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Discussions

Flow regime change in an Endorheic basin in Southern Ethiopia

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Abstract

Endorheic basins, often found in semi-arid and arid climates, are particularly sensitive to changes in climatological fluxes such as precipitation, evaporation and runoff, resulting in variability of river flows as well as of water levels in end-point lakes that are often present. In this paper we apply the Indicators of Hydrological Alteration (IHA) to characterise change to the natural flow regime of the Omo-Ghibe basin in Southern Ethiopia. This endorheic basin is considered relatively pristine, with the basin being the main source of flow to Lake Turkana, the end-point lake in the East-African rift valley. The water level in Lake Turkana shows significant fluctuation, but an increasing trend can be observed over the past 20 yr. The reasons are currently not well understood.

Of the five groups of metrics in the IHA, only those related to magnitude were found to show significant trends, with the main trend being the increase of flow during the dry season. This trend was not reflected in climatological drivers such as rainfall, evaporation, and temperature (which shows an increasing trend), but rather is attributed to the substantial changes in Land Use and Land Cover (LULC) in the basin. The impact on the basin hydrology is apparent mainly in the more humid part of the basin. The significant shift from forest and woodland to grassland and cropland results in a decrease of actual evaporation and subsequent increase in (dry season) runoff. The long term trend of the increasing levels in lake Turkana are related to these trends in dry season flows, while shorter term fluctuations of the lake levels are attributed primarily to anomalies in consecutive wet and dry season rainfall.

1 Introduction

Understanding the hydrology of a river and its historical flow characteristics is essential for water resources planning, developing ecosystem services, and carrying out environmental flow assessments. Key hydrological variables can be used to characterise the natural flow regime (NFR) of a river. These can be assessed statistically to understand the extent of change to that flow regime and support of hydrological and ecological assessment for ecosystem conservation (Carlisle et al., 2010).

The NFR approach was introduced in aquatic ecology to support the conservation and restoration of ecosystems. It is defined based on five major indicators; magnitude, duration, timing, frequency and variability (Richter et al., 1996; Poff et al., 1997b), and has recently been widely used in hydrology to analyse the variability and characteristics of stream flow as well as to help determine key parameters favourable to biota in the river basin (Poff et al., 1997a; Stanford et al., 1996).

Additional to characterising the NFR, the parameters used to describe the NFR support the analysis of change resulting from changing climatological and hydrological characteristics (Poff et al., 1997a; Assani et al., 2010). Anthropogenic activities such as damming, impounding, land use land cover (LULC) change, diversion and abstraction of water and geomorphological change can impact the natural flow regime. Longer term climate change also influences hydrological flows (Risbey and Entekhabi, 1996; Sankarasubramanian et al., 2001).

The NFR governs the fundamental nature of streams as variations in flow regulate the taxonomic composition and abundance of aquatic organisms (Hart et al., 2002; Beche et al., 2006), and can thus be considered as a template for the spatial and temporal distributions of ecosystems (Poff and Ward, 1989; Horwitz, 1978; Schlosser and Angermeier, 1995; Poff and Allan, 1995; Pusey et al., 2000). In the analysis of the flow regime and its ecological functions, it is important to give due attention to high and low flow events, their magnitude, duration, timing, frequency and rate of change because these parameters are ecologically relevant and impose critical stresses and opportunities for a wide array of riverine species (Poff et al., 1997b).

Though the parameters used to define the NFR can be used as an indication of change in a river basin, these do not provide information as to the cause of those changes. Several studies have focused on trends in stream flow characteristics and found the drivers of these changes to include changes to rainfall distributions and patterns, Land Use/Land Cover (LULC) change and human activities such as abstraction, damming, as well as climate change (Adnan and Atkinson, 2011; Rientjes et al., 2011a; Van Kirk and Naman, 2008).

While most of these studies focus on flow regime classification (Harris et al., 2000; Krasovkaia, 1997; Gottschalk, 1985; Haines et al., 1988) and restoration of basins impacted by damming, diversion and abstraction (Poff and Zimmerman, 2010), few basins that are as yet undisturbed have been assessed (Poff et al., 1997b). This holds equally for basins that are endorrheic. Endorheic or closed basins are mostly located in semi arid to arid climates and often have a terminal lake. The water balance in these terminal lakes is dominated by a high evaporation loss (up to 95–100 % of the inflow) as in Lake Turkana, the Okavango basin, Lake Chad, the Aral Sea and several other endorheic basins (Cretaux et al., 2010; Wolski et al., 2005; Avery, 2010; Kadukin and Klige, 1991; Yuretich and Cerling, 1983). The water levels in these lakes typically show a highly seasonal variability, with longer term trends in water levels attributed to changing climate such as changing rainfall patterns, global warming and human influences like LULC change (World Bank, 2006; Magole et al., 2009; Hopson, 1982).

The Indicators of Hydrologic Alteration (IHA) is a software program that can be applied in establishing the flow regime indicators, as well as testing for trends and changes in the flow regime (The Nature Conservancy, 2009). Several options for parametric and non-parametric statistical tests are available in the model. The model analyses 67 hydro-ecologically important indicators using a daily streamflow data as an input. The IHA models have been applied in several basins throughout the world to understand the NFR and to characterise the anthropogenic and climate impacts on water resources of the riverine system and to analyse environmental flows (Maidment and Hersh, 2006). The model can be applied to any type of daily hydrologic data, such as stream flow, river stage, ground water levels, or lake levels. It provides a powerful means for hydrologic data analysis and can be used to summarise long periods of daily hydrologic data into a much more manageable and graphically illustrative set of hydrologic indices (The Nature Conservancy, 2009).

Several researchers have demonstrated how LULC change impacts streamflow. Wooldridge et al. (2001) used a simple model for forest and non-forest and its hydrologic response. Lorup et al. (1998) applied model and statistical tests to investigate the change in hydrological response due to LULC change. LULC change such as the conversion of forest land to crop land resulted in an increase of flow due to reduction of evaporation and infiltration (Fissekis, 2007; Newson, 1997; Rost et al., 2008; Pikounis et al., 2003). Okie et al. (2011) reach a similar conclusion on the impact of LULC change on precipitation, potential evaporation and streamflow by using a simple water balance based on the Budyko equations (Budyko, 1974).

In this paper we apply the Natural Flow Regime approach to the hydrology of Omo-Ghibe basin. Through the parameters that characterise the NFR we investigate if there are changes to the hydrology of the basin, and if these changes are significant. We analyse the temporal and spatial variability of the NFR change using the IHA to identify the driving forces of these changes. Additionally we investigate if the changes in the basin are related to the variability of the water levels in the Lake Turkana.

2 Materials and methods

2.1 Study area

The Omo-Ghibe basin (79 000 km^2) has the third largest water potential in Ethiopia, draining the southern Ethiopian highlands and ends in Lake Turkana (Fig. 1a). The basin is largely natural or little disturbed in terms of development, though this is recently starting to change. The basin is characterised by a wide topographic and climate variability. The lower part of the basin is flat and semi arid to arid, with an elevation of 365 m at the mouth in Lake Turkana, while the Northern upper part is mountainous, with elevations up to 4000 m and a wet and humid climate. The precipitation and temperature variability is high with high rainfall and lower temperatures in the upstream highlands to lower rainfall and high temperatures in the downstream lowlands.

Lake Turkana, found on the border of Ethiopia and Kenya (Fig. 1), receives more than 80 % of its water from the Omo-Ghibe basin (Beadle, 1981). Water from the lake is lost only through evaporation as there is no observed surface outlet, nor any identified subsurface outflow (Survey of Kenya, 1977). Water levels of the lake fluctuate unpredictably (Velpuri et al., 2012; Avery, 2010). The reasons for the lake level fluctuations and in some cases quite drastic changes are currently not well understood.

2.2 Data availability, quality and selection

Streamflow: daily flow data for 32 gauging stations in the Omo-Ghibe River and its tributaries are available with periods of record ranging from 14 to 46 yr. For some of these the data quality is, however, not sufficient, requiring the data to be carefully screened before application. Five homogenous regions were determined (Fig. 1b), and from each region the stations with the best data in terms of quality and record length in excess of 20 yr were selected for characterising the natural flow regime and variability. For most stations the period of record available spanned from about 1982 to 2008, with the exception of the stations at Abelti and Asendabo, where data was available from 1963 and 1967 respectively.

Rainfall: rainfall data are also scarce and the distribution of gauges is unequal with most stations being in the upstream part of the basin (Fig. 1b). The period of record of many of these stations is good when compared to that of the stream flow gauges. As with the streamflow data, we have identified stations with adequate data quality in terms of randomness, trend persistency and homogeneity. We have sorted the stations based on the available period of record and data quality. In each of the five homogenous regions, at least four stations with more than 20 yr of daily data were selected for the analysis of rainfall variations and trends. Most of the rainfall stations had data available from around 1970 through to 2008, though for the station at Areka data was only available from 1988.

Temperature: there are only a few stations that have daily minimum and maximum temperature data in the study area. We have selected 13 stations which results in two to three stations in each homogeneous region that have data with sufficient quality as shown on Fig. 1b. The stations that have 20 or more years of record of both minimum and maximum mean monthly data were used for trend analysis in the time period of 1970–2008.

Lake Turkana water levels: the entire basin that drains into Lake Turkana has an area of about 130 860 km^2, of which some 57 % is formed by the Omo-Ghibe basin, Ethiopia. The lake is 250 km long, has a mean width of 30 km and a surface area of about 6750 km^2. The average depth is 35 m, with a maximum of 115 m. The mean annual temperature at the lake is 30 °C, while the mean annual rainfall is below 255 mm yr^{-1} (Survey of Kenya, 1977). The evaporation rate is 2335 mm yr^{-1} (Ferguson and Harbott, 1982). As there is no direct observational data of the lake levels available, we used satellite altimetry data obtained from TOPEX/Posiedon, Janson-1, 2 and ENVISAT (Crétaux et al., 2011), with a temporal resolution of 10 days from 1992 to 2012. The accuracy of the lake level using this altimetry satellite data is estimated to be in the range of a few centimetres (Birkett, 1995; Mercier et al., 2002). As there are no gauges available on the lake, and stations are virtually absent in the lower part of the basin, the precipitation and temperature data on the lake were taken from global climate database, CRU TS 2.1 (Mitchell and Jones, 2005).

Selection of Homogenous regions

Homogenous regions (HR) are a useful technique to identify groups with minimal variation of data within a region, with a larger high spatial variability between regions (Hall and Minns, 2009; Dikbas et al., 2013). There are various approaches for defining regions of hydrologic homogeneity (Borujeni and Sulaiman, 2009; Hosking, 1990; Viglione et al., 2007). We applied conventional moment and L-moment (Hosking and Wallis, 1997) methods for regionalization of HR in the basin. The Discordance measure test (Hosking and Wallis, 1993) was used to determine if the data in each region are homogeneous.

The results of the L-moment parameters: L-coefficient of variation (t), L-Skewness (t_3) and L-Kurtosis (t_4) and discordance test (D_i) that are used for classification of homogenous regions are given in Table 1.

By using the average obtained results of L-moment coefficient variation (L-C_v), the basin was delineated into five homogenous regions. These do not include the lower un-gauged part of the basin (Fig. 1b). The final shape of the homogenous regions was adjusted based on the watershed flow direction. The identified regions are reasonable when verified from physical characteristics such as topography, land use land cove and climate. For example, the northern highlands with intensive agricultural and moderate rainfall are defined as one region (region 2), whereas the middle basins with higher forest cover, medium altitude and medium to high rainfall are categorised under region one and four. In order to help understand the natural flow variability in each of HR two to four flow stations with good data quality and a long period of record were selected in each.

2.3 Natural flow regime analysis and characterising the basin

The natural flow regime and is characterisation is analysed based on the five hydrological metrics; magnitude, timing, duration, frequency and variability (Richter et al., 1996; Poff et al., 1997b). These parameters can be used to illustrate ecologically relevant components of the hydrologic regime. Among 171 hydrological indicators currently in use in natural flow regime analysis (Olden and Poff, 2003), we selected 29 indicators. Table 2 lists the selected indicators, divided across the five hydrological metrics; magnitude (14), timing (5), duration (5), frequency (3) and variability (2).

Daily records for a sufficiently long period are required to reliably calculate the IHA indices. The period of record that is sufficient has been indicated by many authors as being 20 yr or more, with up to 35 yr of daily data required to account for natural climatic variability for very variable rivers (Richter et al., 1997; Huh et al., 2005). Statistical indices were calculated using Indicators of Hydrologic Alteration (IHA) model for daily flows at 12 gauging stations. The non-parametric Mann–Kendall test was used for detecting significance of trends found (Mann, 1945; Kendall, 1975) at the 5 and 10 % two tail significance level.

2.4 Driving forces for natural flow regime variability and change

Drivers that could affect natural flow regimes are mainly climate variability and human activities such as structures for water resource development, water abstraction and a wide range of anthropogenic changes in catchments. Specific examples include construction of water retention structures (Beavis et al., 1997), deforestation and clearing of land cover, expansion of agricultural land (Masih et al., 2011), urbanisation and catchment change and increased abstraction of water for irrigation and industries, and impoundment of water (Alemayehu et al., 2007) and modification of the morphology of the riverine system (Van Steeter and Pitlick, 1998). In some cases, these variations may change evapotranspiration and the surface energy balance, thereby also affecting the local climate (Cassardo and Jones, 2011). We categorise the driving forces into two major categories; climate variability and anthropogenic change.

2.4.1 Climate variability

Climate variability is assessed though monthly rainfall and temperature. Monthly rainfall in the Omo-Ghibe basin is characterised in a dry season (October–May) and a wet season (June–September). The month with the lowest rainfall is January. The rainfall characteristics and variation were analysed using the monthly rainfall data. Trends and significance of trend were analysed using the Mann Kendall trend analysis.

For detecting trends in temperature we selected mean monthly minimum temperature and mean monthly maximum temperature in each homogenous region. We examined long term variability and trends of 13 stations with a period of record of more than 20 yr. The actual and potential evapotranspiration from remotely sensed data of MODIS 16 (Mu et al., 2011) was used for trend analysis on catchment and Lake Turkana (http://modis.gsfc.nasa.gov/data/).

2.4.2 Anthropogenic influences

Although a series of dams has recently been built in the Omo-Ghibe basin, including the Ghibe I, II and III dams (EEPCO, 2004a, b, 2009), there was no large scale infrastructure in the basin during the period of record of the data used, and as such the only anthropogenic influences considered are land use and land cover change (LULC). For the analysis of LULC, we used two sets of land cover data that coincide with the period of record of the streamflow data. These are the global land cover of NASA/NOAA Pathfinder Land (PAL) data set of 1981–1994 of 1 km resolution from the Advanced Very High Resolution Radiometer (AVHRR) produced by the University of Maryland Department of Geography (UMDG) (Hansen et al., 1998) hereafter known as 1990's LULC map and the dataset of 2009 with a resolution of 300 m produced by the European Space Agency (ESA, 2010), hereafter known as 2009 LULC map. These two datasets were modified to be compatible by reprocessing the images based on their legend codes, band values and vegetation classes and physical observations. Both datasets use the same FAO Land Cover Classification System (LCCS) (FAO, 2000). We redefined the UMDG map to obtain the same naming convention as the 2009 ESA map based on LCCS to identify the changes of LULC between the two periods of time as shown in Fig. 3. Dominant LULC in each of the five regions in the basin were assessed through GIS analysis of the two maps.

3 Results

3.1 Natural flow regime change

The natural flow regime in the Omo-Ghibe basin was analysed based on the daily flow data for the 20–30 yr of available data at each of the 12 selected stations. These stations are distributed spatially across the basin in four homogenous regions. There are no stations with a sufficiently long data record in region five (in the lower part of the basin, see Fig. 1) while in the lowest part of the basins there are no stations at all. These two regions were therefore not considered in the analysis. We calculated 29 indices at each of the stations and assessed the presence of trend using Sen's slope estimator (Sen, 1968).

Table 3 provides an overview of the number of streamflow stations from the 12 analysed at which an increasing or a decreasing trend was detected (columns 2 and 5 respectively). Columns 3 and 6 show the number of stations at which the increasing or decreasing trend was significant at the 5 % level, whereas column 4 and 7 shows the number of stations that displayed trend at the 10 % significance level.

The first fourteen indicators in Table 3 reflect changes to the magnitude of flows in the basin. For most of the stations the general trend indicates these are increasing, though this increase is only significant at selected stations. Average annual flows show a generally increasing trend in the majority of the stations, most of which significantly as shown by annual Flow Duration Curve (FDC). Most of the indicators concerned with low flows (Dry season mean, 7 day and 90 day minimum flow, Base flow index, Dry Season FDC) equally show an increasing trend. This increasing trend is, however, less apparent for the high flow indices (Wet season flow, 7 day and 90 day max flow, Wet Season FDC), with the number of stations showing increasing trends balanced by the number of stations with a decreasing trend, and only very few stations showing trend at the 5 % significance level. This is also reflected in the flow duration curves shown in Fig. 6. These show the Annual FDC, as well as the FDC for the dry and wet months. These curves are developed for two 15 yr periods (from 1970 to 1995, and 1996 to 2008). Overall these results suggest that the dry season and annual flows are higher in the second period for the majority of the stations, while the wet season flows remain almost the same.

The following five indicators consider the timing of the high and low flow peaks. While there is some suggestion in the general trend that these are decreasing, which means these are occurring earlier in the year, these trends are found to be significant at only very few stations, suggesting little change in the seasonality of the flows in the basin.

The hydrologic indicator of duration is represented by five indices (duration of low and high pulses, and duration of low-, high- and small floods). For these indices, the majority of the stations show a decreasing trend. This would indicate that the duration of both high flows as of low flows is getting shorter, but again the trend is observed to be significant at only very few stations.

Indicators associated to frequency include the frequency of extreme low flows, high flows and small flood flows. The extreme low flow frequency (i.e. the recurrence interval of extreme low flows) shows a significantly decreasing trend in most stations, while for high flows and small flood frequencies, the trend was found to be insignificant at the majority of the stations. This is consistent with the observation that dry season flows are increasing, while wet season flows are largely unchanged. A similar pattern can be seen in the indicators of flow variability, represented by the low- and high pulse counts. The low flow pulse count shows a decreasing trend and the latter an increasing trend, though in this case both trends are insignificant.

The results show that changes in the NFR are significant only for the indicators of magnitude, though the change was only significant at selected stations, in particular those in regions 1 and 4. In the majority of the stations the changes suggest an increase in the dry season flow, and consequent increase in annual flows. Trends are also shown for other indicators of timing, duration, frequency and variability, but these were found to be significant at very few stations.

3.2 Changes in climate variability

Change to rainfall patterns and magnitude is one of the possible drivers of the change to the natural flow regime. We analysed possible changes of rainfall patterns and magnitude for two seasons: the wet season or “Kiremet”, which is the major rainy season for most stations from June to September (in region 4, this is slightly shifted and is taken as being from May to September) and the dry season which includes the second rainy season or “Belg” and the remaining months. 21 rainfall stations with a data record of sufficient length and quality were selected in the analysis (Table 4). In none of the four regions, a dominant trend was found to be significant, except for two stations in region 2 and 3, which both showed a decreasing trend. A shift of the timing of the main rainfall hyetograph was also not found.

The other climatic variable with an influence on the basin hydrology is temperature. The potential and actual evapotranspiration rates are highly influenced by temperature. We used 13 stations with sufficient records of monthly mean minimum, maximum and mean monthly temperature from each region in the upstream catchments. Results in Table 5 show that for almost all except two stations an increasing trend for maximum, minimum and mean monthly temperature was found. In addition, these trends are significant in a majority of the stations.

From the CRU TS 2.1 global climate database (http://cru.csi.cgiar.org), the rainfall and temperature data over Lake Turkana have been analysed for trends from 1981 to 2002 at the monthly scale, showing a significantly increasing trend of the mean, minimum and maximum temperature at the 5 % significance level.

MODIS remote sensed data was used to investigate possible trends in actual evaporation (AET) and potential evaporation (PET), and to understand if these reflect the trends found in the temperature data. Although this data has not been validated against observed data in the basin due to the lack of measurements from for example flux towers (Trambauer et al., 2013), it can be applied for detecting trends. We investigate the presence of trends in the five homogenous regions and downstream un-gauged region using monthly values of remotely sensed AET and PET data from 2000–2011. These show a decreasing trend for PET, though this is significant only in regions 2 and 4. The AET shows an increasing trend in regions 2, 5 as well as in the un-gauged part of the basin though this trend is not found to be significant. A decreasing trend is found in the middle part of the basin (region 1, 3, 4) and is significant in regions 1 and 4 as shown in Table 6.

The dryness index (DI = PET/P) and evaporative index (EI = AET/P), the mean annual value of PET, AET and precipitation (P) (mm yr^{-1}) were analysed for 70 spatially distributed points that represent all of the types of LULC averaged over the regions.

These show that most of the regions are water limited (i.e. DI > 1.0). Only region 4 and to some extent region 1 tend towards being energy limited, as shown in Fig. 2. Based on the aridity index (AI = P/PET), (UNEP, 1997), regions 1 and 4 are categorised as humid, while regions 2, 3 and 5 are categorised as dry sub-humid. The downstream un-gauged part of the basin is categorised as semi-arid.

The increasing trend in the temperature clearly would be expected to have an influence on evapotranspiration and consequently on streamflow, but other factors like LULC change (canopy resistance, leaf area and interception) make this a complex phenomenon and the overall impacts depend on dominant change in the types of land use (Zhang et al., 2001; Yang et al., 2012).

The trend found in AET does not always reflect the increasing trend in temperature, such as in regions 1 and 4, despite the importance of temperature to evaporation, which would suggest that it may depend more on the dominant LULC change.

3.3 Change detection of Land use land cover (LULC)

Land use and land cover (LULC) in the basin were analysed for two periods using the available remotely sensed LULC maps from the 1990's and 2009. These show that there have indeed been significant changes in the LULC, though these changes differ across the basin. In all regions, forest land (FL), woodland (WL) woody grassland (WG) and shrub land (SL) decreased, except in regions 2 and 3 where the FL is increasing. This increase in FL is, however, offset by the decrease in WL and WG. In contrast, cropland (CL), grassland (GL) and bare land (BL) increased almost in all of the regions as shown on Fig. 3a, b and Table 7. Overall, the FL, WL WG and SL decreased by 53 %, while the area of CL and GL increased by 83 %.

LULC change from FL, WL WG and SL to CL and GL would be expected to contribute to reduced interception, less infiltration, lower actual evaporation and hence result in higher runoff.

3.4 Variability of Lake Turkana water levels

We analysed the water levels in Lake Turkana (LT) using the satellite altimetry data that was available at monthly time steps from October 1992 to May 2012 (Fig. 5). Over the whole period a significantly increasing trend of lake levels can be seen, with levels at the end of the period some 2 m above those at the beginning. Seasonal and interannual peaks and troughs in the lake level across the years can be seen. The maximum level is reached mostly in the months of November to January, followed by a rapid drawdown to the lowest level in February to May. In rare cases the minimum level occurs in June or even in July. In the period considered, the maximum level the lake reached was 365.21 m in November 1998. The lowest level was 360.47 m in February 1996. There was a dramatic increase from the low level of 361.47 m in March 1997 to a peak level of 365.21 m in November 1998. From the peaks of 1998 to the lowest level of June 2006 a continuous downward trend with some seasonal fluctuation is observed. The maximum drop of 4.21 m is observed between late 1992 and 2011.

The delay between the peak rainfall in the upper catchments and the peak flow at the mouth of the lake is one to two months, with a further three to five months delay between the peak flow and the peak lake level. Peak rainfall occurs from July to September, peak flows in August to October, while peak lake levels are found in November to January. After adjusting for these delays, a clear correspondence between the variation of rainfall, inflow and lake level is found as shown in Fig. 9, despite the decreasing trend of the lake levels in this period. The flows at the mouth shown in the figure were calculated using a simple water balance model (Abera, 2012), and though these modelled results appear to overestimate real flows, the correspondence of the pattern in the inflows to the variability of lake levels is clear.

In order to help us understand the lake level variability and the driving forces, we categorised the period of investigation into four distinct times of remarkable lake level changes as shown in Fig. 8. The first period is from the end of 1992 to mid 1996, during which the lake reached its lowest level (360.47 m). The peak during the period was only about 362 m. In this period, low rainfall, below the basin average, was found in the years 1994 and 1995 in almost all stations in the upstream basin, as well as on the lake (where rainfall was obtained from the CRU dataset).

The second period is from early 1996 to early 2003; a period where the lake level reached the maximum level (365.21 m) and the lowest level was 361.58 m. High rainfall was recorded in consecutive dry and wet seasons (see Fig. 5) in the period 1996–1998 which results in the peak lake levels of 1998. This was followed by low rainfall in 1999 and 2000 with lake level declining from the peak of 1998 to a low level in 2003 with some seasonal fluctuations, and a short rise after the large wet season rainfall of 2001. A high rainfall event across East Africa in 1997/98 that caused a lot of damage and resulted in record river flows and lake levels in the region (Anyamba, 2002; Conway, 2002) likely contributed to the record high lake levels in 1998.

The third period from early 2003 to mid of 2007 shows a drastic decline of the lake levels, reaching a low of 360.99 m, and a peak of only 362.73 m. There was a recorded drought in 2004/05 in the region (Ebei et al., 2010), reflected also in the consecutive low dry and wet seasons rainfall (Fig. 5).

The fourth period is from mid 2007 to the mid 2012 where the lake level rises again from the low period to peak at 363.75 m, with a low for the period of 361.85 m. The beginning of the rise of lake level coincides with the August 2006 floods in the Omo basin which caused many deaths and displaced many people at the mouth of the river in Lake Turkana. Additionally the July 2007 high flows of Omo (EEPCO, 2009) contributed to the rise.

From these four periods as well as from the historical records of lake levels (Conway, 2002), the fluctuation of the Lake Turkana water levels can be seen to be seasonal with multiannual trends. The water balance of Lake Turkana constitutes inflow to the lake from the major rivers like the Omo-Ghibe, Turkwel and Kerio; rainfall on the lake, evaporation from the lake and groundwater inflow and outflow. The inflow to the lake is dominated by the Omo-Ghibe basin (80–90 %) (Beadle, 1981), with the other two large tributaries being intermittent and contributing significantly less. Mean annual rainfall on the lake is 258 mm yr^{-1} from CRU data base analysis and shows an increasing trend. Velpuri et al. (2012) show that the rainfall on Lake Turkana is less than 30 % of evaporation loss, with the evaporation showing an increasing trend, thus confirming that the two main components in the water balance of the lake are the inflow from the Omo-Ghibe basin and evaporation from the Lake.

4 Discussion

4.1 Changes to the flow regime in the Omo-Ghibe basin

The natural flow regime (NFR) analysed at selected hydrological stations with respect to 29 hydrological indices for indicators of magnitude, timing, duration, frequency and flow variability. Significant changes in these indices in time were observed primarily for indicators describing the magnitude of flows. For other variables including those for timing, duration, frequency and variability some indications of trend were observed, but with little statistical evidence at the 5 % significance level. The increasing trends in the indicators of magnitude were found mainly in those describing low (dry season) flows, with high (wet season) flows displaying very little significant trends. Of the indices of frequency, only that for extreme low flow frequency showed a significantly decreasing trend. This trend compliments the increase in the magnitude of dry season flows. The trends found in the magnitude of the dry season flows reflect changes found in several other basins in Ethiopia, including the Nile Basin and the Didessa basin (Sayed, 2008; Sima, 2011).

Using an average of all stations in Ethiopia, Cheung et al. (2008) show a significant decrease of rainfall in the Kiremet season (main rainy season), with an (insignificant) increase for the Belg season (minor rainy season) in the Omo-Ghibe basin. While such increases of rainfall during the Belg season could contribute to the increase in dry season flows, the trend in rainfall over the Omo-Ghibe basin were not found to be significant in this study, for either of the rainy seasons. Significant trends were only found at three stations of 20 evaluated, though this trend was mainly decreasing, and increasing only for the wet season at the station at Beto. Trends for mean monthly, minimum and maximum monthly temperature were found to be significant in all except a few stations, as reported also for the whole of Ethiopia by the Climate Change National Adaptation Programme of Action (NAPA) of Ethiopia (FDRE National Meteorological Agency, 2007; Ogallo, 2009). Despite this, trends in potential evaporation (PET) and actual evaporation (AET) using remotely sensed data from MODIS were found to contradict what would be expected from the temperature trend. PET is found to be decreasing in all regions, although this is significant only in regions 2 & 4. AET is shown to be significantly decreasing in regions 1 & 4.

Land Use and Land Cover (LULC) change was examined for two distinct periods using land use maps of the 1990's and 2009. The changes found were significant, and broadly similar to those found in several other studies in Ethiopia (Rientjes et al., 2011b; Emiru et al., 2012). Forested land, Woodland, Woody Grasslands and Shrubs land dramatically declined by some 14–73 %, while Grasslands and Croplands increased in the range of 21–261 %, depending on the region in the study area. These LULC changes clearly have a strong influence on the hydrologic response of the basin (Nejadhashemi et al., 2011; Schilling et al., 2008; Mao and Cherkauer, 2009; Siriwardena et al., 2006). The changes in LULC observed could be expected to trigger quicker surface runoff and decrease infiltration, thus leading to increased surface runoff during the high flow (wet) season, though these changes were less clear. The change in the hydrological response that leads to the observed increase in the dry season flows can, however, be explained by the lower AET and interception resulting from the decrease of area of FL, WL and WG. Additionally, CL and GL are seasonal and have shallow root depths compared to FL and WL and WG (Fissekis, 2007; Poff et al., 2006; Rientjes et al., 2011a) again resulting in increased runoff mainly in the dry season. The increase in dry season flows was found to be significant mainly in the more humid regions in the basin (regions 1 and 4, with an aridity index close to 1), which in contrast to the more arid regions of the basin are closer to being energy limited and thus more sensitive to small changes in the water balance caused by the LULC changes. In the more arid regions (regions 1, 3 and 5), the variability in the climatic drivers would be expected to be more influential than LULC change (Yang et al., 2009).

4.2 Changes to the water levels in Lake Turkana

As an endorheic lake, the levels in Lake Turkana depend solely on the balance between the inflow to the lake which is dominated by the Omo-Ghibe basin, and the difference between evaporation and precipitation over the lake (Ngaira, 2006). Velpuri et al. (2012) show rainfall over the lake to be less important than evaporation from the lake and with the significant increase in temperature found evaporation from the open water in the lake could be expected to equally show an increasing trend. This increasing trend could unfortunately not be verified using the MODIS data as evaporation is not represented over large water bodies. Despite the expected increase in evaporation, lake levels over the last 20 yr have, however, been rising. For this long time span it would seem plausible that the increasing water levels in the lake result from the increasing trend in the flows from the Omo-Ghibe basin, in particular in the flows during the dry season. Over the 20 yr, lake levels have increased about 2 m, which would roughly equate to a change in average annual flows of some 20 $m^3 s^{-1}$. While this is difficult to corroborate given the absence of river flow stations in the lower basin, the magnitude of the average change in the flow duration curve at the station at Asendabo in the upper basin, which is the most downstream station on the main stem of the river (see Fig. 4), would suggest that this is not unrealistic.

That the lake levels are sensitive to inflows is clear when shorter term fluctuations are considered. The shorter term fluctuations are clearly linked to the variability of the inflow to the lake from the Omo-Ghibe river (as shown by the concordance of the variability lake levels to the inflows established by Abera, 2012) when lag-times are considered. Arnell et al. (1996), Bergonzini (1998) show that lakes in Africa (mostly in rift valley) are very sensitive to climate variations, particularly those that are endorheic and located in semi to arid regions such as Lake Turkana and Lake Chad. Additional to the seasonal variations and the longer term trends, multi-annual trends in lake levels are influence by extended drought or anomalous wet seasons. These fluctuations of levels are also observed in other lakes in the East African rift valley including Lakes Victoria, Tanganyika and Malawi, with substantial drops during droughts and abrupt rises following large flood events (Mercier et al., 2002; Ngaira, 2006; Birkett et al., 1999).

5 Conclusions

In this paper we apply the Indicators of Hydrological Alteration (IHA) to study interannual trends of the natural flow regime (NFR) of an endorheic basin in Southern Ethiopia. Such endorheic basins, found primarily in arid and semi-arid climates are very sensitive to changes in the climatic drivers such as rainfall, evaporation and temperature. The Omo-Ghibe basin in Southern Ethiopia is such an endorheic basin, and is the main source of water to Lake Turkana, on the Ethiopian-Kenyan border. Lake water levels fluctuate considerably at the seasonal time scale, but there are also significant longer term trends, including a statistically significant rising trend in the water levels over the past 20 yr. These fluctuations are poorly understood. Overall the water resources infrastructure of the Omo-Ghibe basin has until recently been poorly developed, though there data in particular in the remote lower part of the basin is scarce.

We applied a non-parametric statistical method of the IHA model to analyse the trends in the 20–30 yr of available hydrological and meteorological data in the basin. We selected 29 hydrologically relevant indicators from the IHA, including indicators of magnitude, timing, duration, frequency and variability of flow and assessed significance of trends found using the non-parametric Mann–Kendall test. Trends in rainfall and temperature from terrestrial stations and evaporation from remotely sensed MODIS data were evaluated.

Of the 29 indicators considered, mainly those representing magnitude of dry season and annual flow were found to show significantly increasing trend. Indicators related to frequency of low flows also show a significantly decreasing trend, which reflects the increase in magnitude of low (dry season) flows. Little trend was found in either rainfall or wet season flows. The trend in temperature was found to be significantly increasing across the basin, but conversely trends in both potential and actual evaporation were found to be decreasing.

Land use and land cover data showed that this had changed significantly in the past 20 yr, with a significant shift from forested land, woodland and woody grassland to grasslands and crop lands. This change to more seasonal and shallow rooted land cover results in a decrease in actual evaporation and consequent increase of dry season flows. These changes are most apparent in the -humid parts of the basin, and less so in the more arid parts. In the more humid parts of the basin evaporation is on a balance between being energy limited rather than water limited, which means that an increase in the available water will more readily lead to an increase in runoff.

Variations and trends in the water levels of Lake Turkana were analysed using data from TOPEX/Posiedon, Janson-1, 2 and ENVISAT satellites as there are is no ground-based data available. These data show that significant variations of lake levels over the past 20 yr period, including seasonal fluctuations correlated to the dry and wet season flow of the Omo-Ghibe basin. Multi-annual fluctuations in lake levels were related to periods of drought or anomalously wet rainy seasons. As a significant trend in the wet season flows could not be detected based on the available data, the increasing trend in lake levels over the 20 yr period is considered to result from the increase in dry season flows, and thus connected to the changes in land use and land cover in the basin.

Through applying the IHA to in the Omo-Ghibe basin, and relating trends found in the hydrological data to trends in climatological and land use data, we have identified the main drivers of change in the Omo-Ghibe basin to likely be due to changes in land use and land cover in the humid parts of the basin, which have led to changes in the hydrological processes, resulting in dry season flows, and subsequently to a rising trends in Lake Turkana, the end-point lake of this sensitive endorheic basin. These conclusions should, however, be considered with care as very little is as yet known of the hydrological processes in the remote lower part of the basin, where no hydrological or climatological data are available.

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Table 1. Homogenous regions and their L-moment and discordance test values with the stations chosen in each region for the analysis of the natural flow regime.

	Regional Weighted L-moments				Selected stations
Group	t	t_3	t_4	D_i	
Region1	−0.007	−0.017	−1.478	0.32-1.65	Ghibe @ Abelti, Ghibe @ Asendabo, Bidru, Seka
Region 2	0.083	0.664	1.516	0.03–2.3	Megech, Wabi, Amara
Region 3	−0.031	−1.673	0.249	0.22–0.7	Ajancho, Shapa
Region 4	0.053	0.368	−1.050	0.22–1.39	Gojeb, Dincha, Sheta
Region 5	0.17	1.50	3.78		Record data less than 20 yr

Table 2. Table 29 Hydrological Indices used for characterising the natural flow regime.

S.No	Hydrological Indices	Category	Description of Indices
1	Annual	Magnitude	Mean annual flow ($m^3 s^{-1}$)
2	Dry Season		Mean dry season flow (Nov–May/Jun) ($m^3 s^{-1}$)
3	Wet Season		Mean rainy season flow (Jun/Jul–Oct) ($m^3 s^{-1}$)
4	7 day min flow		Annual 7 day minimum flow mean ($m^3 s^{-1}$)
5	90 day min		Annual 90 day minimum flow mean ($m^3 s^{-1}$)
6	7-day max		Annual 7 day maximum flow mean ($m^3 s^{-1}$)
7	90 day max		Annual 90 day maximum flow mean ($m^3 s^{-1}$)
8	Base flow Index		7 day minimum flow/mean flow for year (dimensionless)
9	FDC (annual)		Annual flow duration curve ($m^3 s^{-1}$)
10	FDC (dry season)		Driest month/s flow duration curve ($m^3 s^{-1}$)
11	FDC (wet season)		Wettest month/s flow duration curve ($m^3 s^{-1}$)
12	Extreme Low flow peak		A low flow below a threshold value (10 %) of daily flow ($m^3 s^{-1}$)
13	Small flood peak		A high flow peak of flood of two years return period event ($m^3 s^{-1}$)
14	High flow peak		A peak of high flow above a threshold value (75%) of daily flow ($m^3 s^{-1}$)
15	Date of minimum flow	Timing	Julian date of annual 1-day minimum flow (days)
16	Date of maximum flow		Julian date of annual 1-day maximum flow (days)
17	Extreme Low flow time		Julian date of annual extreme low flow (days)
18	High flow time		Julian date of annual extreme high flow (days)
19	Small flood time		Julian date of annual extreme small flood (days)
20	Extreme Low flow duration	Duration	Number of days of extreme low flow in a year (days)
21	Low pulse duration		Number of days of low pulses in a year (days yr^{-1})
22	High pulse duration		Number of days of high pulses in a year (days yr^{-1})
23	High flow duration		Number of days of high flow in a year (days yr^{-1})
24	Small flood duration		Number of days of small flood in a year (days yr^{-1})
25	Extreme Low flow frequency	Frequency	Frequency of extreme low flow in a year
26	High flow frequency		Frequency of high flow in a year
27	Small flood frequency		Frequency of small flood in a year
28	Low pulse count	Variability	The number of low pulses in a year (events yr^{-1})
29	High pulse count		The number of high pulses in a year (events yr^{-1})

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Table 3. 29 Hydrological indices analysed at 12 stations and the number of stations that show a generally increasing or decreasing trend, as well as the number of stations at which the trend is significant at the $\alpha = 5\,\%$.

	Increasing			Decreasing		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Hydrological Indices	Increasing	$\alpha = 5\,\%$	$\alpha = 10\,\%$	Decreasing	$\alpha = 5\,\%$	$\alpha = 10\,\%$
Annual flow	8	2	2	4	1	1
Dry Season flow	9	2	4	3	0	0
Wet Season flow	6	2	2	6	1	1
7 day minimum flow	7	4	4	4	1	1
90 day min. flow	6	3	3	6	0	0
7 day max. flow	8	2	2	4	2	2
90 day max. flow	6	1	2	6	1	1
Base flow Index	8	5	7	4	0	1
FDC (Annual)	8	7	8	4	3	3
FDC (Dry season)	6	5	5	6	4	5
FDC (Wet season)	6	3	3	6	3	4
Ext.Low flow peak	5	1	1	7	0	0
High flow peak	7	1	1	5	1	1
Small flood peak	8	1	1	4	0	0
Date of min. flow	3	0	0	9	2	3
Date of max. flow	2	0	0	9	0	0
Ext.Low flow time	5	0	0	7	1	1
High flow time	7	1	1	5	0	0
Small flood time	4	0	0	7	1	1
Low pulse duration	5	0	1	7	1	1
High pulse duration	3	1	1	9	2	4
Ext. Low flow duration	2	0	0	9	0	1
High flow duration	4	1	2	7	2	2
Small flood duration	5	1	1	6	0	0
Ext. Low flow frequency	2	1	2	7	4	4
High flow frequency	5	1	2	2	1	1
Small flood frequency	0	0	0	1	1	1
Low pulse count	3	0	0	6	2	2
High pulse count	5	2	2	2	0	0

Table 4. Rainfall trend in the dry and wet season and the significance level for trends found in each of the stations in the five homogenous regions, with $\alpha = 5\,\%$ or $10\,\%$ significance level (S = significant with the value in brackets indicating at what level this is found to be significant, NS = Not significant).

Season		Dry Season				Wet season			
Regions	Stations	Sen's slope	Z	Trend	Significance	Sen's slope	Z	Trend	Significance
Region 1	Asendabo	0.11	0.919	Increasing	NS	−0.125	0.488	Decreasing	NS
	Chekorsa	0.25	1.462	Increasing	NS	−0.16	0.442	Decreasing	NS
	L.Genet	0.04	0.303	Increasing	NS	−0.01	0.054	Decreasing	NS
	Jimma	0.15	0.884	Increasing	NS	0.07	0.238	Increasing	NS
Region 2	Butajira	0.12	0.697	Increasing	NS	0.38	1.549	Increasing	NS
	Gedo	−0.31	2.583	Decreasing	S (0.05)	−1.87	4.912	Decreasing	S (0.05)
	Weliso	−0.09	1.084	Decreasing	NS	−0.06	0.334	Decreasing	Ns
	Welkite	0.06	0.52	Increasing	NS	0.17	0.665	Increasing	Ns
Region 3	Areka	0.03	0.195	Increasing	NS	−0.285	0.681	Decreasing	NS
	Bele	−0.055	0.395	Decreasing	NS	−0.93	2.351	Decreasing	S (0.05)
	Hosana	0.085	0.714	Increasing	NS	−0.02	0.162	Decreasing	NS
	Walaita	0.19	0.969	Increasing	NS	0.44	1.36	Increasing	NS
Region 4	Bonga	−0.02	0.145	Decreasing	NS	0.25	0.69	Increasing	NS
	Mizan	−0.02	0.056	Decreasing	NS	−0.22	0.938	Decreasing	NS
	Sokeru	−0.05	0.393	Decreasing	NS	−0.37	1.106	Decreasing	NS
	Tepi	0.01	0.023	Increasing	NS	−0.665	2.172	Decreasing	NS
Region 5	Beto	0.3	1.784	Decreasing	S (0.1)	0.81	1.784	Increasing	S (0.1)
	Jinka	−0.07	0.453	Decreasing	NS	0.08	0.453	Increasing	NS
	Kemba	0.035	0.097	Increasing	NS	−0.485	0.779	Decreasing	NS
	Keyafer	0.18	0.649	Increasing	NS	0.63	1.2	Increasing	NS
	Konso	−0.13	0.898	Decreasing	NS	-0.165	0.423	Decreasing	NS
Lake Turkana*			2.11	Increasing	S				

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Table 5. Monthly minimum, maximum and mean temperature trends and its significance at $\alpha = 5\,\%$ and at $10\,\%$ (in brackets) significance level test for 13 stations in the study area.

	Selected Stations	Maximum Temperature		Significance	Minimum Temperature		Significance	Mean monthly Temperature		Significance
Regions		Sen's slope	Z		Sen's slope	Z		Sen's slope	Z	
Region1	Jimma	0.054	4.64	S	0.026	2.02	S	0.036	5.00	S
	Asendabo	−0.023	1.90	S (0.1)	0.076	3.67	S	0.022	2.09	S
Region2	Welkite	0.25	4.35	S	0.056	2.53	S	0.153	5.0	S
	Weliso	0.029	2.43	S	0.076	3.28	S	0.059	3.62	S
	Butajira	0.08	4.51	S	0.025	0.38	NS	0.046	1.80	S
Region3	Hosana	−0.013	0.79	NS	0.063	4.87	S	0.012	1.55	NS
	Walaita	0.25	4.00	S	0.069	5.28	S	0.072	4.19	S
Region4	sokeru	0.015	0.89	NS	0.026	1.40	NS	0.007	1.03	NS
	Chira	0.282	2.37	S	0.053	3.12	S	0.053	2.40	S
	Tepi	0.024	1.98	S	−0.036	2.03	S	−0.006	−0.24	NS
Region5	Jinka	0.026	2.54	S	0.024	2.15	S	0.023	3.25	S
	Sawla	0.045	1.69	S (0.1)	0.025	1.33	NS	0.022	1.63	NS
	A.Minch	0.016	0.93	NS	−0.054	2.62	S	−0.014	1.10	NS
Lake	Turkana	0.08	1.91	S(0.1)	0.29	2.44	S	0.17	2.73	S

Table 6. Remotely sensed data from MODIS16 actual- and potential evapotranspiration trend and significance test at 5 % in the homogenous regions of the study area and climate class based on UNEP 1997 Aridity Index (UNEP, 1997).

Regions	Actual Evapotranspiration		Potential Evapotranspiration		Aridity Index (P/PET)	Climate class
	Z	Trend	Z	Trend		
Region1	−2.2	S decreasing	−1.27	NS	0.85	Humid
Region2	0.89	NS	−1.99	S decreasing	0.53	Dry sub-humid
Region3	−1.3	NS	−0.76	NS	0.58	Dry sub-humid
Region4	−2.9	S decreasing	−2.63	S decreasing	1.01	Humid
Region5	0.15	NS	−0.76	NS	0.57	Dry sub-humid
Un-gauged	1.56	NS	−0.71	NS	0.24	Semi-Arid

Table 7. Land use and land cover changes in the five homogeneous regions of the basin.

Regions	Land Cover type	1990s Area (1000 ha)	2009 Area (1000 ha)	Area change (%)
1	Forest, Woodland & Woody grass land and shrub land	608	161	−73
	Grassland and Cropland	362	809	123
2	Forest, Woodland & Woody grass land and shrub land	409	118	−71
	Grassland and Cropland	771	1062	38
3	Forest, Woodland & Woody grass land and shrub land	201	115	−43
	Grassland and Cropland	241	327	36
4	Forest, Woodland & Woody grass land and shrub land	1521	541	−64
	Grassland and Cropland	376	1356	261
5	Forest, Woodland & Woody grass land and shrub land	856	740	−14
	Grassland and Cropland	560	676	21
	Total area (ha)	5905	5906	
	Total Forest, Woodland, Woody grassland, shrub land	3595	1676	−53
	Total Grassland and Cropland	2310	4230	83

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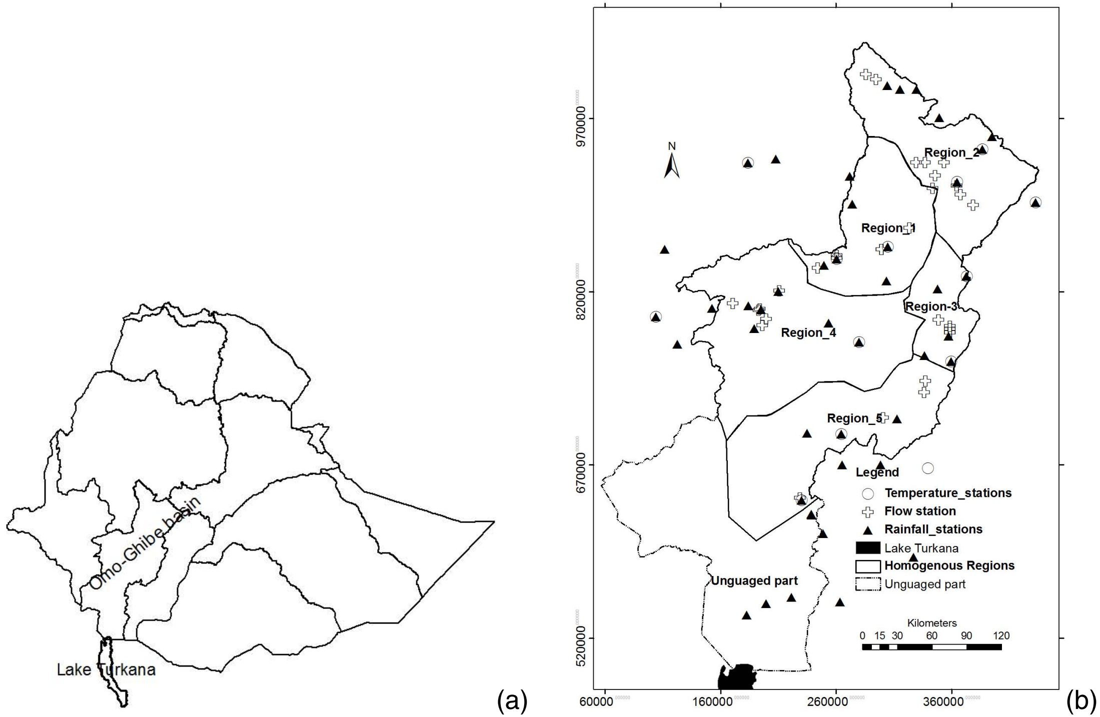

Fig. 1. (a) the 12 major basins of Ethiopia (MoWR, 2011) and **(b)** the Omo-Ghibe, showing Lake Turkana at the outlet and the five homogenous regions. Flow- and rainfall stations in the study area are shown.

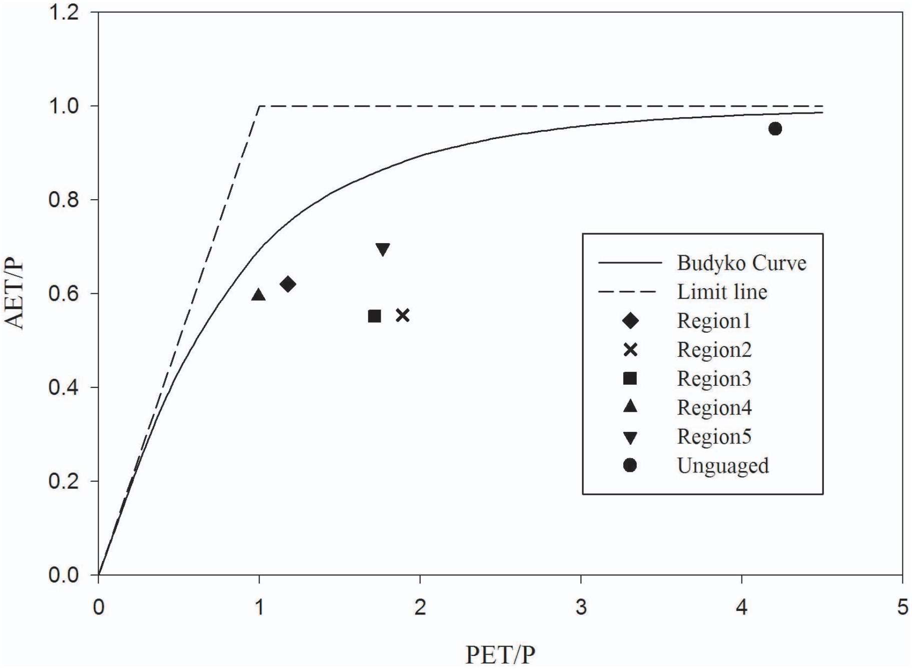

Fig. 2. The average aridity index (PET/*P*) and the evaporative index (AET/*P*) of the study area for the five homogenous regions and ungauged part of the basin compared to the Budyko Curve (Budyko, 1974).

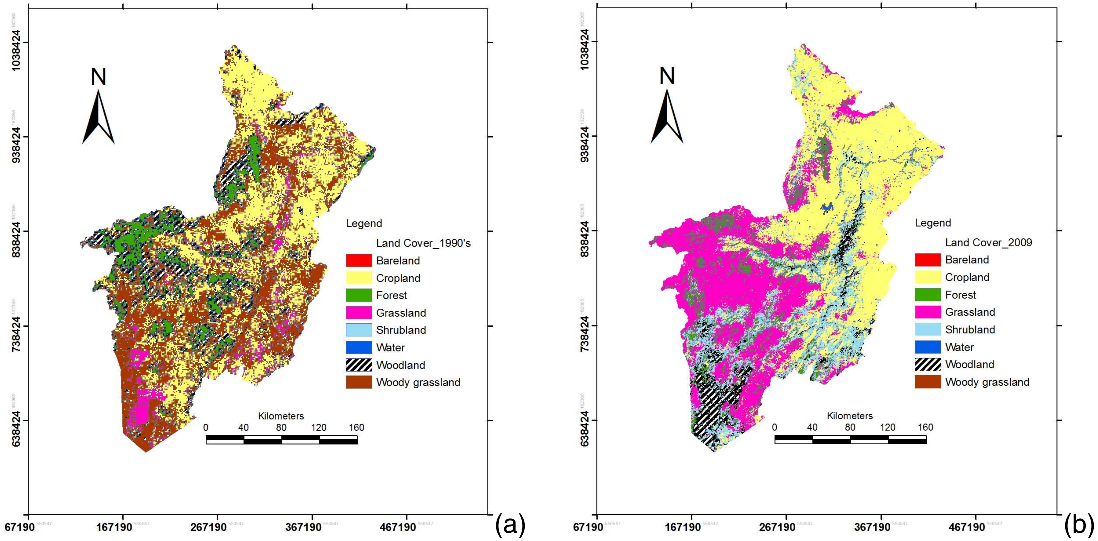

Fig. 3. Comparison of land use land cover map of the study area for the year 1990s **(a)** and 2009 **(b)**.

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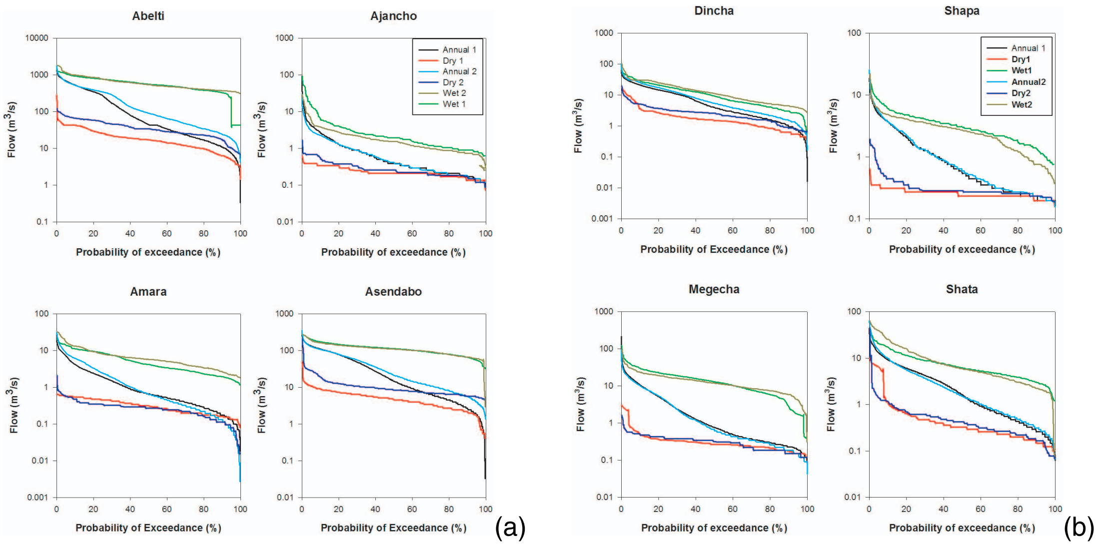

Fig. 4. (a) and **(b)** Flow duration curves for gauging stations used in the analysis, for Annual, Dry and Wet months change over two periods before 1995 (Annual 1) and after 1995 (Annual 2).

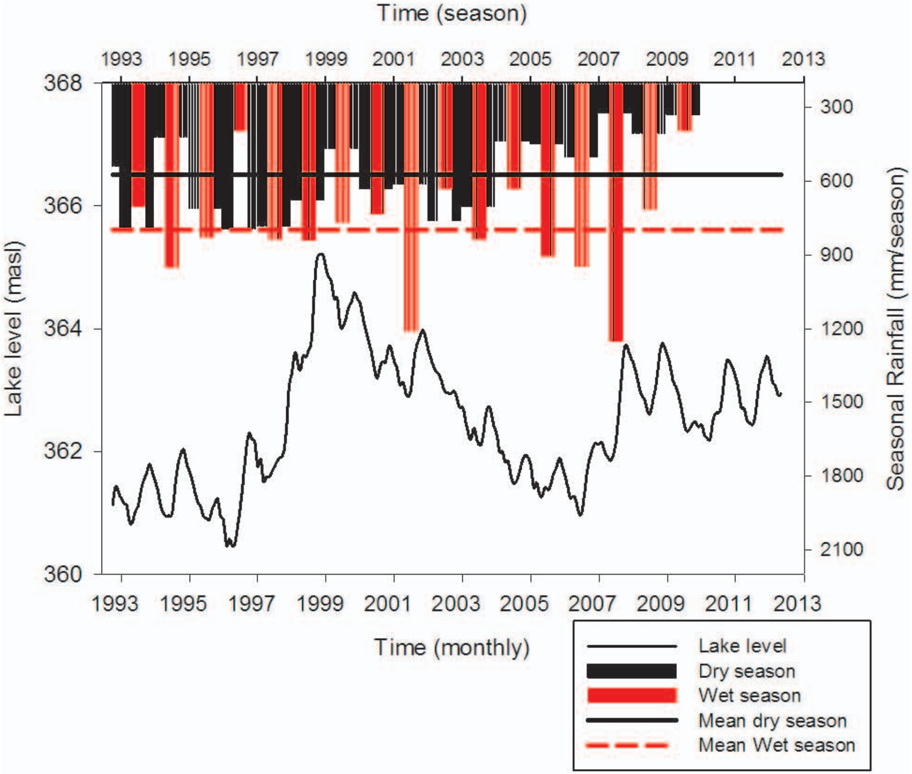

Fig. 5. Lake Turkana water level fluctuation from late 1992 to early 2012 derived from satellite altimetry data and Omo-Ghibe basin areal rainfall. Areal rainfall is averaged for the dry (black) and wet season (red), with the mean rainfall for each season shown as a horizontal dotted line.

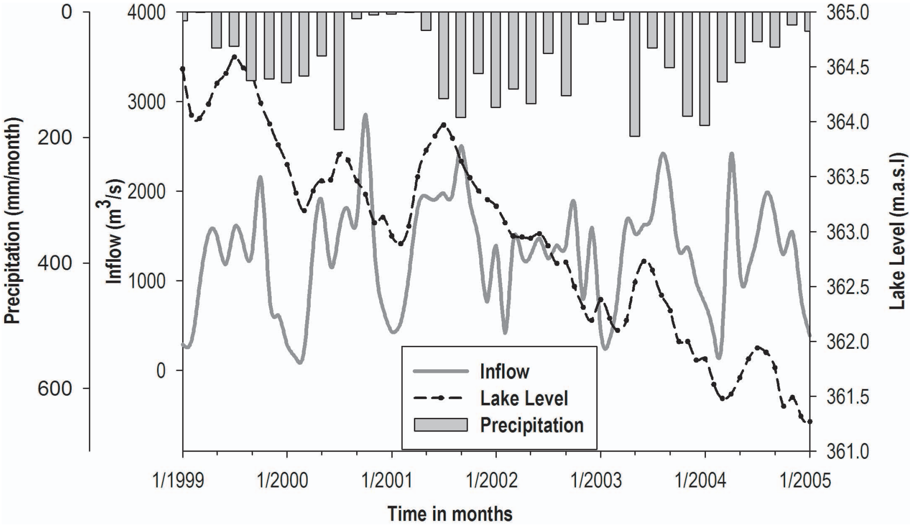

Fig. 6. Comparison of lake level variation versus Omo-Ghibe inflow (Abera, 2012) and average areal precipitation on the basin.