Original Research Article

Analysis of water exchange processes between groundwater and surface water in the Usangu Plains, Tanzania

ABSTRACT

The groundwater and surface water interface has been proved evident by the existence of effluent and influent streams. Still, the irrigation sector in sub-Saharan Africa, Tanzania included, is predominantly using surface water and groundwater conjunctively without a clear understanding of the contribution of each of the two water sources. This study was conducted to analyze the water exchange processes between groundwater and surface water in the Usangu Plains. Constrained by data scarcity in the study area, only three hydrograph separation techniques (Sliding interval, Fixed interval, and Local minimum) of the Baseflow Index model third version (BFI+ 3.0) were used.These techniques were applied to estimate baseflow, surface runoff and baseflow indices using river discharge data from six gauging stations across six different rivers. Further, the Mann-Kendall (MK) test was used for trend analysis of the long-term time series baseflow index. Results indicate that the groundwater-surface water interaction exists and the baseflow contributes substantially to the sustainable river flows in the Usangu Plains during both dry and wet seasons. Except for the Great Ruaha River at Msembe, the other five rivers manifested a great reliance on the baseflow with more than 90% of it in the river flows. The MK test revealed that at annual, wet, and dry season scale there are statistically non-significant increasing and decreasing trends in the baseflows. Land and water management strategies such as water allocation measures, sound water usage practices and afforestation may be better approaches to counteract the declines of water flows in rivers of the Usangu Plains, especially in the dry season.

***Key words**: surface water, groundwater, interactions, baseflow index, Usangu Plains.*

1. INTRODUCTION

The understanding of groundwater and surface water interaction is vital for the water resources management and sustainable utilization. For many years, groundwater and surface water have been considered as separate components of the hydrological cycle in the application of water management policies (Yang, 2018). In contrast, these two water sources are hydraulically connected (Raz *et al.*, 2017). Groundwater and surface water interactions occur by means of different mechanisms on varying levels and affect the recharge-discharge processes of groundwater and surface water (Sophocleous, 2002). The groundwater and surface water interface has been proved evident where the effluent and influent streams were identified as the proof of that inter-connectedness (Matthews, 2013). Water availability in any catchment relies on the relationship between groundwater and surface water (Mul, 2007).

Globally,groundwater withdrawal has increased from a base level of 100-150 km^3 in 1950 to 950-1000 km^3 in 2000 (Shah *et al.*, 2013).In addition, the unevenly distributed groundwater withdrawal in 2018 declined to 978 km^3 (UN, 2022) and it has been peaking on average at 625 km^3/year around mid-century, followed by a decline through 2100 (Niazi *et al.*, 2024).Apart from domestic use, livestock and industries, about 70% of the global freshwater is estimated to sustain the irrigated agriculture which is likely to be the most important water use sector (Siebert *et al.*, 2010). Still, the irrigation sector in sub-Saharan Africa is predominantly using surface water and groundwater conjunctively without a clear understanding of the contribution of each of the two water sources (Siebert *et al.*, 2010). However, groundwater discharges plays a capital role in sustaining surface water bodies (Foster, 2016) especially during dry seasons. Certainly, the knowledge of groundwater and surface water interconnectedness is needed as soon as possible to sustainably manage the available water resources for the betterment of its all users.

In Tanzania, as well as other African countries, the quantification of groundwater discharges to surface water bodies is challenged by the deficiency of data, technical skills and financial support (Mahoo *et al.*, 2015). These, in addition to ineffective policies, have led to an uncontrolled exploitation of the two water sources for human and economic activities. In the Usangu Plains located in the southern highlands of Tanzania, it was evoked that the increase of groundwater withdrawal may be another possible cause of reducing surface water storage and further studies were recommended for its sustainable management (Kashaigili *et al.*, 2006; Mbaga *et al.*, 2015). Furthermore, the quantification and understanding of the interaction between groundwater and surface water are necessary for the suitable management of riparian ecosystems (Kalbus *et al.*, 2006).

Several authors have applied various methods for identifying and quantifying the amount of surface water being contributed to the aquifers as well as groundwater contributing to wetlands, rivers or lakes by (Huizenga, 2015; Kalbus et al., 2006; Madlala, 2015; Matthews, 2013; Sophocleous, 2002). To counteract the data scarcity challenge, a number of studies emphasize on quantifying the river baseflow (Kelly et al., 2019) to determine the contribution of groundwater discharges to rivers. The baseflow time series, though considered to measure groundwater dynamics within a catchment, has an index that reflects the contribution of catchment stores to river discharge (Querner et al., 1997). While baseflow indices are commonly correlated to hydrological, soil and geological properties (Querner et al., 1997), these details are hardly available at appropriate scale in large areas like Usangu Plains. Nevertheless, Stahl et al., (2010) advised the streamflow-derived indices to be used as baseflow indices. Benedict (2019) and Magbalot et al., (2019) identified the mixing of subsurface baseflow with surface water and recharge of groundwater by river in lower elevation at Ndembera river of the Usangu catchment using the stable isotopic and SWAT (Soil and Water Assessment Tool) model. But the interaction between the two water sources is still limitedly understood specifically in areas with visible streamflow-level declines like Usangu catchment.

The aim of this study was to analyse the water exchange processes between groundwater and surface water in the Usangu Plains. The specific objectives were to (1) separate the groundwater discharges from surface runoff of the river flows, (2) assess the temporal relationship between baseflow and streamflow and (3) analyze the trend of rivers’ baseflow indices. We used three hydrograph separation techniques of the Baseflow Index model third version (BFI+ 3.0; Gregor, 2010) to improve the clear understanding of the groundwater and surface water interconnectedness. The results of this study are expected to enhance the sustainable management of the water resources in the Usangu Plains, Tanzania.

2. MATERIALS AND METHODS

2.1. Description of the study area

The Usangu Plains are in the upper part of the Rufiji River Basin at an average elevation of 1100 m above mean sea level (a.m.s.l). The area is delimited by the Kipengere, Poroto and Chunya mountains with an elevation reaching 3000m a.m.s.l in the southern highlands of Tanzania. The Usangu Plains cover an area of approximately 20 810 km^2(Kadigi *et al.*, 2004) and lie between latitudes 7^{o}41’ and 9^{o}25’ South and longitudes 33^{o}40’ and 35^{o}40’ East. The Usangu Plains’ rainfall distribution varies spatially and is very localized depending on the altitude (Kashaigili *et al.*, 2006). In Usangu catchment, areas below 1100m of altitude are defined as lowlands while areas above 1100m represent highlands (SMUWC, 2001). The mean annual rainfall is between 1000 and 1600 mm within the highlands while the central plains in the lowlands receives 500-700 mm (Malley *et al.*, 2009). Surface runoff originating from the highlands feeds the central plains and seasonally floods the wetlands ecosystem (Tumbo *et al.*, 2015).The Usangu Plains’ mean annual temperature is between 18^{o}C and 28^{o}C in the highlands and lower parts, respectively and its mean annual potential evapotranspiration goes up to 1900mm (SMUWC, 2001). The Usangu Plains are drained by the Great Ruaha River, with an outlet at a point called NG’iriama, where a rock outcrop acts as a natural dam controlling the flow from the Eastern Wetland (Kashaigili *et al.*, 2006).The hydrogeology of the Usangu Plains is made of various formations such as terrestrial deposits, quartzites, meta-volcanics, gneisses, extrusive basalt and many more. The catchment may be divided into a number of provisional hydrogeological zones namely upland zone, rungwe volcanic zone, scarp zone, alluvial fans andlake deposits. (SMUWC, 2001). Mbarali, Kimani, Chimala and Ndembera rivers, with confluences in the Usangu central Plains, are the major tributaries to the Great Ruaha River (Figure 1). These rivers account for 85% of the whole discharge from the rivers of Usangu Plains and have their sources at high elevations given the high amount of rainfall in the highlands (SMUWC, 2001). The main water suppliers to the Eastern Wetland is the Great Ruaha River and the Ndembera River, which flows from the Western Wetland through the constriction at Nyaluhanga, which discharges into it from the north-east, respectively (Kashaigili *et al.*, 2006).

2.2. Data source

The river discharges data were collected from the Rufiji Basin Water Board (RBWB) operating from Mbeya region. Streamflow data were recorded from six (6) river flow gauging stations as illustrated in Table 1. The river discharge data were recorded in m^3/s on a daily resolution at all the gauging stations and the data period ranges from the 01st of January 2010 to the 31st of December 2019. Referring to the SMUWC (2001) report categorizing highlands and lowlands, only Msembe gauging station of the GRR is found in the lowlands with 838m of altitude. Missing data were filled in relying on the hydrological yearbook of 2010-2019 from the Ministry of Water [https://www.maji.go.tz/pages/articles, site visited on 06/04/2021].This book covers river discharges of almost all the national basins including the Rufiji Basin where the Usangu Plains are found. Rainfall (Figure 2)data used in this study were sourced from the Climatic Research Unit [https://crudata.uea.ac.uk, site visited on 13/04/2021] on a monthly temporal resolution and 0.5 degrees of spatial resolution.

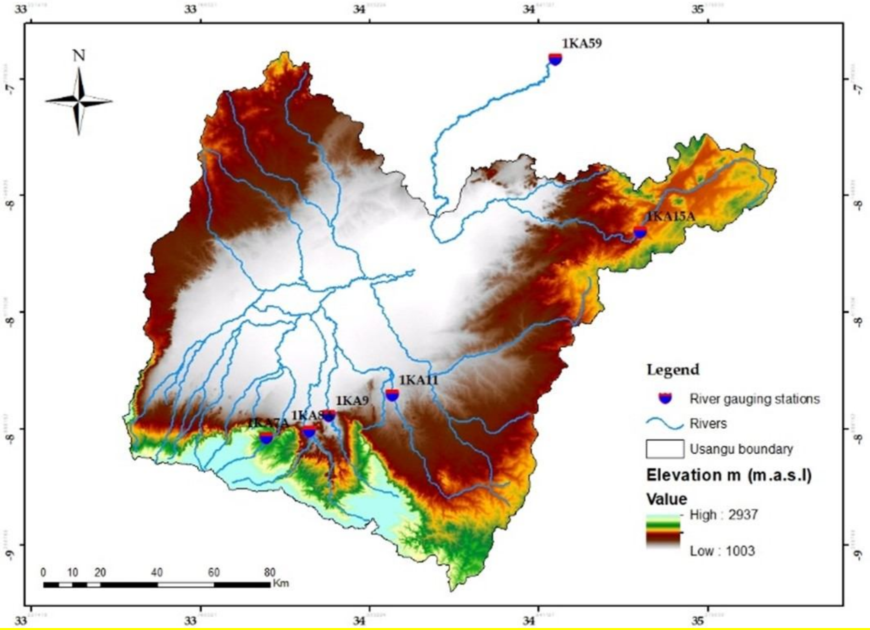

Figure 1: Map of the Usangu Plains with river gauging stations and elevation

Table 1: River gauging station details

No	Name	Location	Code	Easting (X)	Northing (Y)	Altitude (m)	Mean annual flow (m^3/s)	Area (km^2)
1	Chimala	Chitekelo	1KA7A	607306	9014062	1907	950.5	168
2	G. Ruaha	Salimwani	1KA8A	622243	9016503	1152	5718.4	785
3	Kimani	GNR	1KA9A	629183	9021765	1079	2022.4	451
4	Mbarali	Igawa	1KA11A	651581	9028846	1119	3982.2	1553
5	Ndembera	Ilongo	1KA15A	738361	9086002	1673	1748.7	1105
6	G. Ruaha	Msembe	IKA59A	709328	9146923	838	9384.6	23527

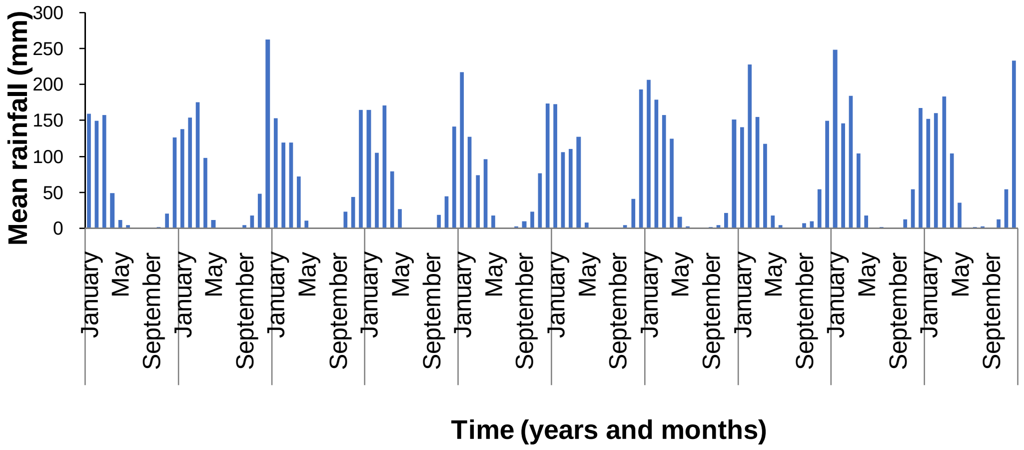

Figure 2: Monthly rainfall of the Usangu catchment

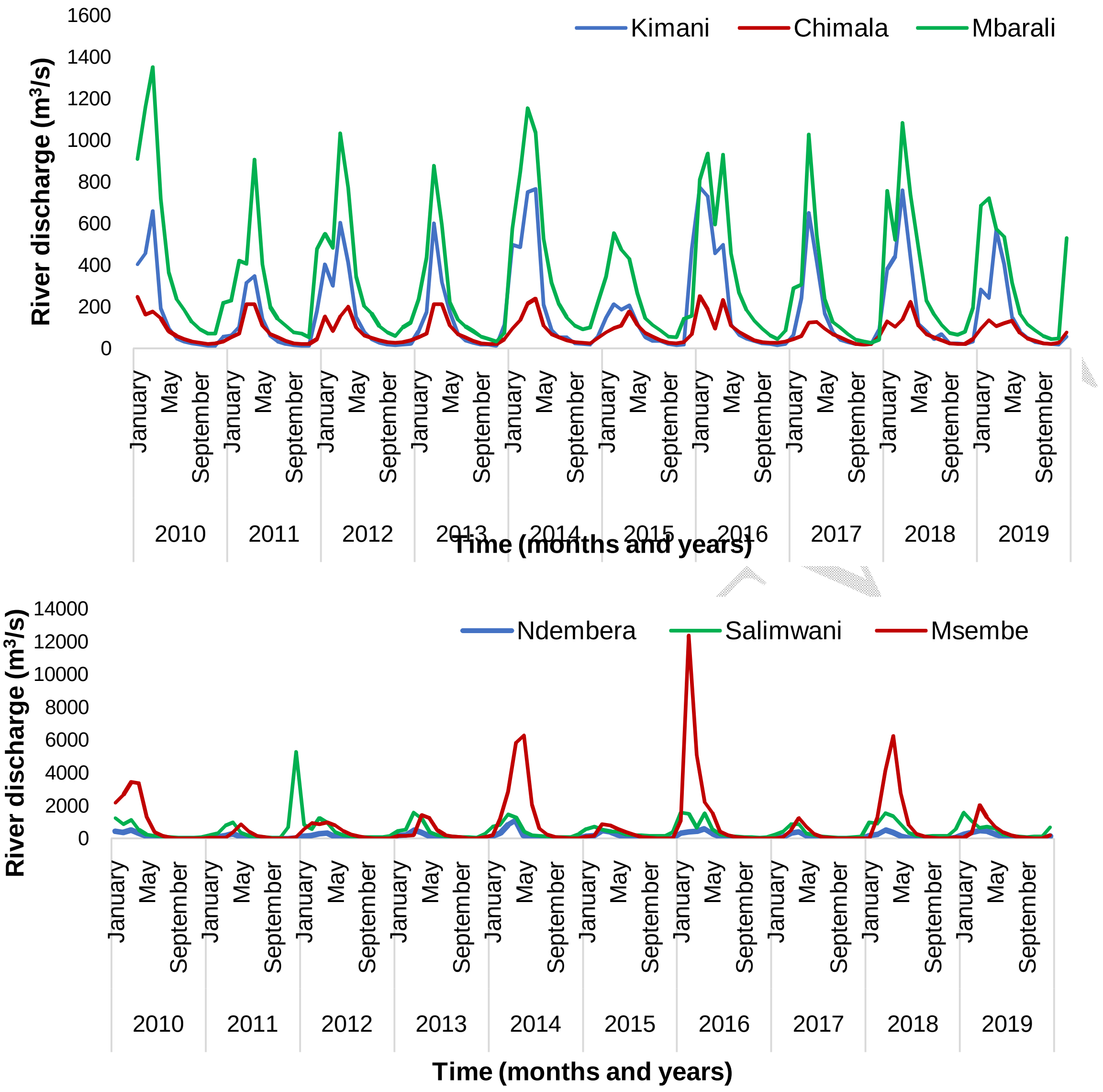

Figure 3: Monthly specific discharge data for the six rivers

Table 2: Mean monthly river flows (mm) for the six river gauging stations

Months	Kimani	Mbarali	Chimala	Ndembera	Salimwani	Msembe
January	60	30	61	16	93	1.6
February	65	34	56	21	85	7.1
March	106	48	79	33	115	7.3
April	77	40	96	32	108	8.7
May	27	20	55	14	50	6.1
June	13	11	35	5	24	2.2
July	8	8	27	2	17	0.8
August	7	6	19	1	13	0.3
September	4	4	13	1	11	0.1
October	3	3	11	0	11	0.0
November	3	4	13	0	17	0.0
December	21	12	25	3	87	0.2

2.3. Methodology

2.3.1. Hydrograph separation techniques

There are various hydrograph separation techniques that have been used to categorize the streamflow components. Nathan and McMahon (1990) distinguished two different methods of baseflow separation, the ones which consider that the baseflow results from a rainstorm event simultaneously with surface runoff and the others that assume that baseflow recession continues after some time the surface runoff starts. The former methods generally divide the river flow in two parts using an automated temporal separation: a) quick and b) delayed parts. The quick flow part representing the surface runoff while the delayed part is meant to be the flow originating from groundwater storage and other tardy water sources (Querner *et al.*, 1997).

With respect to this study, the baseflow separation techniques which assume that streamflow responds to a storm occurrence concurrently with surface runoff were applied to analyze the river discharges.Combalicer *et al.* (2008),aftercomparing groundwater recharge and baseflow in the Bukmoongol small-forested watershed of Korea, concluded that the BFI method appeared consistent and gave stable results.Baseflow Index model third version (BFI+ 3.0) of the HydroOffice 2012 software package was used to estimate the baseflow and surface runoff components of the streamflow (Gregor, 2010). Among its 11 methods, three baseflow separation techniques were chosen with regard to data limitationsin the study area and their simplicity: a) sliding interval method, b) fixed interval method and c) local minimum method. All these techniques use the same formula and approximately the same algorithms which are described in Appendix 1.

$$N=(0.8*A)^{0.2} \text{ (Equation 1) (Gregor, 2010)}$$

where N represents the number of days for the surface runoff and A the river catchment area. The surface runoff duration (N) was calculated based on each river catchment area (Table 1). The hydrograph separation techniques used in this study generate baseflow, surface runoff and baseflow index (BFI). The surface runoff was calculated as the difference between baseflow and total river discharge.Annual and seasonal BFI were analyzed to determine the temporal interaction of rivers and baseflow. A comparison among rainfall, river velocities and baseflow was performed to confirm the influence of rainfall-driven seasonality on the streamflow variations. The river flow, baseflow and surface runoff values were converted from m^3/s to mm/month for better comparison. The conversion was made by multiplying the mean monthly cumecs (m^3/s) with 24h, 3600seconds, the number of days of a month and 1000mm, and later dividing the value by the river catchment area (which was converted from km^2 to m^2).

2.3.2. Trend analysis

The Mann-Kendall (MK) test was used to analyze the long-term time series baseflow index and determine if there is a statistically significant trend (Table 3). The MK test is a non-parametric method built on rejecting or not the null hypothesis which assumes that there is no trend in the data. It has been used by several researchers worldwide and was recommended by the World Meteorological Organization (WMO) to perform trend analysis for hydrometeorological variables (Kelly *et al.*, 2019; Nagy *et al.*, 2020; Sobral *et al.*, 2019 and Shu and Villholth, 2012). This MK test was integrated in the statistical software package named XLSTAT which is a Microsoft Excel Add-In.

Table 3: Trend classification for 5% of level of significance (Sobral *et al.*, 2019)

Classes	Code	Scale
Significant increasing trend	+2	$Z^* > 1.96$
Non-significant increasing trend	+1	$0 < Z > 1.96$
No trend	0	$Z = 0$
Non-significant decreasing trend	-1	$-1.96 < Z < 0$
Significant decreasing trend	-2	$Z < -1.96$

[*] Z is the Mann-Kendall test statistic

3. RESULTS AND DISCUSSIONS

All baseflow separation techniques indicated that the groundwater-surface water interaction exists and the baseflow contribute substantially to the sustainable river flows in the Usangu Plains during both dry and wet seasons, but especially in dry seasons (Figures 4-10).GRR at Salimwani has the highest value of total flow in the wet seasons with 578 mm in December 2011, with all the flow values below 50 mm in dry seasons except 74 mm in November 2011. It is seconded by Kimani River at GNR having the peak value of 149 mm in January 2016 and the peak of 13 mm in dry seasons; August 2018. The total monthly river flow for Ndembera at Ilongo and GRR at Msembe are below 50 mm while Mbarali river at Igawa is discharging the flow below 100 mm, for both dry and wet seasons. Table 2 illustrates the temporal variability of river discharges for the period of 2010 to

2019, where the majority peak values occurred in wet seasons (from December to June) while the lowest flows happenedobviously in dry seasons (July to November). Among all the rivers, GRR at Salimwani takes the lead in highest values throughout all the seasons, except from May to September where Chimala river at Chitekelo comes first.

3.1. Groundwater discharge separation from total river flow

The baseflow separation techniques used are sliding interval (SI) method, fixed Interval (FI) method and local minimum (LM) method. All are incorporated in the BFI+ tool and use the same Equation 1 though having slightly different algorithms. N, number of days for runoff duration, depends up on the river catchment as Equation 1 indicates. N values (Table 4) in parentheses are rounded off for the model does not accept decimal values.

Table 2: River details and N values for each river catchment

No	River Name	Station	Code	Area (km^2)	N Value
1	Chimala	Chitekelo	1KA7A	168	2.66 (3)
2	Great Ruaha	Salimwani	1KA8A	785	3.63 (4)
3	Kimani	GNR	1KA9A	451	3.25 (3)
4	Mbarali	Igawa	1KA11A	1553	4.16 (4)
5	Ndembera	Ilongo	1KA15A	1105	3.88 (4)
6	Great Ruaha	Msembe	IKA59A	23527	6.41 (6)

The total mean groundwater discharges from all the baseflow separation techniques along with the total flow for all the rivers can be seen in Figure 4. It is noticeable that the sliding interval method estimated high values compared to fixed interval method. But the local minimum method appeared to show the lowest values of baseflow throughout the period and for all river gauging stations.The results of this study agreed with the findings of Benedict (2019) who reported the decreases of Ndembera river discharges due to changes in land use/land cover in the catchment and illegal water withdrawal to irrigate onions and rice along the river. At Ilongo gauging station of Ndembera river, about 43% of the time range have flow values below 1 m^3/s in dry season.

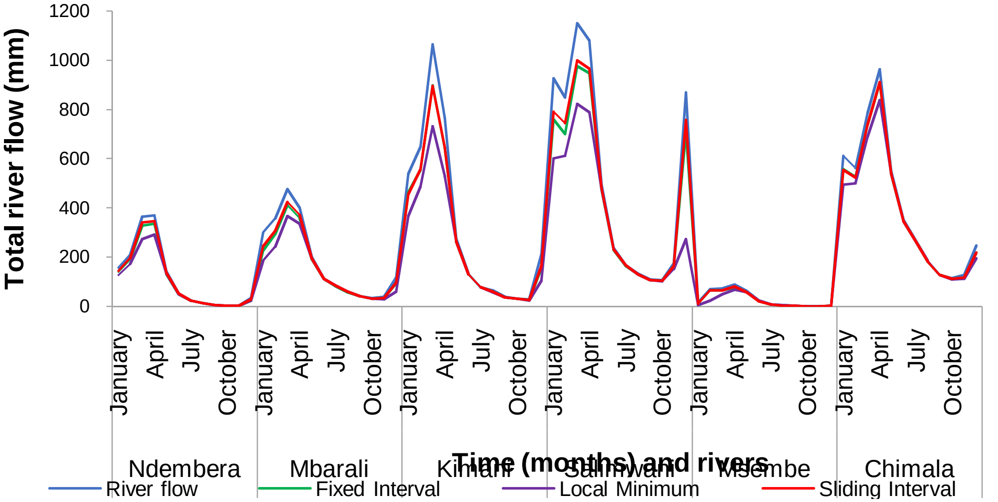

Figure 4: Comparison of baseflow separation methods against total river flow

3.1.1.Chimala River at Chitekelo

For all the techniques, the baseflow contribution to the river flow happened all over the whole period (2010-2019) in both wet and dry seasons. During rainy season (December to June), the baseflow indices kept on fluctuating downwards and upwards, which implies the contribution of surface runoff and/or the surface water contributions to the groundwater storage. But, through dry season (July to November) the groundwater discharges decreased and the baseflow indices seemed to be somehow stable. Figure 5 shows the comparison of different methods of baseflow separation for Chimala river against their respective baseflow indices (BFI_FI: Baseflow Index for Fixed Interval, BFI_LM: Baseflow Index for Local Minimum, BFI_SI: Baseflow Index for Sliding Interval). According to Figure 5, it is visible that the sliding interval estimated the highest values of baseflow (1.16% in April 2014) which denoted its great baseflow indices. During the wet seasons, the local minimum estimates less values whereas in dry seasons all techniques tend to estimate almost the same values of baseflow.

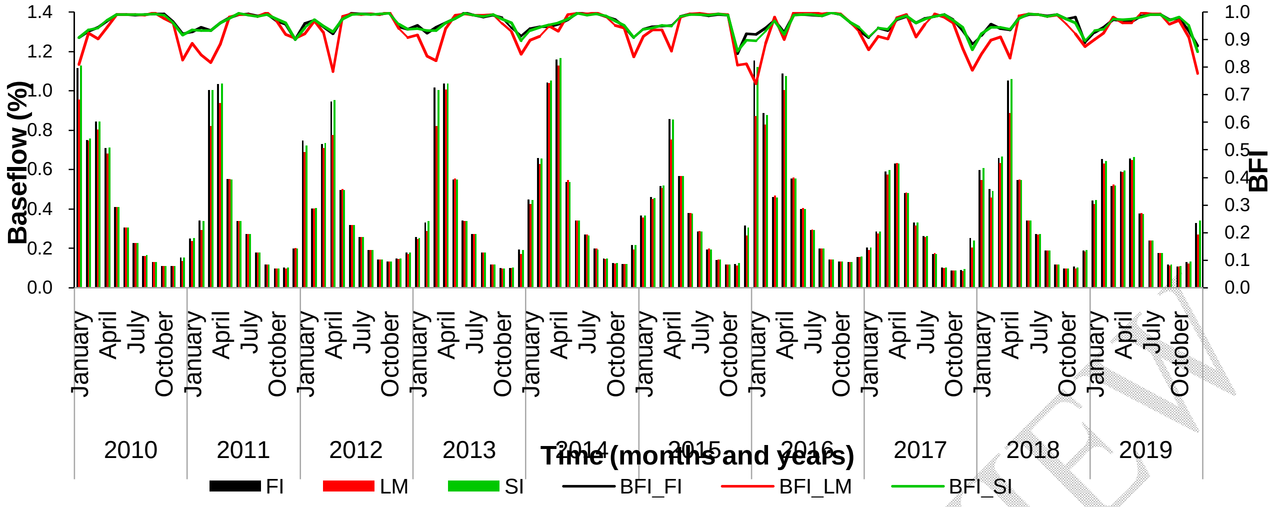

Figure 5: Baseflow separation techniques along with BFI for Chimala at Chitekelo

3.1.2.GRR at Msembe

The Msembe gauging station is located out of the Usangu plains boundary and has recorded several zero flow values (Table 5). This implied the absence of both baseflow and runoff contribution to the river within the no flow periods. However, the results showed that the input of baseflow to the river occurred in both dry and wet seasons during flow periods. The sliding interval method has the highest baseflow estimation (0.43%) in February 2016 as Figure 6 represents it. The annual baseflow decreased in 2011 but augmented extremely in 2016.GRR at Msembe dried up in all the years of the period for several days except for 2014 and 2015 (Table 5). There were about 128 days throughout the time range (2010-2019) where discharges of GRR at Msembe fluctuated between 0.001 and 1.00 m^3/s. These results were in agreement with those reported by Kashaigili *et al.* (2006) indicating that GRR dried up for some days from 1994 to 2004.The decline of GRR flow at Msembe can be subjected to anthropogenic activities mainly irrigated agriculture happening in the catchment as narrated by Kashaigili *et al.* (2006).

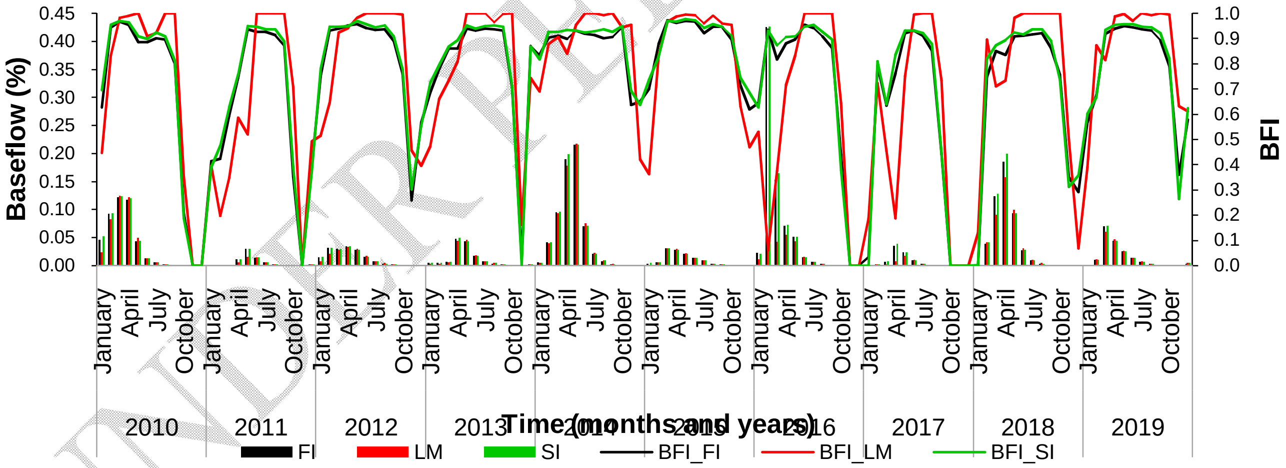

Figure 6: Baseflow separation techniques along with BFI for GRR at Msembe

Table 3: Periods of zero flow in the Great Ruaha River at Msembe (2010 to 2019)

Year	Flow stopping date	Flow resuming date	Days of no flow
2010	October 12	January 9 2011	90
2011	October 23	December 10	48
2012	November 21	December 11	20
2013	November 3	November 28	25
2016	October 21	January 30 2017*	97
2017	September 23	January 29 2018	127
2018	November 7	November 9	2
2019	November 18	November 29	11

*With some in-between start and stop to flow.

Considering the Sliding Interval method, the baseflow indices were found varying between 89% and 98% for other rivers except GRR at Msembe where the indices are 71%, 75% and 77% for dry, wet and annual seasons, respectively (Table 7). The findings of this study for GRR at Msembe differ from the results of Kashaigili et al. (2006) showing that 89% of the annual (1958-1973) river discharge are from the baseflow using the Desktop Reserve Model.

3.1.3.GRR at Salimwani

At Salimwani gauging station of the Great Ruaha river, the sliding interval method has high baseflow indices seconded by the fixed interval method. In 2011, there was a high baseflow estimated by all techniques, but sliding method comes first with 5.07% in December 2011 while the local minimum estimated less. From 2011, the groundwater discharges to the river kept on fluactuating seasonally, this was also affecting the baseflow indices as depicted in Figure 7.

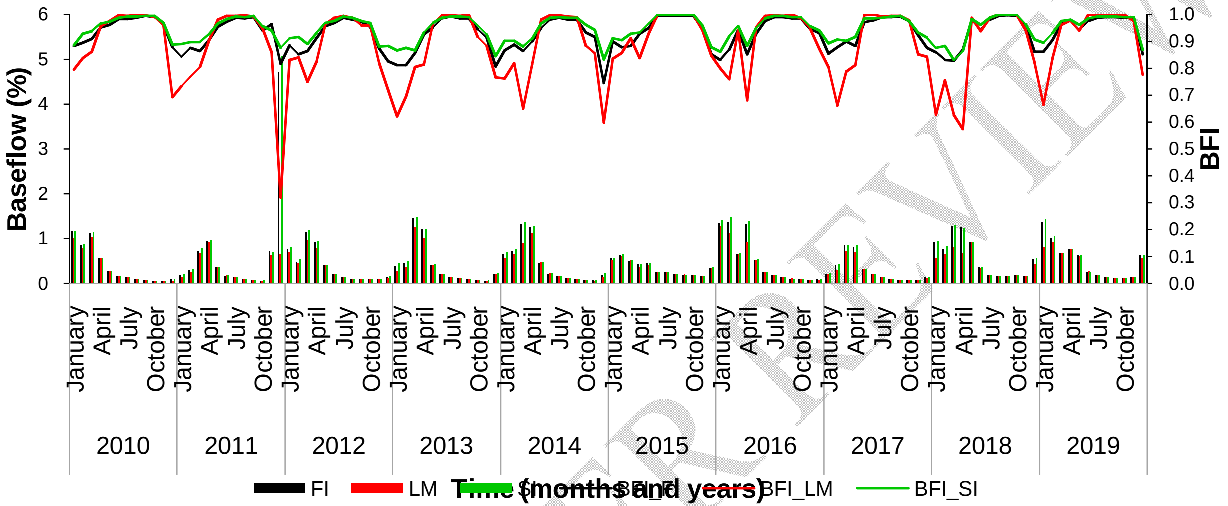

Figure 7: Baseflow separation techniques along with BFI for GRR at Salimwani

3.1.4.Kimani at GNR

From all the separation methods, the baseflow occurred all along the period and in all seasons. As Figure 8 displays, the baseflow indices increased in dry seasons which depicts the contribution of groundwater discharges to the river. However, in wet seasons, the baseflow indices decreased considerably due to the rainfall contribution. Additionally, the peak of baseflow happened in March 2018 (1.37%) as estimated by sliding interval method. This peak is proved by the apparent increase of Kimani River flow during the wet seasons.

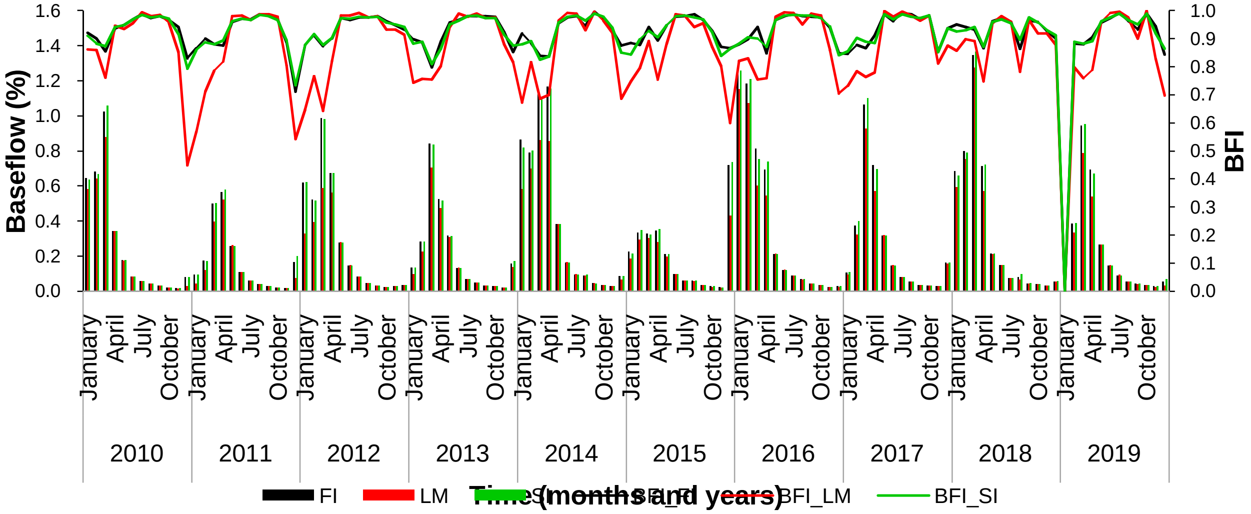

Figure 8: Baseflow separation techniques along with BFI for Kimani at GNR

3.1.5.Mbarali at Igawa

The relationship between groundwater discharge and river flow occurred during the whole period ranging from 2010 to 2019. Through wet and dry season, the baseflow contributions to the river are evident. Likewise, the baseflow indices increased in dry seasons and decreased in wet seasons as it appears in Figure 9, indicating the contribution of baseflow to the river flow. Among all the techniques, the sliding interval method appears to have the highest baseflow indices in wet seasons while being almost the same as for the fixed interval method during the dry seasons.

GRR at Salimwani, Chimala river, Kimani River and Mbarali river showed high values of flows in wet seasons but declined not significantly in dry seasons. The sliding interval method was found to have high baseflow indices (Table 7) compared to fixed interval and local minimum methods similarly to the results reported by Mohammadlou and Zeinivand (2019) and Helena (2016).

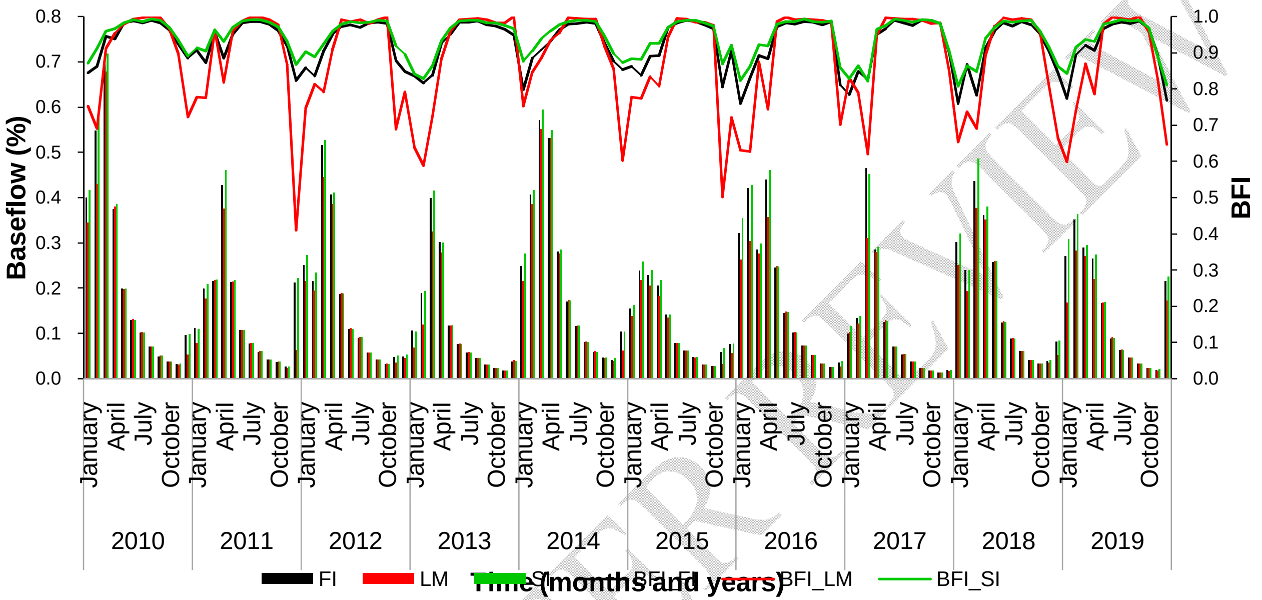

Figure 9: Baseflow separation techniques along with BFI for Mbarali river at Igawa

3.1.6.Ndembera at Ilongo

The groundwater discharge and Ndembera river flow interactions at Ilongo gauging station are remarkable all along the period and in all the seasons. In April 2014, the sliding interval method registered a high baseflow value (0.8%). But as it can be seen in Figure 10, there were significant decrease of baseflow during dry seasons, hence the low river discharges. Apart from 2014, groundwater discharges remained below 0.5% in wet seasons and less than 0.05% in dry seasons throughout the time range (Figure 10).

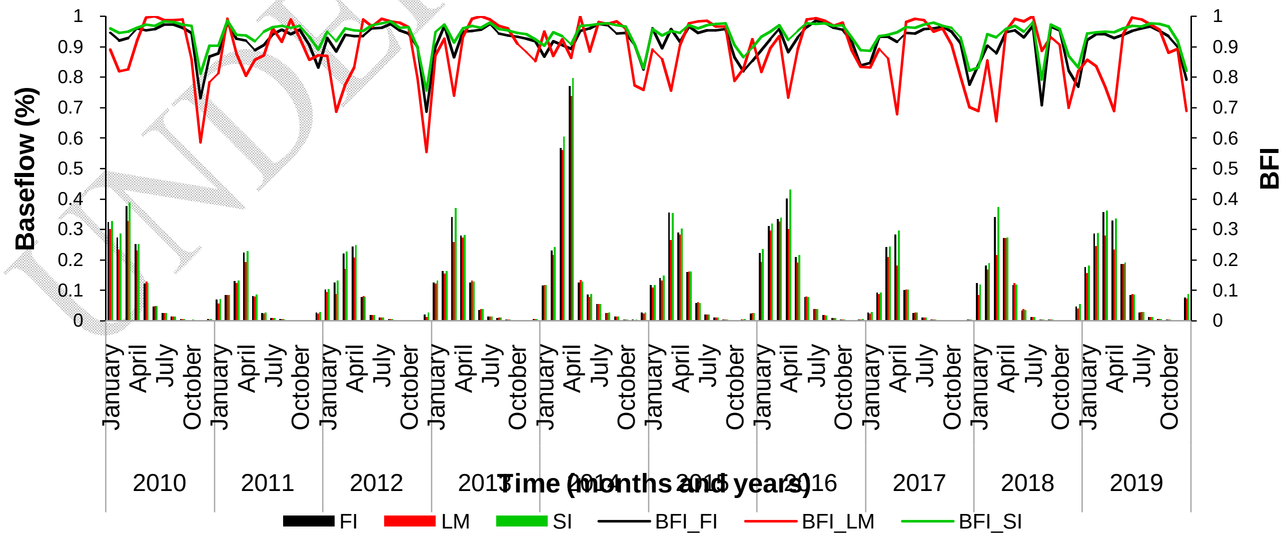

Figure 10: Baseflow separation techniques along with BFI for Ndembera at Ilongo

3.2. Assessment of temporal relationship between baseflow index and river flow

Table 6 shows the mean annual and seasonal (wet and dry) baseflow indices derived from the three hydrograph separation techniques used in this study for the six river gauging stations. The GRR at Msembe station registered the BFIs varying from 68% to 80% for the three techniques with the period ranging from 2010 to 2019. For the five remaining rivers (Chimala, GRR at Salimwani, Kimani, Mbarali and Ndembera), this study found the baseflow indices' contribution fluctuating from 80% to 98% as it appears in Table 6. As the Sliding Interval was found the method with high baseflow indices, it is considered in the BFI-River flow temporal relationship assessment and in the baseflow trends analysis. On the annual basis, Chimala river discharges are made of 96% of groundwater discharges, GRR at Msembe receives 75% of baseflow, GRR at Salimwani gets 95% of baseflow. Kimani river is recharged by 92% from groundwater discharges while Mbarali and Ndembera are having 94% of baseflow. Seasonally, the groundwater discharges to river flows decreases during the wet season compared to the increase of baseflow registered in the dry season. This does not apply to the GRR at Msembe, where the baseflow augmented trough the wet season (77%) but declined in the dry seasons (71%). The decrease of groundwater discharges to rivers in the wet season is obviously occasioned by the surface runoff and rainfall contributions to rivers. In summary, the majority of dry-season river flow originates from groundwater in the highlands and central plains, significantly contributing to the water balance of the perennial swamp of the Usangu Plains.

Table 4: Mean annual and seasonal baseflow indices for the six-river gauging stations

River	Period	FI	LM	SI
Chimala	Annual	0.96	0.94	0.96
	Wet	0.95	0.92	0.95
	Dry	0.98	0.97	0.98
Msembe	Annual	0.73	0.74	0.75
	Wet	0.76	0.68	0.77
	Dry	0.70	0.81	0.71
Salimwani	Annual	0.93	0.89	0.95
	Wet	0.90	0.83	0.92
	Dry	0.97	0.97	0.98
Kimani	Annual	0.92	0.87	0.92
	Wet	0.89	0.81	0.89
	Dry	0.96	0.94	0.96
Mbarali	Annual	0.93	0.88	0.94
	Wet	0.90	0.83	0.92
	Dry	0.96	0.96	0.97
Ndembera	Annual	0.92	0.89	0.94
	Wet	0.91	0.87	0.93
	Dry	0.93	0.92	0.95

3.3. Temporal BFI trend analysis

The Mann-Kendall (MK) test was used to analyze the statistically significant trends of the BFI of the six river gauging stations. The findings are illustrated in Table 7 where Z is the test statistic of MK test, T standing for trend category and -1 meaning non-significant decreasing trend, +1 signifies non-significant increasing trend and 0 indicates no trend at all (Table 7). In general, for all rivers' catchments, there are non-significant baseflow trends either increasing (+1) or decreasing (-1) according to the results of the MK test. This specifies that, though statistically non-significant, the groundwater discharges to rivers in the Usangu Plains is not stable.

For Chimala and Mbarali rivers, this study found the baseflow unhurriedly declining during all seasons. The groundwater discharges to GRR at Salimwani slowly increase annually, in dry and wet seasons. A non-significant baseflow increase is visible annually and in dry season to the GRR at Msembe while it decreases in wet season. The baseflow contribution to Kimani River tends to increase in the annual and wet season, though it decreases in dry season. Centrally, the groundwater discharges to Ndembera river tends to decrease in annual and wet season while it increases in dry season. Even though the baseflow trends are non-significant, the increasing trend shows the cumulative variation of groundwater discharges to rivers while the opposite applies to the decreasing baseflow trend.

The groundwater discharges to rivers (Chimala, Ndembera, Mbarali, Kimani and GRR at Salimwani) appeared very high in the dry season (Table 7) and low in wet season due the seasonal variations of rainfall (Figure 11) and surface runoff. The decline of baseflow to GRR at Msembe during dry season confirmed the literature stating that groundwater abstractions for irrigation, domestic use, brick-making are the major causes of low baseflow (Benedict, 2019; Kashaigili *et al.*, 2006). This study revealed that the rivers located in the highlands are more dependent on groundwater discharges than the GRR at Msembe which is in the lowlands (Table 1 and Figure 1). This is similar to the fact that the highlands are considered as recharge zones while lowlands are discharge zones (SMUWC, 2001).

Table 5: Results of MK statistical test for the BFI of six river gauging stations

River	**Period**	**FI**		**LM**		**SI**	
		Z	**T**	**Z**	**T**	**Z**	**T**
Chimala	Annual	-0.38	-1	-0.07	-1	-0.38	-1
	Wet	-0.24	-1	0.07	+1	-0.38	-1
	Dry	-0.24	-1	-0.38	-1	-0.32	-1
Msembe	Annual	0.11	+1	0.07	+1	0.07	+1
	Wet	-0.07	-1	0.07	+1	-0.11	-1
	Dry	0.29	+1	0.29	+1	0.25	+1
Salimwani	Annual	0.16	+1	0.07	+1	0.07	+1
	Wet	0.11	+1	0.02	+1	0.07	+1
	Dry	0.38	+1	0.33	+1	0.38	+1
Kimani	Annual	-0.02	-1	0.24	+1	0.02	+1
	Wet	0.16	+1	0.24	+1	0.16	+1
	Dry	-0.38	-1	-0.38	-1	-0.16	-1
Mbarali	Annual	-0.69	-1	-0.29	-1	-0.87	-1
	Wet	-0.73	-1	-0.29	-1	-0.69	-1
	Dry	-0.02	-1	-0.07	-1	-0.16	-1
Ndembera	Annual	-0.07	-1	-0.24	-1	-0.11	-1
	Wet	-0.29	-1	-0.29	-1	-0.38	-1
	Dry	0.11	+1	0.02	+1	0.11	+1

The statistical results of the Mann-Kendal test for the baseflow indices of the river flows are similar to the observed flows in the GRR at Msembe which indicated a non-significant trend in the annual flows (Kashaigili *et al.*, 2006). According to Kelly *et al.* (2019), lack of increasing or decreasing trend suggests that the groundwater discharges to rivers are stable and that the catchment might be enduring minimal human impacts. However, this study found that during annual, wet, and dry seasons there are increasing and decreasing trends in the baseflow though they are statistically non-significant. Increasing trends indicate a rising in groundwater table and are due to the increase in good land conservation, land cover, forestation, high amount of rainfall and less surface runoff while the opposite produces the decreasing trends in baseflow (Ahiablame *et al.*, 2017; Benedict, 2019, Salila et al., 2020).

4. Comparison of rainfall against river discharges of all gauging stations

The interaction between river discharges and rainfall in the wet and dry seasons is illustrated in Figure 11. As for Chimala at Chitekelo, Kimani at GNR and GRR at Salimwani, the discharges exceeded the amount of rainfall from May to September. This implies the interaction between the two rivers and the groundwater in their respective catchments. However, the GRR at Msembe seemed highly dependent on rainfall for the discharges variate accordingly in wet and dry seasons.

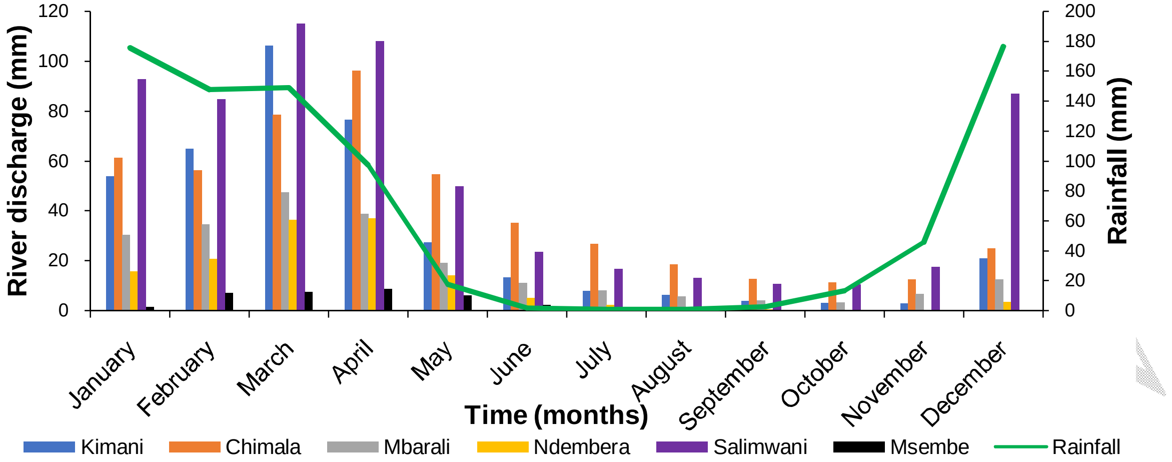

Figure 11: Mean-monthly relationship of rainfall and river discharges for 2010-2019

CONCLUSION

In conclusion, this Study used three different hydrograph separation techniques to estimate the contribution of groundwater discharges to the river flow at six different locations within the Usangu Plains. GRR at Msembe showed no flows during a number of days. To that, existing literature attributes the observed declines in river discharges to human activities such as irrigation, domestic water use and livestock management.The comprehensive understanding of groundwater discharges to rivers in the Usangu Plains is of immense capital in the management and utilization of the water resources. Except GRR at Msembe, the other five rivers manifested a great reliance on the baseflow with more than 90% of it in the river flows. This calls for the need of studies on how to conjunctively use the surface and groundwater in the Usangu Plains for enhancing the welfare of the water users. Land and water management strategies such as water allocation measures, sound water usage practices, and afforestation may be better approaches to counteract the declines of water flows in rivers of the Usangu Plains, specifically in the dry season. Moreover, placement of observation wells close to the river gauging stations could benefit in evaluating the seasonal variability of groundwater discharges to rivers. Also, future studies should use the methods which consider the evapotranspiration, hydraulic heads and groundwater abstraction information to quantify the groundwater-surface water interaction in the Usangu plains.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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