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Analysis of the Performance of Base Flow Separation Methods Using Chemistry and Statistics in Sudano-Sahelian Watershed, Burkina Faso

Bouraïma Kouanda[1*], Paulin Coulibaly[2], Dial Niang[1], Tazen Fowe[1], Harouna Karambiri[1] and Jean Emmanuel Paturel[3]

[1]*Laboratory of Water, Hydrosystems and Agriculture, International Institute for Water and Environmental Engineering, Ouagadougou, Burkina Faso*

[2]*Water Resources and Hydrologic Modelling Lab, McMaster University, Hamilton, Canada*

[3]*Research Institute for Development (IRD), University of Montpellier, Rue Auguste Broussonnet, France*

[*]**Corresponding author:** Bouraïma Kouanda, Laboratory of Water, Hydrosystems and Agriculture, International Institute for Water and Environmental Engineering (2iE), Ouagadougou, Burkina Faso, Tel: +22670497191; E-mail: ibkouanda@gmail.com

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Abstract

This research aims to determine appropriate methods for base flow separation under Sudano-Sahelian climate in West Africa. Four Recursive Digital Filtering (RDF) methods and the Conductivity Mass Balance (CMB) method were used. Daily streamflow of the Mouhoun River (formerly Black Volta River) at Samendeni gauge station has been separated into base flow and runoff. The RDF methods are easy to use but cannot take into account the actual hydrological processes within the watershed, while CMB method does it well. But, given that regular discharge measurement is rarely coupled with Electrical Conductivity measurements, it is therefore not possible to apply CMB method over time at each outlet. The CMB method is frequently used on a short time as a reference to assess the performance or to calibrate RDF methods. In the present study, CMB method was used for the year 2017, especially during the rainy season (from July to October) to produce more realistic base flow values. Statistical analysis was used to compare RDF and CMB methods. It was found that all the four RDF methods used are significantly different from the CMB method in the study area. Among the RDF methods, the Eckhardt method which is two parameters filtering method was successfully calibrated using CMB method Base Flow Index (BFI) as constraint. With the calibration process, the parameter BFI_{max} of the Eckhardt method was adjusted to 0.32 in the study area context. The achievements of this study can have several implications such as adequate base flow estimation over time at Samendeni gauge station and at other similar gauges of the Mouhoun watershed which will be particularly beneficial to the critical issue of assessment of climate change impact on base flow in the study area.

Keywords: Base flow separation; Methods evaluation; Daily streamflow; Sudano-sahelian zone; Mouhoun River; Burkina Faso

Introduction

Base flow is generally regarded as sourced from groundwater discharging into streams [1]. It is the ground water contribution to stream flow [2,3]. In some cases, base flow is also considered as the result of natural processes such as delayed flow through wetlands and lakes, and anthropogenic processes such as flow regulation and wastewater discharge [4]. Runoff can be considered as the non-base flow portion of the total flow hydrograph [5].

Several recent studies revealed the importance of base flow in water resources management. Metrics of base flow provide useful information in analyses of water quantity and quality and aquatic habitat [4,6,7]. Base flow recession analysis is required to estimate the long-term reliable component of the hydrograph and water cycle, and for drought management, inflow design and analysis, and contaminant and nutrient transport [8]. Base flow separation is also important for obtaining critical parameters for hydrological models [9], assessing the effects of water use and climate change on water resources [1] and understanding runoff generation in catchments [10].

In literature review, several methods exist to determine the base flow. Analysis of the hydrographs base flow component had been done since 1904 with an empirical experience [11]. With some recent publications [9,12,13], approaches for base flow estimation can be grouped into two categories: Graphical Hydrograph Separation (GHS) methods, which need only daily streamflow data, and tracer Mass Balance (MB) methods, which rely on chemical constituents in the streams, streamflow discharges, and the streamflow end-member constituent concentrations (runoff and base flow). The GHS methods include: (i) recession curve methods (ii) analytical methods and (iii) Recursive Digital Filtering (RDF) methods. Artificial intelligence techniques are also used [14]. Unfortunately, the definitions of basin-specific parameters used in GHS methods are generally subjective and not based on hydrologic processes [13,15]. Only the Mass Balance methods take seriously into account the watershed hydrologic processes. There are also different Mass Balance methods. One of the commonly used MB method is the Conductivity Mass Balance (CMB) method. This method uses of Electrical Conductivity (EC) as a chemical tracer for hydrograph separation [13,16-18].

The advantage of CMB method over other types of MB methods is that EC is relatively easy and inexpensive to measure. In addition, high frequency of EC measurements can be obtained using *in-situ* EC probes [13,16]. Besides CMB method is generally considered to be more objective than GHS methods. But its application is limited by the fact that it requires high frequency EC records that are not always widely available over long time periods or spanning large numbers of watersheds.

Multiple studies developed methodologies to calibrate GHS estimates of base flow to CMB estimates of base flow [9,13,15,19]. The need to calibrate or to assess the performance of base flow separation

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methods has been shown in a large number of recent works [6,8,12,20-26]. Besides rare are the studies about the performance of base flow separation methods on African basin climate, hydrology and hydrogeological context. Available literature are essentially limited to the South African basin [24,27,28]. This weakness should be a relevant challenge.

The main objective of the present study is to determine appropriate methods for base flow separation under Sudano-Sahelian climate in West Africa, particularly on the Mouhoun River. To achieve this objective, four RDF methods proposed by Chapman [29], Chapman and Maxwell [30], Lyne and Hollick [31] and Eckhardt [21] and the CMB method are used for base flow separation. The RDF methods are compared statistically to CMB method to find if they are similar or not. The Eckhardt method which is a two-parameter filtering method was also calibrated by using CMB results as constraint [6,16]. This research is part of the National Program for the Integrated Water Resources Management (IWRM) in Burkina Faso. It has to find some decision support tools to assist in the process of implementation of Water Development and Management Plan.

Materials and Methods

Study area

The study area (called Samendeni watershed) is located in the South West of Burkina Faso in West Africa (Figure 1). The Samendeni watershed covered by the Sudanese and Sudano-Sahelian zones, is drained by a transboundary perennial river called Mouhoun or Black Volta River. The outlet of Samendeni watershed is the Samendeni gauging station located at the upstream part of the Black Volta watershed. The Black Volta watershed is shared between three countries in West Africa (Burkina Faso, Ghana and Cote d'Ivoire). The Samendeni watershed is fed by several water sources (springs) and contributes to keep the Black Volta River permanent. There are about forty seven (47) springs in the Samendeni watershed and about forty (40) are perennial. Thus, groundwater contributes significantly to the hydrological processes in this watershed. The area of Samendeni watershed is about 4580 km^2. In the study area the inter-annual mean precipitation was 1063 mm over the period 1950-2013 (Bobo-Dioulasso synoptic station). The rainy season is generally from June to October. The inter-annual average of potential evapotranspiration is 1955 mm over the period 1961-2013. Daily temperature varies between 18.8°C (January) to 38.6°C (March). Tables 1 and 2 present the summary of the important hydro-climatic properties of the study area. According to Dakouré [32] and Derouane [33], the study area is entirely in a sedimentary zone and dominated by sandstones. Figure 2 shows the details of the geology of the study area.

In the study area, there are several projects in progress: the construction of the large Samendeni Dam to mobilize 1.05 billion m^3, an irrigation project of 21000 ha, a hydropower project etc. This presents a challenging situation of an intense pressure on the available water resources in the coming years. Besides, at the downstream of Samendeni watershed, there exist a situation of high demand of water (more than 8000 ha of irrigated area on Sourou valley, drinking water system of Koudougou city, industrial uses, mining and livestock).

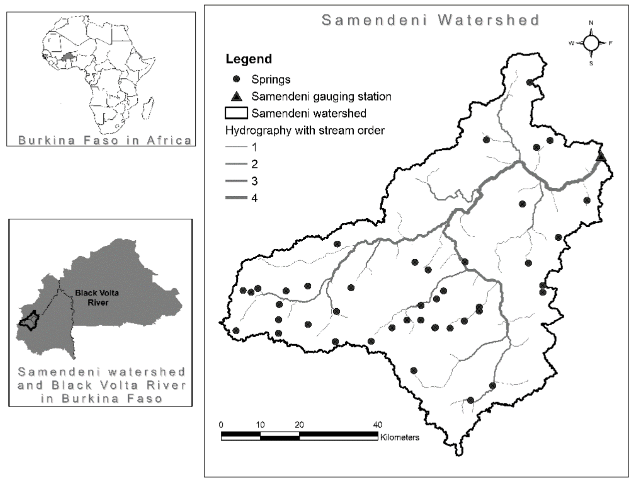

Figure 1: Study area.

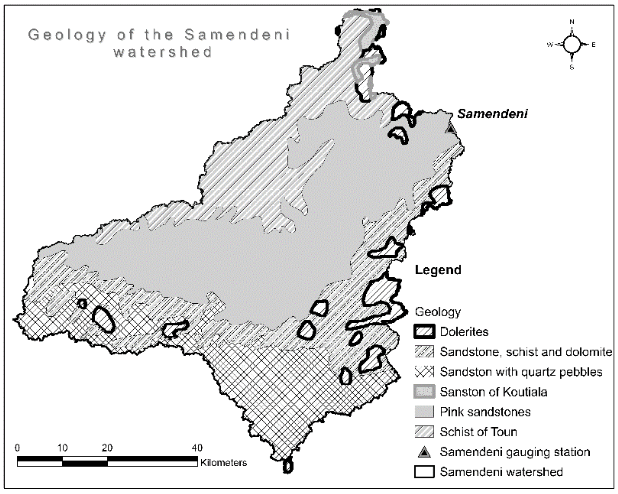

Figure 2: Geology of Samendeni watershed.

Data collection

In general, in Burkina Faso there is no rain during the period from November to May. During that period the streamflow is essentially due to the springs on Samendeni watershed and the total streamflow can be considered as base flow. The separation of the total streamflow into base flow and runoff concerns essentially the rainy period (From June to October). Therefore, during the year 2017, from July to October (rainy season) the Electrical Conductivity (EC) were measured daily at Samendeni gauge station as additional data to the discharge measurements. November 2017 and December 2017 (dry season) were also concerned by the EC measurements in order to determine the plausible EC value of base flow. The multiparametric probe HI 98129 was used for the measurements.

Station	Data	Period	Annual Average	Minimum	Maximum	Standard Deviation
Bobo Dioulasso	Daily rainfall (mm)	1950-2013	1063	775	1552	203
	Daily potential evapotranspiration (mm)	1961-2013	1955	1737	2202	116
	Daily minimum temperature (°C)	1961-2013	22	20	23	0.47
	Daily maximum temperature (°C)	1961-2013	33	32	34	0.56

Table 1: Meteorological properties of Samendeni watershed (Source of data: National Agency of Meteorology).

Gauging station	Coordinates (degree-minute)	Approximate altitude (m)	Drainage Area (km^2)	Inter-annual average of discharge (1960-2013) ($m^3.s^{-1}$)
Samendeni	11°28' N 04°28' W	287	4580	15.7

Table 2: Samendeni gauging station and its general features.

Base flow separation methods

Daily mean streamflow data at Samendeni gauge station were separated into surface flow and base flow during the rainy season (from July to October 2017). Four popular Recursive Digital Filtering (RDF) methods (Chapman, Chapman and Maxwell, Eckhardt, Lyne and Hollick) and the Conductivity Mass Balance (CMB) method were used (Table 3).

Gauging station	Basic Statistics	Base flow Index (BFI)				
		Conductivity Mass Balance	Chapman	Chapman and Maxwell	Lyne and Hollick	Eckhardt
Samendeni	Mean	0.45	0.52	0.53	0.57	0.68
	Min	0	0.05	0.05	0.05	0.05
	Max	0.92	1	1	1	1
	Standard deviation	0.3	0.29	0.29	0.3	0.27

Table 3: Base Flow Index (BFI) characteristics at Samendeni gauging station (from July to October 2017).

Recursive Digital Filtering methods (RDF): The mechanism of how RDF methods operate is similar to signal or in frequency analysis. The filter is used to separate (in hydrograph analysis) the quick flow component (high-frequency signal) and the base flow component (analog to low-frequency signal). The process is repeated over the period of record. Several algorithms for RDF methods exist in the literature [6,21,29-31,34-39]. The problem of RDF methods is that several methods exist, but no technique is universally accepted [5]. They need sometimes to be calibrated by considering the hydrological and hydrogeological characteristics of the watershed. In this study, four digital filters proposed by Chapman, Chapman and Maxwell, Lyne and Hollick, and Eckhardt were applied to the time series of daily streamflow data in order to determine the base flow. The principle of base flow separation by the digital filters is described by Equation 1 [21].

$y_k = f_k + b_k$ Eq(1)

with

y_k: Total streamflow,

f_k: Runoff,

b_k: Base flow,

k: the time step

The filters proposed by the authors cited above are described by Equation 2, Equation 3, Equation 4 and Equation 5.

Lyne and Hollick filter [31]:

$$b_k = ab_{k-1} + \frac{1-a}{2}(y_k + y_{k-1});\, b_k \le y_k \qquad Eq(2)$$

Chapman filter [29]:

$$b_k = \frac{3a-1}{3-a}b_{k-1} + \frac{1-a}{3-a}(y_k + y_{k-1});\; b_k \le y_k \qquad Eq(3)$$

Chapman and Maxwell filter [30]:

$$bk = \frac{a}{2-a}b_{k-1} + \frac{1-a}{2-a}y_k;\; b_k \le y_k \qquad Eq(4)$$

Eckhardt filter [21]:

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$$b_k = \frac{(1-BFI_{max})ab_{k-1} + (1-a)BFI_{max}y_k}{1-aBFI_{max}} \qquad Eq(5)$$

Where a is the filter parameter and BFI_{max} in the Eckhardt method is the maximum value of Base Flow Index (BFI). BFI is cumulative base flow divided by cumulative total discharge over the period of record of analysis. The filter parameter a describes the rate at which the streamflow decreases over the time following a recharge event. It can be derived by recession analysis [6,9,21]. In this study, the filter parameter (a) was determined by recession analysis as suggested by Eckhardt [6].

The possible value of the parameter BFI_{max} in the Eckhardt filter depends on the watershed hydrological and hydrogeological characteristics of the watershed. BFI_{max}=0.80 for perennial streams with porous aquifers; BFI_{max}=0.50 for ephemeral streams with porous aquifers; BFI_{max}=0.25 for perennial streams with hard rock aquifers [21].

According to Derouane [33,40] the study area can be considered as a porous aquifer. Besides it has perennial streams. Based on these considerations BFI_{max} value of 0.8 was initially used. A calibration of Eckhardt method was also done to find the adequate value of the parameter BFI_{max} in the climate, hydrological and hydrogeological conditions for Samendeni watershed.

The Conductivity Mass Balance (CMB) filtering method: The advantage of the mass balance method is that site-specific variables are measured, and the chemical or isotopic constituents of stream flow are related to physical processes and flow paths within a basin [1,15,41]. As mentioned by Longobardi [16], the Mass Balance method is based on the assumption that base flow has different chemical characteristics compared with surface runoff due to the different flow paths of these two types of flows. As a consequence, total streamflow hydrograph can be separated into different components. The electrical conductivity EC, as proxy of the Total Dissolved Solids (TDS) mass balance is one of the most widely used technique. The base flow component has generally greater EC value compared to the surface runoff conductivity and for this reason EC can be used as a natural tracer of the streamflow component [16]. This behavior is shown in Figure 3, where the measured EC approaches the largest values during the low flow period. According to this assumption, it is possible to consider the following equation system (Equation 6) [16].

$$\begin{cases} q_{tot}(t) = q_{sf}(t) + q_{bf}(t) \\ q_{tot}(t).\ EC_{tot}(t) = q_{sf}(t).\ EC_{sf}(t) + q_{bf}(t).\ EC_{bf}(t) \end{cases} \qquad Eq(6)$$

With

q_{tot}=measured total streamflow ($m^3.s^{-1}$);

q_{sf}=surface streamflow component ($m^3.s^{-1}$);

q_{bf}=base flow streamflow component ($m^3.s^{-1}$);

EC_{tot}=measured streamflow EC ($\mu S.cm^{-1}$);

EC_{sf}=surface component EC ($\mu S.cm^{-1}$);

EC_{bf}=base flow component EC ($\mu S.cm^{-1}$);

During the dry season the EC becomes practically a constant value close to 58 $\mu S.cm^{-1}$. This value is assumed to be the signal of base flow EC [13,16]. The EC of the base flow and runoff components are assumed to remain constant over the period of observation [13,15]. Previous studies [1,15] have proved that the lowest EC values correspond to a predominance of runoff. These lowest values are observed with the peak flow (Figures 3 and 4) and are all close to 19 $\mu S.cm^{-1}$. So the EC value of 19 $\mu S.cm^{-1}$ is considered as the runoff Electrical Conductivity. The values for base flow EC and runoff EC can reasonably be considered to be constant for each individual stream gage location [15,19].

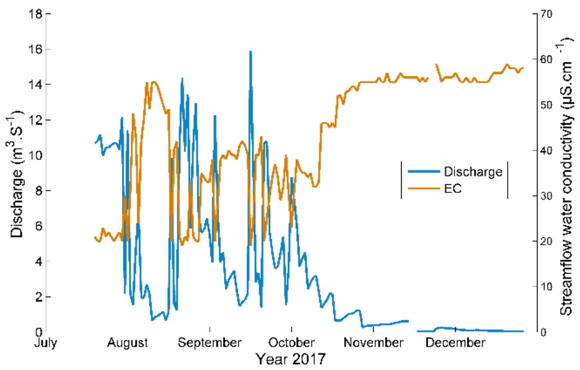

Figure 3: Discharge and electrical conductivity measurements at the Samendeni gauge station.

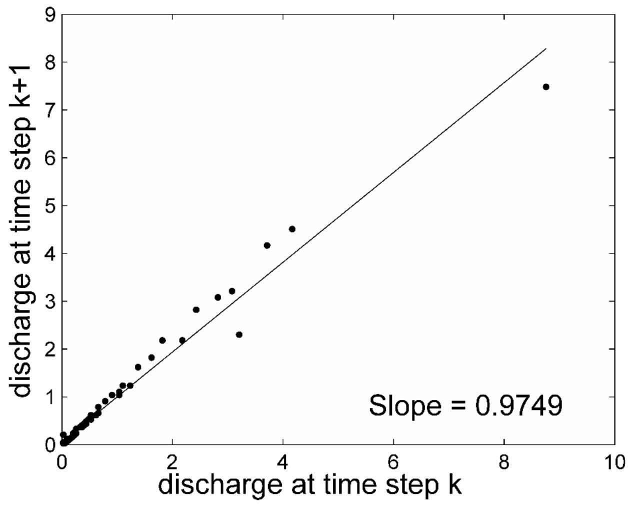

Figure 4: Scatter plot of discharge at time step k+1 versus discharge at time step k during recession periods. The slope of the line through origin about 0.975 represents the recession constant [6].

Statistical analysis

Statistical analysis were performed in order to compare the results obtained through RDF methods and CMB method. Firstly, boxplots were used to show the range of base flow values for each method. Secondly the correlation between each RDF method and CMB method was analysed (Figure 5). Thirdly, a statistical test (Kruskal-Wallis mean rank test) was performed to check if there is a RDF method which is similar to the CMB method. The choice of this statistical test was justified by the fact that base flow data are not normally distributed in the case of this study. Therefore, the appropriate statistical tests are those based on rank (Figure 6).

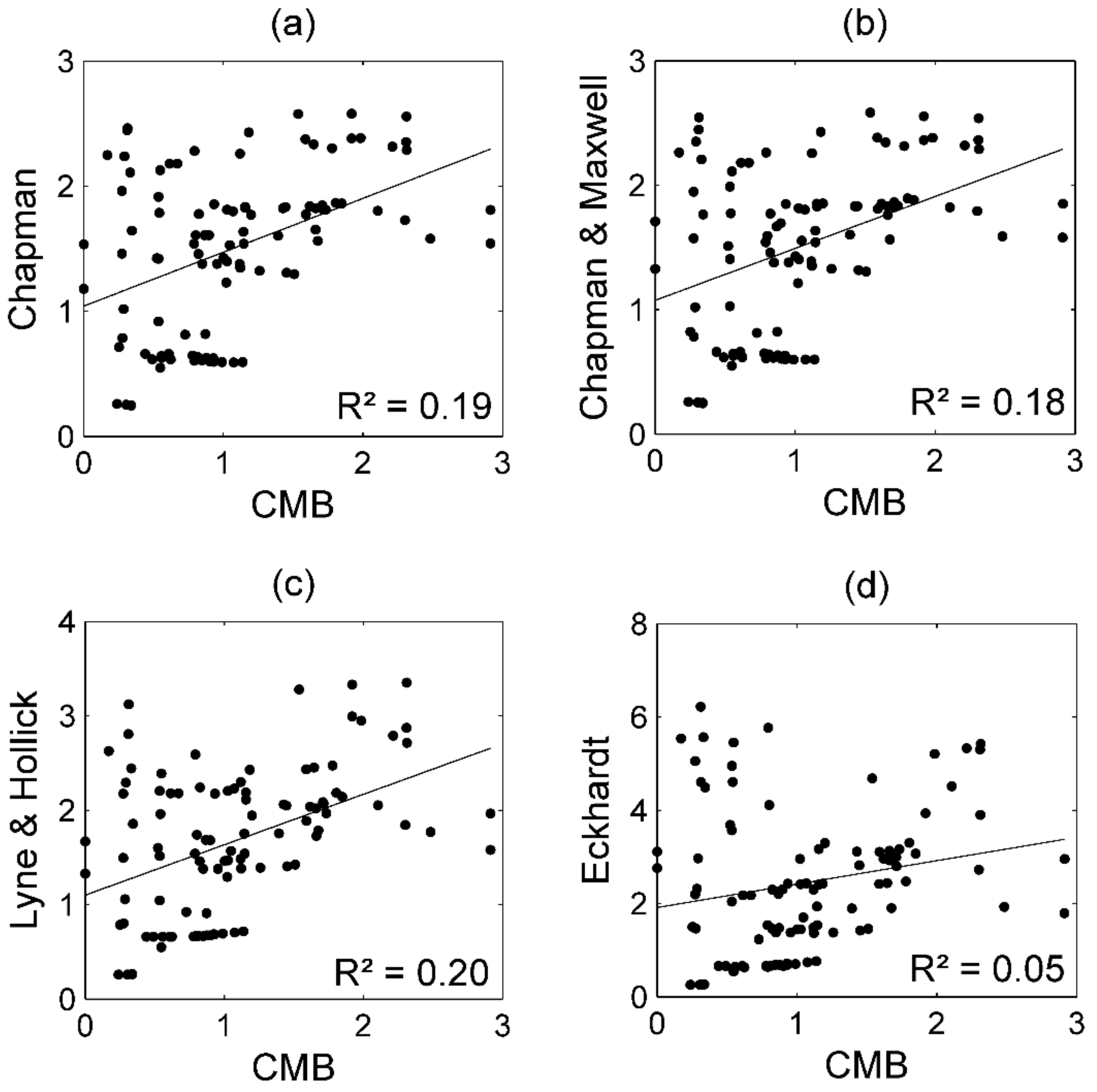

Figure 5: Linear correlation scatter plots between uncalibrated RDF methods and CMB method. (a): Chapman vs CMB, (b): Chapman & Maxwell vs CMB, (c): Lyne and Hollick vs CMB, (d): Eckhardt vs CMB.

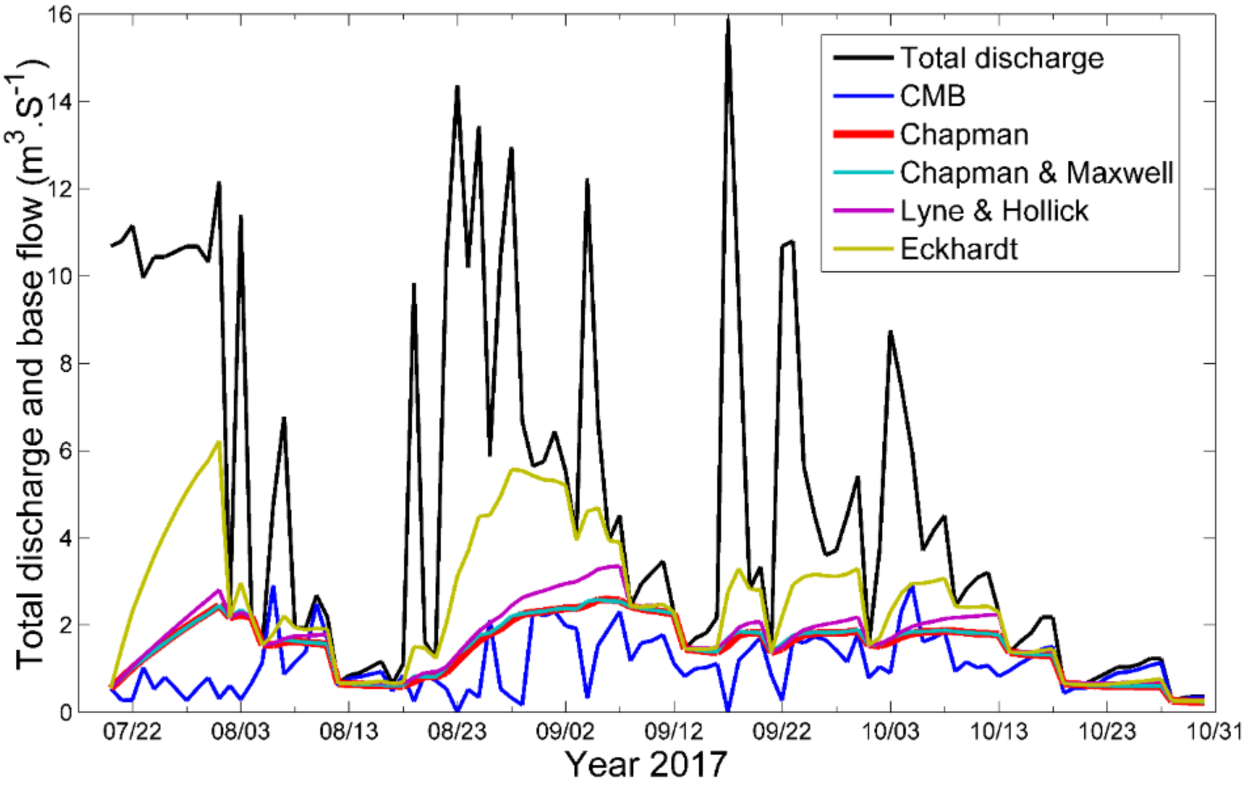

Figure 6: Temporal evolution of the total discharge and base flow from uncalibrated RDF methods and CMB method.

Calibration of Eckhardt filter method

As mentioned above, Eckhardt method is a two parameters filter method. The first is the recession constant (a) and the second is the BFI_{max}. The second parameter depends to the hydrological and hydrogeological features of the watershed. This parameter can be adjusted through a calibration process [6]. To calibrate the Eckhardt method, the CMB filtering results have been considered a constraint. A set of four criteria percent bias (PBIAS), Root-Mean-Square Error (RMSE), Nash Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) were used to evaluate the performance of the Eckhardt calibrated method by referring to Moriasi et al. [42] and Mehan et al. [43].

Results of statistical analysis

Boxplots: The boxplots (Figure 7) showed the range of data falling between the 25th and 75th percentiles, horizontal line inside the box showing the median value, and the whiskers showing the complete range of the base flow values for each method. The minimum value of base flow (0.0 $m^3.S^{-1}$) was observed with the CMB method which takes into account the real hydrological processes in the watershed. This value was generally observed during the peak flows when the discharge is essentially rain water (period with lower EC values). The median value of base flow from CMB method was smaller than each median obtained with RDF methods (Figure 7). The same conclusion was stated above with the mean values of base flow (Table 4). Eckhardt method particularly gave base flow with a strong variability. Eckhardt [21] suggests 0.8 as BFI_{max} in porous aquifer with permanent streamflow. In the case of this study, the above assumption was used in reference to the study of Derouane [33,40]. However, the study area is large and might not be entirely porous. Therefore the value of BFI_{max} was adjusted by calibration process in order to obtain accurate values of the base flow. For the other three RDF methods (Chapman, Chapman and Maxwell and Lyne and Hollick), the base flow values distributions seemed to be similar. But their quantiles (Q1, M, Q3) were significantly different from those of CMB methods. Statistical test was thus used to support this conclusion.

Statistical test: The Kruskal Wallis mean rank test rejected the null hypothesis which supposed that each RDF method was similar to the CMB method with 95% confidence interval. Figure 8 gave more information about the results of the Kruskal Wallis mean rank test. Each RDF method was significantly different from CMB method. These conclusions supported those mentioned above with Figures 3-5 and the boxplots analysis. Therefore, the need to calibrate the used RDF methods in hydrology and hydrogeology context of the study area was evident. The Eckhardt method which has a parameter (BFImax) depending of the watershed features was calibrated.

Gauging station	Basic Statistics	Total discharge ($m^3.S^{-1}$)	Base flow ($m^3.S^{-1}$)				
			Conductivity Mass Balance	Chapman	Chapman and Maxwell	Lyne and Hollick	Eckhardt
Samendeni	Mean	4.8	1.1	1.5	1.5	1.7	2.5
	Min	0.3	0	0.2	0.2	0.3	0.3
	Max	15.9	2.9	2.6	2.6	3.4	6.2
	Standard deviation	4.1	0.6	0.6	0.6	0.8	1.5

Table 4: Total streamflow and base flow characteristics in Samendeni station (from July to October 2017).

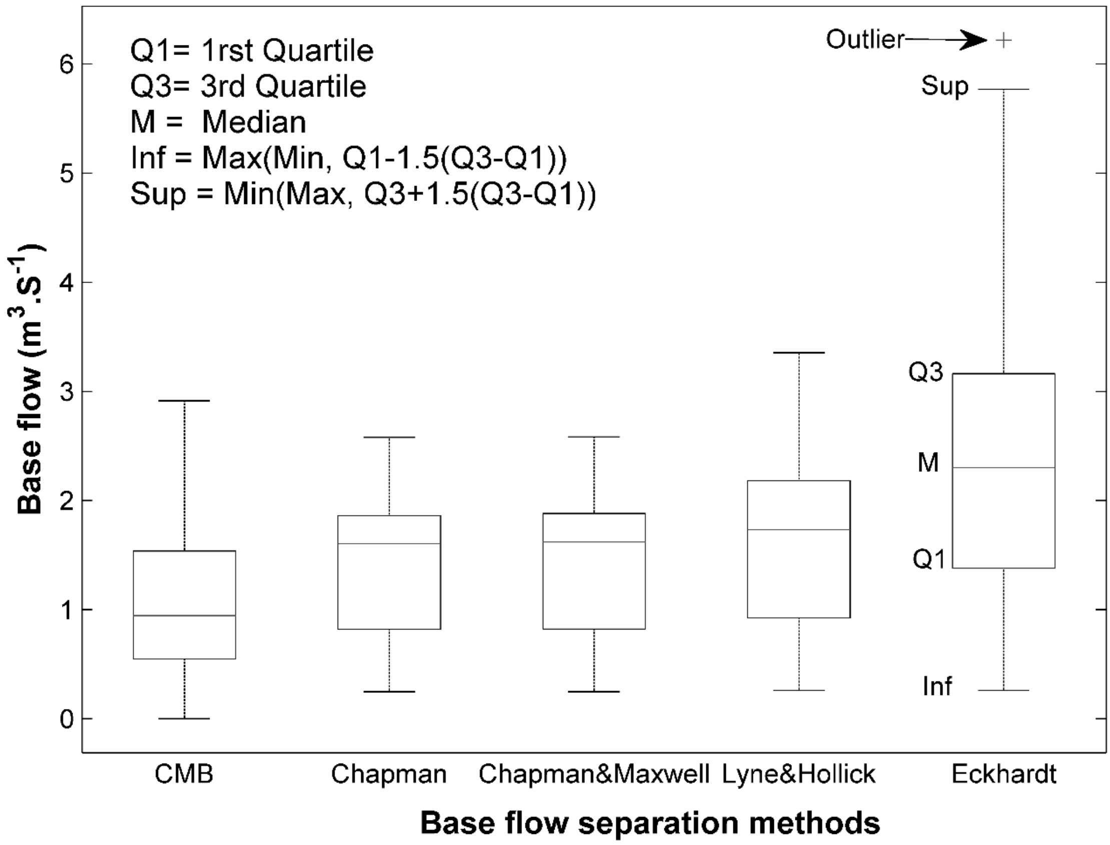

Figure 7: Distribution of base flow values from RDF and CMB methods at Samendeni station.

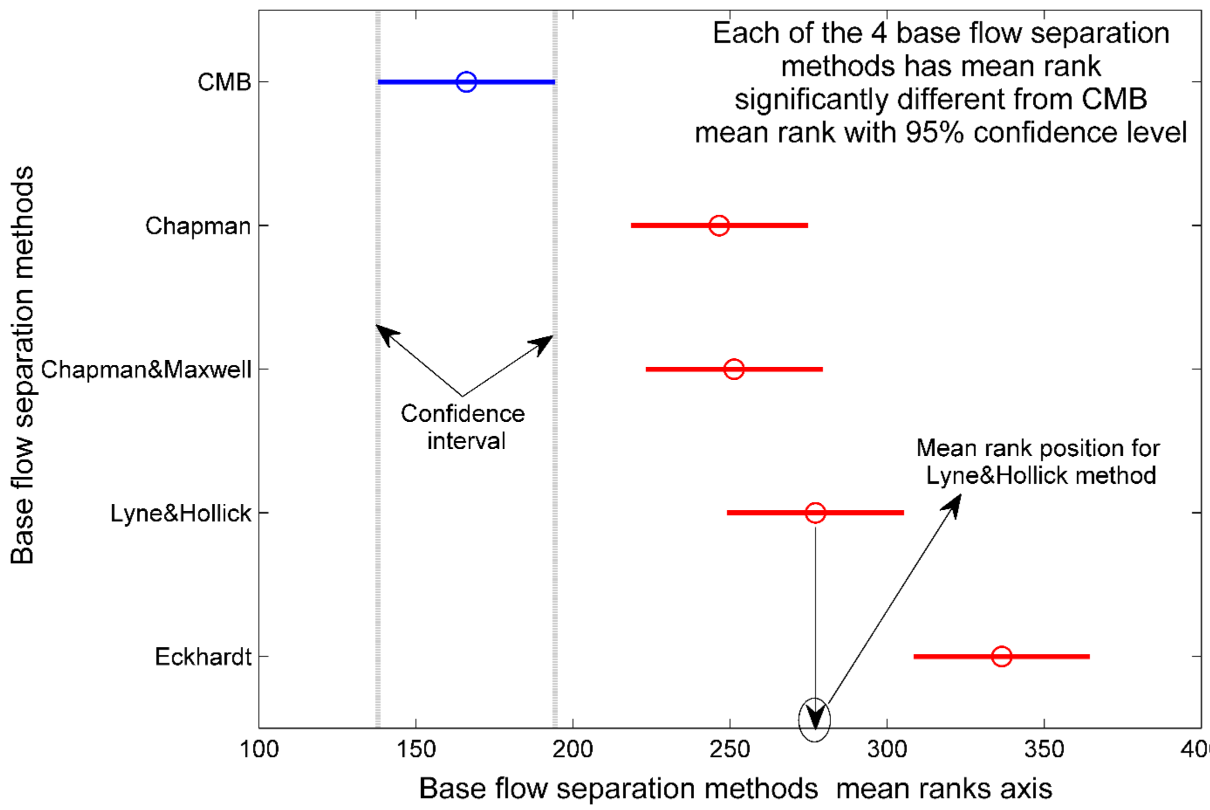

Figure 8: Comparison of RDF methods and CMB method using Kruskal Wallis mean rank test at Samendeni gauge station.

Eckhardt method base flow calibration: To calibrate the Eckhardt method, the CMB method BFI values were used as constraint. The Eckhardt filter parameter BFI_{max} was adjusted to 0.32 in the study climate, hydrology and hydrogeology context. The calibrated results showed a significant improvement of Eckhart method although some of the extreme (highest and lowest) values did not match perfectly with those of the CMB method (Table 5). However, globally the calibration results appeared satisfactory based on the performance statistics (NSE=0.90, R^2=0.91, RMSE=0.09, Pbias=-0.49) [42-45]. The Figure 9b presented a good linear correlation between CMB BFI and Eckhardt calibrated BFI and the Figure 9c showed a good linear correlation of base flow values between Eckhardt calibrated method and CMB method. Besides the Kruskal Wallis mean rank test performed with Eckhardt calibrated method and CMB method confirmed that they were similar with 95% confidence level (Figure 9d).

Basic statistics	Base flow CMB	Eckhardt	Base flow index (BFI)	
			CMB	Eckhardt
Mean	1.1	1	0.45	0.41
Min	0	0.2	0	0.05
Max	2.9	1.3	0.92	1
Std	0.6	0.3	0.3	0.27

Table 5: Comparison between Eckhardt calibrated and CMB methods.

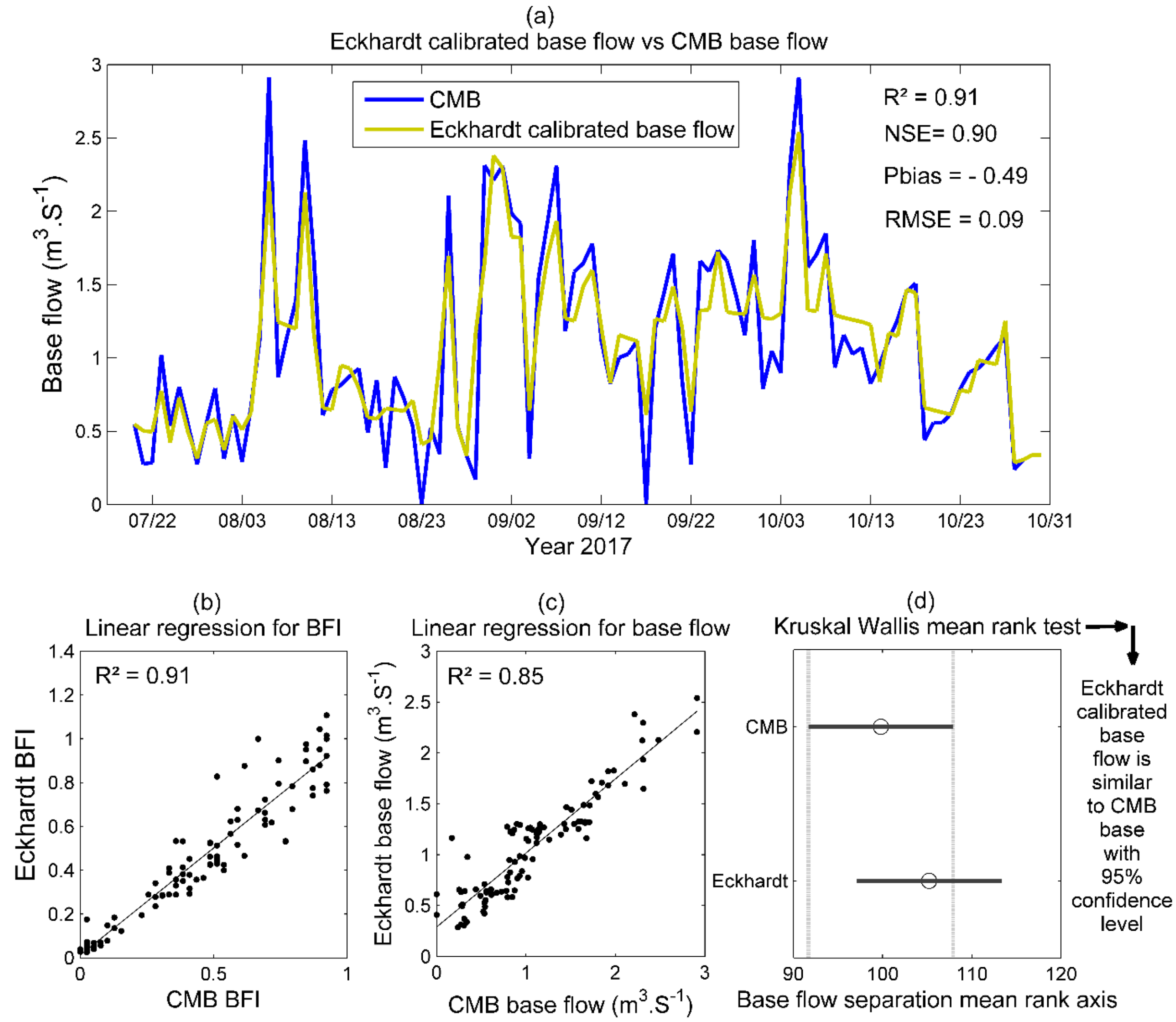

Figure 9: Comparison between Eckhardt calibrated method and CMB method. (a) Temporal evolution of CMB base flow and Eckhardt calibrated base flow, (b) linear regression (Eckhardt calibrated BFI vs CMB BFI), (c) linear regression (Eckhardt calibrated base flow vs CMB base flow), (8d) Kruskal Wallis mean rank test (Eckhardt calibrated base flow vs CMB base flow).

Conclusion

Several base flow separation methods are available in the literature, however identifying adequate method for a given watershed and hydro-climatic conditions remains a challenging task. In general, the Mass Balance (MB) methods for base flow separation are considered to be more objective or to produce actual base flow values. Therefore, the performance of four RDF methods (Chapman, Chapman and Maxwell, Lyne and Hollick and Eckhardt) which are among the existing streamflow separation methods frequently used in the literature has been examined on a watershed in Sudano-Sahelian zone (West Africa). The Conductivity Mass Balance (CMB) method was used during the rainy season in 2017 (from July to October) to produce base flow values. Through statistical analysis, it was found that the four RDF methods are significantly different from the CMB method in the study area context.

Then the Eckhardt method which has a parameter (BFI_{max}) depending of the watershed features (hydrology and hydrogeology) has been calibrated using CMB method as constraint. Eckhardt [21] suggested the use of 0.8 as BFI_{max} in porous aquifer with permanent streamflow. In the case of the Samendeni watershed, the above assumption has been used by referring to Derouane's study [33,40]. As the study area is so large it is possible that, it is not porous everywhere. The value of BFI_{max} was adjusted by the calibration to 0.32. The calibrated results show a significant improvement of Eckhart method although some of the extreme (highest and lowest) values do not match perfectly with those of the CMB method. However, globally the calibration results appear satisfactory based on the performance statistics (NSE=0.90, R^2=0.91, RMSE=0.09, Pbias=-0.49) [42-45].

With the Eckhardt calibrated method, the mean value of BFI is 0.41 very close to the mean value of the CMB method (0.45). Furthermore, the Kruskal Wallis mean rank test confirms that the Eckhardt calibrated method is similar to the CMB method at the confidence level of 95%.

The achievements of the present study have several potential applications: (i) the calibrated method can be used to compute daily base flow values over time from daily discharge at Samendeni gauge station or in other watersheds with similar hydrology and hydrogeology, (ii) the outputs of the calibrated method can be used for hydrological model calibration or (iii) for the investigation of climate change impact on base flow and groundwater or (iv) water management purposes.

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References

1. Lott DA, Stewart MT (2016) Base flow separation: A comparison of analytical and mass balance methods. Journal of Hydrology 535: 525-533.
2. Gottschalk L, Perzyna G (1989) A physically based distribution function for low flow. Hydrological Sciences Journal 34: 559-573.
3. Aksoy H, Wittenberg H (2011) Nonlinear baseflow recession analysis in watersheds with intermittent streamflow. Hydrological Sciences Journal 56: 226-237.
4. Piggott AR, Moin S, Southam C (2005) A revised approach to the UKIH method for the calculation of baseflow. Hydrological Sciences Journal 50: 0-920.
5. Koskelo AI, Fisher TR, Utz RM, Jordan TE (2012) A new precipitation-based method of baseflow separation and event identification for small watersheds (<50km^2). Journal of Hydrology 450-451: 267-278.
6. Eckhardt K (2008) A comparison of baseflow indices, which were calculated with seven different baseflow separation methods. Journal of Hydrology 352: 168-173.
7. Price K (2011) Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. Progress in Physical Geography: Earth and Environment 35: 465-492.
8. Stadnyk TA, Gibson JJ, Longstaffe FJ (2014) Basin-Scale Assessment of Operational Base Flow Separation Methods. Journal of Hydrologic Engineering 20: 04014074.
9. Zhang R, Li Q, Chow TL (2012) Baseflow separation in a small watershed in New Brunswick, Canada, using a recursive digital filter calibrated with the conductivity mass balance method. Hydrological Processes 27: 2659-2665.
10. Stewart MK (2015) Promising new baseflow separation and recession analysis methods applied to streamflow at Glendhu Catchment, New Zealand. Hydrol Earth Syst Sci 19: 2587-2603.
11. Boussinesq J (1904) Theoretical studies on the flow of groundwater infiltrated into the ground and on the flow of the sources. Journal of Pure and Applied Mathematics 5: 5-78.
12. Indarto I, Novita E, Wahyuningsih S (2016) Preliminary Study on Baseflow Separation at Watersheds in East Java Regions. Agriculture and Agricultural Science Procedia 9: 538-550.
13. Miller MP, Johnson HM, Susong DD, Wolock DM (2015) A new approach for continuous estimation of baseflow using discrete water quality data: Method description and comparison with baseflow estimates from two existing approaches. Journal of Hydrology 522: 203-210.
14. Gerald CD (2007) Baseflow Separation Techniques for Modular Artificial Neural Network Modelling in Flow Forecasting | Cluster Analysis | Statistical Classification. Scribd 53: 491-507.
15. Stewart M, Cimino J, Ross M (2007) Calibration of Base Flow Separation Methods with Streamflow Conductivity. Groundwater 45: 17-27.
16. Longobardi AG, Cuomo D, Vilani A, Paolo P (2014) Chemical streamflow analysis as a support for hydrograph filtering in small size watersheds: the Ciciriello experimental catchment.
17. Cimino J (2003) Empirical mass balance calibration of analytical hydrograph separation techniques using electrical conductivity. Graduate Theses and Dissertations.
18. Nakamura R (1971) Runoff analysis by electrical conductance of water. Journal of Hydrology 14: 197-212.
19. Lott DA, Stewart MT (2012) A Power Function Method for Estimating Base Flow. Groundwater 51: 442-451.
20. Jozsef S (2004) Heuristic Continuous Base Flow Separation. Journal of Hydrologic Engineering 9: 311-318.
21. Eckhardt K (2005) How to construct recursive digital filters for baseflow separation. Hydrological Processes 19: 507-515.
22. Gonzales AL, Nonner J, Heijkers J, Uhlenbrook S (2009) Comparison of different base flow separation methods in a lowland catchment. Hydrol Earth Syst Sci 13: 2055-2068.
23. Romanowicz R (2010) An application of a log-transformed low-flow (LTLF) model to baseflow separation. Hydrological Sciences Journal 55: 952-964.
24. Welderufael W, Woyessa Y (2010) Stream flow analysis and comparison of methods for base flow separation: Case study of the Modder river basin in South Africa. European Water Journal 31: 3-12.
25. Rouhani H, Malekian A (2012) Automated Methods for Estimating Baseflow from Streamflow Records in a Semi-Arid Watershed. Desert 17: 203-209.
26. Şengörür B, Dede C, Doğan E (2014) The examination of the performances of methods used in separating the total stream flow in different rivers. Geofizika 31: 1-12.
27. Arnold JG, Allen PM (1999) Automated methods for estimating baseflow and ground water recharge from streamflow records. JAWRA Journal of the American Water Resources Association 35: 411-424.
28. Hughes DA, Hannart P, Watkins D (2003) Continuous baseflow separation from time series of daily and monthly streamflow data. Water SA 29: 43-48.
29. Chapman TG (1991) Comment on "Evaluation of automated techniques for base flow and recession analyses" by Nathan RJ and McMahon TA. Water Resources Research 27: 1783-1784.
30. Chapman TG, Maxwell AI (1996) Baseflow Separation - Comparison of Numerical Methods with Tracer Experiments. Hydrology and Water Resources Symposium 1996: Water and the Environment, pp: 539-545.
31. Lyne V, Hollick M (1979) Stochastic Time-Variable Rainfall-Runoff Modeling. In: Australian National Conference Publication, pp: 89-93.
32. Dakoure D (2003) Hydrogeological and geochemical study of the South-eastern border of the Touadeni sedimentary basin (Burkina Faso-Mali) - Modeling test. PhD Thesis, Pierre and Marie Curie University-Paris VI.
33. Derouane J (2008) Hydrogeological study and mathematical modeling of the aquifer system of the Taoudenni sedimentary basin in Burkina Faso.
34. Pettyjohn WA, Henning RJ (1979) Preliminary estimate of ground-water recharge rates, related streamflow and water quality in Ohio.
35. Nathan R, McMahon T (1990) Evaluation of automated techniques for base flow and recession analyses. Water Resources Research 26: 1465-1473.

36. Grayson R, Argent R, Nathan R (1996) Hydrological Recipes: Estimation Techniques in Australian Hydrology. Cooperative Research Centre for Catchment Hydrology. Water Resources Research 37: 2709-2722.
37. Furey P, Gupta V (2001) A physically based filter for separating base flow from streamflow time series. Water Resources Research 37: 2709-2722.
38. Tallaksen L, Lanen H (2004) Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater.
39. Brodie RS, Hostetler S, Slatter E (2008) Comparison of daily percentiles of streamflow and rainfall to investigate stream-aquifer connectivity. Journal of Hydrology 349: 56-67.
40. Derouane J (2010) Hydrogeological study and mathematical modeling of the aquifer system of the Taoudenni sedimentary basin in Burkina Faso.
41. Matsubayashi U, Velasquez GT, Takagi F (1993) Hydrograph separation and flow analysis by specific electrical conductance of water. Journal of Hydrology 152: 179-199.
42. Moriasi DN, Arnold JG, Liew MWV (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations.
43. Mehan S, Neupane RP, Kumar S (2017) Coupling of SUFI 2 and SWAT for Improving the Simulation of Streamflow in an Agricultural Watershed of South Dakota. Hydrology: Current Research 8: 280.
44. Dis MO, Anagnostou E, Zac F (2015) Evaluating Multi-Scale Flow Predictions for the Connecticut River Basin. Hydrology: Current Research 6: 1-13.
45. Njogy IN, Kitheka JU (2017) Assessment of the Influence of Rainfall and River Discharge on Sediment Yield in the Upper Tana Catchment in Kenya. Hydrology: Current Research 8: 1-9.