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Similarity between runoff coefficient and perennial stream density in the Budyko framework

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Abstract

Streams are categorized into perennial and temporal streams based on flow durations. Perennial stream is the basic network, and temporal stream (ephemeral or intermittent) is the expanded network. Connection between perennial stream and runoff generation at the mean annual scale exists since one of the hydrologic functions of perennial stream is to deliver runoff. The partitioning of precipitation into runoff and evaporation at the mean annual scale, on the first order, is represented by the Budyko hypothesis which quantifies the ratio of evaporation to precipitation (E/P) as a function of climate aridity index (E_p/P, ratio of potential evaporation to precipitation). In this paper, it is hypothesized that similarity exists between perennial stream density (D_p) and runoff coefficient (Q/P) as a function of climate aridity index, i.e., $\frac{D_\mathrm{p}}{D_\mathrm{p}^*}\left(\frac{E_\mathrm{p}}{P}\right)$ and $\frac{Q}{P}\left(\frac{E_\mathrm{p}}{P}\right)$ where D_p^* is a scaling factor and Q is mean annual runoff. To test the hypothesis, perennial stream densities for 185 watersheds in the United States are computed based on the high resolution national hydrography dataset (NHD). The similarity between perennial stream density and runoff coefficient is promising based on the case study watersheds. As a potential application for macroscale hydrological modeling, perennial stream density in ungauged basin can be predicted based on climate aridity index using the complementary Budyko curve.

1 Introduction

Total drainage density, defined as the total length of channels per unit area (Horton, 1932), is known to vary with climate and vegetation (Melton, 1957), soil and rock properties (Carlston, 1963; Kelson and Wells, 1989), and topography (Montgomery and Dietrich, 1988). Melton (1957) explored the dependence of drainage density on the Thornthwaite's (1931) precipitation effectiveness index (i.e., P-E index) which is a measure of the availability of moisture to vegetation, and found a negative correlation was found between drainage density and *P*-*E* index for the watersheds. Madduma Bandara (1974) extended the samples to cover watersheds in humid Sri Lanka and a positive correlation was found between drainage density and *P*-*E* index. Therefore, the drainage density decreases but then increases from arid to humid regions (Abrahams and Ponczynski, 1984), and this trend has been explained by the vegetation imparted to the soil (e.g., Moglen et al., 1998) and demonstrated in landscape models (e.g., Perron et al., 2007; Collins and Bras, 2010).

Functional patterns offer an insight on the mechanisms and processes driving the observed natural structure (Sivapalan et al., 2011). The functional approach may provide answers as to why streams and their associated densities organize the way they do. The basic functions of a watershed include partition of collected water into different flowpaths, storage of water in different parts of the watershed, and release of water from the watershed (Wagener, et al., 2007). Delivering the runoff generated in a watershed is one of the major hydrologic functions of stream network. On this basis, the stream density should be related to runoff in a watershed. Berger and Entekhabi (2001) and Sankarasubramanian and Vogel (2002b) studied the correlations between runoff coefficient and physiographic and climate variables (i.e., climate aridity index, drainage density, median slope, relief ratio, infiltration capacity), and found that the ratio of potential evaporation (E_p) and precipitation (P), which is called climate aridity index (E_p/P), explains most of variability of observed runoff coefficient which is also correlated with drainage density. Drainage density is also linked to frequency regimes of peak flows (Merz and Blöschl, 2008; Pallard, et al., 2009).

In a watershed, the flowing stream network expands to respond rainfall events and contracts during drought periods (Blyth and Rodda, 1973; Gregory, 1976; Day, 1978). From the perspective of flow duration, streams are categorized into perennial stream and temporal stream. Perennial stream, i.e., the basic stream network, flows for much of the year is governed by groundwater flow and therefore depends upon mean annual precipitation as modified by watershed characteristics; the temporal streams, i.e., ephemeral and intermittent streams, occurs once or more each year and is a response to individual rainfall event (Gregory, 1976). De Wit and Stankiewicz (2006) studied the relation between perennial stream density (D_p) and mean annual precipitation in Africa. They found that D_p is close to zero when precipitation is less than 400 mm; from 400 mm to 1000 mm, D_p increases with precipitation and then decreases when precipitation is larger than 1000 mm.

However, runoff at the mean annual scale is not only controlled by water supply but also energy supply. Budyko (1958) postulated that mean annual evaporation from a watershed could be determined, to first order, from precipitation and potential evaporation. Based on world-wide data on a large number of watersheds, Budyko (1974) demonstrated that the partitioning of precipitation is primarily controlled by climate aridity index. Perennial stream density may be dependent on both mean annual precipitation and potential evaporation similar to mean annual runoff.

Interactions between climate, soil, vegetation, and topography contribute to the generation of observed patterns in natural watersheds, and the patterns contain valuable information about the way they function (Sivapalan, 2005). The dependence of perennial stream density on mean climate deserves further investigation for assessing potential climate change impact on water supply availability. The purpose of this research is to explore the dependences of both runoff and perennial stream density on climate aridity index and the correlation between the two dependences. Particularly, the connection between Budyko hypothesis and perennial stream density will be discussed.

2 Methodology

2.1 Data sources

The international Model Parameter Estimation Experiment (MOPEX) watersheds are chosen as case study watersheds because precipitation, potential evaporation and runoff data is available. The MOPEX dataset is described by Duan et al. (2006) and can be downloaded from ftp://hydrology.nws.noaa.gov/. This dataset includes daily values of areal precipitation, climatologic potential evaporation, and streamflow with an adequate number of precipitation gauges. Several recent studies have been based on the MOPEX watersheds (e.g., Sivapalan et al., 2011; Wang and Hejazi, 2011). Due to the missing data in both MOPEX data and perennial stream data for some watersheds, 185 watersheds are selected in this study. Over the study watersheds, the climate aridity index ranges from 0.24 (humid) to 4.58 (arid); the minimum mean annual precipitation is 277 mm, and the maximum mean annual precipitation is 2770 mm.

Perennial streams are obtained from the national hydrography dataset (NHD) which is a comprehensive set of digital spatial data that encodes information about naturally occurring and constructed streamlines (http://nhd.usgs.gov/). The map scale of the high-resolution NHD is 1:24 000. All flow lines have been classified as perennial, intermittent, ephemeral streams, and others. In NHD, perennial streams contain water throughout the year, except for infrequent periods of severe drought. The stream classification is based on digitizing the "blue line mapping" and stream symbolization on US Geological Survey (USGS) 7.5 min quadrangle topographic maps. The blue-line mapping and perennial and temporal classifications on topographic maps used in NHD are based on aerial photo interpretation and have been extensively verified by field reconnaissance by the USGS at the time the map was compiled or revised (Simley, 2003). Errors may occur in the process of digitally capturing the topographic map information and incorporating it into the NHD flow lines.

In the high-resolution NHD, each feature has its unit code which is five-digit integer value comprised of the feature type and the combinations of characteristics and values. In the dataset, streamlines are classified into perennial (46006), intermittent (46003), ephemeral streams (46007), and others. Some perennial streams with human interferences are classified as artificial path (55800), connecter (33400), or others. Therefore, these types of flow lines located in main channel should also be accounted into perennial streams when the total perennial stream length is computed. It should be noted that the value of total stream length, particularly for intermittent and ephemeral streams, depends on the resolution of the map from which the streams were obtained (Montgomery and Dietrich, 1988). However, this research is focused on perennial stream which is much more reliable than temporal streams in the NHD dataset.

2.2 Budyko hypothesis and complementary Budyko curve

The pattern of mean annual evaporation can be described by the Budyko curve, which shows a predictable relationship between annual water balance and the climatic drivers of precipitation and potential evaporation (Budyko, 1974). Based on datasets from a large number of watersheds, Budyko (1974) proposed a relationship between mean annual evaporation ratio (E/P) and mean annual climate aridity index (E_p/P):

$$\frac{E}{P} = \sqrt{\frac{E_p}{P}\left[1 - \exp\left(-\frac{E_p}{P}\right)\right]\tanh\left(\frac{1}{E_p/P}\right)} \qquad (1)$$

where E is the mean annual evaporation. Other functional forms of Budyko-type curves have been developed for assessing long-term water balance (e.g., Pike, 1964; Fu, 1981; Zhang et al., 2001; Sankarasubramanian and Vogel, 2002a; Yang et al., 2008). As shown in Fig. 1, evaporation ratio captured the Budyko curve (red line) increases from humid to arid regions. The slope of the Budyko curve is steep in energy-limited regions (i.e., $E_p/P < 1$), and becomes flat in water-limited regions ($E_p/P > 1$).

The mean annual precipitation, potential evaporation, and runoff (Q) for the study watersheds are computed based on the available data of daily precipitation, runoff, and climatologic potential evaporation. Increases in precipitation across the United States during the twentieth century have been reported (Small et al., 2006) and a step change of rainfall and streamflow has been identified around 1970 (McCabe and Wolock, 2002). Wang and Hejazi (2011) quantified the relative contribution of the climate and direct human impacts on mean annual streamflow in the study watersheds by defining 1948–1970 as pre-change period and 1971–2003 as post-change period. To minimize the non-stationary signals of water balance, the mean annual E/P and E_p/P are computed during 1971–2003. As shown in Fig. 1, the observed mean annual evaporation ratio for the study watersheds (i.e., blue circle) is along the mean curve (i.e., red line) estimated by Budyko using world-wide data. There is considerable scatter in the water balance estimates around the Budyko curve, which may be caused by other controlling factors (Milly, 1994; Zhang et al., 2001; Donohue et al., 2007; Yang et al., 2007; Yokoo et al., 2008; Zhang et al., 2008).

At the mean annual scale, the steady-state condition can be assumed for water balance. The mean annual runoff (Q) can be estimated by the complementary Budyko curve:

$$\frac{Q}{P} = 1 - \sqrt{\frac{E_\mathrm{p}}{P}\left[1 - \exp\left(-\frac{E_\mathrm{p}}{P}\right)\right]\tanh\left(\frac{1}{E_\mathrm{p}/P}\right)} \tag{2}$$

where Q/P is the runoff coefficient. Opposite to evaporation ratio, runoff coefficient decreases with E_p/P.

2.3 Normalized perennial stream density

The differentiation between perennial and temporal streams is not quantitatively definite, and subject to a variety of definitions adopted by regulation agencies and academics with a need to classify stream-flow durations. Therefore, definitions of perennial and temporal streams vary widely among regulatory agencies. For example, a perennial stream is defined as a river channel that has continuous flow on the stream bed all year round during years of normal rainfall (Meinzer, 1923). Perennial streams are defined as having 7-day, 10-yr low flows greater than zero by Hunrichs (1983). During unusually dry years, a normally perennial stream may cease flowing, becoming intermittent for days, weeks, or months depending on severity of the drought (Ivkovic, 2009). Since the NHD dataset is used in this study, perennial stream is defined as a solid blue line on the USGS 7.5 min quadrangle topographic map.

Generally, perennial stream density (D_p) is higher in humid regions than that in arid regions. The perennial stream network is mainly controlled by mean climate as well as other factors such as lithology and topography. The hydrologic function of perennial streams is to deliver runoff at the mean annual scale. The patterns of Q/P can be captured by the complementary Budyko curve which is described by Eq. (2). In order to compare the similarity between runoff coefficient and perennial stream, perennial stream density needs to be converted into a dimensionless number since runoff coefficient is dimensionless. The perennial stream density in each watershed is then normalized by a constant denoted as D_p^*. The normalized perennial stream density will be plotted in the Budyko framework and compared with the complementary Budyko curve, of which the maximum possible value is 1. As a result, the normalization factor is set to the maximum density of perennial streams observed in the study watersheds:

$$D_\mathrm{p}^* = \max\left\{D_\mathrm{p}\right\}. \tag{3}$$

The normalized perennial stream density, $D_\mathrm{p}/D_\mathrm{p}^*$, is in the range of 0 and 1. Since both runoff generation and perennial streams are dependent on mean climate which is represented by E_p/P, these dependences can be compared and the similarity between $\frac{D_\mathrm{p}}{D_\mathrm{p}^*}\left(\frac{E_\mathrm{p}}{P}\right)$ and $\frac{Q}{P}\left(\frac{E_\mathrm{p}}{P}\right)$ will be investigated in the following section.

3 Results and discussions

The perennial stream length and density are computed for each study watershed based on the NHD dataset. The spatial distribution of perennial stream densities is shown in Fig. 2. As we can see, the perennial stream density is high in the Eastern US and low in the Great Plains. The minimum perennial stream density is 0 km^{-1} and the maximum perennial stream density is 1.59 km^{-1}. De Wit and Stankiewicz (2006) reported the perennial stream densities in Africa and the values vary from 0 to 0.14 km^{-1}. In a small peatland headwater catchment in UK, the perennial stream density is 1.41 km^{-1} when water tables fall below 180 mm; but the total drainage density is 29.98 km^{-1} when the stream network is fully expanded (Goulsbra et al., 2012). The perennial stream density in the Turnhole Bend Groundwater Basin in Kentucky is reported in values ranging from 0.24 km^{-1} to 1.13 km^{-1}. Johnston and Shmagin (2008) reported that the average perennial stream density of several watersheds located in the US Great Lakes is 0.42 km^{-1}. Perennial stream density in the Northern Rockies Eco-region is relatively high and the values reported range from 0.9 km^{-1} to 1.2 km^{-1} (McIntosh et al., 1995). Wigington et al. (2005) reported that perennial stream density of agricultural watersheds in Western Oregon varies from 0.24 km^{-1} to 0.66 km^{-1} even though the total stream density varies from 2.90 km^{-1} to 8.00 km^{-1}. The perennial stream density for the four case study watersheds located in Western Oregon are 0.1 km^{-1} (USGS gage 14308000), 0.26 km^{-1} (USGS gage 11497500), 0.29 km^{-1} (USGS gage 14080500), and 0.67 km^{-1} (USGS gage 11532500) as shown in Fig. 2. The perennial stream density computed based on the NHD dataset is consistent to the reported values in the literature.

To explore the climate control on perennial stream density, normalized perennial stream densities of all the study watersheds are plotted as a function of climate aridity index (Fig. 3a). The blue dot represents the normalized perennial stream density which monotonically decreases from energy-limited region to water-limited region. The data cloud shows the strong dependence of perennial stream density on mean annual climate aridity index. De Wit and Stankiewicz (2006) studied the mean annual precipitation control on perennial stream density in Africa, and proposed a non-monotonic relationship. Annual precipitation has usually been the main focus in studies of climate control on drainage density (e.g., Abrahams and Ponczynski, 1984). To include the effect of energy, *P*-*E* index proposed by Thornthwaite (1931) contains both precipitation and actual evaporation which is implicitly related to temperature (Moglen et al., 1998). However, from the perspective of water balance, the hydrologic basis of the *P*-*E* index is not strong as that of the climate aridity index proposed by Budyko (1958). Gregory (1976) compared the pattern of total drainage density as a function of climate aridity index, but no explicit pattern was discovered. The reason is that the dependence of temporal streams on mean climate is not strong as perennial streams. As we expected, a monotonic trend is identified for perennial streams as a function of climate aridity index in this paper.

To compare similarity between runoff coefficient and perennial stream, the indicator for perennial stream density needs to be non-dimensionless and within the range between 0 and 1 like runoff coefficient. Therefore, normalized perennial stream densities ($D_\mathrm{p}/D_\mathrm{p}^*$) are plotted in Fig. 3a. The runoff coefficient (Q/P) computed by the complementary Budyko curve described in Eq. (2) is represented by the red line. The complementary Budyko curve fits the data points of normalized perennial stream density very well. Therefore, the proposed similarity between $D_\mathrm{p}/D_\mathrm{p}^*$ and Q/P as a function of E_p/P, i.e., $\frac{D_\mathrm{p}}{D_\mathrm{p}^*}\left(\frac{E_\mathrm{p}}{P}\right)$ and $\frac{Q}{P}\left(\frac{E_\mathrm{p}}{P}\right)$ is promising based on the case study watersheds. Figure 3b compares the normalized perennial stream density and mean annual runoff coefficient directly. The root mean square error (RMSE) between $D_\mathrm{p}/D_\mathrm{p}^*$ and Q/P is 0.16.

One of the purposes for this research is to develop a simple model to predict perennial stream density. For example, De Wit and Stankiewicz (2006) applied the step-wise linear relationship between mean annual precipitation and perennial stream density to assess the climate change impact on perennial stream density in Africa. In this research, complementary Budyko curves are proposed to predict perennial stream density. Like E/P versus E_p/P in Fig. 1, data points of normalized perennial stream density scatter around the complementary Budyko curve. The scatters reflect the impact of other factors on perennial streams such as lithology and topography. To incorporate these effects, Budyko-type curve with single parameter can be applied following the work on water balance (e.g., Pike, 1964; Zhang et al., 2001) The parameter values can be estimated using the observed normalized perennial stream densities. Then empirical relationship between the parameter and the other factors can be constructed so that perennial stream density can be predicted more accurately under climate change. In global hydrological models, an estimate of the perennial stream density for each grid cell (e.g., $0.5^\circ \times 0.5^\circ$) is needed in order to model the local groundwater level and the groundwater discharge (Van Beek and Bierkens, 2008; Wu et al., 2011). The findings from this research will provide a framework to modeling perennial stream density for macroscale hydrological model development.

The limit lines for runoff coefficient are represented by black lines in Fig. 3a. When climate aridity index is less than 1, the lower bound for runoff coefficient is the line of $Q/P = 1 - E_\mathrm{p}/P$; when climate aridity index is larger than 1, the lower bound of runoff coefficient is zero. Due to the uncertainty in the hydro-climatic data, several data points (E/P) are located above the limit line, i.e., the 1:1 line shown in Fig. 1. However, more data points for $D_\mathrm{p}/D_\mathrm{p}^*$ are located below the limit line in Fig. 3a. Besides uncertainty of perennial stream data in the NHD dataset, the value of D_p^* can also affect the position of these points. Higher value of D_p^*, more data points below the limit line. In this study, the maximum value of perennial stream density over all the case study watersheds is used for D_p^*. The value of D_p^* is 1.59 km^{-1} for Snoqualmie River watershed in the State of Washington with climate aridity index of 0.27. It should be noted that the D_p^* used in this study is not the maximum perennial stream density in the world. Long-term climate may not be the main controls in some special watersheds and perennial stream density is high due to topography and existence of lakes and reservoirs. The data points in Fig. 3a may be not necessarily above the limit line, i.e., $D_\mathrm{p}/D_\mathrm{p}^* > 1 - E_\mathrm{p}/P$. Even though the similarity exists in the runoff coefficient and perennial stream density dependence on long-term mean climate, the controls of other factors on water balance and perennial stream are different. This induces the considerable scatter around the line of 1:1 in Fig. 3b and the scatters in Figs. 1 and 3a are different.

4 Conclusions

The observed pattern of perennial stream density can be explained by the hydrologic functions of perennial streams. Corresponding to the mean annual climate, the normalized perennial stream density is strongly correlated with the mean annual runoff coefficient. The scaled perennial stream density can be quantified by the complementary Budyko Curve, which monotonically decreases with the climate aridity index. Therefore, the perennial stream density is one component of coevolution of climate, vegetation, soil, and landscape at the mean annual scale. The proposed similarity between perennial stream density and runoff coefficient as a function of climate aridity index, i.e., $\frac{D_\mathrm{p}}{D_\mathrm{p}^*}\left(\frac{E_\mathrm{p}}{P}\right)$ and $\frac{Q}{P}\left(\frac{E_\mathrm{p}}{P}\right)$ is promising based on the case study watersheds in this research.

In this study, we only focus on the first order control (i.e., mean climate) on perennial stream density. The scatters of the normalized perennial stream density in the Budyko framework are due to other factors such as vegetation type and coverage, soil, topography, and geology etc. Future efforts can investigate the impact of these factors on the perennial stream density from the perspective of hydrologic functions in the Budyko framework. The maximum perennial stream density, which is the normalization factor, is estimated based on the study watersheds. The normalization factor is important since the shape of data points in Fig. 3a depends on the normalization factor. The theoretical value of the maximum perennial stream density is open for further investigation. Considering the limit lines and the value of the normalization factor, function forms which are different from Budyko-type equations may need to be developed for predicting perennial stream density.

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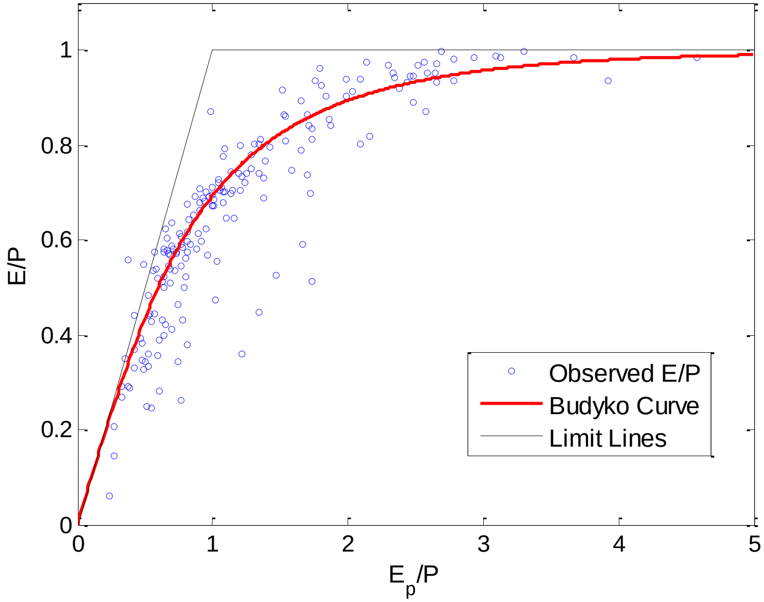

Fig. 1. Comparison of observed evaporation ratio (E/P) with estimates based on Budyko curve at 185 MOPEX catchments.

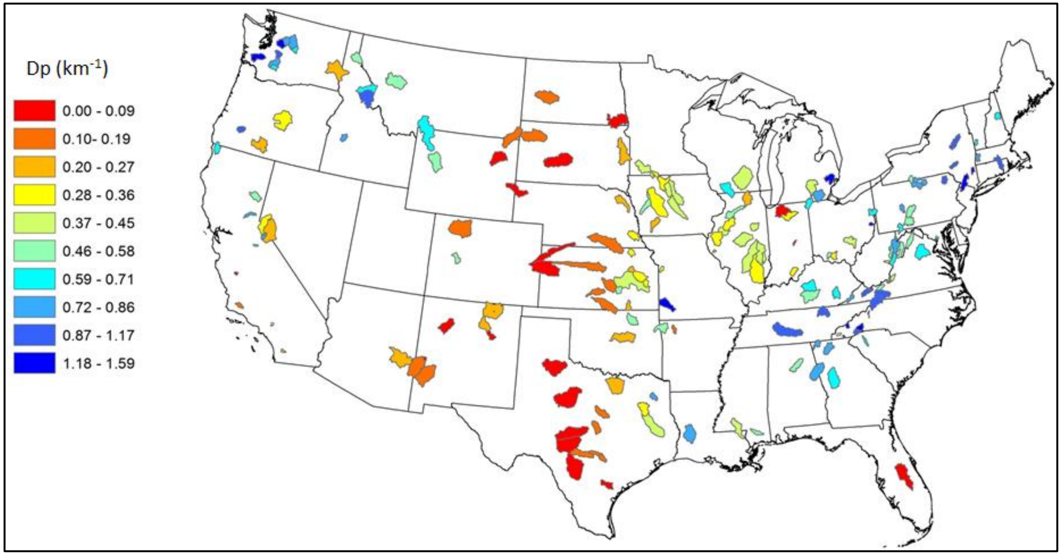

Fig. 2. Spatial distribution of perennial stream densities for the study watersheds.

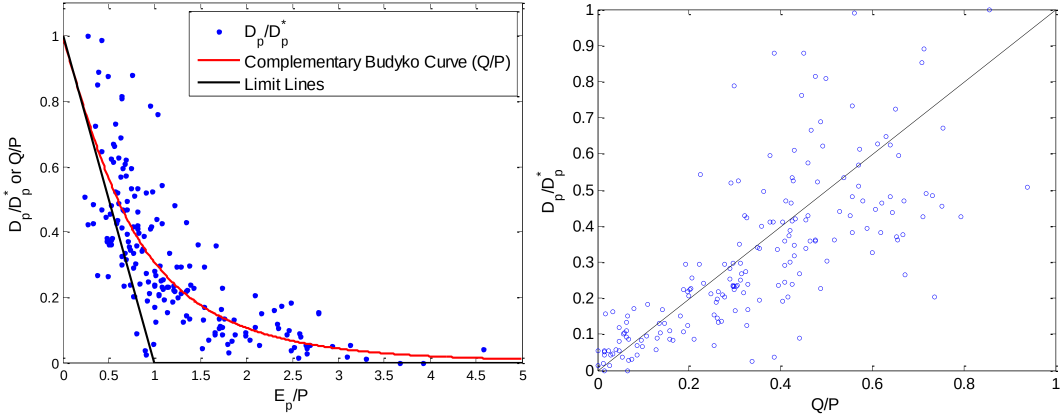

Fig. 3. The perennial stream density (D_p) normalized by D_p^* versus climate aridity index **(a)**; normalized perennial stream density versus mean annual runoff coefficient **(b)**.