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Automated Baseflow Separation and Estimation of Groundwater Recharge Using Master Recession Curve Technique in the Sissili Basin

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Abstract

The accurate estimation of baseflow and groundwater recharge is key to effective groundwater resources management. Both groundwater recharge and baseflow have been widely used in calibrating hydrological and groundwater models. This study aimed to estimate groundwater recharge and baseflow in the Sissili River basin, a subcatchment of the White Volta Basin in Ghana, using the recession curve analysis method and digital baseflow separation filters. Six different digital filters or methods from four tools were used to estimate the baseflow. An attempt was made to test the performance of the baseflow filters during the dry seasons and recession periods, while recharge estimation was based on the hydrograph recession method. The recession curve analysis yielded recharge rates ranging from 29 mm to 68 mm, accounting for 3% and 9% of the annual rainfall in 2004 (971 mm) and 2005 (761 mm), respectively. The estimated average recharge was 47.3 mm for the period 2003-2008, representing 5% of the average annual rainfall of the period, which was 949.6 mm. The estimated yearly baseflow, based on the six methods, ranged from 19.1 to 69.8 mm, or from 2% to 7% of the annual rainfall.

Keywords

Baseflow Separation, Digital Filter, Automated Master Recession Curve, Flashiness Index, Groundwater Recharge, Sissili Basin

1. Introduction

Streamflow can be divided into two main components: direct flow and baseflow. Such separation is good for the planning and management of water resources [1]. Separation of baseflow from direct flow has been used to assess groundwater recharge and discharge [2], flood [3], and the impact of land use and climate change on water resources [4].

Baseflow is the withdrawal of groundwater after the end of groundwater recharge. Many definitions of baseflow have been used, depending on their intended purpose. Common expressions include groundwater flow, low flow, percolation flow, under-run, seepage flow, and sustained flow [5]. Author [5] defined it as the component of flow originating from groundwater storage or other delayed sources. It is also described as groundwater recession or groundwater discharge [6]. Similar to most water balance components, baseflow depends on catchment characteristics, including land use and land cover, geology, soil, topography, climate, and temperature [7]. It is also time and space-dependent. Sometimes, it is assumed to be equal to groundwater recharge [8]. This approximation is feasible in areas where underflow, evapotranspiration from riparian vegetation, and other groundwater losses from the watershed can be neglected [9]. Because baseflow is less than the actual amount of water that recharges the aquifer, terms such as "effective recharge", "base recharge", or "observable recharge" have been used to refer to this approximated recharge [10]. Baseflow has been demonstrated to be a reliable parameter for calibrating and validating hydrological models. However, estimating baseflow can be difficult. Several techniques have been designed to study the baseflow recession. These techniques employ various approaches, including manual, automated, and chemical or field-based methods [6] [11]-[13]. Each method has advantages and drawbacks that depend on the catchment's characteristics. Chemical approaches offer the most effective means of estimating baseflow but are expensive. Manual methods, used as an alternative to estimating baseflow, are time-consuming and can yield inconsistent results [14]. The automated techniques, known as the digital baseflow filter, are based on mathematical equations. They are less time-consuming and help compare the baseflow of different catchments. These digital baseflow filters estimate baseflow from streamflow based on signal analysis. Estimation is based on the assumption that baseflow is the low-frequency component of streamflow [15]. The recent past two decades have witnessed tremendous development and the use of these methods. One challenge in using filters to separate baseflow is defining the filter's parameter values, which introduces uncertainty in the resulting baseflow. The number of these filter's parameters ranges from one to five. To validate the separated baseflow, the best practice is to compare the filtered baseflow results with estimates from field measurements, such as tracers, geochemistry, or groundwater levels, which can be somewhat time-consuming and costly. According to [16], validations of baseflow determined using baseflow filters are rarely conducted, as they are constrained by data scarcity in many catchments and are subject to uncertainties due to the complexity of hill slope hydrochemistry and spatial heterogeneity. Furthermore, as baseflow recession changes over time [17], the present-day baseflow recession characteristics may differ from those of the past, rendering this approach unsuitable for calibrating past baseflow. In this regard, many alternative solutions have been proposed. Author [18] proposed two criteria to evaluate the performance of a baseflow filter. But these criteria are relevant to filters applied without constraints, allowing baseflow to exceed total stream flow or be negative.

As is already known, streamflow is primarily composed of baseflow during recession periods. Therefore, comparing separated baseflow with streamflow during recession periods could be the best approach for testing the model's performance. Before conducting baseflow separation and recharge estimation, hydrograph recession analyses were performed to evaluate the performance of the baseflow filter models and recharge estimation. Four automated tools designed for hydrograph separations were used to estimate baseflow and baseflow index (BFI). These were: Web-based Hydrograph Analysis Tool (WHAT) [13], AdUKIH [11], the EcoHydRology (EcoHydRo) package in R [19], and Aquapak. The baseflow was estimated using three different options implemented in the WHAT tool, whereas the other three use only one method. Hence, six different methods were used. Before separating the baseflow, the groundwater recharge will be estimated using the hydrograph recession method in a spreadsheet developed by [20] and [21].

2. Study Area and Data Sources

2.1. Description of the Study Area

The study area is the Sissili catchment, a subcatchment of the White Volta, with its outlet located at Wiasi in northern Ghana, and it is shared by Ghana and Burkina Faso. The catchment, as depicted in **Figure 1**, spans approximately 12,517 km^2 and is underlain by a crystalline basement, which is covered by a regolith layer reaching a depth of 40 m [22]. The average slope is 1.4%. The dominant land use type is forest (covering 40% of the study area), followed by woodland (26%) and croplands (20%). The cropland is more concentrated in the northern part of the catchment. The elevation in the catchment ranges from 126 m to 400 m above mean sea level. The unimodal rainy season runs from May/June to October/November. Based on the work of [23], the year can be divided into four seasons. The period from January to March is termed the dry season, while July to September is the wet season. The periods from April to June and October to December are identified as dry-wet and wet-dry transition seasons, respectively. The annual rainfall decreases from south to north, following a gradient observed mainly in West Africa. The concentration time of the catchment, approximated by the formula of [24], is about 10.5 days. Major towns in and around the watershed include Koudougou, Gao, Po, and Leo in Burkina Faso, as well as Navrongo and Tumu in Ghana.

2.2. Data Sources

In this study, streamflow time series data from 2003 to 2008 with missing records

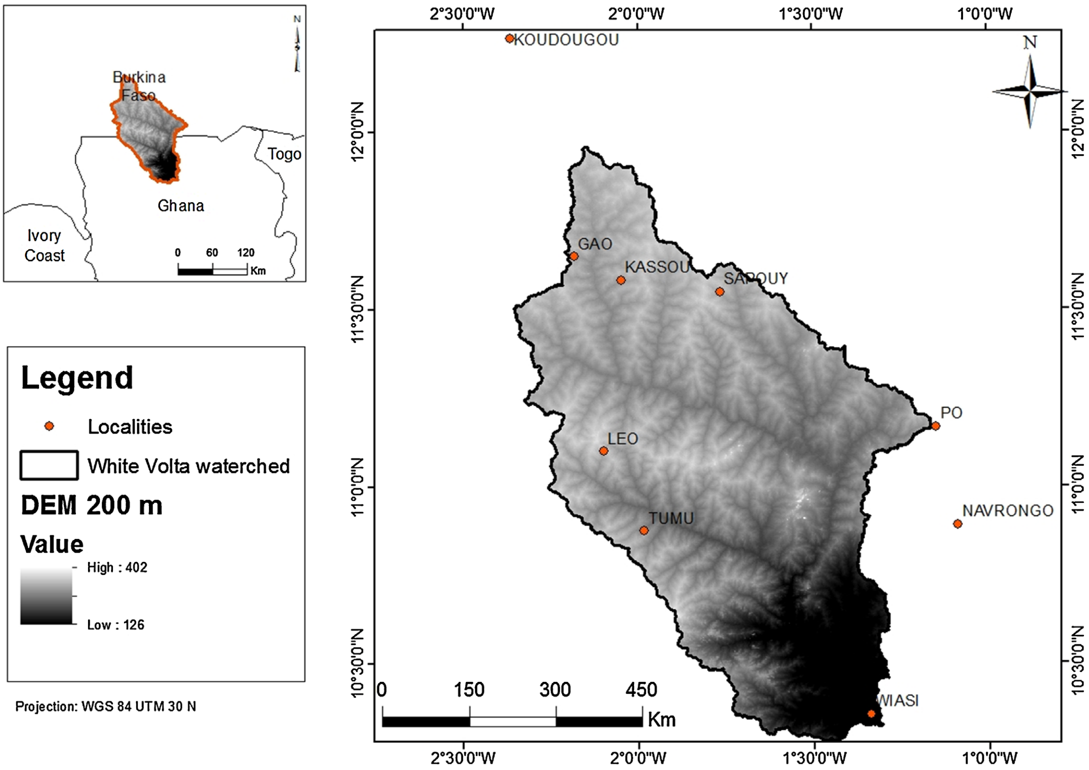

Figure 1. Presentation of the study area.

from April 2007 to June 2007 were used. The three months with missing data were excluded from the analysis. This data was collected from the Ghana Hydrological Services. The Sissili River is permanent, but the data show no flow during two weeks in 2008. The meteorological services of Ghana and Burkina Faso provided the rainfall data covering the study period.

3. Methodology

3.1. Recharge Estimation Using Hydrograph Recession Analysis

3.1.1. Recession Analysis

A Visual Basic Spreadsheet Macro for Recession Curve Analysis, designed by [25], was used to identify the recession period in the streamflow dataset. A detailed description of the spreadsheet is available in the publication mentioned above. This program uses the matching strip method and offers five regression models. This is more advantageous than other methods that utilise the well-known and widely used exponential equation. The five models available in the spreadsheet are: linear ($y = ax + b$), logarithmic ($y = a\ln(x) + b$), second-order polynomial ($x = ay^2 + by + c$), power ($y = bx^a$), and exponential ($y = be^{ax}$). Where y represents discharge and x represents time.

After using the five models to analyse the recession, the model that gave the highest coefficient of determination (R^2) was retained as the most appropriate, and the resulting Master Recession Curve (MRC) from that model was selected as the best for describing the recession of the baseflow in the catchment.

3.1.2. Recharge Estimation

Groundwater recharge was estimated based on an adapted Meyboom's method implemented in a Visual Basic spreadsheet macro designed by [21]. The program requires streamflow data that define recession period preceding (recession 1) and the recession period following (recession 2) groundwater recharge. Recession periods were selected during baseflow-dominated conditions with no precipitation or runoff influence. Recession 1 was chosen prior to the recharge event, and recession 2 was chosen after the recharge. The program fits the exponential regression model available in Microsoft Excel to baseflow recessions 1 and 2. This is to ensure both segments exhibited approximately linear behaviour on semi-logarithmic plots of discharge versus time and similar recession slopes, reflecting unchanged aquifer properties. Then it uses the resulting regression equations to calculate the recharge volume that occurs between these recessions. Recession periods, as determined by recession analysis, provide the basis for estimating recharge. The program uses a step-by-step approach to estimate individual recharge amounts for different recharge periods. For instance, if there are n recharge periods, the program must be run n times. Details of the spreadsheet are available in [21].

3.2. Baseflow Separation

3.2.1. AdUKIH Method

The AdUKIH is a smoothed minima baseflow separation tool for perennial and intermittent streams, designed by [11]. It is a generalised version of the well-known and widely used smoothed minima baseflow separation method developed by the United Kingdom Institute of Hydrology, which is applicable to perennial streams only [25]. In arid and semi-arid environments, such as those in Northern Ghana, baseflow primarily originates from groundwater discharge.

The AdUKIH method described by [11] can be summarised as follows:

Divide the daily flow data into non-overlapping blocks of n days.

Mark the minima of each of these blocks, and call them Q_1, Q_2, …, Q_i and consider them in turns of three (Q_1, Q_2, Q_3), (Q_2, Q_3, Q_4), …, (Q_{i-1}, Q_i, Q_{i+1}). Let us consider (1) and (2):

$$0.9Q_i \le \min\left(Q_{i-1}, Q_{i+1}\right) \tag{1}$$

$$0.9Q_i < \min\left(Q_{i-1}, Q_{i+1}\right) \tag{2}$$

(1) is used in the case of an intermittent stream, whereas (2) is used for a perennial stream. In each case, if the corresponding condition is met, the central value is a turning point of the baseflow line. Continue this procedure until the whole time series has been analysed.

Join the turning points by straight lines to form the baseflow hydrograph. If, on any day, the baseflow estimated by this line exceeds the total flow on that day, the baseflow is set equal to the total flow.

Estimate the volume of water generated by baseflow beneath the baseflow hydrograph (Vbase) between the first and last turning points. The volume is found by summing the individual trapezium areas, i.e., by multiplying the time between turning points by the average discharge of the turning points.

Estimate the volume of water beneath the recorded hydrograph (Vtotal) between the first and last turning points. The volume is calculated by summing the average daily flow values between the first and the previous turning points.

The baseflow index (BFI) is then Vbase/Vtotal.

A schematic representation of the procedure for estimating baseflow using the AdUKIH code is available in the work by [11].

3.2.2. WHAT and Aquapak Tools

WHAT is an acronym of the Web-based Hydrograph Analysis Tool developed by [13] to separate hydrograph components using three methods, namely: BFLOW, Eckhardt digital filters, and the local minimum method. It has been used in many studies [13]. Therefore, to run WHAT, one needs to select one of the three methods. Regarding the local minimum method, it is a straightforward approach that requires no parameters to be entered before running the tool, unlike the other two methods. For the One-Parameter Digital Filter (BFLOW) method, the user can enter the filter parameter. Regarding the Eckhardt digital filter, also known as the Recursive Digital Filter, the user has the option to set the values of two parameters: the filter parameter and BFImax, or to select an aquifer type that will automatically display both parameters. The three types of aquifers are perennial streams with porous aquifers, perennial streams with hard rock aquifers, and ephemeral streams with porous aquifers. For comparison, the Eckhardt digital filter was run on the first two aquifer types, named the Recursive Digital filter for Hard Rock aquifer (RD-HR) and the Recursive Digital filter for Porous aquifer (RD-P). A statistical component has been incorporated to provide useful information for flow frequency and time series analyses.

The BFLOW is the digital filter method first introduced by [26], and it has been used in several studies [27] [28]. This method is presented in (3). As for the Eckhardt [28] digital filter presented in (4), it is a general form of a digital filter based on digital filter parameters and the maximum value of the long-term ratio of baseflow to total streamflow ($\text{BFI}_{\max}$).

$$q_t = \alpha \times q_{t-1} + \frac{1+\alpha}{2} \times \left(Q_t - Q_{t-1}\right) \tag{3}$$

$$b_t = \frac{\left(1-\text{BFI}_{\max}\right) \times \alpha + b_{t-1} + \left(1-\alpha\right) \times \text{BFI}_{\max} \times Q_t}{1-\alpha \times \text{BFI}_{\max}} \tag{4}$$

where b_t is the filtered baseflow at the t time step;

b_{t-1} is the filtered baseflow at the $t-1$ time step;

$\text{BFI}_{\max}$ is the maximum value of the long-term ratio of baseflow to total streamflow;

α is the filter parameter;

and Q_t is the total streamflow at the time step t.

Compared with previous digital filters, $\text{BFI}_{\max}$ is the new variable added by [28]. To minimise the subjective influence of $\text{BFI}_{\max}$ on baseflow separation, representative BFImax values were estimated for various hydrological and hydrogeological conditions by comparing baseflow obtained with conventional separation methods with that from the Eckhardt digital filter method. Author [28] proposed the use of BFImax values of 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with porous aquifers, and 0.25 for perennial streams with hard rock aquifers.

The Aquapak tool, designed by [29], is a digital filter that uses the same [26] method as BFLOW and was presented earlier in (3).

Concerning the local-minimum approach, the duration of surface runoff N, as presented in (5), is first estimated. Then the double of $N(2N)$ is estimated, and in the next step, $2N^*$, which is the closest odd integer to $2N$, is determined. Then each day of a period of record is checked to determine whether it has the lowest discharge within one-half the interval minus 1 day [0.5 ($2N^* - 1$) days] before and after the day being considered. If this condition is satisfied, the discharge value for that day is regarded as a "local minimum" value, and it proceeds to the following day for the same process [30].

$$N = A^{0.2} \tag{5}$$

where the variable N is the number of days after which surface runoff ceases, and A is the drainage area of the watershed in square miles.

3.2.3. EcohydRology Baseflow Filter

The EcohydRology is an R package designed by [19]. The baseflow function separates baseflow from streamflow data series. It is based on the recursive digital filter of [26]. It requires a 1-column data frame with the same number of rows as the streamflow data series and returns a 2-column data frame, where the first column contains baseflow and the second column contains quickflow, both in the same units as the input streamflow data. Because the tool is flexible, to perform baseflow separation, one must specify the filter parameter values and the number of passes, which is the number of times the filter is applied to the data.

For this work, a filter parameter of 0.925 was used as suggested by [27]. Because the streamflow data time step is daily, a pass value of 3 was used as recommended in many baseflow separation studies (e.g., [31]).

3.2.4. Efficiency Test

In the sciences, especially in hydrological science, model results are often evaluated to gauge the model's performance or efficiency in mimicking local conditions. The Nash-Sutcliffe model efficiency coefficient (NSE) in (6), proposed by [20], is a good efficiency indicator. In this study, the NSE criterion was employed to determine the method that most effectively separates baseflow from streamflow in the study area. As measured baseflow data were not available for the study area, two approaches were used in the efficiency analysis. The first one consisted of comparing separated baseflow with streamflow during the dry season, in which all the streamflow is mainly (or exclusively) composed of baseflow. The second approach is to compare the separated baseflow with the flow during the period identified as the recession period by the recession analysis tool [20].

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(q_t - bf_t\right)^2}{\sum_{t=1}^{T}\left(q_t - q_0\right)^2} \tag{6}$$

q_t: observed flow during recession period;

q_0 = mean of observed flow during recession period;

bf = filtered baseflow.

The NSE can range from −∞ to 1. An NSE of 1 means that the model outputs match perfectly the observed data, while an NSE of 0 indicates that the model predictions are as accurate as the mean of the observed data. A negative efficiency suggests that the observed data mean is a better predictor than the model. In that case, the residual variance (the numerator in the expression above) is larger than the data variance (the denominator), and the results are described as unacceptable [32]. The NSE is sensitive to extreme values, and significant outliers in the dataset can lead to suboptimal results.

3.2.5. Flashiness Index

The term "flashy", in the context of streamflow, lacks a fixed definition but is applied to a set of characteristics [33]. However, they stated that flashiness describes how rapidly and frequently streamflow changes over a short period. "Flashy" streams have rapid rates of change, whereas "stable" streams have slow rates of change [34]. The flashiness index has been used in various studies. Several authors have used it to determine the streamflow regime and the impact of land use/cover change on the hydrological cycle (e.g., [33]). Using data from 30 study watersheds, [35] found a good correlation coefficient of 0.67 between BFI and FI; and FI decreases when BFI increases, suggesting that a smaller BFI corresponds to a greater value of FI and vice versa. It is a valuable tool for analysing the impact of land-use change on the hydrological regime of rivers. The new flashiness index (FI), designed by [33] and depicted in (7), was used. Compared with several flow regime indices, it has lower interannual variability [33].

$$\text{R-B Index} = \frac{\sum_{i=1}^{n} 0.5\left(\left|q_{i+1} - q_i\right| + \left|q_i - q_{i-1}\right|\right)}{\sum_{i=1}^{n} q_i} \tag{7}$$

where q_i is the daily flow at time step i, while q_{i-1} and q_{i+1} are the flows of time steps preceding and following this time step, respectively.

The FI index is a dimensionless value, and ranges from 0 to 2 (the maximum theoretical value). A value of FI equal to 0 means no change in discharge over the considered period.

4. Results and Discussion

4.1. Recharge Estimation Using Hydrograph Recession Analysis

4.1.1. Recession Analysis

An example of MRC is shown in **Figure 2**, while **Table 1** presents the performance of the different regression models of the baseflow recession spreadsheet of [20] in fitting the baseflow recession of the Sissili streamflow at Wiasi. The resulting coefficient of determination (R^2) values are all acceptable based on the works of [36] and [37]. The results also show that, except for the linear regression model, all the other models had high coefficient of determination values, indicating that they can fit baseflow recession in the watershed. The power regression is the model that best fits the baseflow recession of the Sissili River. The exponential regression followed it. In decreasing order of performance, the models are listed as follows: power regression, exponential regression, logarithmic regression, and polynomial regression ($y = f(x)$), with the same R^2; polynomial regression ($x = f(y)$); and linear regression. Thus, the plausible baseflow recession in the area may be a power function.

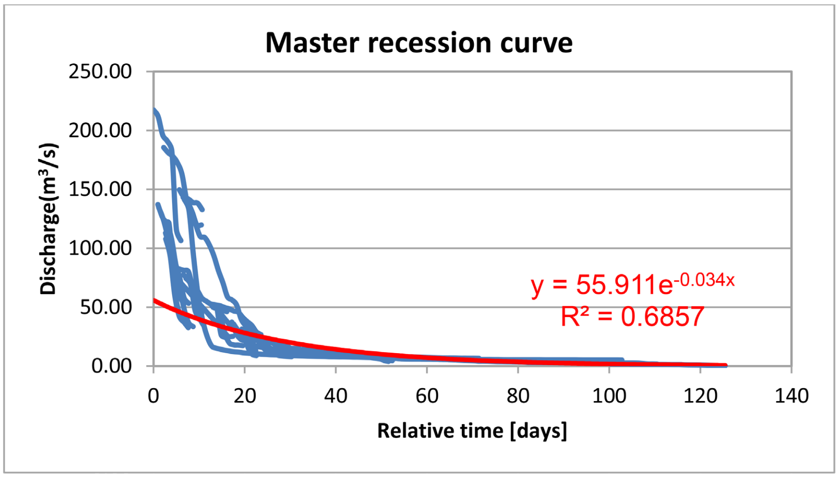

Figure 2. Power regression Master Recession Curve of the Sissili river, tributary to the White Volta River, 2003-2007, Northern Ghana.

Table 1. Performance evaluation of the different recession methods in the study area.

Models	Equation	Coefficient of determination (R^2)
Linear regression	$y = -0.9848x + 73.717$	0.54
Power regression	$y = 435.31x^{1.068}$	0.94
Exponential regression	$y = 55.911e^{-0.034x}$	0.86
Logarithmic regression	$y = -39.86\ln(x) + 162.14$	0.82
Polynomial regression $y = f(x)$	$y = 0.0606x^2 - 6.1083x + 149.86$	0.82
Polynomial regression $x = f(y)$	$y = 0.005x^2 - 1.1565x + 62.21$	0.70

4.1.2. Recharge Estimated by Recession Analysis

Estimated annual recharge ranges from 27 mm in 2004 to 66 mm in 2008 (**Figure 3**). Although the least rainfall occurred in 2005, recharge in that year was higher than the estimate for 2007, when the highest rainfall during the study period occurred, suggesting no linear correlation between groundwater recharge and rainfall amount in the study basin. This corroborates the notion that recharge does not depend solely on rainfall amount, as indicated by several studies (e.g., [38]).

Recharge also depends on rainfall patterns, such as temporal distribution and intensity, as well as on the evapotranspiration. Author [38] found that a better relationship between rainfall and recharge exists only when rainfall exceeded a threshold of 10 mm/day in the Upper Nil basin. The results of this work show that the highest recharge occurred in 2005. The estimated recharge ranged from 3% to 9% of the annual rainfall (**Table 2**), with an average of 5% (approximately 47.3 mm), while the average yearly rainfall during the period was 949.6 mm. The results of this work are consistent with those of several studies conducted in similar geological formations around the study area. The average value is consistent with the findings of [39] and [40], who employed the chloride mass balance method in the Atankwidi catchment in Northern Ghana and in the Kompienga Dam Basin in southeastern Burkina Faso, respectively. The former achieved a long-term recharge of 6% while the latter achieved 5.3%. In the crystalline rock aquifer of southwestern Ghana, [41] used a numerical groundwater model (MODFLOW) to estimate groundwater recharge at rates of 0.25% to 9.13% of annual rainfall. Using three methods, namely CMB, WTF, and a physically based hydrological model (SWAT), [41] obtained an average recharge rate ranging between 7% and 8% in the White Volta River Basin.

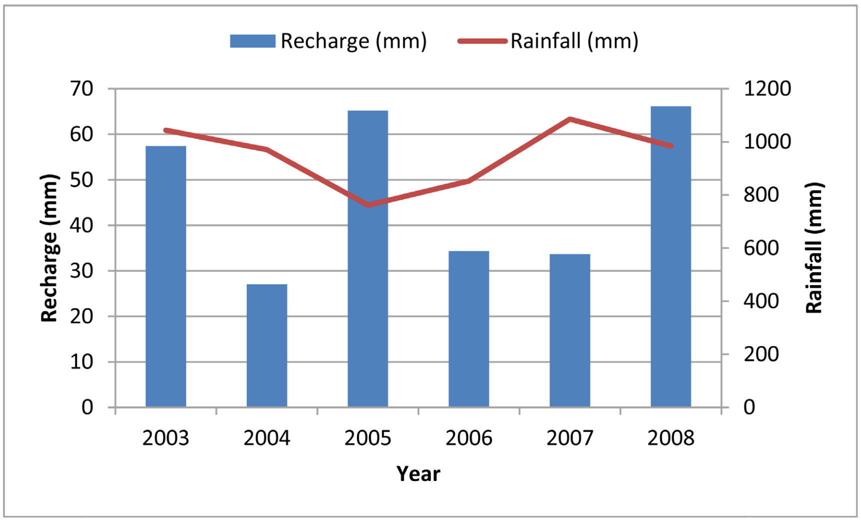

Figure 3. Annual recharge and rainfall amount.

Table 2. Annual recharge in percentage.

Years	Recharge (%)	Weighted average annual rainfall (mm)
2003	5	1044
2004	3	971
2005	9	761
2006	4	852
2007	3	1086
2008	7	984

4.2. Baseflow Separation

Before analysing baseflow, the quality of the flow data was assessed to remove flows contributed by sources other than groundwater discharge and rainfall. It was observed that the highest flow during a given year (the peak flow) typically occurs after the annual rainfall peak, and the lowest flow occurs during the dry season. During the study period (2003-2008), the highest monthly rainfall occurred in August 2007, while the highest peak flow was obtained in September 2008. The different recession models discussed in section 4.1.1 identified all the dry seasons as recession periods. These analyses suggested that the primary sources of streamflow during the dry season are groundwater discharge (baseflow) and rainfall. In other words, the effect of the dam (delay flow) and irrigation water within the watershed can be considered negligible. This therefore implies that the baseflow component of the streamflow data can be equated to the groundwater discharge in the study area. The quality control analysis revealed a lag of approximately one month between the onset of rainfall and the end of recession or the rise in flow. This may be attributed to water losses resulting from relatively high evapotranspiration and the high soil water deficit inherited from the previous dry season [42], as well as to watershed characteristics (e.g., slope, soil type, and land use). As the size of the river channel is large, water losses along the river channel during the period January-May might be considerable.

The highest flashiness index (FI) of the study period is 0.26 and was obtained in June 2005, while the smallest FI of about zero (0) was estimated in January 2006 (**Figure 4**). The highest values of FI are found at the beginning of the rainy season, in which low BFI are obtained, and peak FI is obtained before the annual peak of rainfall. **Figure 5** shows that the smaller the BFI, the higher the FI. In fact, the rapidity of the rise and fall of the peak of streamflow (i.e. the flashiness) is controlled by quickflow, while the baseflow sustains the flow during periods of no rain. The highest monthly average FI during the study period was 0.16, observed

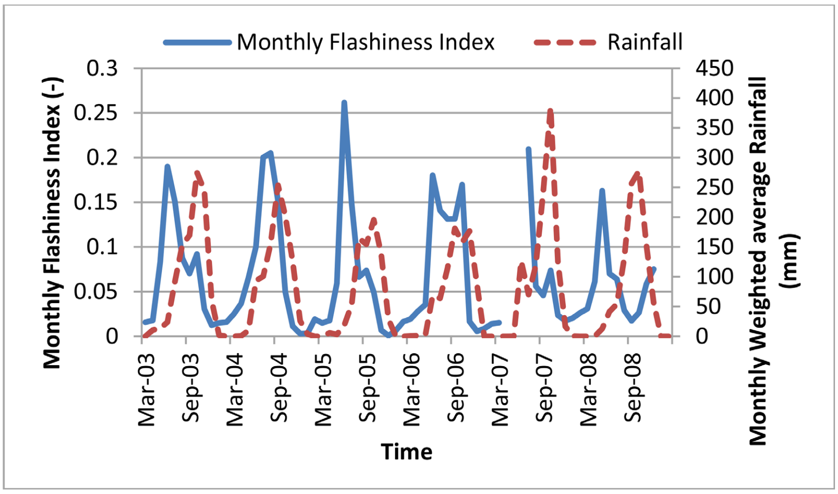

Figure 4. Comparison of the monthly flashiness index and the monthly weighted average rainfall.

in June, although August is the month with the highest rainfall, as noted by many studies (e.g., [42]). The average monthly flashiness index during the study period is 0.06. Therefore, following the work by [33], the Sissili River at Wiasi is classified as a stable river based on both watershed area and flashiness index. On an annual basis, FI ranges from 0.03 to 0.15 (**Figure 6**). It was also observed that as the BFI increases, the FI decreases, and vice versa, revealing an inverse relationship between these two parameters. This result is in agreement with the findings of [35], who compared FI and BFI from across 30 catchments in the Nordic-Baltic region and found a good coefficient of correlation ($R^2 = 0.6794$) with a linear correlation having a negative slope. Baseflow does not increase immediately at the beginning of the rainy season, as noted by [26], who stressed that baseflow takes days or weeks to respond, while streamflow responds more quickly and rises primarily, resulting in high FI. Conversely, after the rainy season begins, baseflow increases,

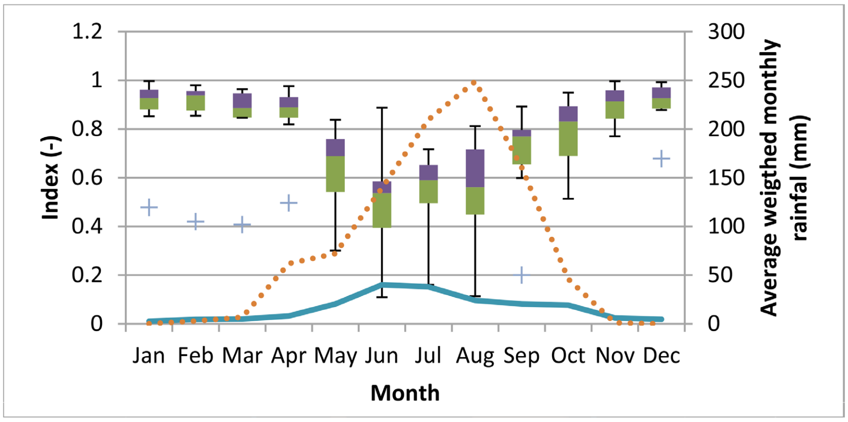

Figure 5. Variation of monthly average baseflow and flashiness indexes for the period 2003-2008. Boxplots represent the average monthly BFI, the solid blue line represents FI, the blue crosses represent outliers, and the discontinued red line represents monthly rainfall.

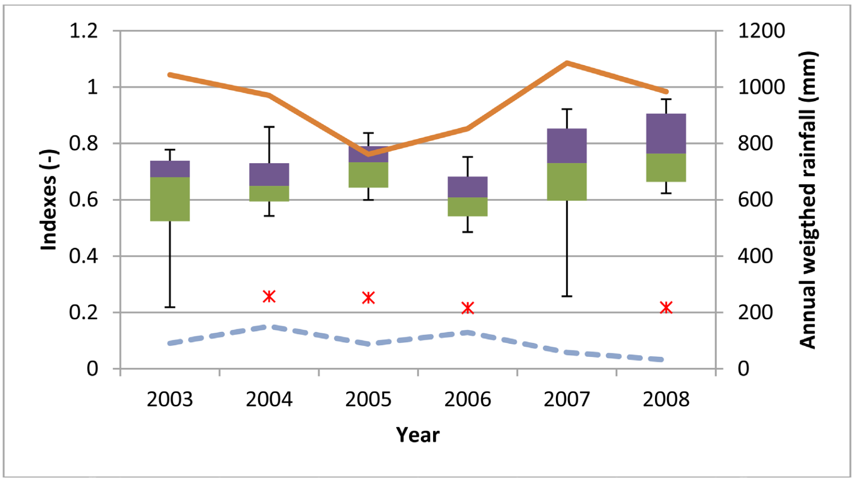

Figure 6. Interannual variability of baseflow index of the Sissili River at WIASI, Northern Ghana. Boxplots represent the average monthly BFI, the solid orange line represents annual rainfall, red asterisks represent outliers, and the discontinued blue line represents annual FI.

acting as a buffer against the drastic drop in flow during dry periods, thereby lowering the flashiness index. The high BFI observed in the study basin, corroborated by the FI, may be attributed to high evaporation rates that reduce surface flow in the study area. It may also confirm that the regolith aquifer is the primary source of water discharging as baseflow. The regolith layer in the study area can exceed 40 m in depth; therefore, the fractured zones are deep and do not discharge into the Sissili River.

Figure 7 illustrates the range of BFI estimates obtained using the various baseflow separation methods. The Recursive Digital filter for the Hard Rock aquifer (RD-HR) yielded the lowest BFI estimate for the entire study period. This was followed by the EcohydRology and Aquapak tools, in an increasing order. The BFIs obtained with the recursive digital filters (RD-P and RD-HR) exhibit low inter-annual variability, a result of using the BFImax parameter in this method. With the WHAT system [13], the BFImax is 0.8 for RD-P and 0.25 for RD-HR. Generally, all the baseflow separation methods yielded the highest BFI values in 2008, except for the Local Minimum and RD-HR, which had the highest BFI values in 2007. Although the BFLOW filter, the EcohydRology filter, and the Aquapak filter use the same method [26], they yield different results. This behaviour of the baseflow filter was pointed out by [31]. For all the study years, the "BFLOW method" is the only method that estimated BFI greater than 0.7, while the RD-HR method gave a BFI below 0.3 (**Figure 7** and **Figure 8**). **Figure 9** shows that the highest BFI were obtained in 2008. In 2005, the year with the smallest annual rainfall, the BFI is higher than in some years (2003, 2004, and 2006) that received more rain. This may be explained by the fact that the baseflow of a given year also depends on rainfall in the preceding year. In other words, baseflow contributing to flow does not come only from water that recharged the aquifer in that year. Statistical analysis of the BFIs estimated by all the methods shows that the BFI obtained with the RD-HR method is an outlier in 2003 and

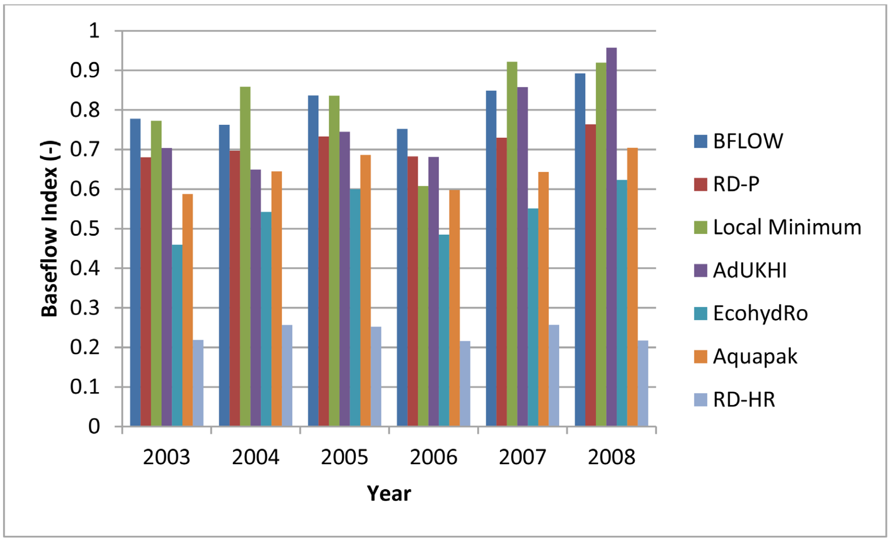

Figure 7. Range of annual BFI estimated by the different methods.

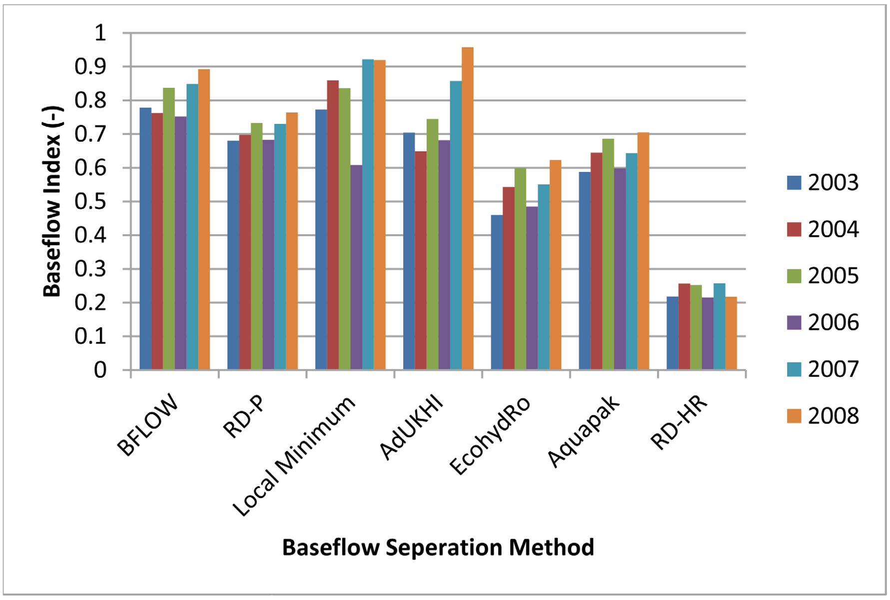

Figure 8. Variation of the annual BFI with respect to the different filter methods.

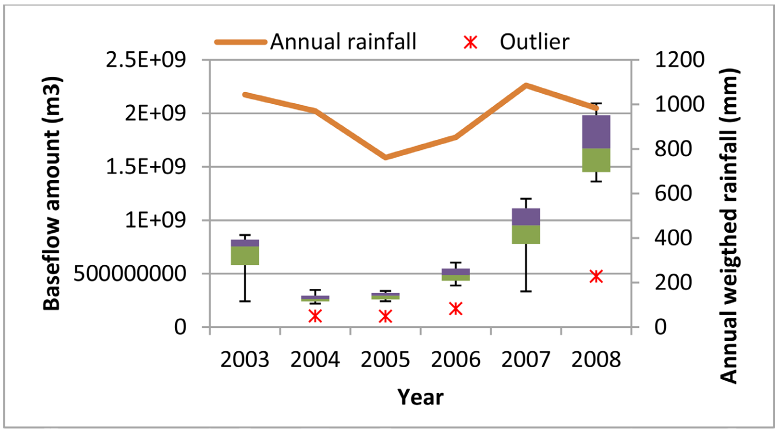

Figure 9. Comparison of baseflow and annual rainfall amount. Boxplots represent the range of baseflow estimated by the different methods; asterisks represent outliers, and the orange line represents annual rainfall.

2007. Compared to the results (BFI range of 0.033 - 0.33) obtained by [43], who used the recession method proposed by [44] to separate baseflow in five sub-catchments within the Volta basin, only the RD-HR method used in the current study had results within the range of that study.

Baseflow increased from 2004 to 2008 (**Figure 9**). The combined analysis of rainfall and baseflow indicates that rainfall amount is not the only factor governing baseflow. For instance, annual rainfall in 2003 is higher than in 2008, but baseflow in 2008 is higher than that in 2003. Relative to the median, the spread of baseflow amount estimated by the different methods is wider for high baseflow estimates and narrower for low baseflow estimates. The estimated annual baseflow based on the various techniques used in this study ranged from 2.4×10^8 m^3 (19.07 mm) to 9×10^8 m^3 (69.8 mm), representing 2% to 7% of the annual rainfall. The local minimum method yielded the highest baseflow estimate for the entire study period, with the lowest being obtained using the RD-HR (**Figure 10**). These results are in line with findings of [43], who obtained baseflow ranging from 2 mm to 42 mm in some sub-catchments of the White Volta and Black Volta rivers in Northern Ghana. Both baseflow and rainfall decrease from 2003 to 2004, while they increase from 2005 to 2007, indicating a link between them, although baseflow does not depend solely on rainfall amount.

Regarding the performance of the various baseflow separation methods, the BFLOW digital filter outperformed the others, yielding the highest NSE during the entire dry season and the recession period (**Table 3**). Conversely, the RD-HR method performed worst, with the lowest NSE, indicating limited ability to estimate baseflow during the dry season, particularly during the recession period.

Since the analysis is based on a six-year streamflow record, which may not fully capture longer-term climate variability and hydro-climatic extremes such as multi-year droughts or unusually wet periods. As a result, the estimated groundwater recharge percentages primarily reflect the prevailing climatic conditions during the study period rather than long-term average behaviour. This limitation constrains the direct generalisation of the derived recharge fractions to other periods with different climate regimes. Nevertheless, the results remain valuable

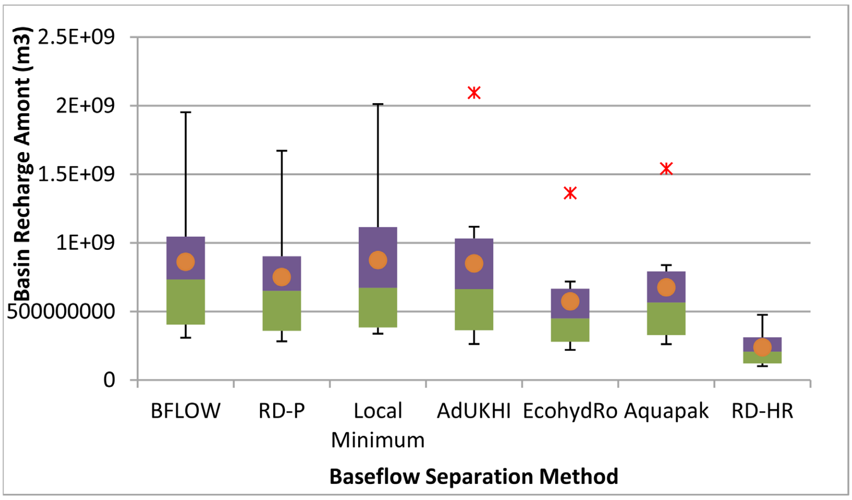

Figure 10. Range of baseflow estimated by baseflow tools for the 2003-2008 period. The red asterisks represent outliers, and the dots represent the mean values.

Table 3. Performance of baseflow methods during dry and recession periods in the Sissili basin at Wiasi, Ghana.

	BFLOW	RD-P	RD-HR	Local Minimum	AdUKHI	Eco-Hydro	Aquapack
NSE in the recession periods	0.90	0.83	0.19	0.68	0.75	0.56	0.68
NSE in dry season flow	0.99	0.45	0.00	0.60	0.00	0.74	0.84

for understanding recharge dynamics and relative magnitudes under recent conditions, and they provide a useful baseline for comparison with future studies using longer hydrological records or climate-scenario-based simulations.

5. Conclusion

This study aimed to estimate recharge and baseflow in the Sissili River basin (a subcatchment of the White Volta Basin) using the recession curve analysis method and digital baseflow separation filters. An attempt was made to test the performance of the baseflow filters during the dry seasons and recession periods. Findings suggest that recharge ranges from 3% to 9% of annual rainfall, with an average of 5%. The results also showed that the BFLOW filter yielded the best performance in estimating baseflow during the period (2003-2008) considered for the analysis. Recharge estimates based on recession and baseflow separation methods are considered potential recharge values and need to be validated against actual estimates from methods such as tracers, water table fluctuation, and chloride mass balance. The average monthly flashiness index suggests that the Sissili River at Wiasi is stable.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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