Hydrologic partitioning and vegetation response in selected moist zone catchments of Ethiopia: analyzing spatiotemporal variability

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ABSTRACT

Analysis relating spatiotemporal variability of hydrologic budget with that of catchment-vegetation is one of the avenues to explore vegetation response to climate variability and the resulting impact on water resources dynamics. Here the spatiotemporal variations of hydrologic budget and Normalized Difference Vegetation Index (NDVI) in six moist zone catchments of Ethiopia during 2000-2006 were analyzed and their relationship explored. It was found that the fraction of precipitation potentially available to catchment-vegetation (Wetting; W) ranged from 0.73 to 0.96, meaning up to 27% of precipitation was not available to vegetations. A significant positive correlation was observed between Humidity Index (HuI) and W, making HuI a good indicator of catchment wetness, and thus soil moisture condition. Horton Index (HI) (a.k.a. catchment-vegetation water use factor) ranged from 0.42 to 0.92, leaving up to 58% of wetting not consumed by vegetation in some catchments, and in others this unused fraction was as low as 8%. Although HI showed strong inter-catchment variation, it was relatively constant from year-to-year and can be considered a catchment characteristic. However, HI alone is not sufficient to indicate whether vegetation growth is limited by moisture availability, as NDVI of 0.77 was observed in a catchment with lowest HI and NDVI of 0.56 was observed in another catchment with highest HI. Moreover, inter-regional variability in the timing of observed lag between monthly precipitation and NDVI peaks was noticed. Our results demonstrate that catchments within the same climate zone exhibit variable hydrologic partitioning and vegetation response behavior.

Keywords: catchment-vegetation; hydrologic partitioning; moist zone; spatiotemporal variation

1. Introduction

Hydrologic budget and vegetations are closely coupled. Hence, identifying hydrologic budget and vegetation link is one means of exploring vegetation response to climate variability and the resulting impact on catchments water resources. Because, on one side, vegetations primarily control hydrologic budget of catchments usually through depleting soil moisture (Brutsaert, 1988; Thompson *et al.,* 2011a). The seasonal variability of vegetations also affects the seasonality of water cycles and surface energy budget (Kim and Wang, 2005). While, on the other front, hydrologic budget integrates the impacts of climate variability on vegetations structure and functions (Mora and Iverson, 1997; Zhou *et al*., 2003). In this regard, Brooks *et al.* (2011) suggests that symmetries in spatiotemporal patterns of catchment-scale hydrologic budget are suggestive of patterns of acclimation and adaptation of vegetations.

Improving our knowledge of hydrologic budget and vegetation coupling is essential to precisely predict the impacts of climate variability and to better manage catchments. It is also important to understanding the potential feedbacks between surface hydrology and the global climate system (Thompson *et al*., 2011b). In addition, exploring how radical land cover changes alter vegetation processes and affect the catchment's hydrologic budget is an urgent need (Wilcox, 2010). However, understanding this coupling is challenging. The possible reasons are: lack of data (e.g. evapotranspiration and soil moisture) at finer spatiotemporal scales, complexity of catchment processes and lack of appropriate mechanism to scale information at patch level up to catchments (Sivapalan *et al.,* 2011). Likewise, lack of consensus on how changes in climate will affect regional vegetation, and shifts in regional climate patterns complicate the prediction of hydrologic response of vegetations (Wagener, 2007; Voepel *et al*., 2011).

Despite all these challenges, scientists are trying to solve the big unknown questions behind hydrologic and ecologic processes with the help of models and satellites. However, careful selection of water balance model and remotely sensed vegetation greenness index is essential to depict reasonable result. For example, L'vovich water balance theory (L'vovich, 1979) is one of the frequently used approaches to quantify annual catchment-scale hydrologic budget. Considering satellites applications, Normalized Difference Vegetation Index (NDVI) is the most commonly used (Justice *et al*., 1985; Davenport and Nicholson, 1993) and has proven to be a robust indicator of terrestrial vegetation productivity (Wang *et al.,* 2001, 2003; Dong *et al.,* 2011).

Various previous studies have related L'vovich's theory based hydrologic budget estimates and NDVI, although the geographic focus is entirely in the conterminous United States. For example, Brooks *et al.* (2011) compared the estimates of plant available water to NDVI in order to evaluate the ability of a catchment derived index of water availability to capture responses in vegetation. They found out that catchment-scale hydrologic partitioning provides information on both the fractions of precipitation available to and used by vegetation, and it is important for quantifying regional ecohydrological response to climate variability and/or vegetation change. Sivapalan *et al*. (2011) similarly stated that L'vovich water balance theory provides a promising framework to evaluate both how plant available water at catchment-scale varies from year-to-year, and how vegetation responds to this inter-annual variability. Voepel *et al.* (2011) also investigated controls on hydrologic partitioning at the catchment-scale across many different US eco-regions, and compared the resulting estimates of catchment wetting and vaporization to NDVI. Their results revealed that catchment-vegetation water use factor (a.k.a. Horton index) is a basic tool to explore interactions between hydrologic and ecologic processes.

Therefore, understanding hydrologic budget and vegetations coupling can be considered as a critical step towards understanding climate-vegetation-hydrology interaction. The latter is important for studies on climate variability, catchment management and terrestrial carbon sink. In this paper, we quantify hydrologic budget and NDVI in an attempt to explore their coupling and examine their spatiotemporal variability in selected catchments found in the mostly moist climate regime of Ethiopia. Our main goal is to show that issues like catchment management and the impact of climate variability on catchment-vegetation should be treated differently regardless of similarity in climate regime of catchments. This is important given how critical water resources are for the economic development in Ethiopia.

2. Methods

2.1.Study areas description

The study was conducted in six catchments located in the moist climatic zone of Ethiopia, East Africa (Figure 1). The term moist climatic zone represents an annual humidity index of greater than 0.65 (Mersha, 2000). This zone, in Ethiopia, encompasses strong variation of spatial gradient, and seasonality in vegetation and water resources. It is also a site for various water resource projects. The catchments were selected from four different river basins: Blue-Nile, Baro-Akobo, Omo-Ghibe and Genale-Dawa. The selection was primarily based on three parameters: land cover type, rainfall seasonality and availability of hydro-climatic observations (i.e. stream flow, precipitation and temperature). Receiving catchment-average annual rainfall between ~885mm and 1872mm, their drainage area ranges from 161km^2 to 1622km^2 (Table 1). Land cover is mainly evergreen forest, cultivation, bushland and grassland. Each catchment is primarily covered by specific land cover type (Table 1). However, cultivation prevails in all catchments although its area coverage differs.

Table 1. Physiographic, hydrologic, climatic and land cover characteristics.

Study catchments		*Koga*	*Nashe*	*Sor*	*Mazie*	*Mormora*	*Shawe*
Drainage area (km^2)		244	350	1622	937	1375	161
Elevation, a.m.s.l, (m)	Low	1926	2074	1550	932	1617	1416
	High	3048	2663	2621	3452	3017	3522
Mean daily discharge (m^3/sec)		5.61	7.52	46.40	5.54	18.61	2.85
Mean annual precipitation (mm)		1434	1604	1872	1136	1113	885
Rainfall seasonality		unimodal	unimodal	unimodal	bimodal	bimodal	bimodal
Mean annual temp. (^{o}C)	Max	26.7	23.4	24.9	30.3	23.7	24.4
	Min	10.2	10.9	11.7	15.0	10.9	11.0
Major landuse / landcover		cultivated	cultivated	evergreen forest	grassland and bushland	evergreen forest	evergreen forest

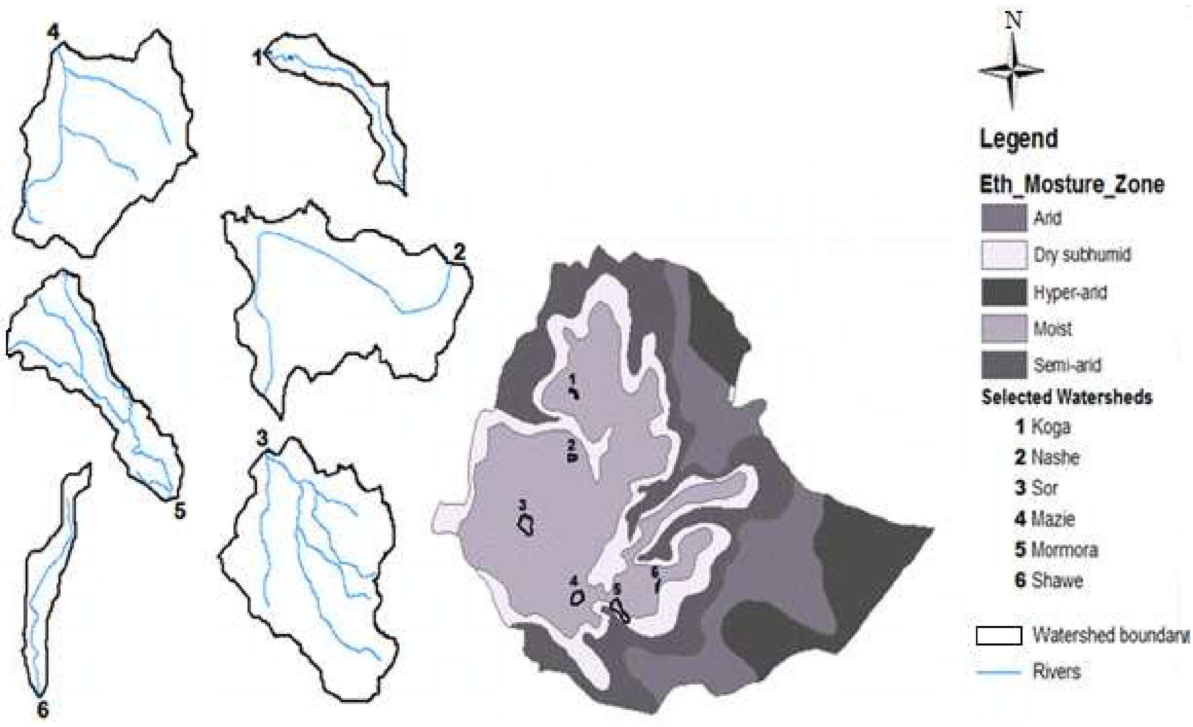

Figure 1. Ethiopia moisture zones (Mersha, 2000), flow gauging stations locations and geographic locations of the study catchments.

2.2.Data collection and preprocessing

Daily stream flow observations were obtained from the Ministry of Water and Energy of Ethiopia. The monthly climate data (precipitation, minimum temperature and maximum temperature) were collected from the National Meteorological Service Agency of Ethiopia. The Moderate Resolution Imaging Spectroradiometer (MODIS's) Terra-Aqua combined land product (MCD43A4 collection version 5) was used to quantify NDVI. MCD43A4 is disseminated by Land Processes Distributed Active Archive Center (LP DAAC, webpage: *http://*lpdaac.usgs.gov, accessed on June 18, 2012).

The climate data is a merged product that combines both ground stations and satellites observations. The product is made available at 10km spatial resolution, and ten day, monthly and yearly temporal scales for the year 1983 up to present (Dinku *et al.*, 2011). MCD43A4 is a 16days composite reported every 8days with a spatial resolution of 500m and 12bits radiometric resolution. We spatially averaged the monthly climate data to create monthly and annual time series of precipitation and temperature for each catchment. Missing stream flow observations were filled and data quality assessment identified no significant suspect. We then preprocessed the stream flow and climate records to cover the 2000-2006 period to obtain data contemporaneous with NDVI at all study catchments.

2.3. *Hydrograph separation*

The aim of hydrograph separation is to distinguish two stream flow components (baseflow and surface runoff). Baseflow is the relatively slowly varying component of stream flow, and it is frequently the result of groundwater discharging into wetlands, lakes and rivers. Surface runoff (a.k.a. quick flow), on the other hand, is the response to rainfall events. The one parameter recursive digital filtering algorithm (Nathan and McMahon, 1990) was used in order to separate baseflow and surface runoff. The recursive digital filters are routine tools in signal analysis and processing, and are used to remove the high-frequency surface runoff signal to derive the low-frequency baseflow signal (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Sloto and Crouse, 1996; Eckhardt, 2012). Despite the lack of explicit consideration for physical processes and hydrological basis, these techniques do provide an objective, repeatable and easily automated index that can be related to the baseflow response of a catchment (Nathan and McMahon, 1990; Arnold *et al*., 2000; Smakhtin, 2001). The one parameter recursive digital filtering algorithm developed by Nathan and McMahon (1990) is given as:

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

$$B_t = Q_t - S_t \quad (2)$$

Both Equations 1 and 2 are subject to B_t, $S_t \geq 0$ or B_t, $S_t \leq Q_t$; where S_t, B_t and Q_t are surface runoff, baseflow and total river flow at the t^{th} sampling instant, respectively, and α is the filter parameter.

An α value of 0.925 was initially recommended by Nathan and McMahon (1990) to use in Equation 1. The same value was adopted in different literatures including for example Smakhtin (2001); Troch *et al.* (2009); Welderufael and Woyessa (2010); Brooks *et al.* (2011), and Voepel *et al.* (2011). We similarly set the value of filter parameter to 0.925. The filter was passed over the daily stream flow data three times (forward, backward and again forward in time). The number of passes determines the degree of smoothing and the reverse pass nullifies any phase distortion of the data due to the forward pass of the filter (Nathan and McMahon, 1990). Passing the filter two or three times is also important to obtain more precise estimation of the baseflow especially for the beginning of the time series (Troch *et al*., 2009; Brooks *et al*., 2011). Daily values obtained from the filter were then summed to obtain annual stream flow, baseflow and surface runoff.

2.4. *Hydrologic partitioning*

Hydrologic partitioning is first defined by L'vovich (1979) as the two-stage partitioning of water at the land surface (Figure 2). The incoming precipitation is first divided between wetting and surface runoff. Next, the wetting component is partitioned into vaporization and baseflow. Here, vaporization is the sum of all evaporation and transpiration. It comprises over 60% of terrestrial water balance (Shiklomanov, 1998), and nearly equal to rainfall in semi-arid and arid regions (Budyko, 1974; Zhang *et al*., 1999). L'vovich (1979) proposed a linked set of water balance equations at annual time scale assuming year-to-year change in soil moisture storage is negligible. This change is only less than 1.5% of annual precipitation (L'vovich, 1979) and his assumption is useful as a first approximation (Ponce and Shetty, 1995). Similarly, Zhang *et al.* (1999) stated that deep percolation or recharge and change in soil moisture storage is often only

5-10% of the annual water balance, and therefore can be neglected on practical grounds. Given that P, S and B are known, we applied L'vovich's equations to calculate W and V as:

$$W = P - S \tag{3}$$

$$V = P - (S + B) = P - Q \tag{4}$$

where, P, Q, S, B, W and V are precipitation, total river flow, surface runoff, baseflow, wetting and vaporization at annual time scale, respectively.

The concept of hydrologic partitioning proposed by L'vovich (1979) enables a better water balance than conventional methods, and it provides a clearer understanding of all the water balance components for a given gauged catchment (*http://*saltonsea.sdsu.edu, accessed on July 23, 2012). Deemed to characterize the functioning of the catchments at the annual time scale, the L'vovich's approach provides a promising framework to evaluate both how plant available water at the catchment scale varies from year-to-year and how vegetation responds to this inter-annual variability (Brooks *et al*., 2011; Sivapalan *et al.*, 2011).

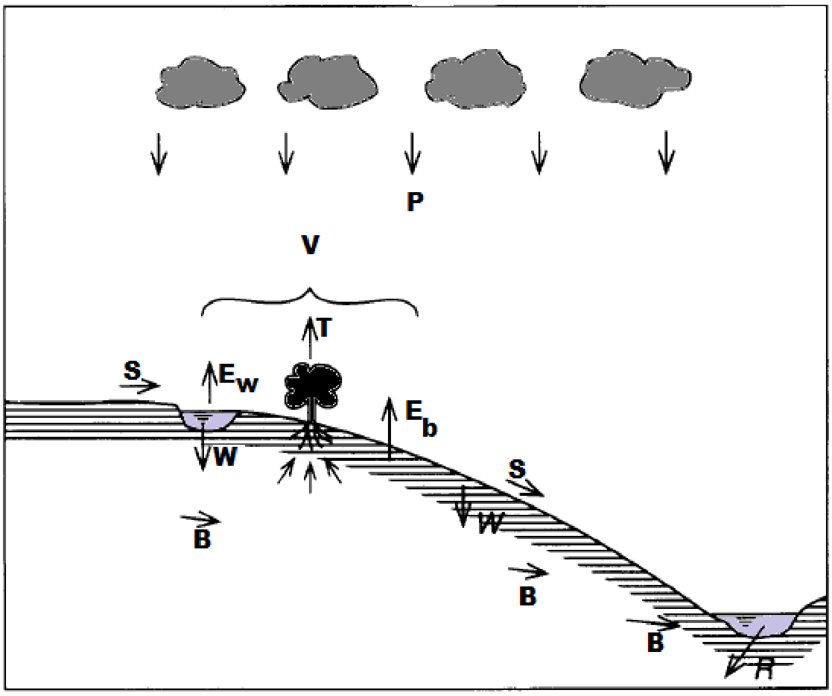

Figure 2. Conceptual model of the hydrologic partitioning at the land surface according to L'vovich (1979) and elements of L'vovich's water balance (after Ponce and Shetty, 1995). First, precipitation (P) is partitioned between surface runoff (S) and wetting (W). Then, W is divided between vaporization (V) and baseflow (B). V includes evaporation from water bodies (E_w), bare soil evaporation (E_b) and plant transpiration (T).

The ratio of V to W (termed the Horton Index (HI), see Troch *et al*., 2009) is a function of the energy and water available to plants, and can be used to evaluate how climate interacts with the terrestrial vegetation (Brooks *et al.*, 2011). HI is less dependent on the method of baseflow separation used (Troch *et al.*, 2009), and it is relatively insensitive to the values of α (in this case 0.5, 0.925 and 0.975) adopted in Equation 1, as per sensitivity test in this study. Knowing that there are many ways in which precipitation is quickly released from the landscape to the channel network (Beven, 2006), the catchment-derived HI is calculated as:

$$\mathrm{HI} = \frac{\mathrm{V}}{\mathrm{W}} \tag{5}$$

The catchment-average annual Humidity Index (HuI), the ratio of annual precipitation and annual potential evapotranspiration (see Hulme *et al.*, 1992) (Equation 7), was computed for all study catchments. Monthly PET was calculated from monthly maximum and minimum temperature using the 1985 Hargreaves equation (Hargreaves and Samani, 1985) (Equation 6). Monthly values were then summed to obtain annual PET. The 1985 Hargreaves approach is one of the simplest and most reliable of empirical equations to estimate PET (Allen, 1995). It has been widely used globally to provide reliable prediction of PET in data short situations (as is the case in our study areas) for weekly or longer periods (Hargreaves and Allen, 2003).

$$\mathrm{PET} = 0.0023\mathrm{Ra}(\mathrm{Tm} + 17.8)\sqrt{\mathrm{Td}} \tag{6}$$

$$\mathrm{HuI} = \frac{\mathrm{P}}{\mathrm{PET}} \tag{7}$$

Here, Ra is water equivalent of extraterrestrial radiation (in same unit as PET, usually mm/day) (obtained from *http://*www.fao.org/docrep/X0490E/x0490e0j.htm, accessed on August 13, 2012), Tm is mean monthly air temperature in ^{o}C, estimated from minimum and maximum temperatures as ($\frac{\mathrm{Tmax + Tmin}}{2}$), and Td is monthly temperature difference in ^{o}C, calculated as $\mathrm{Tmax - Tmin}$.

2.5.NDVI time series

NDVI has been proved to be an excellent indicator for characterizing variations in vegetation cover, productivity, biomass and eco-environmental quality from local to global scales (Dong *et al.,* 2011). It is influenced by the fractional coverage of the ground by vegetation, vegetation density and vegetation greenness. NDVI is determined by the degree of absorption by chlorophyll in the red wave length and reflectance of near-infrared by spongy mesophyll (Tucker *et al.,* 1979). We used MODIS's MCD43A4 product to create catchment-average monthly and annual NDVI time series. Importantly, MCD43A4 is corrected for bidirectional effects (nadir view and standard sun angles) in addition to corrections for cloud contamination, atmospheric variability and aerosols (Schaaf *et al.,* 2002). The two bands used for NDVI calculation are Band 1 (620nm – 670nm, red) and Band 2 (841nm – 876nm, near infrared) which is defined as:

$$\mathrm{NDVI} = \left[\frac{\text{Band 2 - Band 1}}{\text{Band 2 + Band 1}}\right] \tag{8}$$

3. Results

3.1.Catchment-scale hydrologic partitioning variation

Precipitation and wetting in addition to total flow and baseflow were closely related in all catchments. The probability of vaporization lower than baseflow on annual basis was nearly zero except in Shawe where vaporization was below baseflow for more than 70% of the time analyzed (Figure 3). Statistically, the vaporization estimated for Shawe in some years was detected as outliers when compared with that of other catchments (Figure 4). Also, the estimated PET of this catchment was 5.81 times higher than V while in other catchments this factor was only up to 2.55 (Table 2). No unique similarity was observed among all selected catchments in the variability of individual water balance components (Table 2). In two catchments (Koga and

Sor), precipitation was highly variable compared to other hydrologic budget whereas highest variability in vaporization was observed in others (Nashe and Mazie) during the same period. Similarly, in Shawe catchment, total river flow and baseflow showed the highest variability over the same period 2000-2006.

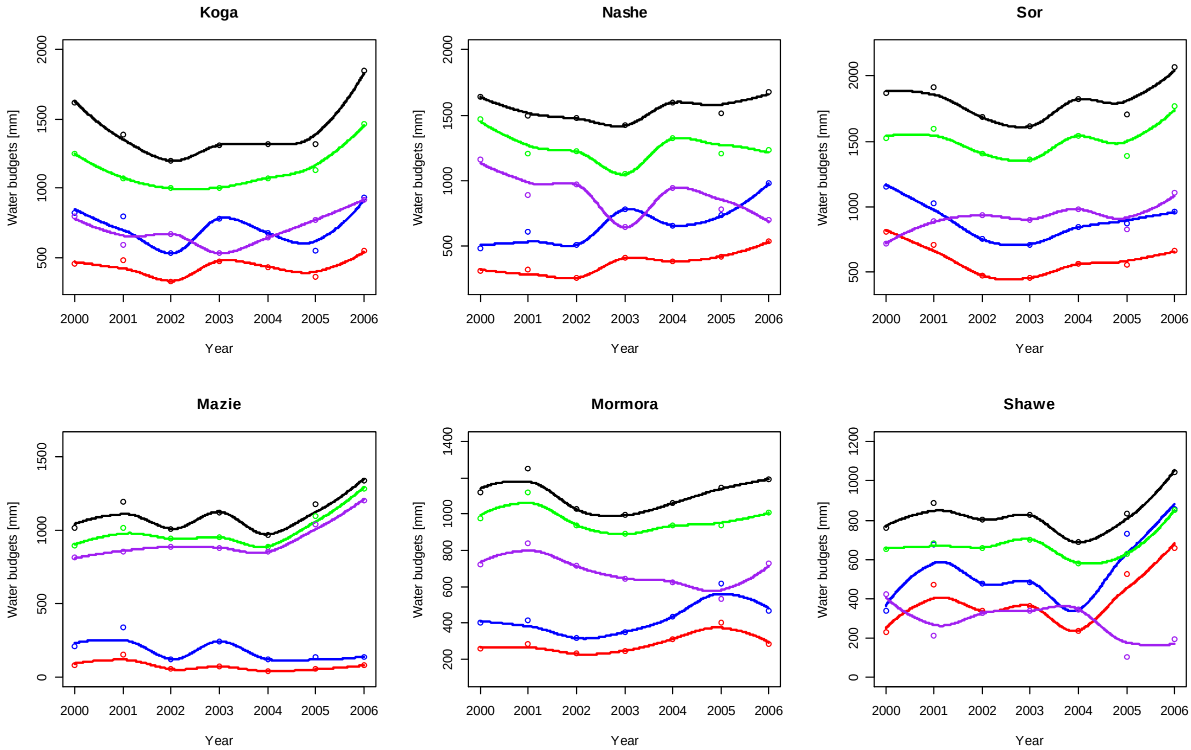

Figure 3. Climographs demonstrating the patterns of hydrologic budgets in the study catchments during 2000-2006. In this Figure, black is for P (precipitation), blue is for Q (total river flow), red is for B (baseflow), green is for W (wetting) and V (vaporization) is represented by purple color.

The total river flow of Mormora was more than two times higher than that of Mazie's while the two catchments received nearly equal amount of average annual rainfall during 2000-2006 (Table 2). Although there are different factors responsible for the observed variance, high groundwater contribution towards total flow or high Base Flow Index (BFI) in Mormora had a significant contribution. Note that BFI can be used as an indicator for the amount of groundwater contribution towards total river flow, and therefore it indicates baseflow percentage in a given river. The BFI of Mormora was over 0.25 higher than that of Mazie's (Table 3). Across the study areas, a 30% difference in the fraction of groundwater contribution towards total flow was observed (Table 3). Unlike the large magnitude of variability in precipitation and wetting, the fraction of annual precipitation that reached the catchment outlet as surface runoff showed small inter-catchment difference (Figure 4). This fraction, when averaged over the period of analyses, was in between 10% and 20%. Moreover, four of the six catchments (Koga, Nashe, Sor and Shawe) had a value greater than or equal to 17%. The gap between 25th and 75th percentiles of surface runoff was also small, showing little inter-catchment variation compared to other hydrologic budgets (Figure 4).

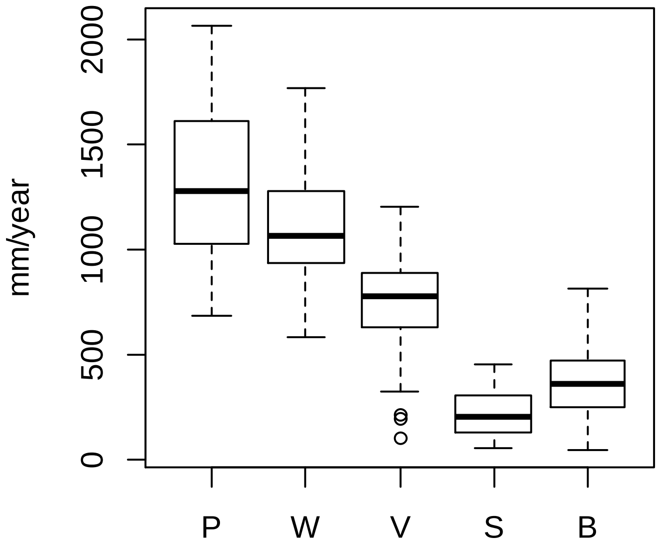

Figure 4. Boxplots showing inter-catchment variation of annual hydrologic budget. P, W, V, S and B represents precipitation, wetting, vaporization, surface runoff and baseflow, respectively. In this Figure, the median (50th percentile, line in the box), upper quartile (75th percentile, upper hinge of the box), lower quartile (25th percentile, lower hinge of the box), minimum values (lower end of whiskers), maximum values (upper end of whiskers) and suspected outliers (circles) are shown.

Table 2. Mean annual values (±standard deviations) of hydrologic budget over 2000-2006.

Hydrologic budget (mm/year)	Study catchments					
	Koga	Nashe	Sor	Mazie	Mormora	Shawe
Precipitation	1428 (225)	1546 (95)	1811 (157)	1117 (129)	1113 (92)	836 (113)
Total river flow	726 (149)	678 (171)	903 (156)	186 (83)	427 (97)	559 (200)
Baseflow	439 (76)	374 (90)	603 (129)	77 (38)	287 (58)	403 (158)
Wetting	1141 (165)	1242 (128)	1511 (145)	1008 (139)	973 (75)	680 (85)
Vaporization	702 (133)	868 (177)	908 (122)	931 (139)	686 (96)	277 (111)
PET	1790 (85)	1472 (25)	1631 (51)	1940 (27)	1529 (43)	1605 (63)

A significant positive correlation was observed between HuI and W (Figure 5). This indicates both across years and across catchments higher humidity index tends to be accompanied by higher catchment wetting. Thus, HuI is a sensitive indicator of the amount of water potentially available to vegetations. It also reveals that catchment-scale climate variables and hydrologic partitioning are strongly related. Because, HuI carries information for two basic climate variables (precipitation and temperature) and W is the output of hydrologic partitioning.

However, the result shown in Figure 5 might also be an instance of spurious correlation, and should be treated with caution. Hence, the linear correlation between HuI and W is valid provided that two necessary conditions hold:

a) 1/PET ~ constant. Since PET is usually quite invariant from year-to-year (e.g. see Table 2), this is usually true.
b) V = αPET, where α is a constant. For relatively small inter-annual fluctuations in HuI (e.g. see Table 3), this will also generally be true.

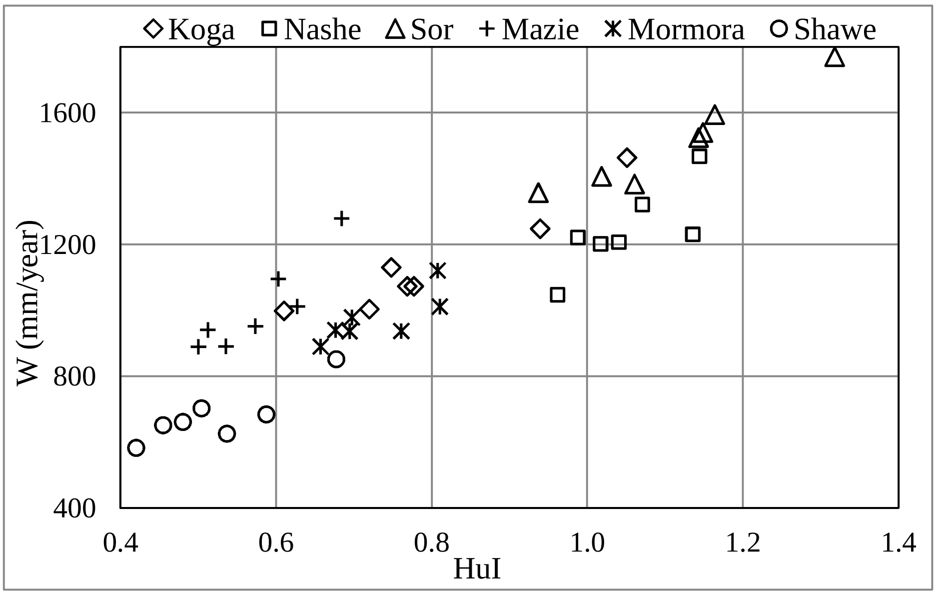

Figure 5. The correlation between Humidity Index (HuI) and catchment wetting (W) across the study catchments over the seven years analyzed (2000-2006).

3.2.Catchment-derived hydrologic and vegetation indices variation

Like precipitation and wetting (Figure 4), during 2000-2006, the annual humidity and Horton indices were also highly variable across the study areas (Figure 6). The inter-catchment range of HuI was from 0.4 to 1.3. Although some HI values for Shawe during some years were detected as statistically outliers compared with that of other catchments, the inter-catchment range of HI was from 0.16 to 0.96. It was observed that only Nashe and Sor had an annual HuI greater than or equal to 1.0 for more than 85% of the time analyzed while the other four catchments had a value less than 1.0 in all years. Thus, on yearly basis, vegetation in Nashe and Sor barely encountered any water limitation during the period analyzed. However, vegetation water limitation might happened if the available water and available energy to derive evapotranspiration were out of phase. That is, water was available but vegetation lacked enough energy to consume the available water probably due to the presence of cloud cover which hinders sunlight from reaching the Earth's surface.

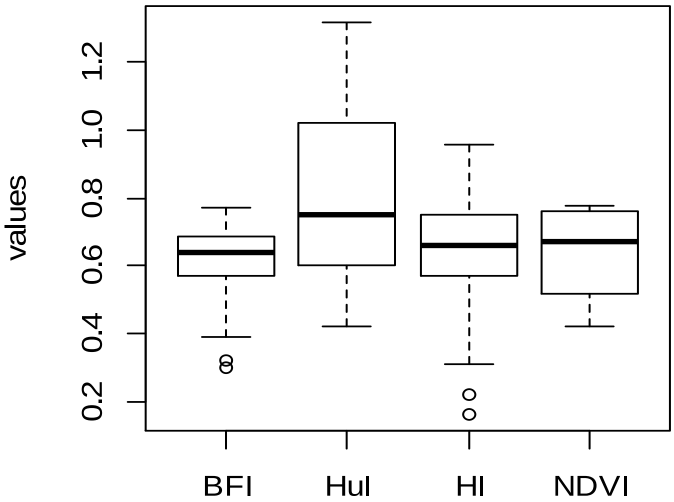

Figure 6. Boxplots indicating inter-catchment variation of annual hydrologic and vegetation indices during 2000-2006. In this Figure, BFI, HuI, HI and NDVI represents BaseFlow Index, Humidity Index, Horton Index and Normalized Difference Vegetation Index, respectively. The median (50th percentile, line in the box), upper quartile (75th percentile, upper hinge of the box), lower quartile (25th percentile, lower hinge of the box), minimum values (lower end of whiskers), maximum values (upper end of whiskers) and suspected outliers (circles) are shown.

The inter-catchment range of wetting averaged over the seven years was from 0.73 to 0.96, meaning up to 27% of precipitation was not available to vegetations. Similarly, strong inter-catchment variability in the fraction of mean annual wetting vaporized by vegetations was observed. This vegetation water use factor was in the range of 0.42 to 0.92 over the same period across the study areas (Table 3). This indicates that some catchments-vegetations leave up to 58% of potentially available water unused while others left only as low as 8% of the available water unused during the stated period. In some catchments (e.g. Mazie), nearly equal vegetation water use was observed over different years although catchment wetness showed an inter-annual variability of up to 400mm. On the contrary, in other catchments like Shawe, the inter-annual difference in vegetation water use reached up to 20% for same amount of wetting. Despite rainfall inter-annual variability, the vegetation water use factor or HI was relatively constant from year-to-year in all catchments except Shawe (Table 3). The observed inter-annual variability of HI in these catchments was as low as 9%.

Table 3. Mean annual values (±standard deviations) of hydrologic and vegetation indices over 2000-2006.

	Study catchments					
Indices	Koga	Nashe	Sor	Mazie	Mormora	Shawe
BFI	0.61(0.03)	0.55(0.05)	0.66(0.03)	0.42(0.09)	0.68(0.04)	0.72(0.03)
HuI	0.80(0.15)	1.05(0.07)	1.11(0.12)	0.58(0.07)	0.73(0.06)	0.52(0.09)
HI	0.61(0.06)	0.69(0.09)	0.60(0.07)	0.92(0.04)	0.70(0.07)	0.42(0.19)
NDVI	0.44(0.01)	0.51(0.02)	0.76(0.01)	0.56(0.03)	0.71(0.02)	0.77(0.01)

Of the six catchments, strong negative correlation between HuI and HI was observed only in Shawe catchment. Very weak (-0.35 < Pearson's r < 0.04) and statistically insignificant (p > 0.45) correlations were observed in the rest of catchments. It was visualized that in Shawe annual HI showed a tendency of converging to the maximum possible value as annual HuI decreased (Figure 7). Also, comparing catchments with different wetness or humidity, high HI was observed in less wet catchment (e.g. Mazie) while relatively low HI was observed in very wet catchments (e.g. Nashe and Sor) (Figure 7). These are some indications that vegetation water use increases as water availability decreases. It also implies the ability of vegetation to maximize productivity by consuming the largest possible amount of water available in the catchment.

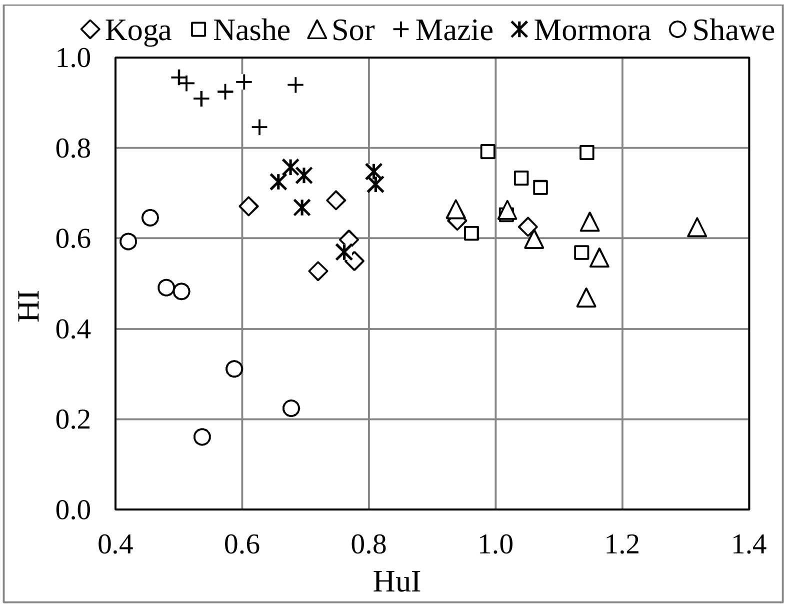

Figure 7. Scatterplots showing the correlation between catchment-derived annual Humidity Index (HuI) and Horton Index (HI) in the study areas during 2000-2006.

Relatively, lower mean annual NDVI was observed in a catchment with highest mean annual HI, whereas highest NDVI was observed for the lowest HI in another catchment (Table 3). This has two implications. First, a larger fraction of wetting vaporized by the vegetations (high HI) does not necessarily lead to greater vegetation greenness (high NDVI). Because, there are also other factors which affect the growth of vegetation like nutrient availability, radiation and temperature. Second, a larger vegetation water use does not always mean vegetation got enough water for maximizing greenness (presumably productivity), as the type of vegetations also matters. The observed correlations between catchment-derived annual HI and NDVI were weak and statistically not significant except for the Sor catchment (Figure 8). However, Pearson's r and p values looked reasonable in the unimodal-rainfall receiving catchments compared to those with bimodal-rainfall. The Pearson's r for the HI and NDVI correlations was also positive in catchments with unimodal-rainfall seasonality while it was negative in others (Figure 8).

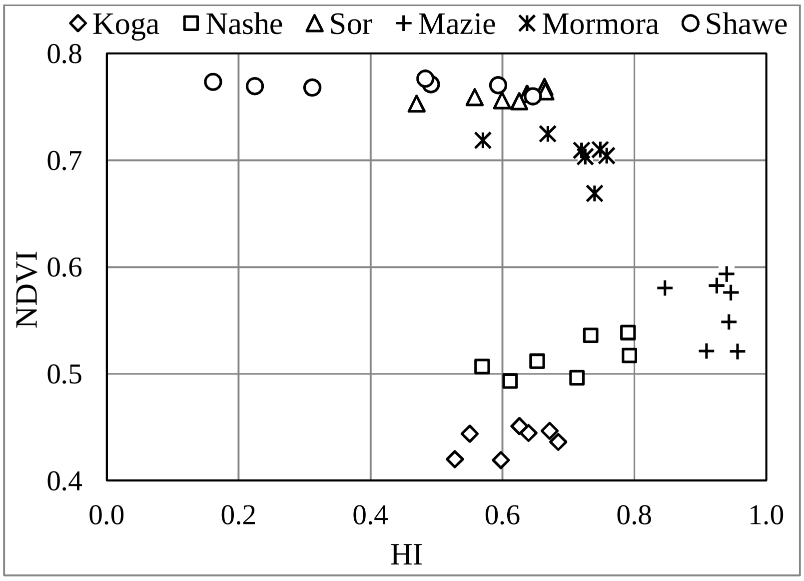

Figure 8. The correlation between catchment-derived annual Horton Index (HI) and corresponding Normalized Difference Vegetation Index (NDVI) in the study areas during 2000-2006.

3.3.Variation of vegetation response to rainfall

The catchment-average annual rainfall and NDVI showed good correlation only in Mazie (Figure 9). Weak correlations (-0.4<Pearson's r<0.4) that are statistically not significant (p>0.40) were observed in the rest of catchments. The logarithmic relation (annual NDVI versus LOG (annual rainfall)) was also checked and no improvement was observed. Although the annual rainfall standard deviation of 92mm to 225mm was noticed (Table 2), the annual variability of NDVI was not higher than 0.03 in all catchments (Table 3). Thus, it is difficult to detect inter-annual rainfall variability from annual NDVI measures except in Mazie. Also, comparing seven years annual NDVI and wetting data, one will note that higher vegetation greenness is not always expected from highly wet catchment.

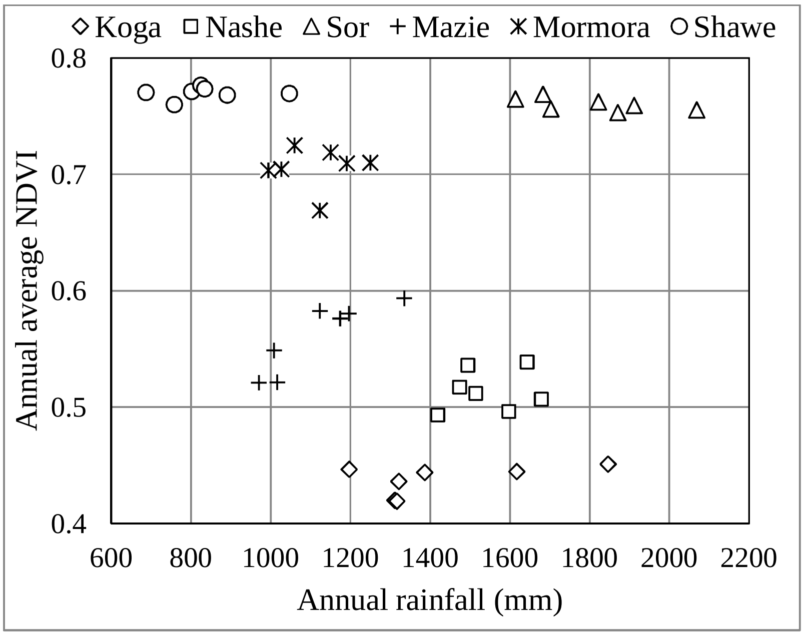

Figure 9. The annual average rainfall and Normalized Difference Vegetation Index (NDVI) relationships in the study areas during the years analyzed (2000-2006).

At monthly time scale, catchment-based time series of rainfall and NDVI showed variability in amplitude, seasonality and lag time across the study areas (Figure 10). In catchments with unimodal-rainfall seasonality (Koga, Nashe and Sor), the monthly rainfall peak was in July and corresponding monthly NDVI maxima was in September except for Sor. Results for the Sor catchment showed a plateau monthly NDVI peak that extends from June to October. Thus, in general, the time lag between monthly rainfall peak and monthly NDVI peak reach up to two months. This indicates, in the dry season, vegetation might be water-limited in these catchments even though the mean annual precipitation amount is high. In the wet season however, vegetation might be radiation-limited since the peak NDVI occurred when precipitation starts to decrease (Figure 10). On the other hand, in catchments with bimodal-rainfall seasonality (Mazie, Mormora and Shawe), the first monthly rainfall peak was in May while the second peak was in September. However, distinct monthly NDVI peaks were not observed except in Mazie where single NDVI peak was in May. The time lag between monthly rainfall and NDVI peaks was therefore less than one month. In these catchments, NDVI in dry seasons was about the same as NDVI during wet seasons, and most of plant functional types were evergreen all year long. This is a typical case of water not being the main limiting factor, and vegetation grows relatively more during the dry season when cloud cover is low. This indicates that these sites could be potential areas for growing especially deep rooted crops. However, solar radiation, land cover type, nutrient availability and temperature might be controlling the phenology of vegetation in these catchments.

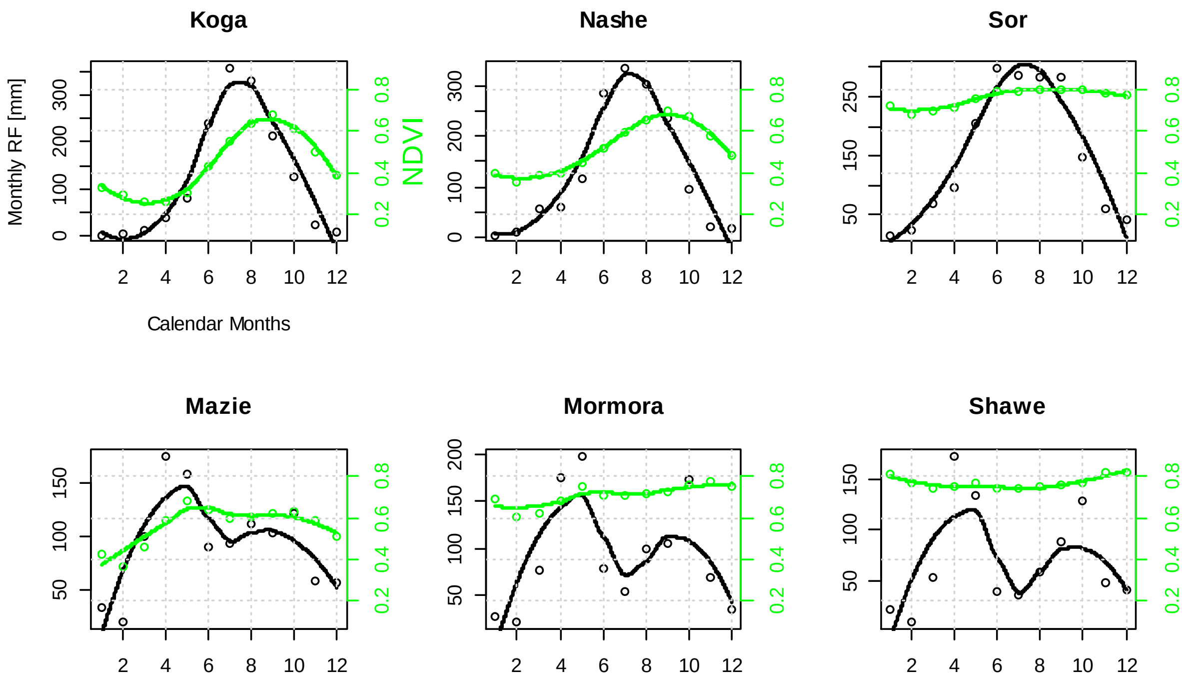

Figure 10. Seven years average (2000-2006) monthly rainfall and Normalized Difference Vegetation Index (NDVI) seasonality. In this Figure, rainfall is represented by black plot and NDVI is represented by green plot. Also, axes titles for the other five plots are the same as that of the first plot.

4. Discussion

Our research goal is to show that whether selected catchments in the Ethiopia's moist zone exhibit variable or similar hydrologic partitioning and vegetation response behavior. This is important to better assess issues like catchment management and the impact of climate variability on catchment-vegetations, mainly. With this in mind, we quantified hydrologic budgets, calculated three basic hydrologic indices (BFI, HI and HuI) and derived NDVI for all catchments during 2000-2006. Then, we analyzed the spatiotemporal variability of hydrologic budget and vegetation response, and examined the coupling between the two. Receiving the highest amount of rainfall in the country, the study zone is a location for most of country's rivers and various vegetation types. We used one parameter recursive digital filtering algorithm (Nathan and McMahon, 1990) to divide total river flow into quick flow and baseflow. L'vovich water balance theory (L'vovich, 1979) was adopted to estimate the hydrologic budgets. Next, ratio-based hydrologic indices (HI and HuI) were calculated and MODIS NDVI was derived followed by statistical analyses using R.

Vegetation, climate and physical catchment characteristics govern temporal and spatial variability of hydrologic partitioning within a particular catchment and variability among catchments. For example, in steep terrains, a higher fraction of precipitation leaves the catchment as quick flow, reducing catchment wetting (Voepel *et al.*, 2011). Hence, the possibility of vegetations being water-limited is higher in steep terrains than in flat terrains. The timing, intensity and duration of precipitation affect quick flow (Brooks *et al.,* 2011). Thus, as much of precipitation goes to quick flow, the wetting component of hydrologic budget decreases. The inter-catchment variability of mean annual precipitation was in between 836mm and 1811mm. However, the fraction of this precipitation contributing to either quick flow or catchment wetting was relatively constant, as the inter-catchment variability was less than 10% in each case. This suggests that precipitation was partitioned between its major components in nearly similar ways in all catchments.

Vaporization (evaporation plus transpiration) is largely under the control of climate and vegetations (Troch *et al*., 2009; Brooks *et al.,* 2011; Voepel *et al.,* 2011). Strong inter-catchment variability of vaporization was observed. Its magnitude run closely parallel with precipitation in Mazie catchment, but mostly falls below baseflow in Shawe during 2000-2006. The difference could be due to land cover and temperature variation, mainly. Mazie is primarily characterized by open grassland, dense bushland and high temperature while evergreen forest and relatively low temperature prevails in Shawe. Likewise, huge inter-catchment difference was observed in the magnitude of wetting. Further, some catchments (namely Mazie and Mormora) received nearly equal mean annual rainfall during 2000-2006. However, their total river flow differs by a factor of more than two during same period. It was largely due to relatively higher contributions of groundwater towards the total river flow in Mormora catchment. These are some indications for the inter-catchment variability of hydrologic partitioning and vegetation response although the sites correspond to similar climate regime. This closely agrees with Brooks *et al.* (2011) who states "catchments within the same climate regime exhibit variable hydrologic partitioning behavior depending on local landscape characteristics". Consequently, it is clear that multiple catchment management practices are needed and vegetation response to climate variability may vary in catchments within the same climate regime.

Inter-catchment variability in the magnitude of HI was noticed. Inter-annually, however, it was relatively constant with less than 9% standard deviations in five of six catchments. This is in-line with previous studies (e.g. Horton, 1933; Troch *et al.,* 2009, and Brooks *et al.,* 2011). According to Horton (1933), negligible HI inter-annual variability is an indication that vegetations can utilize the largest possible proportion of wetting. HI is a catchment characteristic much like well known physical catchment characteristics (e.g. soil, geology, topography and vegetation). Besides, it can be considered as an additional signature for studies on catchment management and vegetation response to climate variability. Although weak and statistically not significant, negative correlation was observed between HI and HuI. This suggests that vegetation water use efficiency increases as water availability decreases, as it was also revealed by Troch *et al.* (2009). Because, HuI is a good indicator of vegetation water availability and HI is vegetation water use factor. Relative to very humid (annual HuI $\geq$ 1.0) catchments (Sor and Nashe), Mazie is characterized by low vegetation water availability (annual HuI $<$ 0.7), higher and less variable catchment-vegetation water use (HI $\geq$ 0.85 with STDEV $\leq$ 0.04), and more bushland and grassland cover. This indicates that water limitation prevails in Mazie. Brooks *et al*. (2011) similarly revealed sites with highest fraction of bushland and grassland reflects water limitation.

In catchments with mostly evergreen forest land cover (Sor, Mormora and Shawe), NDVI stays nearly constant over different years. Deeper roots of forests may allow access to moisture in deeper soil or even groundwater and minimize the possibility of vegetation being water limited. In these sites, vegetation stays evergreen and does not show significant response to changes in the amount of water available all year long. Compared to hydrologic indices, NDVI showed little inter-annual variability in all catchments showing rare natural and/or anthropogenic impact on vegetations. Relatively, annual average NDVI magnitude is smaller in catchments primarily covered by cultivation. It is reasonable to accept this result that significant greenness is observed only twice a year (i.e. during cultivation period) in these catchments.

Like the previous research by Davenport and Nicholson (1993) conducted in Eastern Africa specifically Kenya and Tanzania, the vegetation phenology closely resembles the seasonal cycle of rainfall. Peak vegetation greenness appeared to lag rainfall by up to two months in catchments with unimodal-rainfall seasonality. Whereas, only less than one month lag was perceived in those catchments with bimodal-rainfall. Globally, a time lag of 1-2 months in the monthly timing of NDVI extremes that is closely associated with seasonal patterns in precipitation is reported by Potter and Brooks (1998). On the other hand, two distinct monthly NDVI maxima were not noticed despite bimodal rainfall. Because, only in the drier areas does NDVI show two distinct maxima within the year unlike bimodal-rainfall (Davenport and Nicholson, 1993). Additionally, NDVI show insignificant variability all year long if land cover is primarily evergreen forest. In most areas of East Africa, NDVI is a sensitive indicator of the inter-annual variability of rainfall (Davenport and Nicholson, 1993). Yet, this is the case only in one of six catchments considered in our study. This is reasonable, as the dominant land cover of the other five catchments is either cultivation (using irrigation in some areas) or evergreen forest, both showing little responses to rainfall events.

5. Conclusion and Future Directions

This study has focused on quantifying catchment-average hydrologic budget and NDVI in an attempt to understand hydrologic partitioning and vegetation response behavior. We demonstrate inter-catchment variability in the hydrologic partitioning. In this regard, water available to vegetation, vegetation water use and groundwater contribution towards total river flow differentiate among catchments. Like the previous studies, we found relatively constant annual HI magnitude during 2000-2006. HI can be considered a catchment characteristic and as an additional signature for studies on catchment management and vegetation response to climate variability. Our results further indicate that the seasonal cycle of catchment-average NDVI closely resembles that of precipitation, mostly. However, inter-catchment difference was observed in the time lag between monthly precipitation and NDVI peaks. The observed variability is mainly due to catchment's rainfall seasonality (unimodal or bimodal) and land cover type. In general, we clearly revealed that catchments found within the same climate regime exhibit variable hydrologic partitioning and vegetation response behavior. Therefore, for successful water resources development, issues like catchment management and the impact of climate variability on vegetation should be treated differently regardless of similarity in climate regime.

The small number of catchments, short analysis period and drawbacks arising from some of the methods adopted are potential limitations. Although these methods are selected carefully, they are potential sources of errors due to different assumptions incorporated in them. Thus, we suggest future researches to include more representative catchments and longer analysis period. We believe this will help to provide a clear depiction of hydrologic partitioning and vegetation response behavior in catchments within similar climate regime. In addition, performing the analysis at finer time-scale (preferably seasonal instead of annual) may help to further understand the results.

Acknowledgements

Fasil. T. Worku was supported by the United States Agency for International Development (USAID) under the USAID/HED funded grant in the Africa-US Higher Education Initiative (grant number: HED052-9740-ETH-11-01). Prof. Guiling Wang's contribution was supported by a NSF Climate and Large Scale Dynamics grant (grant number: AGS-1063986). We are grateful to Dr. Sally E. Thompson for her constructive comments and suggestions. We are also indebted to Prof. Paul D. Brooks for his input on earlier draft.

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