow variability in New Zealand Rivers and its relationship to in-stream habitat and biota. *N. Z. J. Mar. Freshw. Res.* **1990**, *24*, 305–317.
11. Poff, N.L.; Allan, J.D. Functional organization of stream fish assemblages in relation to hydrological variability. *Ecology* **1995**, *76*, 606–627.
12. Pusey, B.J.; Arthington, A.H.; Read, M.G. Freshwater fishes of the Burdekin River, Australia: Biogeography, history and spatial variation in community structure. *Environ. Biol. Fish.* **2000**, *53*, 303–318.
13. Snelder, T.H.; Weatherhead. M.; Biggs. B.J.F. Nutrient concentration criteria and characterization of patterns in trophic state for rivers in heterogeneous landscape. *J. Am. Water Resour. Assoc.* **2004**, *40*, 1–13.
14. Monk, W.A.; Wood, P.J.; Hannah, D.M.; Wilson, D.A.; Extence, C.A.; Chadd, R.P. Flow variability and macroinvertebrate community response within riverine systems. *River Res. Appl.* **2006**, *22*, 595–615.

15. Snelder, T.H.; Biggs, B.J.F. Multi-Scale river environment classification for water resources management. *J. Am. Water Resour. Assoc.* **2002**, *38*, 1225–1240.
16. Arthington, A.H.; Bunn, S.E.; Naiman, N.L. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol. Appl.* **2006**, *16*, 1311–1318.
17. Nathan, R.J.; McMahon, T.A. Identification of homogeneous regions for the purposes of regionalization. *J. Hydrol.* **1990**, *121*, 217–238.
18. Olden, J.D.; Kennard, M.J.; Pusey, B.J. A framework for hydrologic classification with a review of methodologies and applications in ecohydrology. *Ecohydrology* **2012**, *5*, 503–518.
19. Kennard, M.J.; Pusey, B.J.; Olden, J.D.; Mackay, S.J.; Stein, J.L.; Marsh, N. Classification of natural flow regimes in Australia to support environmental flow management. In *Freshwater Biology*; Blackwell Publishing Ltd: Queensland, Australia, 2010; Volume 55, pp.171–193.
20. Cheng, L.; Yaeger, M.A.; Coopersmith, E.; Ye, S.; Viglione, A.; Sivapalan, M. Exploring the physical controls of regional patterns of Flow Duration Curves: Part 1 Insights fromstatistical analyses. *Hydrol. Earth Syst. Sci*. **2012**, *16*, 4435–4446.
21. Castellarin, A.; Galeati, G.; Brandimarte, L.; Brath, A.; Montanari, A. Regional flow–duration curves: Reliability for ungauged basins. *Adv. Water Resour*. **2004**, *27*, 953–965
22. Yaeger, M.A.; Ye, S.; Coopersmith, E.; Cheng, L.; Viglione, A.; Sivapalan, M. Exploring the physical controls of regional patterns of Flow Duration Curves: 4. A synthesis of empirical analysis, process modeling and catchment classification. *Hydrol. Earth Syst. Sci*. **2012**, *16*, 4483–4498.
23. Ye, S.; Yaeger, M.A.; Coopersmith, E.; Cheng, L.; Sivapalan, M. Exploring the physical controls of regional patterns of Flow Duration Curves: 2. Role of seasonality and associated process controls. *Hydrol. Earth Syst. Sci*. **2012**, *16*, 4447–4465.
24. Huxter, E.H.H.; van Meerveld, H.J. Intermittent and Perennial Stream flow Regime Characteristics in the Okanagan. *Can. Water Resour. J.* **2012**, *37*, 391–414.
25. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Prestegaard, K.L.; Richter, B.D.; Sparks, R.E.; Stromberg, J.C. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* **1997**, *47*, 769–784.
26. Henriksen, J.A.; Heasley, J.; Kennen, J.G.; Niewsand, S. *Users' Manual for the Hydroecological Integrity Assessment Process Software (Including the New Jersey Assessment Tools)*; Open File Report, 2006–1093; U.S. Geological Survey: Fort Collins, CO, USA, 2006.
27. Olden, J.D.; Poff, N.L. Redundancy and the choice of hydrologic indices for characterizing stream flow regimes. *River Res. Appl*. **2003**, *19*, 101–121.
28. Erkossa, T.; Kidanu, S.; Mamo, T.; Abebe, M. Effect of Land preparation methods on runoff and soil loss on a Vertisol at Ginchi, Ethiopia. *Ethiop. J. Natl. Resour.* **1999**, *1*, 1–15.
29. Solomon, A. *Land Use Dynamics, Soil Degradation and Potential for Sustainable Use in Metu Area, Illubabor region, Ethiopia*; University of Berne: Berne, Switzerland, 1994; p. 135.
30. Berhanu, B.K.; Seleshi Y.; Melesse, A.M. *Surface and Ground Water Resources of Ethiopia:Potentials and Challenges of Water Resources Development, a Chapter in Ecohydrological Challenges, Climate Change and Hydropolitics*; Melesse, A.M., Abtew, W., Setegn, S.G., Eds.; Springer: Cham, Switzerland, 2014; Volume 15, pp. 97–117.
31. Arthington, A.H.; Pusey, B.J. Flow restoration and protection in Australian rivers. *River Res. Appl.* **2003**, *19*, 377–395.

32. Likens, G.E.; Bormann, F.; Pierce, R.S.; Eaton, J.S.; Johnson, N.M. *Biogeochemistry of a Forested Ecosystem*; Springer-Verlag: New York, NY, USA, 1977.
33. Richte, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174.
34. Levick, L.J.; Fonseca, D.; Goodrich, M.; Hernandez, D.; Semmens, J.; Stromberg, R.; Leidy, M.; Scianni, D.P.; Guertin, M.T.; Kepner, W. *The Ecological and Hydrological Significance of Ephemeral and Intermittent Streams in the Arid and Semi-arid American Southwest*; EPA/600/R-08/134, ARS/233046; U.S. Environmental Protection Agency: Washington, DC, USA; USDA/ARS Southwest Watershed Research Center: Tucson, AZ, USA, 2008; p. 116.
35. Romesburg, H.C. *General Features of Cluster Analysis*; Lulu Press: Raleigh, NC, USA, 2004; pp. 29–52.
36. Moliere, D.R.; Lowry, J.B.C.; Humphrey, C.L. Classifying the flow regime of data-limited streams in the wet-dry tropical region of Australia. *J. Hydrol.* **2009**, *367*, 1–13.
37. Oueslati, O.; de girolamo, A.; Abouabdillah, A.; Lo porto, A. Attempts to flow regime classification and Characterization in Mediterranean Streams Using Multivariate Analysis. In Proceedings of the International workshop advances in statistical hydrology, Taormina, Italy, 23–25 May 2010.
38. Kim, K.; Hawkins, R.H. Classification of environmental hydrologic behaviors in the northeastern unitedstates. *JAWRA* **2007**, *29*, 449–459.
39. Baker, D.B.; Richards, R.P.; Loftus, T.T.; Kramer, J.W. A new flashiness index: Characteristics and applications to Midwestern Rivers and Streams. *J. Am. Water Resour. Assoc.* **2004**, *95*, 503–522.
40. Fongers, D.; Day, R.; Rathbun, J. *Application of the Richards-Baker Flashiness Index to Gaged Michigan Rivers and Streams*; MI/DEQ/WRD-12/028; Michigan Department of Environmental Quality: Lansing, MI, USA, 2012.
41. Snelder, T.H.; Datry, T.; Lamouroux, N.; Larned, S.T.; Sauquet, E.; Pella, H.; Catalogne, C. Regionalization of patterns of flow intermittence from gauging station records: *Hydrol. Earth Syst. Sci*. **2013**, *17*, 2685–2699.
42. Matthews, W.J. North American streams as systems for ecological study. *J. North Am. Benthol. Soc.* **1988**, *7*, 387–409.
43. Brown, T.A. *Confirmatory Factor Analysis for Applied Research*; Guilford Press: New York, NY, USA, 2006.
44. Legendre, P.; Legendre, L. *Numerical Ecology*; Elsevier Scientific: Amsterdam, The Netherlands, 1998.
45. Assani, A.A.; Lajoie, S.; Tardif, F. Statistical analysis of factors affecting the spatial variability of annual minimum flow characteristics in a cold temperate continentalregime (southern Quebec, Canada). *J. Hydrol.* **2006**, *328*, 753–763.
46. Principal Component Analysis with FactoMineR. Available online: http://www.statistik.tuwien.ac.at/public/filz/students/seminar/ws1011/hoffmann_ausarbeitung.pdf (accessed on 17 June 2015).
47. Sauquet, E.; Catalogne, C. Comparison of catchment grouping methods for 685 flow duration curve estimation at ungauged sites in France. *Hydrol. Earth Syst. Sci*. **2011**, *15*, 2421–2435.
48. Searcy, J.C. *Flow Duration Curves*; United States Geological Survey Water Supply: Washington, DC, USA, 1959.

49. Vogel, R.M.; Fennessey, N.M. Flow duration curves II: A review of applications in water resources planning. *J. Am. Water Resour. Assoc.* **1995**, *31*, 1029–1039.
50. Yokoo Y.; Sivapalan M. Towards reconstructionof the flow duration curves Development of a conceptual framework with a physical basis. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 2805–2819.
51. Peters, N.E. Water-quality variations in a forested Piedmont catchment Georgia, USA. *J. Hydrol.* **1994**, *156*, 73–90.
52. Claps, P.; Fiorentino, M. Probabilistic flow duration curves for use in environmental planning and management. In *Integrated Approach to Environmental Data Management Systems*; NATO-ASI Series; Harmancioglu, N.B., Alpaslan, M.N., Ozkul, S.D., Singh, V.P., Eds.; Kluwer: Dordrecht, The Netherlands, 1997; Volume 2, pp. 255–266.
53. Croker, K.M.; Young, M.D.Z.; Rees, H.G. Flow duration curve estimation in ephemeral catchments in Portugal. *Hydrol. Sci. J.* **2003**, *48*, 427–439.
54. Fennessey, N.M.; Vogel, R.M. Regional flow-duration curves for ungauged sites in Massachusetts. *J. Water Resour. Plan Manag.* **1990**, *116*, 531–549.
55. Franchini, M.; Suppo, M. Regional analysis of flow duration curves for a limestone region. *Water Resour. Manag.* **1996**, *10*, 199–218.
56. LeBoutillier, D.V.; Waylen, P.R. Regional variations in flow-duration curves for rivers in British Columbia, Canada. *Phys. Geogr.* **1993**, *14*, 359–378.
57. Mimikou, M.; Kaemaki, S. Regionalization of flow duration characteristics. *J. Hydrol.* **1985**, *82*, 77–91.
58. Quimpo, R.G.; Alejandrino, A.A.; McNally, T.A. Regionalised flow duration curves for Philippines. *J. Water Res. Plan. Manag.* **1983**, *109*, 320–330
59. Singh, R.D.; Mishra, S.K.; Chowdhary, H. Regional flow-duration models for large number of ungauged Himalayan catchments for planning microhydro projects. *J. Hydrol. Eng.* **2001**, *6*, 310–316.