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Quantification of Temporal Variations in Base Flow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi

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Abstract: This study investigated how sporadic river datasets could be used to quantify temporal variations in the base flow index (BFI). The BFI represents the baseflow component of river flow which is often used as a proxy indicator for groundwater discharge to a river. The Bua catchment in Malawi was used as a case study, whereby the smoothed minima method was applied to river flow data from six gauges (ranging from 1953 to 2009) and the Mann-Kendall (MK) statistical test was used to identify trends in BFI. The results showed that baseflow plays an important role within the catchment. Average annual BFIs > 0.74 were found for gauges in the lower reaches of the catchment, in contrast to lower BFIs < 0.54 which were found for gauges in the higher reaches. Minimal difference between annual and wet season BFI was observed, however dry season BFI was >0.94 across all gauges indicating the importance of baseflow in maintaining any dry season flows. Long term trends were identified in the annual and wet season BFI, but no evidence of a trend was found in the dry season BFI. Sustainable management of the investigated catchment should, therefore, account for the temporal variations in baseflow, with special regard to water resources allocation within the region and consideration in future scheme appraisals aimed at developing water resources. Further, this demonstration of how to work with sporadic river data to investigate baseflow serves as an important example for other catchments faced with similar challenges.

Keywords: baseflow; base flow index; hydrograph; groundwater; Malawi

1. Introduction

Understanding temporal variations in baseflow are crucial for sustainable water resources management [1]. Baseflow is defined as the proportion of river flow derived from groundwater and other stored sources [2,3]. Other stored sources may include connected lakes, wetlands, melting snow, temporary storage in the banks of the river channel and slow-moving interflow [4]. Baseflow varies spatially and temporally influenced by several factors including geology, topography, climatic season and anthropogenic activities [5]. Baseflow can sustain river flows during prolonged periods of dry weather. Although dry season flows are significantly reduced and in some rivers approach zero flow, this water can be a vital life source for those who depend on it. Although globally pertinent, it is particularly crucial for semi-arid countries who experience long dry seasons each year [6]. Long term changes in baseflow can indicate unsustainable catchment management practices. Baseflow is thus a key consideration in many sustainable management approaches such as integrated water resources management (IWRM) and conjunctive water use. They are also a major focus of many worldwide initiatives including the United Nation Education Scientific and Cultural Organization (UNESCO) International Hydrological Programme [7]. Subsequently, it can be considered to underpin the United Nations Sustainable Development Goal (SDG) 6 'ensure availability and sustainable management of water and sanitation for all'.

There is a multitude of methods available to investigate baseflow which can be categorized into desk-based methods and field methods. Desk-based methods include hydrograph analysis (baseflow separation [8], frequency analysis [9] and recession analysis [10]), hydrogeological mapping [11], modelling [12] and mass balance [13]). Field methods, as described in Turner [14] include temperature profiling, seepage flux measurement, seepage meters, environmental tracers, artificial tracers, geophysics, remote sensing and ecological indicators. In some countries, however, investigation methods are limited to hydrograph analysis, specifically baseflow separation, which utilizes existing river flow data and provides estimates of baseflow without the need for complex modelling, detailed knowledge of soil characteristics or costly site investigations [15]. Such countries are usually those who experience long dry seasons each year and where baseflow knowledge is perhaps most pertinent. These are also countries often challenged by limited technical knowledge, lack of financial resources and experienced hydrological and hydrogeological staff.

Base flow index (BFI) is an important baseflow characteristic [16]. Originally developed as a parameter to index catchment geology and the ability of a catchment to store and release water, BFI is a numerical representation of the baseflow component of river flow [2]. BFI is calculated as the ratio of the flow under the baseflow hydrograph (the baseflow volume) to the flow under the river hydrograph (total flow volume) as presented in Equation (1) [17]. BFI is applied in hydrology and hydrogeology where it is used as a catchment descriptor in low flow studies [6], a groundwater availability indicator [18], and as a key engineering parameter for environmental flow requirements (EFR), which set a minimum flow required in a river to sustain its ecological health [19]. BFI is a popular means of providing a proxy indicator of groundwater discharge from the aquifer. [4,17,20]. A relative measure with no units, BFI ranges from near 0.0 to 1.0. A BFI close to 0.0 means a river has a low proportion of baseflow, an example would be a flashy river with relatively impermeable geology and little groundwater. A BFI close to 1.0 has a high proportion of baseflow, an example would be a stable river with relatively permeable geology and a lot of groundwater. [6,21]. In periods of dry weather, river flows can be significantly reduced, however, rivers with high BFI indicate that groundwater inflow is sustaining these reduced flows. Many countries and academics are now recognizing the importance of quantifying BFI including a global assessment based on over 3000 catchments worldwide [16], a national scale assessment in New Zealand [22], regional studies such as the Loss Plateau, China [23] and an experimental watershed in the Gulf Atlantic Coastal Plain, USA [4].

Equation (1) base flow index equation:

$$\text{Base Flow Index (BFI)} = \frac{\text{Baseflow volume}}{\text{Total flow volume}} \tag{1}$$

Baseflow is particularly important in Malawi, a semi-arid country known as the warm heart of Africa (Figure 1a). Malawi is rich in both groundwater and surface water resources in comparison to other African countries, however, these are unevenly distributed in time and space. Malawi experiences a distinct dry season each year with minimal to no rainfall. Many rivers still have some flow in the dry season, and it is presumed that they are sustained by baseflow from the region's superficial aquifers. However, anthropogenic activities such as over-abstraction of groundwater and deforestation are threatening flows in Malawi by negatively impacting baseflows. For example, sustained over-abstraction of groundwater can draw down the water table and result in reduced groundwater discharge to any connected rivers. Similarly, deforestation increases overland flows and leaves less water for infiltration and groundwater recharge. This can ultimately lead to reduced water available for groundwater discharge to connected rivers. Although, deforestation is widely reported in Malawi [9,24], there are no published studies confirming the over-abstraction of groundwater. The Ministry of Agriculture, Irrigation and Water Development has reported, based on internal assessments, a decline in groundwater levels and river flows which have resulted in the drying up of major rivers [25].

To date, few studies have been published which investigate baseflow and quantify BFI in Malawi. Preliminary work done by the South Africa FRIEND (flow regimes from international experimental and network data) programme produced an annual BFI map for South Africa which included Malawi however, the project has been inactive for a long time and the data that were collected are largely out of date [15]. More recently, a global BFI study reports estimates of annual BFI for Malawi [16] and the International Water Management Institute's tool; the Global Environmental Flow Information System also includes Malawi and provides estimates of annual baseflow [26]. Studies which are more site-specific, reporting annual BFI include Kumambala [27] who examined four stations along the Shire River in Southern Malawi and Ngongondo [18] who examined the Mulunguzi catchment. Only a few studies identify long term trends in baseflow; Ngongondo [18] identifies a trend in baseflow in the Mulungzui river showing a decline of approximately 50% from 1954 to 1998. In contrast, Kambombe et al. [28] identify an increase in baseflow in the Mulungzui catchment between 1970 and 1999. Kambombe et al. [28] also found a significant decreasing trend in baseflow of the Domasi, Likangala and Thondwe catchments during that period [28]. Further, baseflow is currently evaluated by the Surface Water Division of the Ministry of Agriculture, Irrigation and Water Development (MoAIWD) in Malawi, through use of their time series data management system 'HYDSTRA', however, focus appears to be mainly on annual baseflows. All these studies address BFI to a limited spatial and temporal coverage of flow data, with a focus on annual baseflow values. A gap in the research, therefore, exists to quantify seasonal and long-term trends in BFI for gauged catchments in Malawi.

This task is challenged by the lack of current data as river flow monitoring coverage has declined in Malawi since around 2010 and indeed is representative of sub-Saharan Africa [29]. Further, the data which is available is sporadic in nature, characterized by missing values.

This study demonstrates how to work with sporadic river flow data, using baseflow separation, to produce meaningful estimations on temporal variations in baseflow. We demonstrate this by using the Bua Catchment in Malawi as a case study, whereby the river data is considered representative of the wider Malawi. The objectives of this research were to (1) quantify the annual BFI; (2) quantify the seasonal BFI and (3) identify trends in the BFI. The results will provide important new insights on the behavior of baseflow in the catchment. It will also serve as an example to other catchments challenged by sporadic river data.

This study forms part of on-going research on baseflow in Malawi and has important implications for the sustainable management of water resources in the country. It offers support to the Government of Malawi in their journey towards SDG6 and as such, the research was conducted in a manner that will permit the exchange of knowledge with the water sector.

In Section 2 below, the study area is described in addition to the data and analysis methods. Specifically, the decision procedure for selection of the baseflow separation method and the implementation tool is described and the baseflow separation steps followed are provided. The results and discussion are discussed in Section 3, while the conclusions are summarized in Section 4.

2. Materials and Methods

2.1. Study Area

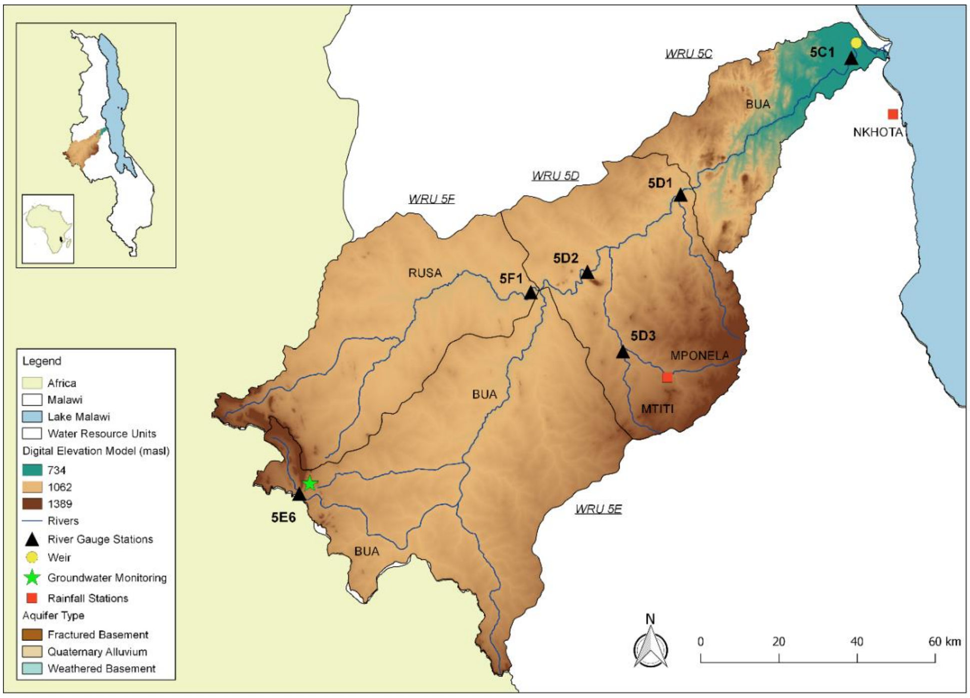
The Bua river originates on the western border of Malawi and flows in a northeasterly direction through Central Malawi to its outflow into Lake Malawi (Figure 1a). The Bua is joined by five major tributaries (Mphelele, Kasangadzi, Rusa, Ludzi and Namitete) and has numerous minor tributaries. It has a catchment area of 10,658 km^2 which is approximately 186 km in length and its width varies from approximately 87 km in the west to approximately 16 km is the east.

The catchment comprises three distinct hydrological zones; the flat plateau, steep slopes on the highland which rise from the plateau and the rift valley escarpment, and the lakeshore plain [30]. The plateau is generally at 1000–1100 m above sea level (masl). Towards the southwest are the Mchinji mountains which rise to over 1750 masl. Towards the west, where the river meets the lakeshore plain, the catchment drops rapidly through a series of steep slopes. High levels of sedimentation occur at the lakeshore plain as the gradient becomes gentle.

The Bua catchment is assigned Water Resource Area (WRA) 5 within the National Water Resources Master Plan (NWRMP) of Malawi [31]. WRA 5 is subdivided into four water resource units (WRUs) named 5C, 5D, 5E and 5F (Figure 1a). Both WRAs and WRUs are based on river basin boundaries. WRA 5 lies within the administrative districts of Mchinji, Kasungu, Nkhotakota, Lilongwe, Dowa and Ntchisi.

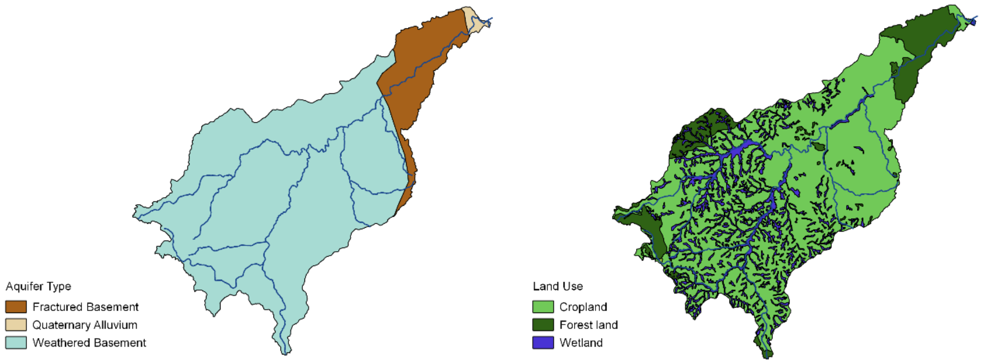
Land use in WRA 5, as shown in Figure 1c, mainly comprises cropland; arable agriculture of mainly maize crops and tobacco, and forest land; including Mchinji Forest Reserve and Kasungu National Park to the west, and Nkhotakota Game Reserve to the far east [32]. Wetlands or dambos are also scattered throughout the catchment. These wetlands become saturated in the wet season and provide a good source of water in the dry season [33]. The dambos are generally considered to drain the plateau area [30].

The climate of WRA 5 can be generally represented as sub-tropical [31]. The climate is divided into three weather variations; the warm wet season (1 November–30 April); the cool dry season (1 May–31 August); and the hot dry season (1 September–31 October), however, it's generally accepted to be bimodal referring to the wet season and the dry season [31]. Over 95% of the annual rainfall falls in the warm wet season or rainy season. The exact length of the wet season varies depending on the location within Malawi, reported to end in March in the south of the country, and April/May in the north [34]. No average annual rainfall or temperature values were available for the wet and dry season. The average annual rainfall for WRA 5 is 897 mm, with a range of 800–1000 mm [33]. The average annual temperature in WRA 5 ranges from 20 to 24 °C [33].



(**a**)

Figure 1. *Cont.*



(**b**) (**c**)

Figure 1. (**a**) Location of Malawi in Africa (insert), location of the Bua catchment in Malawi (insert) and digital elevation model of the Bua catchment (WRA 5) with rivers, river gauges, weir, rainfall stations and groundwater monitoring; (**b**) aquifer type map [35]; (**c**) land use map [32].

Malawi's groundwater occurrence is classified into three hydrogeological domains or aquifer types; (1) alluvial aquifers, (2) sedimentary aquifers and (3) basement aquifers. The sedimentary aquifers are subdivided into semi consolidated and consolidated aquifers, and the basement is subdivided into weathered and fractured aquifers [31]. Figure 1b shows the aquifer types in WRA 5. The basement aquifer considered one of Malawi's major aquifers underlays most of the Bua catchment [35]. In the west, the weathered basement is present over most of the plateau area and fractured basement occurs in the area of the Mchinji Forest Reserve. In the east lakeshore plain, the basement is overlain by the other major aquifer type, the alluvium aquifer with some pockets of the fractured basement also present [35]. There has been little published work on the hydrogeology and soils of the Bua catchment, however, a bulletin from 1983 presents details of the soil's patterns and the hydrogeological conditions of the weathered basement aquifer of a plateau area [30].

2.2. Data

This study focused on data from six river gauges within the Bua catchment (Table 1). Other gauges do exist, however, there was no data available for them. Four gauges monitor the main Bua river (5C1, 5D1, 5D2 and 5E6) which is a regulated river with a weir located downstream of gauge 5C1. Photos of the weir taken January 2019 and are provided in the Supplementary Material, Figure S1. The Rusa river, a major tributary of the Bua, is monitored by a fifth gauge, 5F1, and the Mtiti river (a tributary to the Kasangadzi river) is monitored by the final gauge, 5D3. Daily flow rate data were available for each gauge as follows; 5C1 (1957–2009), 5D1 (1958–2007), 5D2 (1953–2007), 5D3 (1958–2003), 5E6 (1970–2008) and 5F1 (1964–2005). Data coverage appears substantial ranging from 38–52 years, however, it is expected to have missing values throughout. Data were obtained from the Surface Water Division of the Department of Water Resources of Malawi.

Where possible, rainfall and groundwater data in the vicinity of the river gauges were also examined to provide support for the BFI analysis. Daily rainfall data for Nkhota station (18 km away from gauge 5C1 in a southeasterly direction) and Mponela station (13 km away from 5D3 in a southwesterly direction) were used. Stations are managed by the Department of Meteorological Services who provided the data. The rainfall data is of very good coverage with minimal missing values. Groundwater levels are monitored in WRA 5 via four monitoring boreholes, constructed around 2009/2010. The boreholes are managed by the Groundwater Division of the Department of Water Resources who provided the data. Only one of the monitoring boreholes, at Mchinji Water Office (GN196), had enough data coverage (2009–2013) to examine.

Table 1. Evaluation of baseflow separation tools against required criteria.

Require Criteria/Baseflow Separation Tools	Flow Screen R	FORTRAN BFI	SWAT	WEST Pro	BFlow	HYSEP	HydroClimATe	SAAS	RAP	WHAT	BFI+ 3.0	BFI Programme
Automated	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Easily accessible	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y
Free to obtain and operate	Y	-	Y	-	-	Y	Y	Y	Y	Y	Y	Y
Requires minimal training to use	N	-	N	-	-	N	N	Y	N	Y	Y	Y
Can select seasonal periods	-	-	N	-	-	-	-	Y	Y	N	N	Y

Where: Y = yes; N = No.

2.3. Decision Procedure for Selection of Baseflow Separation Method and Implementation Tool

Baseflow separation was selected to analyze the river data and determine BFI. Baseflow separation is categorized into graphical methods which are performed manually, and filtering methods which are automatically performed by a computer. [36]. There are a wide variety of filtering methods available, and a significant number of computer programs to implement the chosen method [37]. Although there is subjectivity involved in selecting an appropriate filtering method and an associated tool to implement it, merit holds in use of any of them as long as the use is consistent throughout the study [6,15,37]. The decision to select a filtering method and implementation tool is generally based on the criteria required for the study.

In this study, the selection of an appropriate implementation tool took precedence over the selection of a filtering method. The tool was required to meet certain criteria to allow the exchange of knowledge with the Government of Malawi. The tool needed to be automated, easily accessible, free to obtain and operate, require minimal training to use and capable of selecting seasonal periods from input data to quantify BFI. Several tools were evaluated against the required criteria including Flow Screen package for R [38], Formula Translation (FORTRAN) BFI program [39], Soil and Water Assessment Tool (SWAT) [40], Water Engineering Time Series PROcessing Tool (WEST PRO) [41], web-based BFlow [42], HYSEP [43], HydroClimATe: hydrologic and climate analysis toolkit [44], Streamflow Analysis and Assessment Software (SAAS) [45], River Analysis Package (RAP) [46], Web-based Hydrograph Analysis Tool (WHAT) [47], BFI + 3.0 of Hydro Office [48] and the BFI programme [6]. The evaluation assessment is presented in Table 1. Although both the BFI programme and SAAS met all of the criteria, the BFI programme was selected for analysis in this study.

The BFI programme is an excel based tool developed by Martin Morawietz at the Department of Geosciences in the University of Oslo, Norway. It was originally prepared for the textbook; Hydrological Drought-Processes and Estimation Methods for Streamflow and Groundwater [6]. It is free to download on the European Drought Centre website http://europeandroughtcentre.com/. The textbook provides working examples of how to use the tool. The tool implements the filtering method called the 'smoothed minima procedure' [21]. It uses smoothing and separation techniques to process a river hydrograph. Daily river flow data is partitioned into 5-day increments and the minimum flow in each period is identified [49]. Turing points are identified in the series of minimum flows and connected to draw the baseflow hydrograph. The precise details of the procedure are provided in the Low Flow Studies Report No 3 by the Institute of Hydrology [21] and by Wahl [39].

2.4. Baseflow Separation Steps

The raw river data were screened prior to baseflow separation to identify the periods of missing data. Before proceeding to analysis, there were two options available to deal with the missing data; (1) infill the missing data or (2) ignore the missing data and analyze only the raw data. Although there are merits to infilling data [50,51], most studies agree with the recommendation by Ladson et al. [52] that BFI should be determined from raw data only [20,23,53,54]. As such, this study did not infill data and analyzed the raw river flow data only. To do this, the flow data were prepared by dividing into periods of non-missing values [52].

The assessment periods selected were annual and seasonal periods defined by months. The annual period was taken as the hydrological year in Malawi as used by the Government of Malawi Water Resources Department and coincides with the start of the wet season and runs to the end of the dry season (1 November–31 October). The seasonal periods selected were the wet season defined as 1 November–30 April, and the dry season defined as 1 May–31 October. These periods are based on the weather variations recognized in Malawi and used in water resources assessments by the Water Resources Department [55] and the country's national irrigation master plan and investment framework [56].

The following steps were taken to perform the baseflow separation using the BFI programme:

(1) The baseflow separation was performed for each year of river data (1957–2009) producing a separate annual BFI value for each year where there was enough data in the period. It is commonly recommended in the literature to determine the long-term BFI which uses all the data successively [6,15], however here, it was not possible due to missing data. The mean annual BFI was therefore determined based on the individual years;
(2) The baseflow separation was performed for each season of data (1957–2009) in the same manner as the annual period described above;
(3) The total flow, baseflow and surface runoff flow from each baseflow separation were summed for each period;
(4) Descriptive statistics (average, maximum and minimum, standard deviation and coefficient of variation) were determined for the annual and seasonal periods.

2.5. Statistical Trend Analysis

The non-parametric Mann-Kendall (MK) statistical test [57,58] was used to identify if the BFI results had statistically significant increasing or decreasing trends. The test is prominently used in hydrology studies. For example, it is popular when identifying trends in streamflow [50,59–61], baseflow [50], BFI [4,62,63] and the vertical exchange fluxes between streambeds and connected aquifers [64]. It is also widely applied in identifying trends in rainfall [59,60]. Application of non-parametric testing is appropriate due to hydrological data not being normally distributed [61]. One of the main advantages of the MK test is that it is insensitive to missing data, which was a key challenge with the data in this study.

The hypothesis for the test, H0, was defined as 'there is no trend in the data', and the alternative hypothesis, Ha, was defined as 'there is a trend in the data'. If the p-value calculated was lower than the significance level, the H0 was rejected and the alternative Ha accepted, and a trend was indicated. If the p-value was greater than the significance level, no trend was indicated. The significance level is referred to as a Type 1 error and is the probability of rejecting the null hypothesis when it is true [61]. The direction of the trend was indicated by the test statistic, S, where a negative S value indicates a declining trend and a positive S value indicates an increasing trend. Details of the MK equations can be found in the literature [58].

The selection of the test parameters is important in statistical testing as they have a direct impact on the resulting trend. In this study, the following parameters were selected for the MK test; the 'exact p' method was used, the significance level was set to 0.01 (or 1%) and the equations were set to ignore missing data. Further, the 'normal' MK test was selected over the 'seasonal' MK test. Due to the decision not to infill data in this study, the BFI data was partitioned into annual and seasonal periods and as such the normal MK was applicable. If the data had been infilled, and there was no need to partition the data, the use of the seasonal MK test would have allowed comparison of the seasonal periods. The statistical programme XLSTAT, available at www.xlstat.com was used to perform the MK test [65].

3. Results and Discussion

3.1. Annual and Seasonal BFI Analysis Coverage

Annual and seasonal BFI was calculated for gauges 5C1, 5D1, 5D2, 5D3, 5E6 and 5F1. The results of the analysis for 5C1 are presented in Table 2 and the results of the other gauges are presented in Tables S1–S5.

Table 2. Results of the annual and seasonal BFI (base flow index) analysis (tabular) for the Bua River, gauge station 5C1, 1957–2009 (52 years).

Period	Annual BFI	Wet Season BFI	Dry Season BFI	Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.94	1983/1984	-	-	-
1958/1959	0.66	0.65	0.85	1984/1985	-	-	-
1959/1960	0.53	0.48	0.96	1985/1986	-	0.80	-
1960/1961	-	0.44	-	1986/1987	0.81	0.80	0.99
1961/1962	0.83	0.81	0.91	1987/1988	0.62	0.58	0.95
1962/1963	-	-	0.99	1988/1989	-	-	-
1963/1964	0.77	0.75	0.98	1989/1990	0.77	0.75	0.92
1964/1965	0.79	0.77	0.96	1990/1991	0.76	0.74	0.97
1965/1966	-	0.69	-	1991/1992	0.43	0.41	0.87
1966/1967	0.48	0.40	0.94	1992/1993	-	0.50	-
1967/1968	0.58	0.54	0.83	1993/1994	-	-	0.95
1968/1969	-	-	0.81	1994/1995	0.60	0.60	0.91
1969/1970	-	-	-	1995/1996	0.54	0.53	0.84
1970/1971	-	-	-	1996/1997	0.76	0.75	0.89
1971/1972	-	0.64	-	1997/1998	0.90	0.90	0.87
1972/1973	-	0.47	-	1998/1999	0.76	0.74	0.92
1973/1974	0.68	0.62	0.94	1999/2000	0.75	0.73	0.87
1974/1975	0.72	0.72	0.99	2000/2001	-	-	0.95
1975/1976	0.69	0.61	0.95	2001/2002	0.94	0.88	0.98
1976/1977	0.81	0.77	0.99	2002/2003	-	0.85	-
1977/1978	-	-	0.91	2003/2004	-	-	0.99
1978/1979	0.80	0.76	0.99	2004/2005	0.84	0.82	0.92
1979/1980	-	0.65	-	2005/2006	0.90	0.82	0.98
1980/1981	0.75	0.71	0.99	2006/2007	0.87	0.81	0.96
1981/1982	-	-	-	2007/2008	0.92	0.87	0.99
1982/1983	-	0.64	-	2008/2009	0.88	0.81	0.99

- denotes no BFI determined due to insufficient data in that period.

As expected, the river data was characterized by missing values and this was seen across all datasets. This meant it was not possible to determine a BFI for all periods. To quantify the coverage of analysis, the number of periods for which a BFI was determined was counted and converted to a percentage based on the number of years of data (Table 3). For example, for 5C1, a BFI was determined for 30 full annual data periods, 39 wet seasons, and 37 dry seasons which equates to 58%, 75% and 71 % coverage for the respective periods. Data for each gauge ranged from 38 to 52 years and the percentage of coverage for each period (annual, wet and dry season) was consistently over 50%, with some periods as high as 80% coverage (Table 3). The results show, despite the sporadic nature of river flow data in Malawi, that such datasets can be analyzed to extract observations on baseflow. This is an important finding for Malawi and countries which hold similar datasets. They can begin to utilize such datasets and assess baseflow using minimal labor and financial resources.

Table 3. Percentage of data coverage in annual and seasonal BFI analysis for the gauges in WRA 5.

Gauge ID	River Name	Period of Data Coverage	No of Years of Available Data; No of Annual, Wet Season, Dry Season Periods with Data	Annual	Wet Season	Dry Season
5C1	Bua	1957–2009	52; 30, 39, 37	58%	75%	71%
5D1	Bua	1958–2007	49; 25, 29, 31	51%	59%	63%
5D2	Bua	1953–2005	52; 34, 42, 35	65%	81%	67%
5D3	Mtiti	1958–2003	45;27, 30, 36	60%	67%	80%
5E6	Bua	1970–2008	38; 23, 27, 26	61%	61%	68%
5F1	Rusa	1964–2005	41; 24, 28, 27	59%	68%	66%

3.2. Average Annual BFI

Average annual BFI for the gauges were determined based on the BFI analysis results in Section 3.1. The results are presented in Figure 2 and Table 4.

Traditionally BFI has been determined on an annual basis. This study found high average annual BFIs for the gauges located on the lower elevation reaches of the Bua; 0.74 for 5C1, 0.75 for 5D1 and 0.76 for 5D2. This indicates that the river has a moderately high baseflow component of approximately 74–76% of the total annual river flow in the lower catchment. This finding is consistent with the annual BFI of 0.71 for 5C1 and 0.86 for 5D1 sourced from the HYDSTRA system in use by the Malawi Surface Water Division [33]. It also matches BFIs reported by Smith-Carington [30] of 0.85 (5D1) and 0.86 (5D2). Previous studies by UNESCO [15] and Beck et al. [16] reported similar annual BFI for Malawi in the range of 0.6 to 0.7 and 0.6 to 0.8 respectively. A moderately high baseflow was also found for 5F1 on the Rusa with a BFI of 0.80, or 80% of the total annual river flow which compares with a BFI of 0.81 from HYDSTRA.

In contrast, lower BFI values were found for the gauges located at higher elevations in the catchment. A BFI of 0.54 was found for 5E6, the highest gauged reach of the Bua. This doesn't match the BFI of 0.74 found from HYDSTRA. Finally, 5D3 on the Mtiti found a BFI of 0.48. There was no BFI available from HYDSTRA. Comparisons are provided for context only, it is important to bear in mind, that it's not generally recommended to compare BFIs across studies as different baseflow separation techniques and different data lengths will produce different baseflow volumes and this will affect the BFI [52]. Based on this study's annual average values, the Bua, the Rusa and the Mtiti rivers are considered perennial in nature with a stable flow regime.

3.3. Average Seasonal BFI (Wet and Dry Season)

Recent studies in BFI have sought to make seasonal adjustments, appreciating the variations that occur in baseflow both temporally and spatially and that annual BFI may not represent the true picture [66]. This study presents the first findings on seasonal BFI in the Bua catchment. Average seasonal BFI for the gauges was determined based on the BFI analysis results in Section 3.1. The results are presented in Figure 2 and Table 4.

For all gauges assessed, the results found minimal difference between the annual and the wet season BFI, however, in the dry season, all BFIs increased to over 0.80 (or 80% of the dry season flow was attributed to baseflow) as shown in Figure 2 and Table 4. For example, 5C1 had a BFI of 0.69 in the wet season increasing to 0.94 in the dry season. The increase in dry season BFI is indicative of the catchment geology. As mentioned in the literature, a high BFI indicates permeable catchment conditions whereby the catchment is storing water during the wet season and discharging it to the river during the dry season [6,17]. To support these BFI findings, it would have proved useful to compare river levels to groundwater levels near each gauging station. Unfortunately, however, of the groundwater data available there was none suitable for such a comparison.

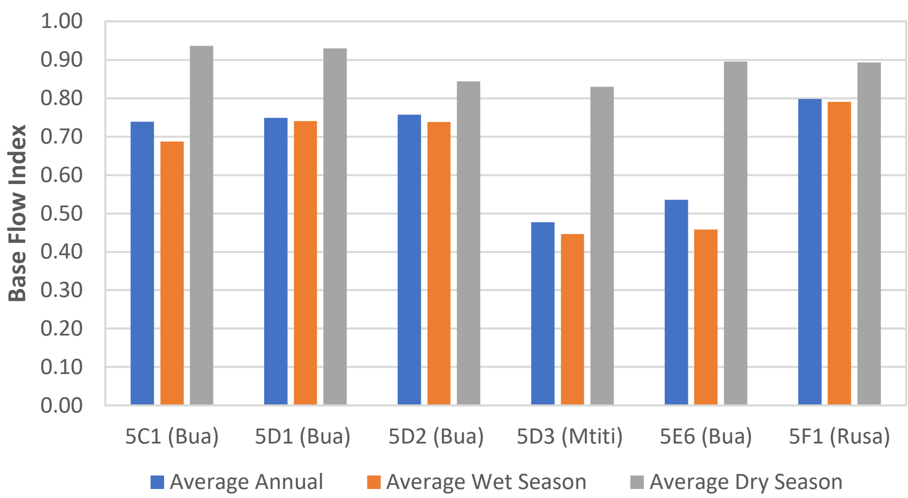


Figure 2. Results of annual and seasonal BFI analysis for the gauges in WRA 5 (graphical).

Table 4. Results of annual and seasonal BFI analysis for the gauges in WRA 5 (tabular).

Gauge ID (River)	5C1 (Bua)	5D1 (Bua)	5D2 (Bua)	5D3 (Mtiti)	5E6 (Bua)	5F1 (Rusa)
Data record	1957–2009	1958–2007	1953–2005	1958–2003	1970–2008	1964–2005
ANNUAL						
Average BFI	0.74	0.75	0.76	0.48	0.54	0.80
Minimum Average BFI	0.43	0.43	0.11	0.05	0.37	0.26
Maximum Average BFI	0.94	0.94	0.98	0.84	0.70	0.98
Standard Deviation	0.13	0.17	0.24	0.28	0.09	0.18
WET SEASON						
Average BFI	0.69	0.74	0.74	0.45	0.46	0.46
Minimum Average BFI	0.40	0.41	0.11	0.05	0.25	0.25
Maximum Average BFI	0.90	0.93	0.98	0.77	0.90	0.90
Standard Deviation	0.14	0.17	0.22	0.26	0.13	0.13
DRY SEASON						
Average BFI	0.94	0.93	0.84	0.83	0.90	0.89
Minimum Average BFI	0.83	0.55	0.55	0.00	0.47	0.61
Maximum Average BFI	0.99	1.00	1.00	1.00	0.98	1.00
Standard Deviation	0.05	0.11	0.11	0.23	0.12	0.10

Interestingly, from the wet season BFI results (Figure 2), there are two gauges which don't follow the high BFI seen in the other gauges; the 5D3 (Mtiti) and the 5E6 (Bua). The lower wet season BFI of these gauges can be attributed to the spatial variations in geology and topography which control baseflow. For example, both gauges are located at elevations of 1200masl, compared to the much lower elevations of 550–1000 masl for the other gauges. 5E6 is located on the headwaters of the Bua and drains the entirety of the Mchinji Forest Reserve (Figure S3) and 5D3 drains part of the Dowa Hills (Figure S4).

There is considerable variability seen across all gauges in the BFI within the annual and wet season periods shown by the minimum and maximum BFIs (Table 4). The coefficient of variation (CV) of the dry season BFI was low, compared to the annual and wet season BFI which was, as expected, much larger. For example, at gauge 5C1, the dry season CV was 6%, compared to the annual CV of 18%, and the wet season of 20%. This difference in variability highlights the varying behavior of baseflow. As mentioned in the literature, BFI is used in hydrology and hydrogeology in a range of applications [6,18,19]. Where there are variations between annual and seasonal values, as seen in these results, it is important to use the appropriate value as the use of an incorrect BFI could lead to inaccurate assessments. Several future scheme appraisals in Malawi would benefit from considering the seasonal BFI results of this study. For example, previous assessments for new investments in Malawi's water sector, which have taken account of EFRs and thus BFI values. The Water Resources Investment Strategy (WRIS) project, under the National Water development Program (NWDP), produced water resource assessments for the 17 WRAs in Malawi, including WRA 5 [33]. The project produced estimates for potential abstractable groundwater and sustainable surface water yield. Further, the National Irrigation Master Plan and Investment Framework (2014–2035), which sets out new investments for expansion of the irrigation sector in Malawi, is also centered around EFR, with one new dam proposed in the lower Bua catchment. It is presumed that these estimations have used annual BFI values which may lead to overestimation of available water resources. Seasonal variations are evidenced in this study and should be considered.

3.3.1. River Flow, Rainfall and Groundwater Patterns

Examining rainfall, river and groundwater patterns support the variation in wet and dry season BFI found above. For example, river flow and rainfall patterns for gauge 5C1 are shown in Figure 3. The baseflow separation divided the daily river flow into its daily baseflow and daily surface runoff components for each annual and seasonal period. Average monthly values for each flow component were determined for the years with no missing data; 30 in total. Figure 3 shows the average monthly flow volumes for the Bua and the average monthly rainfall volumes for Nkhota station. The observed river flow and rainfall patterns highlight the distinct wet and dry season pattern recognized in Malawi.

Rainfall is high during the wet season (November–April) and in response the total river flow volume and the direct runoff increases. The baseflow also increases but to a much lesser extent. River flows start to decrease after the peak river discharge in March. During the dry season (May–October), rainfall and direct runoff are reduced to a minimum. However, the baseflow remains relatively stable and sustains the river. The ratio of baseflow to total river flow is much higher in the dry season than in the wet season, thus resulting in a higher BFI. This pattern is considered generally representative of the other gauges in the catchment.

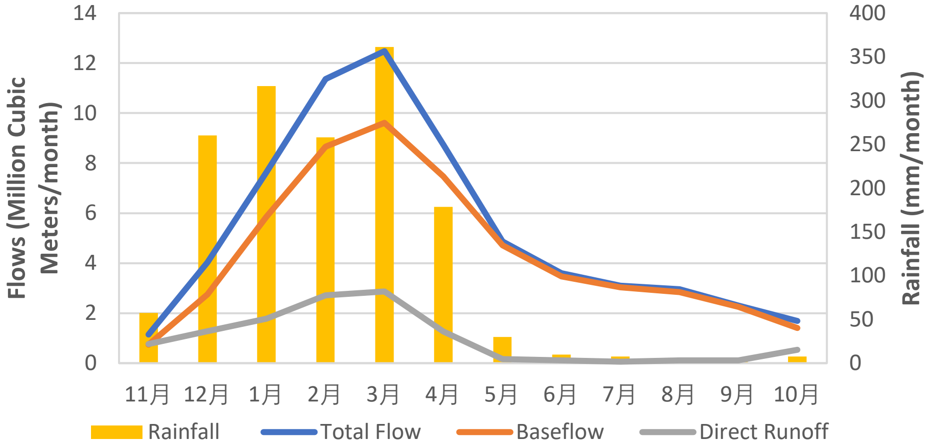


Figure 3. Average monthly flow volumes (total flow, baseflow, direct runoff), for the Bua River, Gauge 5C1, 1957–2009. Rainfall data for Nkhota station, 1960–2009.

There was not enough groundwater monitoring data available in the vicinity of gauge 5C1 for analysis. However, groundwater monitoring data at Mchinji Water Office (2009–2013), located 2 km from gauge 5E6 and at the same topographical elevation did have enough data. The data shows seasonal fluctuations in groundwater levels in line with the rainfall and river patterns above (Figure 4).

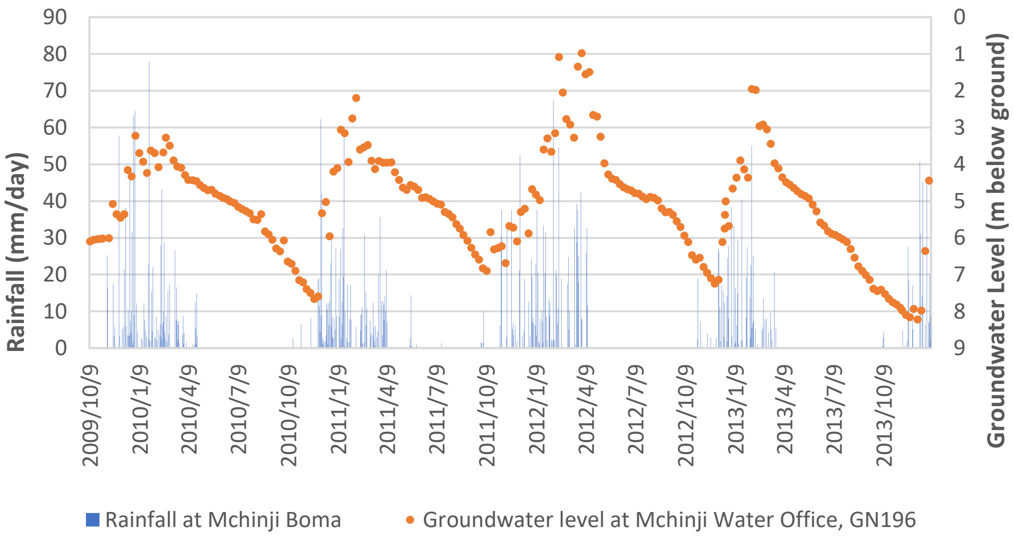


Figure 4. Daily rainfall (at Mchinji Boma) and sporadic groundwater levels (at Mchinji Water Office, GN196), located 2 km from the Bua River, Gauge 5E6, 2009–2013.

3.3.2. Comments on the Source of Baseflow

The baseflow separation approach used in this study assumes that baseflow is derived entirely from groundwater discharge from the aquifer, however, other stored sources can also contribute. The true source of baseflow is impossible to distinguish from baseflow separations alone and would require detailed site investigations to map each flow path [2]. It may be useful to provide some comments on the expected source of baseflow.

Based on the presence of aquifers identified through the literature and geological maps, we conceptualize that groundwater discharge from the local aquifers is the main contributor to baseflow during the wet and dry seasons. For example, an alluvium aquifer is present in the downstream reach of the Bua (5C1) and fractured basement dominates the entire upper catchment of the Bua (5E6) presenting good conditions for water to discharge to the river. Weathered basement aquifers underlay much of the middle reaches (5D1 and 5D2) and may contain pockets of perched aquifers. Further, interflow is expected to contribute to baseflow across all gauges during the wet season, though will not be a major source in the dry season. Finally, Dambos will also contribute to baseflow during the wet season and at the beginning of the dry season. Water is temporarily stored in the dambos and released slowly at the beginning of the dry season whereby it discharges to the river. Once the dambos have drained, the baseflow is maintained entirely from groundwater from the aquifers [30]. Dambos are present in much of the plateau area and the Rusa catchment (5F1) and have been previously identified as contributing to baseflow in the middle reaches of the Bua (5D1 and 5D2) [30].

3.4. Long Term Behavioral Changes in BFI—Statistical Trend Results

Detecting trends in BFI can help us understand the possible links between hydrological processes, anthropogenic activities and environmental changes. The MK test was used to identify increasing or decreasing statistically significant trends in the BFI results obtained in Section 3.1. The MK results are presented in Table 5. This study presents the first findings on detecting trends in BFI in the Bua catchment.

Table 5. Mann Kendall statistical results for BFI for gauges in WRA 5.

Gauge ID (River) Data record	5C1 (Bua) 1957–2009	5D1 (Bua) 1958–2007	5D2 (Bua) 1953–2005	5D3 (Mtiti) 1958–2003	5E6 (Bua) 1970–2008	5F1 (Rusa) 1964–2005
ANNUAL						
MK Statistic 'S'	151	−166	−107	125	−90	−29
Trend (1% sig. level)	Increasing	Decreasing	No trend	Increasing	No trend	No trend
WET SEASON						
MK Statistic 'S'	241	−214	−188	161	−102	−50
Trend (1% sig. level)	Increasing	Decreasing	Decreasing	Increasing	No trend	No trend
DRY SEASON						
MK Statistic 'S'	62	−142	−82	16	4	−17
Trend (1% sig. level)	No trend	No trend	No trend	No trend	No trend	No trend

An increasing trend in BFI in the annual and wet season data was found at 5C1 (Bua) and 5D3 (Mtiti), however, no trend was found in the dry season data. Increases in baseflow have previously been linked to increases in groundwater levels as a result of prolonged increases in rainfall [3]. However, no trends in rainfall were detected in the annual, wet or dry season data from nearby rainfall stations; Nkhota station (close to 5C1) from 1960–2009, and Mponela station (close to 5D3) from 1960–2003 (Table S6). In contrast, a decreasing trend in BFI for the annual and wet season data was found for 5D1 (Bua) and 5D2 (Bua), however, no trend was found in dry season data. Decreases in BFI could be linked to prolonged over-abstraction of groundwater. Declining groundwater levels have been reported in Malawi; however, sparse monitoring of groundwater levels lends to lack of evidence of such trends. The natural vegetation of the plateau area was reported as Miombo woodland but had been cleared for cultivation in the 1980s which may have resulted in major changes to the hydrological cycle [30].

Interestingly, 5E6 (Bua) and 5F1 (Rusa) showed no trends in BFI for the annual, wet season or dry season data. The stability of the BFI here suggests that the systems are in balance, and the baseflow to the river has remained stable over the assessment period; 1970–2008 and 1964–2005 respectively. It may indicate minimal impact to groundwater levels in the area and a well-managed catchment. This is perhaps also true of 5E6 which drains the Mchinji Forest Reserve and can be expected to have minimal impacts from human activities.

These findings suggest that long term behavioral changes have occurred in the annual and wet season baseflow at several gauges in the Bua catchment as described above. Based on the tests being conducted at a significance level of 1%, there is a 1% risk of being wrong or a confidence level of 99% in the results. The trend results should, however, be interpreted with caution as further work is recommended to quantify the magnitude of the trends and examine potential drivers for such changes in baseflow behavior [61].

The above resultsprovide new evidence of temporal variations in baseflow in the Bua catchment. This will be of interest to the new National Water Resources Authority within the Malawi Government for catchment planning.

4. Conclusions

The main aim of this study was to demonstrate, using a case study, how to use sporadic river datasets to produce meaningful observations on temporal variations in baseflow. The findings can be summarized in terms of their contribution to knowledge.

4.1. Catchment Originality

This is the first study to quantify temporal variations in baseflow in the Bua catchment. Annually, average BFIs > 0.74 were found for gauges in the lower reaches of the catchment, with lower BFIs < 0.54 found for gauges in higher reaches. Seasonally, minimal difference was found between the annual and wet season BFI, however, baseflow increased in the dry season across all gauges with BFI all found to be >0.80. Long term trends were found in the annual and wet season BFI indicating behavioral changes in baseflow have occurred within the catchment. No trend was found in the dry season BFI. The source of baseflow is expected to be mainly groundwater discharge from the aquifers underlain the rivers, however, interflow and dambo storage may also play a role. An implication of these findings is that temporal variations in baseflow should be considered in future scheme appraisals in the catchment such as the proposed irrigation infrastructure. Further, the results should be included in catchment management plans set by the new National Water Resources Authority within the Malawi Government, to inform the seasonal allocation of water resources in the catchment.

4.2. Generic Relevance to the Reader and the Wider Research Community

Apart from the Bua catchment case study, this article serves as an important example for other gauged catchments in Malawi, and indeed other countries, which are required to assess variations in baseflow to underpin IWRM and SDG 6, but are faced with similar challenges of sporadic river data. Further research is now needed to quantify temporal variations in baseflow for all gauged catchments in Malawi. Our on-going baseflow research seeks to do this by using the approach demonstrated in this study.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/5/901/s1; Supplementary Material word document containing the following Figures and Tables. **Figure S1**. Pictures of the weir located on the Bua river downstream of gauge 5C1, taken January 2019 by Oliver Phiri; **Figure S2**. Results of the annual and seasonal BFI analysis (graphical) for the Bua River, gauge station 5C1, 1957–2009 (52 years); **Figure S3**. River gauge 5E6 on the Bua river, draining Mchinji Forest Reserve, Google Earth Image, February 2019; **Figure S4**. River gauge 5D3 on the Mtiti river, draining part of the Dowa Hills, Google Earth Image, February 2019; **Table S1**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D1, 1958–2007 (49 years); **Table S2**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D2, 1953–2005 (52 years); **Table S3**. Results of the annual and seasonal BFI analysis (tabular) for the Mtiti river, gauge station 5D3, 1958–2003 (45 years); **Table S4**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5E6, 1970–2008 (38 years); **Table S5**. Results of the annual and seasonal BFI analysis (tabular) for the Rusa river, gauge station 5F1, 1964–2005 (41 years); **Table S6**. Mann Kendall statistical results for rainfall stations in WRA 5; Nkhota (1960–2009) and Mponela (1960–2003).

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