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Comparison of Different Base Flow Separation Methods and Drought Vulnerability in a Rift Valley area

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Comparison of Different Base Flow Separation Methods and Drought Vulnerability in a Rift Valley area

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ABSTRACT: Estimation of groundwater recharge and drought vulnerability assessment was done by comparing Recursive Digital Filtering (TIMESPLOT) and Graphical Hydrograph Separation (HYSEP) methods. In both methods, long term daily stream flow data (1991 - 2003) was used from seven river discharge gauging stations in three physiographic settings (rift, escarpment and highland) and corresponding variable climatic conditions. The results from both methods have similar trend and show general agreement on annual basis with a correlation coefficient of 0.994. Moreover, long-term rainfall-discharge relationship of the sub-basin shows 0.75 correlation. The long term annual weighted catchment recharges are 94.9 mm and 111.9 mm for TIMESPLOT and HYSEP methods, respectively. There is cyclic recurrence of drought roughly every three years. The amount of annual rainfall in drought times is approximately half of the rainfall in good seasons. Moreover, due to the ever-increasing usage of water for different consumptions, even the stream flows in good seasons are highly stretched. The yields of springs are dwindling due to pumping of water around spring sources. This is in spite of the relatively high long-term average annual base flow indices for TIMESPLOT and HYSEP methods which are 0.58 and 0.69, respectively. Those vulnerable to drought are the areas closer to the rift floor. The long-term annual and monthly averages of recharge and base flow indices are more dependent on slope and the hydrogeology of the catchments. Recharge clearly increase with elevation; however, base flow indices increase towards flat-lying alluvial deposited areas.

Keywords: Analytical, Recursive Digital Filtering, Drought vulnerability, Recharge

INTRODUCTION

The Upper Awash River Basin is located in central Ethiopia on the western edge of the Main Ethiopian Rift (MER). It is characterized by three physiographic regimes namely the plateau (highland), escarpment and rift floor. The Upper Awash basin covers a total area of 11,467.34 km^2 which is about 10% of the area of the whole Awash River basin. It stretches from North West to South East between Ginchi and Lake Koka through which Awash River flows for a distance of 195 km.

The basin is the most densely populated and industrialized regions of the country. The capital city, Addis Ababa, and other socially and economically important towns like Modjo, Bishoftu, Sendafa, Holeta, and Sebeta are located inside the sub-basin. As per the Central Statistics Agency of Ethiopia, the 2018 projected population of the sub-basin is 12.43 million. This is about 12.1% of the population of Ethiopia localized in 1.04% of the country's area.

Hydrologically, the basin is characterized by many natural and man-made lakes and perennial rivers. Groundwater recharge takes place along fractured volcanic rocks and step faults in the highlands and fractured volcanic rocks and loose alluvial riverbed and lacustrine deposits in low-lying areas. It should be mentioned that Akaki regulated flows are not accounted in the analysis due to the presence of man-made reservoirs.

The presence of surface water and groundwater attracted the attentions of municipalities, investors and other development actors. As a result, presently, there are huge surface water and groundwater developments for domestic, industrial and irrigation purposes. The Addis Ababa City Water and Sewerage Authority is getting its urban water supply from groundwater (65%) and the rest from dams (Addis Ababa Water and Sewerage Authority, 2018). Moreover, the Oromia Region Irrigation Authority is in the process of implementing irrigation schemes with around 120 deep wells. Many of the bottled waters in the country originate from this basin. This is in addition to thousands of small holder irrigation schemes by the riverside and from pumping of shallow wells.

These fast-growing developments coupled with population growth are triggering human induced land degradation and increased surface water and groundwater abstraction. This tendency is being scaled up even to adjacent basins in order to develop large surface water and groundwater for water supply and irrigation projects (Water Works, Design and Supervision Enterprise (WWDSE), 2017).

On the other hand, in line with these efforts, studying the temporal and spatial variation of the river discharge characteristics and groundwater recharge processes is a key element of the watershed management schemes. Because utilization of water without a basic understanding of the hydrologic system of the basin has become a critical problem in water resources management (Singh et al., 2018; Tenalem A, 2002). Moreover, different types of inputs can impact the water quantity and quality outputs (Singh and Kumar, 2017; Singh et al., 2019).

Corresponding to these, studying the hydrological characteristics of the rivers and their temporal and spatial variations is conducted with the help of graphical (Leh et al., 2018; Pettyjohn and Henning, 1979; Singh and Saraswat, 2016; Sloto and Crouse, 1996) and recursive digital filtering (Lyne and Hollick, 1979; Nathan and McMahon, 1990) methods for quantification of base flow contributions and identification of stream flow generation process. Base flow analysis of stream hydrographs can provide valuable insights into how groundwater contribution to stream flow changes through time (Brodie and Hosteler, 2005). Common base flow separation methods are either graphical which tend to focus on defining the points where base flow intersects the rising and falling limbs of the quick flow response or involve filtering where data processing of the entire stream hydrograph derives a base flow hydrograph (Brodie and Hosteler, 2005).

SCOPE OF THE STUDY AND SITE DESCRIPTION

SCOPE OF THE STUDY

Several studies were done on geology (Abebe T., 1995; Abebe et al., 1998; Abebe et al., 2005; Efrem B., 2010; Mohr, P.A. 1967; Mohr, P.A. 1968; Mohr, P.A. 1983; Mohr, P.A. et al., 1976; Mohr, P.A. et al., 1988) and hydrogeology (Berhanu G., 1996; Birhanu M, 1982; Singh and Bhattarai, 2019; Tilahun A., 2015; WWDSE, 2008 and 2017) of the region. These studies provided an account of the geology, hydrogeology, hydrology and groundwater interface between the Middle Blue Nile and the Upper Awash Basins.

However, the focus of these studies was largely on evaluating geological and hydrogeological patterns and inter-basin groundwater interchange between the Upper Awash basin and Middle Blue Nile basin. Because of these, the sub-basin wide spatial and temporal variation of groundwater recharge assessment was inadequately addressed despite the increased demand of water for urban water supply and irrigation. The problem of groundwater recharge assessment on faulted and fractured volcanic setting with inconsistent hydro-meteorological and hydrological data played a part in the study constraints.

In connection with groundwater recharge, it is commonly estimated by water balance studies in humid areas or by monitoring the movement of water through the vadose zone in drier climates, however, the latter models are being used in drier climates due to lower costs (Tenalem A., 2002). A multitude of approaches have evolved for the latter type of base flow assessment and these can be categorized into three as base flow separation, frequency analysis and recession analysis (Brodie and Hosteler, 2005). In other words, recharge is estimated using conceptual models, recursive filters or a combination of the two (Partington, D. et al., 2011). The use of these models is applicable widely due to availability of stream flow records upon which they are based.

Consequently, two of the three approaches mentioned above are used in this study to compare base flow estimation between two methods. The first method is the hydrograph separation program (HYSEP) based on the Fixed Interval, Sliding Interval, Local Minimum and Institute of Hydrology Low Flow methods (Gustard and Dixon, 1992) and (Pettyjohn, and Henning, 1979). The second method is TIMESPLOT, which employs digital recursive filter to separate base flow from total river discharge on daily basis (Lyne and Hollick, 1979; Nathan and McMahon, 1990). Both methods use total daily river flow records as input. The first approach provides the ratio of base flow and surface runoff (BFI) on daily basis whereas the latter method employs attenuation factor, alpha, to calibrate the program.

In addition to comparing the two base flow separation methods, this study has two main objectives: the first is estimating the groundwater recharge using two independent methods taking all important catchment influencing factors, and the second is to assess the hydrological behavior of the basin from the stand point of the discharge characteristics in relation to the geology, hydrogeology, land use-land cover and slope as well as recurrence of drought.

The contributions of this study will be to allow more accurate assessment of the groundwater recharge rate, which is critical for sustainable conjunctive use of water; and make use of the result for calibration of similar catchments in the region with little hydrological records. It will also help to understand vulnerability to drought.

SITE DESCRIPTION

The Upper Awash basin is a large physiographic structure delineated by chain of volcanic mountains that mark watershed divides with the adjacent basins. The basin is located in the western edge of the Main Ethiopian Rift (MER) and lies between longitudes 37_0 57’ 06 and 39_0 17’ 24’’ East and latitudes 8_0 09’ 02 and 9_0 18’ 12’’. The sub-basin shares borders with the Blue Nile basin in the North and North West; the Gibe Basin in the West and South West; the Rift Valley Lakes basin in the South and the Middle Awash Basin in the East and South East. The catchment has around 1980-meter elevation drop from North and South West to South East. This steep gradient favors the emergence of many springs at different elevation and forms shallow groundwater level in the Adaa and Becho plains (Fig 1).

The present-day landform of the basin is the result of Cenozoic volcano-tectonics followed by later erosion. As a result of the different episodes of volcanism, the basin is dotted by different size volcanic peaks, summits, marrs and crater sinks. The northern mountainous areas are ragged, steep and deeply weathered and hence favored formation of dense drainage networks. Among the rivers in Ethiopia, Awash is peculiar in many ways. First it is the longest of all rivers that flow within Ethiopia, having a length of 1,200 km from its source down to its termination in Lake Abhe at Ethio-Djibouti border, 195 kms of which spanned over the study area. Awash is used for hydroelectric power generation, irrigation, livestock and domestic purpose along its course. The first modern commercial farm development has been started in the Middle and Lower Awash basin in the 1960s.

Moreover, the Upper Awash basin is the most densely populated and most industrialized region of the country. Around 12.34 million people reside in the region. No other basin has many towns and cities as Awash. It is the most fatly industrialized region. The geology of the Upper Awash Basin constitutes the Pre-Rift, Syn-Rift and Main Rift Volcanic Units (Abebe T., 1995; Berhanu G., 1996; Birhanu M., 1982; Efrem B., 2010).

The Pre-Rift Units are Oligocene to Late Miocene plateau flood basalts whereas the Syn-Rift Units comprise Upper Miocene to Quaternary products of pyroclastic rocks of welded to partially welded pyroclastic flows with rhyolitic and trachytic lava domes. The Main Rift Units include Pleistocene to Holocene young central volcanoes. The geotectonic structures of the study area are characterized by two major manifestations: The Yerer-Tullu Wellel Volcano Tectonic Lineament (YTVL) and the NE-SW Rift Fault (Abebe T., 1995). These structures are also impacting the groundwater flow system. The precipitation of the study area is typically characterized by two distinct seasonal weather patterns: the wet season which extends from June to September, contributing much of the annual precipitation and the dry season which covers the period from October to May with a minor rainy spell in March and April well known for its failure.

Temperature and rainfall show strong altitudinal variations. Precipitation decreases from North and North West to South and South East. The opposite happens to temperature. Mean annual temperature is about 15.7 $_0$C in the highlands and around 22.3 $_0$C in the rift. The average annual rainfall ranges from around 905.4 mm (Modjo) in the rift floor to 1,238.2 mm in the northern highlands. Figure 1 displays the location of the study area illustrating main towns and gauging stations whereas Table 1 displays annual average precipitation and temperature for the study area.

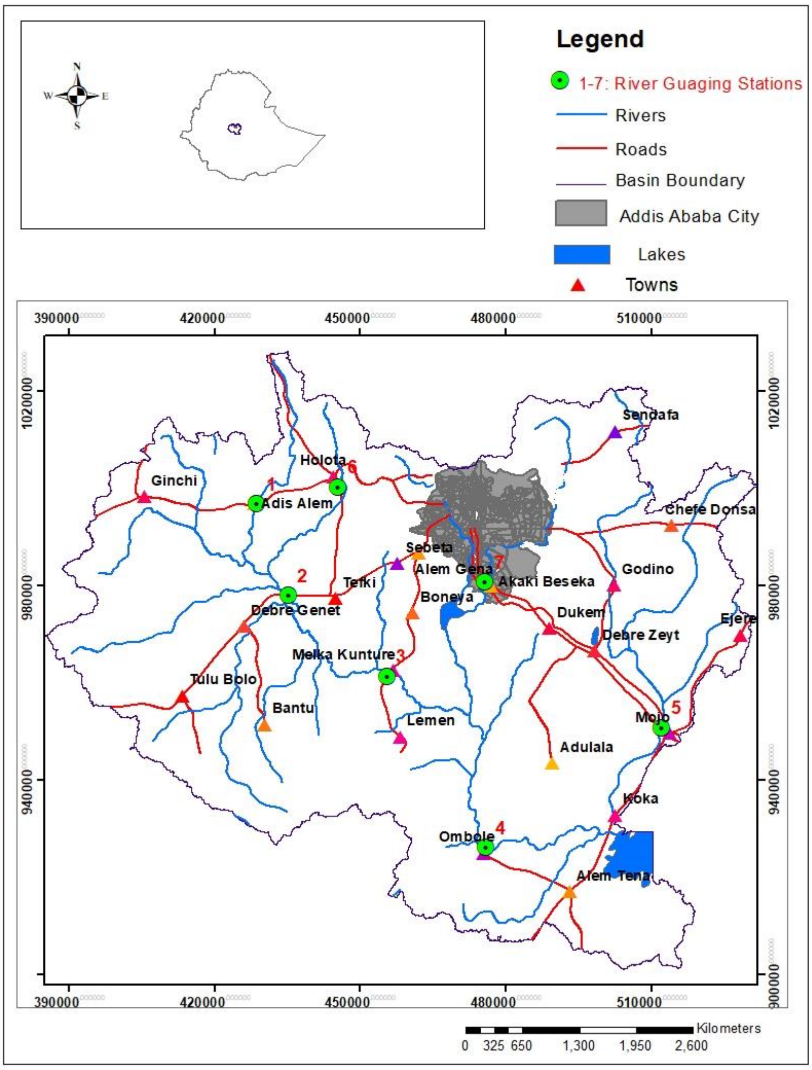

Figure 1. Location map of the study area

River gauging stations: 1-Berga, 2-Bello, 3-Melka Kunture, 4-Hombole, 5-Modjo, 6-Akaki, 7-Holeta

Table 1. Annual rainfall (mm/year) and Temperature (C_0) of Upper Awash Basin

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov.	Dec	Total
Rain Fall	18.3	22.5	59.4	66.2	68.7	124.7	239.0	237.1	113.5	28.0	18.7	15.1	**1,011.2**
Temp	18.6	20.4	20.3	20.7	20.8	20.1	18.8	18.7	19.4	18.7	18.5	17.6	**19.4**

Some portions of the study area especially around Becho flat plain are subject to seasonal flooding almost every year between end of July up to mid-September due to runoff from the surrounding hills and overflow of the Awash River. The soil in the rift floor and adjacent mountain foots are thick and good for agriculture. They are created due to degradation weathering and stream erosion from the highlands. All streams considered for this comparative study are perennial. The watershed areas upstream of gauging stations include Bello (2,568.8 km^2), Berga (248 km^2), Holeta (119 km^2), Hombole (7,656 km^2), Melka Kunture (4,456 km^2), Modjo (1,264.4 km^2) and Akaki (884.4 km^2). The main land use in the sub-basin is dominated by intensively cultivated, moderately cultivated, open grassland, open shrub land, open woodland, urban area and water body.

DATA AND METHODOLOGY

DATA AND APPROACH

Field hydrogeological and hydrological observations were made to develop the preliminary conceptual view of the basin. Daily river flow records were collected from the Ministry of Water, Irrigation and Electricity, however, only data from seven stations was used for flow characterization and groundwater recharge estimation. Others are left out due to missing data and inconsistent recording.

The recording stations used for the study are Holeta, Berga, Bello, Melka Kunture, Hombole, Akaki and Modjo (Figure 1). The flow data used for all rivers covered the period 1991 - 2003. Daily discharges of the sampled watersheds were prepared using Excel Spreadsheet. These files were imported into the two base flow separation soft wares working platform. Characteristics of the upper Awash Basin related to physical property were extracted from the 30m digital elevation model extracted from SRTM Digital Elevation Model, the FAO land use land cover map, hydrogeological and geological maps of the area were used

After collecting the relevant data and conceptualizing the hydrogeological conditions, two independent computer codes (Hydrograph Separation-HYSEP and TIMESPLOT-recursive digital filter) were used to partition stream flow time series data into base flow and direct run off. These methods are widely used in different environments and their increased application is widely accepted.

Calibration process (determining the BFI) using TIMESPLOT was executed on the Excel platform. More analysis, interpretation and visualization of result were prepared using Excel and expert judgment visually and by understanding field hydrological processes and catchment characteristics of each river. Correlation of the two methods and the raw river discharge data with rainfall was compared to assess the agreement between the two methods as well as runoff-rainfall relationship. The flow duration curves (FDC) were used to compare the base flow separation results visually between different seasons and years. Furthermore, graphical results of the hydrographs were evaluated.

The outcomes of the two models are analyzed against the measured catchment runoff using base flow index (BFI). Moreover, BFI was used to compare between watersheds and between seasons. After base flow separation is attained, the processed data are summarized into monthly, yearly and station averages. For TIMESPLOT, each watershade was calibrated manually by using a range of parameter (mailny α) by trail and error on a yearly basis. The trail is stopped when the curve of base flow is closely fitted to the measured dischrage for dry periods. For wet seasons the baseflow curve is compared with HYSEP results.

The catchment influencing factors for each station averages are interpolated in GIS using Kriging method with Gaussian semi-variogram model. The resulting raster surfaces are changed into polyline contours using 3-Dimentional analyst tools. Finally, the two base flow separation techniques are compared by overlaying the resulting contours on geological, hydrogeological, land use and land cover (FAO database), and slope maps of the study area. Moreover, tabular data from base flow results and other maps on catchment runoff influencing factors are used to compare the results.

ESTIMATION METHODS

HYSEP and Institute of Hydrology Low Flow Method

HYSEP is a computer program prepared for stream flow hydrograph separation and analysis. It is graphical (Sloto and Crouse, 1996) and analytical (Darline, 2016) as well as filtering separation technique (Brodie and Hosteler, 2005) where mathematical functions or algorithms are used to calculate base flow directly from discharge and commonly used without calibration.

The program uses three curve fitting methods of hydrograph separation. These are fixed interval, sliding interval and local minimum (Brodie and Hosteler, 2005). The details of these methods are also addressed in Pettyjohn and Henning, 1979. Similarly, the Institute of Hydrology low flow method works based on Gustard et al., 1992 method and is a variant of the HYSEP program called the local-minimum method (Brodie and Hosteler, 2005).

The above four algorithms systematically search and use local minimum flows for each time interval and draw connecting lines between flow hydrographs. The sequence of these lines defines the base flow hydrograph. Pettyjohn and Henning, 1979 stated that the method is more valid where base flow is relatively large enough to reach the stream quickly and established an equation to calculate duration of surface runoff from an empirical relation:

$$N = A^{0.2} \qquad \text{.......} 1$$

where N is the number of days after a peak when surface runoff ceases and A is the drainage area (in square kilometres). The interval used in the program is approximately 2N, since the interval is adjusted to the nearest odd integer in the range of 3 to 11 (Pettyjohn and Henning, 1979). The value of the exponential constant (0.2) can vary depending on catchment characteristics such as slope, vegetation and geology (Brodie and Hosteler, 2005). The Gustard et al, 1992 method algorithm calculates the minima of five day non overlapping consecutive periods and subsequently searches for the turning points in this sequence of minima. The turning points are then connected to obtain the base flow hydrograph. Graphical separation methods, in general, tend to focus on defining the points where base flow intersects the rising and falling limbs of the quick flow response.

The program works with interface and options. The interface uses to interact with the various programs like commands, data panel, instruction panel and special files. The program option comprises default settings, input files, program outputs, hydrograph separation method and base flow separation execution.

TIMESPLOT-Recursive Digital Filter (RDF)

Recursive digital filter, which is a routine tool in signal analysis and processing, is used to remove the high frequency quick flow signal to derive the low-frequency base flow signal (Nathan and McMahon, 1990). The filtering method processes the entire stream hydrograph to derive a base flow hydrograph. It uses a numerical algorithm (a digital filter) for the separation and the process is repetitive for the whole period of the record. Such a filter is simple and robust, but the results are very sensitive to the base flow filter parameter (α), which needs calibration before the results can be considered to be numerically valid.

Brodie and Hosteler, 2005 as well as Indarto et al., 2013 and Indarto et al., 2016 cited the Lyne and Hollick, 1979 and Nathan and McMahon, 1990 formulas to prepare the following filter:

$$\mathbf{q_{f(i)} = \alpha q_{f(i-1)} + (q_{(i)} - q_{(i-1)})\ \frac{1+\alpha}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

$q_{(i)}$	Total flow/observed flow at day i
$q_{f(i)}$	Calculated quick flow/direct runn off at day i
$q_{(i-1)}$	Total flow/observed flow at day i-1
$q_{f(i-1)}$	Calculated quick flow/direct runn off at day i-1
α	Baseflow Filter parameter

The recursive digital filter calculates the base flow for each interval (day i) using information of flow at day (i), day (i-1) and parameter value. The parameter α is calibrated using daily discharge data empirically for each watershed. The method tends not to have any hydrological basis but aim to generate an objective, repeatable and easily automated index that can be related to the base flow response of a catchment (Brodie and Hosteler, 2005). The base flow index (BFI) or reliability index, which is the long-term ratio of base flow to total streamflow, is commonly generated from this analysis

LIMITATIONS

The assumptions in using these base flow separation methods are diversion of upstream river water, water extraction, effluent from treatments, inter-basin groundwater transfer and channel losses are negligible. Actually, even though at lesser scale, the first two cases were the situations in the period 1991 to 2003 in one of the catchments (Akaki). There may be some urban effluents and limited local diversions upstream in Akaki catchment.

Base flow analysis can provide information on the temporal changes but not on the spatial distribution of groundwater inputs along a stream between gauging stations. Moreover, base flow analysis is only applicable for gaining streams (Brodie and Hosteler, 2005). This is also one of the limitations in the study basin.

RESULTS OF MODEL SIMULATION AND ANALYSIS

CORRELATION AND CALIBRATION

The correlation of the results between the two methods on average annual basis is 0.994. This is a very good correlation. Moreover, the 13 years' average rainfall is correlated with equivalent time period total discharge of the biggest catchment (Hombole). It is 0.75. The relatively lower value in the correlation coefficient might be due to delayed response of base flow, withdrawal with pumping or irrigation or inclusion from other sources. Calibration parameters and flow duration curves are tools to observe performance of base flow separation models (Indarto et al., 2013). In this regard, the HYSEP program works without calibration (Darline et al., 2016) but has a flow duration curve to visualize the model performance.

However, for TIMESPLOT program, each catchment was examined by a different range of parameter (α) value used for a trial and error calibration. The maximum and minimum parameter values are 0.994 and 0.979 for Belo and Modjo watersheds, respectively with average value of 0.986. The increase in the parameter value over fits the curve for some watersheds and under fits for others. Because of this, the correlation between the different watersheds produces positive and negative relationship. In general, there is better correlation for watersheds which are far apart and worst correlation for watersheds which are adjacent.

With regard to visualization of perfromances, base flow separated from the total discharge was visualized from Flow Duration Curves (for HYSEP) and the hydrograph graph (for TIMESPLOT).

BASE FLOW INDICES

Base flow Index (BFI), is the ratio of base flow to total flow over the period of analysis. Base flow index is believed to represent the effect of geology, land cover and slope on basin low flows (Gustard et al., 1992). In fact, geology is the most important factor in influencing the BFI in the region as other catchment factors are more or less similar. Base flow indices were compared for the two models. Table 2 displays base flow indices for the Hydrograph Separation and TIMESPLOT methods.

Table 2. Total flows, base flows and base flow indices (BFI) for study area stations

Watershed	Area km2	Measured Total Flow (mm/year)	TIMESPLOT		HYSEP	
			BFI	Base flow (mm/year)	BFI	Base flow (mm/year)
Akaki	884.4	702.98	0.551	387.06	0.527	370.82
Bello	2,568.8	119.68	0.567	67.76	0.802	95.88
Berga	248	368.47	0.502	184.91	0.514	189.63
Holeta	119	476.31	0.517	246.09	0.51	242.75
Hombole	7,656	166.83	0.582	97.05	0.66	110.22
Modjo	1,264.4	98.8	0.53	52.29	0.524	51.75
Melka Kunture	4456	182.34	0.602	109.91	0.731	133.44
Without Akaki	**9,997.6**	**163.06**	**0.582**	**94.9**	**0.685**	**111.93**

The average base flow indices (BFI) for the model period for TIMESPLOT and the HYSEP method, on watershed basis, are 0.582 and 0.685, respectively (Table 2). The HYSEP method tends to produce more base flow than the TIMESPLOT. Moreover, the behavior of the BFIs of the two models were examined over monthly basis. Except August, where the HYSEP method has higher BFI than the TIMESPLOT method, the difference in others is insignificant or does not show clear trend. The evolution of BFI over the 13 years' simulation period show around 10% variation in favour of HYSEP method (Figure 2). For each year, TIMESPLOT produces the lowest BFI values.

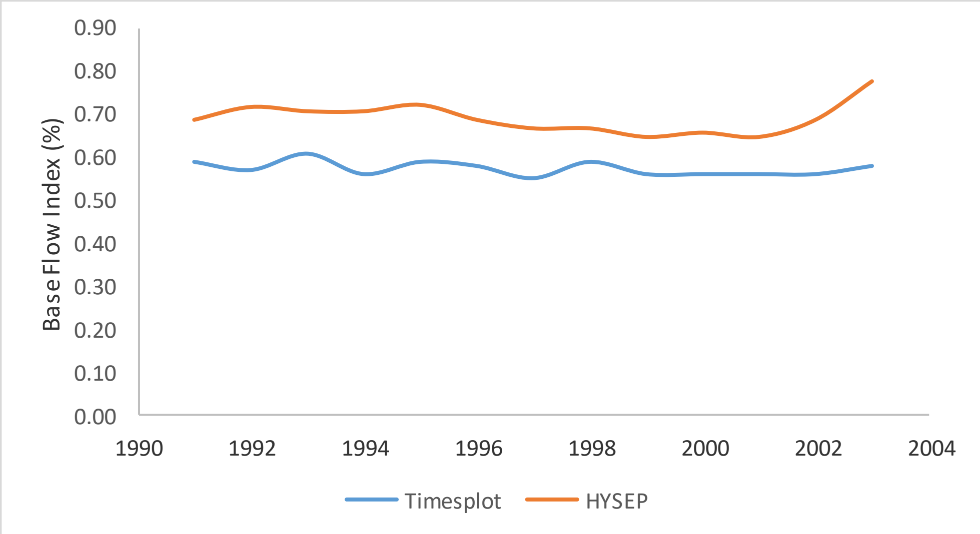

Figure 2. Evolution for BFI over 13 years (%)

Both methods show that not all months and years show similar base flow - surface runoff ratio. On monthly basis, the base flow ranges from 0.49 to 0.94 for TIMESPLOT and from 0.52 to 0.93 for Hydrograph Separation method. The highest values are for dry periods. However, on yearly averages, it is 0.58 for TIMES PLOT and 0.69 for HYSEP method (Figure 2).

Higher BFI values for both methods occur in dry seasons, which are from on average from 0.71 to 0.995. For wet seasons they are from 0.46 to 0.8. This shows that the watershed is mainly influenced by base flow contributions. The significant wet season variations are likely in part attributed to rainfall distribution and land use pattern during wet seasons.

BASE FLOW AND DROUGHT VUNERABILITY

Table 2 displays the measured total flows and base flows for the Hydrograph Separation and TIMESPLOT methods. For comparison, mean weighted annual rainfall values of the studied watersheds are also shown.

The total annual recharge or base flow from the TIMESPLOT and Hydrograph Separation models are 94.9 and 111.93 mm, respectively. This is without Akaki watershed which is more urbanized. The major tributaries of Akaki river drain through Addis Ababa city where there are considerable wastewater form sewage treatments and presence of extended in built areas. Moreover, it is also subjected to huge pumping and other anthropogenic influences. These external stresses are expected to influence base flow separation. Therefore, except using the result for comparison, it is not used in the interpolations and analysis for Akaki.

The TIMESPLOT compares favorably with Hydrograph Separation producing about 17 mm less annual recharge than the later on study area basis. The difference comes from three stations while others almost agreed. This indicates good agreement. Base flow separations conducted with River Analysis Package (RAP) by Tilahun A., 2015, 95% agreed with the TIMESPLOT result for Melaka Kunture (105 mm year) and Bello (63 mm/year). Figure 3 shows that there were high base flows in 1993, 1996 and 1998. However, the years 1994, 1997 and 2000 had low base flows. This may implicate metrological and climatic influences in those periods causing cyclic recurrence of drought roughly every three years. The amount of rain in drought times is roughly half of the rainfall in good seasons.

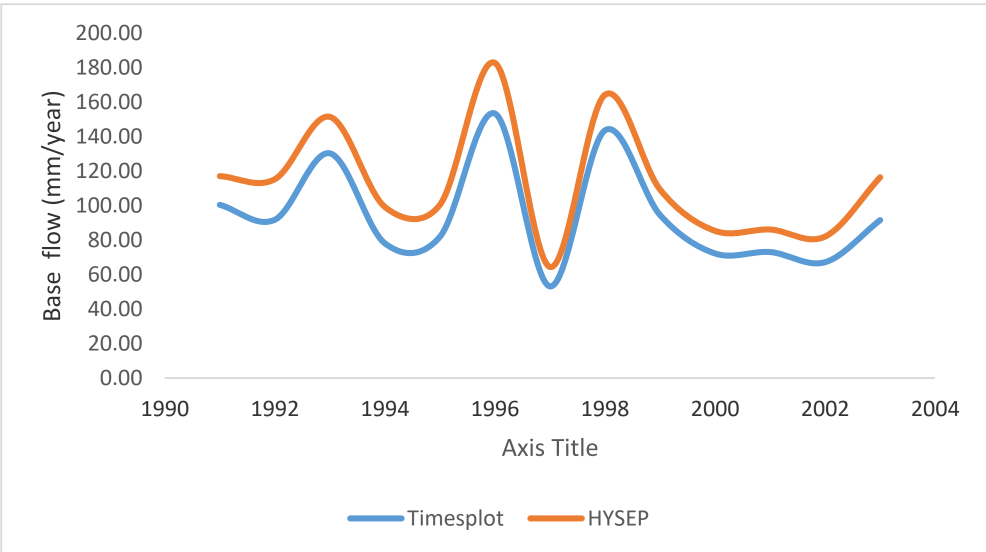

Figure 3. Evolution of base flow over 13 years (mm/year

Moreover, due to the ever-increasing use of water for different consumptive uses, even the stream water in good seasons is highly stretched. The yields of springs and oozing surfaces which are the sources of the majority of the streams are gradually dwindling as a result of pumping and diverting of water adjacent to the lower sides of spring sources. For instance, the yield of some of the springs which are sources to Modjo river decreases from 33.5 liters per second in 2002 to 15 liters per second in 2017 due to irrigation and water abstraction practices around and downstream of the spring source areas (Kumela H., 2017).

Average monthly base flows over the 13 simulation years (Table 3) show that the monthly base flows start climbing in June and recede in October. In general, as per the value of BFI, Figures 2 and 3, and Tables 2, 3, 4 and 5, it is evident that the Upper Awash River flow regime is groundwater dominated. Despite the slight difference, the two methods have similar trend in estimating the different hydrologic behaviours.

Table 3. Monthly average base flow for the two methods (mm)

Months	Base Flow (mm/year)	
	TIMESPLOT	HYSEP
January	13.36	13.4
February	11.62	11.7
March	11.00	11.2
April	12.17	14.4
May	16.16	16.8
June	48.43	46.1
July	209.19	239.2
August	392.92	584.1
September	318.85	310.8
October	67.90	58.8
November	22.09	21.7
December	15.13	15.0
Average	94.90	111.93

Table 4. Yearly average base flow for the two methods (mm)

Years	Base Flow (mm/year)	
	TIMESPLOT	HYSEP
1991	100.52	117.20
1992	91.88	115.42
1993	130.35	151.61
1994	78.17	99.30
1995	82.01	100.55
1996	153.44	182.95
1997	53.21	64.44
1998	143.70	164.48
1999	94.63	109.42
2000	72.28	85.40
2001	73.13	86.20
2002	67.25	82.10
2003	91.63	116.54
Average	94.80	113.51

Table 5. Monthly average base flow index for the two methods (%)

Month	Base Flow Index	
	TIMESPLOT	HYSEP
January	0.89	0.892
February	0.84	0.841
March	0.64	0.652
April	0.50	0.592
May	0.60	0.629
June	0.55	0.516
July	0.52	0.594
August	0.49	0.724
September	0.73	0.719
October	0.76	0.673
November	0.90	0.883
December	0.94	0.933
Average	0.58	0.69

Figures 4 exhibits the hydrograph of the gauging stations for TIMESPLOT method. The same graph for HYSEP method trends identically with the TIMESPLOT graph. The graph also displays areas with low base flows and hence vulnerable for drought. Especially, the lower gauging stations (Hombole, and Modjo) are highly vulnerable for drought.

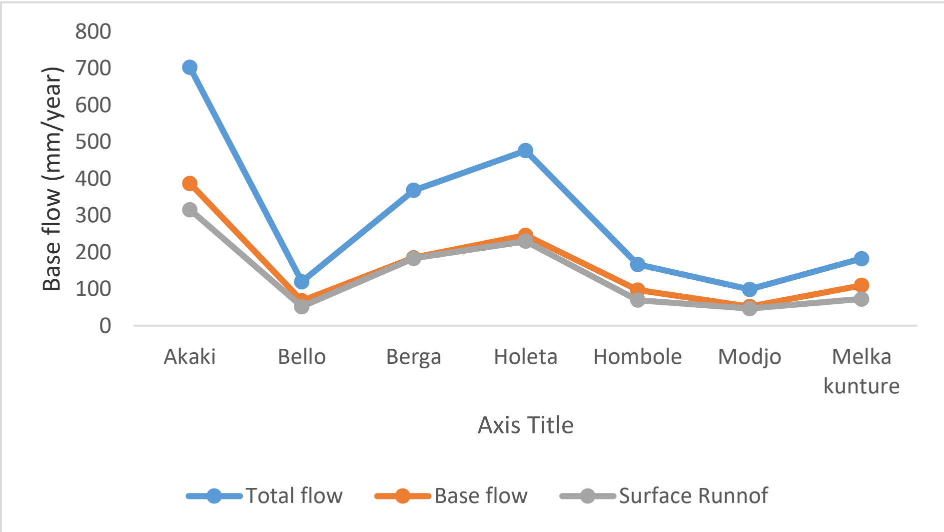

Figure 4. Hydrograph of the six gauging stations for TIMESPLOT method (mm/year)

4.4 ANALYSIS

One of the major unknowns in any hydro-geologic investigation is the rate at which water infiltrates from the land surface to the groundwater table (Pettyjohn and Henning, 1979). In this regard, comparison was made to identify which of the two methods better represent the recharge regime of the study area.

On the other hand, the two methods used in the base flow separation do not have much relation with the physical environment (Arnold and Allen, 1999). Because of this, physical characteristics like geology, hydrogeology, nature of the unsaturated zone (soil moisture), elevation differences, climatic and metrological are not considered in the estimation. For comparison, in addition to the findings listed in the previous subtopics, base flow and base flow indices were plotted on physical properties of the watershed map. Kriging interpolation method with Gaussian method and semi-variogram model was best suited for base flow interpolation and IDW method best suited for BFI interpolation.

Accordingly, the plotted base flow contour maps for the two base flow separation methods show trend with slope, geology and hydrogeology (Figure 5) maps. Recharge or base flow increases with elevation. The base flow contour maps plotted on land use and land cover map show that high forest and dense woodland areas are located in high recharge areas. It is also evident that the highest recharge is in elevated areas and wooded lands.

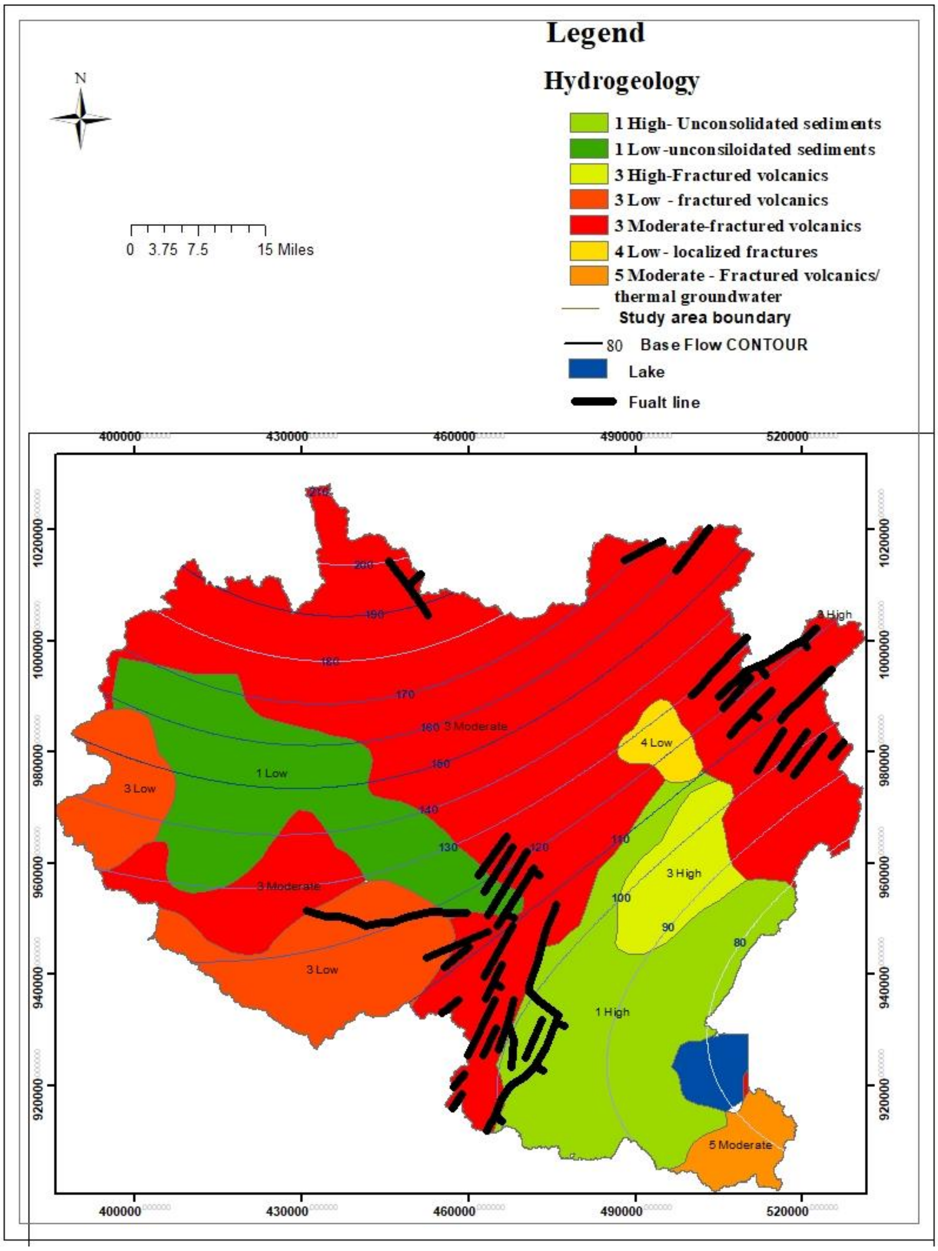

Figure 5. HYSEP Base flow contour map on hydrogeology map of the study area

The presence of fractured and faulted permeable structures in the high and midland created conducive conditions for infiltration. Figures 5 displays overlay of the base flow contour lines on the hydrogeology map. Moreover, clearly, the fault lines are aligned with the contour line (Figure 5). This might show recharge through dense fault lines. On the contrary, even though it is not well-defined as the base flows, the base flow indices of both methods trend with the decrease in elevation. They are high in stations in the rift floor and alluvial plains. As stated earlier, the similarity of both methods in trending in part resulted from their good correlation coefficient which is 0.994.

In almost all sub-watersheds, the less rainfall season stream flow is significantly dominated by base flow contributions. In the main dry season, which is from November to February, the average base flow for the two methods is 0.90 (0.92 for TIMEPLOT and 0.89 for Hydrograph Separation). While the base flow index in dry season is higher for TIMPESPLOT, it is the opposite in the wet seasons. It is 0.61 for Hydrograph separation and 0.51 for TIMESPLOT in wet seasons. Despite the presence of water supply dams, household level irrigation schemes and other residential and industrial uses, the base flow contribution was sustaining the streams during the dry seasons in the simulation period (1991 to 2003) in few streams.

Based on rainfall data and base flow analysis (Figure 3), there is cyclic recurrence of drought roughly every three years. Areas which are vulnerable to drought are those located on the rift floor which are witnessed by Hombole and Modjo river gauging stations. This is in link with cyclic crop failures happening in these rift floor areas. Even the wells, recently drilled in these areas (for irrigation), show relatively deep-water level and high temperatures.

CONCLUSIONS

In general, the different methods applied to estimate BFI are in good agreement. Almost all rivers are groundwater dominated systems. Recharge seems to be reasonably estimated using both methods, although a few limitations exist. The general trends of the two methods were in agreement and results compared favorably. Different recharge assessments by Andarge Y., 2009; Cherenet, T., 1985, Tesfaye C., 1982, Tilahun A., 2015, and WWDSE, 2008 range from 5 to 20% of the catchment annual precipitation. The results obtained in this study were within this range.

In fact, comparisons are important as they indicate which method seems to be more realistic in showing the relative importance of the recharge process in the different physiographic regions. The TIMESPLOT model shows better result in demonstrating the temporal variations and is much better in indicating the relative importance of recharge in the three physiographic regions, i.e., rift, escarpment and highland areas.

The general trends of monthly variations of base flow and surface runoff is similar in both methods. The HYSEP method overestimates base flow in all the three physiographic regimes. Base flow increases with elevation whereas BFI decreases with elevation. BFI is higher around flat lying areas where alluvial deposits cover the volcanic rocks. The use of daily data instead of monthly or yearly averages helped for better estimation. It is also observed that the two methods clearly displayed the occurrence of cyclic droughts (Figure 3). Those vulnerable to drought are the low-lying areas of Hombole and Modjo catchments (Figure 4).

Overall, the study showed that both methods can be applied in the study area and in similar physiographic and geologic settings. Hence, this study has far reaching implications to apply it for many rivers that drain from the volcanic Ethiopian highlands to the rivers. With this approach groundwater recharge could be fairly estimated from river discharge measurements. It was illustrated that all watersheds are influenced by strong contribution of base flow in all seasons.

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