NIPES Journal of Science and Technology Research 2(3) 2020 pp.377 - 385 pISSN-2682-5821, eISSN-2682-5821

NIPES

Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Baseflow Estimation in Otamiri Watershed in Imo State, Nigeria

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Article Info

Received 17 August 2020
Revised 21 August 2020
Accepted 24 August 2020
Available online 31 August 2020

***Keywords*:**
Baseflow separation, Otamiri, River basin, Recession analysis

Crossref
NIPES JOURNALS

https://doi.org/10.37933/nipes/2.3.2020.36

https://nipesjournals.org.ng

Abstract

Understanding historical baseflow characteristics is essential for effective planning and management of water resources in the Otamiri River Basin, Nigeria. Baseflow separation and recession analysis have been two of the main tools for understanding runoff generation in catchments. This study is focused on separating baseflow from 1979-1989 monthly total runoff for Otamiri River watershed using the recession analysis. Baseflow was estimated from the monthly streamflow records as difference using the Hewlett and Hibbert method. The results showed that baseflow accounted for 67.19% of total streamflow indicating that more than half of streamflow in Otamiri River is derived from baseflow.

1. Introduction

Quickflow or direct runoff results from rainfall events and often drops to 0 between events, while baseflow is continuous as long as the stream flows. The important distinction between quickflow and baseflow is the time of release of water particles to the stream (i.e. their transit times through the catchment). They are supplied either by fast or slow drainages within the catchment. Quickflow is supplied by direct precipitation and fast storage reservoirs (soil stores) while slow storage reservoirs (mainly groundwater aquifers) supply baseflow. While quickflow is young, baseflow can be much older with substantial fractions of water having mean transit times beyond and averaging 10 years [1]; [2]. Streamflow is considered to have at least two components which can be obtained by applying baseflow separation to the hydrograph. Streamflow at any time (Q_t) is composed of the sum of quickflow (A_t) and baseflow (B_t).

$$Q_t = A_t + B_t \tag{1}$$

where time steps are indicated by the sequences Q_{t-1}, Q_t, Q_{t+1}, etc.

Baseflow separation methods can be grouped into three categories: analytical, empirical and chemical/isotopic or tracer methods. Analytical methods are based on fundamental theories of groundwater and surface water flows. Examples are the analytical solution of the Boussinesq equation, the unit hydrograph model and theories for reservoir yields from aquifers [3]; [4]; [5]. Empirical methods based on the hydrograph are the most widely used [6], because of the availability of such data. Empirical methods include (i) recession analysis [7], (ii) graphical methods, filtering streamflow data by various methods (e.g. finding minima within predefined intervals and connecting them, [8], (iii) low-pass filtering of the hydrograph [9]; [10], (iv) using groundwater levels to calculate baseflow contributions based on previously determined relationships between groundwater levels and streamflows [11].

Recession segments are selected from the hydrograph and can be individually or collectively analysed to gain an understanding of the discharge processes that make up baseflow. The recession curve is the specific part of the flood hydrograph after the crest (and the rainfall event) where streamflow diminishes [12]. The slope of the recession curve flattens over time from its initial steepness as the quickflow component passes and baseflow becomes dominant. A recession period lasts until stream flow begins to increase again due to subsequent rainfall. Hence, recession curves are the parts of the hydrograph that are dominated by the release of water from natural storages, typically assumed to be groundwater discharge. However, semi-logarithmic plots of individual recessions are commonly curved rather than linear. This is because other natural storages can also contribute to baseflow, and these have different regimes of water release to the stream than that of the groundwater stored in the shallow aquifer [13]. The recession curve is effectively a composite of water discharged into the stream from multiple natural storages. This coincides with the concept that a catchment is a series of interconnected reservoirs (such as rainfall, snow, aquifers, soil, biomass etc), each having distinct characteristics in terms of recharge, storage and discharge [14]. A curved semi-logarithmic plot for recessions means that the storage-outflow relationship is non-linear.

Different approaches have been used in recession analysis to address this non-linearity and variability in recession. [15] approximated the semi-logarithmic plot of the recession curve as three straight lines of different slope and used the gradients of these three lines as the recession constants for the main streamflow components of runoff, interflow and groundwater flow. However, the plotting of the three lines was difficult because of the gradual nature of the change in curvature in the recession. [16] plotted flow ratios (Q_0/Q_t) instead of flow (Q_t) on the semi-logarithmic graph and to facilitate better interpretation of the recession. [17] used a double logarithmic plot of streamflow against time and assumed that any abrupt change in slope is interpreted to mark the transition from quickflow to baseflow. [18] used the parameter averaging method for fitting each of the recession segments in a hydrograph. [13] used a wavelet transform analysis to separate out the low frequency signature of the baseflow by a technique to breaking down a signal into its components as applied in image processing and geophysics. [14] used stream hydrograph data over two or more consecutive years, in which the baseflow was assumed to be entirely groundwater discharged from the unconfined aquifer, to calculate the total potential groundwater discharge (V_{tp}) to the stream during this complete recession phase as:

$$V_{tp} = \frac{Q_o k}{2.3} \tag{2}$$

Where Q_0 is the baseflow at the start of the recession and k is the recession index, the time for baseflow to decline from Q_0 to $0.1Q_{0.}$

Each recession segment is often considered as a classic exponential decay function as applied in other fields such as heat flow, diffusion or radioactivity, and expressed as:

$$Q_t = Q_o e^{-\alpha t} \text{ or } \quad Q_t = Q_o e^{\frac{t}{T_c}} \tag{3}$$

where Q_t is the stream flow at time t, Q_0 is the initial stream flow at the start of the recession segment, α is a constant also known as the cut-off frequency (f_c) and T_c is the residence time or turnover time of the groundwater system defined as the ratio of storage to flow.

The term $e^{-\alpha}$ in this equation can be replaced by k, called the recession constant or depletion factor, which is commonly used as an indicator of the extent of baseflow [19]. The typical ranges of daily recession constants for streamflow components, namely runoff (0-2-0.8), interflow (0.7-0.94) and groundwater flow (0.93-0.995) do overlap [19]. However, high recession constants ($e^{-\alpha} > 0.9$) tend to indicate dominance of baseflow in streamflow. Another parameter interpreted from the recession segment is the recession index (K) which is the time (in days) required for baseflow to recede by one log-cycle i.e. Q_0 to $0.1Q_0$. A similar index called the half-flow period or half-life, which is the time (in days) for flow to halve, can also be calculated. For streams with low baseflow inputs the half-life may be in the range of 7-21 days, while discharge from large stable natural storages can result in a half-life exceeding 120 days [14]. The integrated form of the classic recession function of Equation 3 is:

$$Q_t = \alpha S_t \tag{4}$$

where S_t is the storage in the reservoir that is discharging into the stream at time t.

This relationship is called a linear storage-outflow model and implies that the recession will plot as a straight line on a semi-logarithmic scale. Different storage-outflow models or combinations of storage-outflow models have been used to obtain a better fit to the recession curve. The classic exponential decay function which represents a linear relationship between storage and outflow, have been developed to model discharge from different types of natural storages. [20] added a constant (b) to the linear reservoir equation:

$$Q = Q_o e^{-\alpha t} + b \tag{5}$$

This provided a better fit to recession curves that stabilized to a constant streamflow over time. This constant flow may represent discharge from large groundwater storage or from ice or snow reserves. A model based on linear storages is proposed in this study to provide a better fit to the recession curves for a small forested catchment. The linear reservoir concept is based on analysis of the recession limbs of the streamflow hydrograph and has been used extensively for description of catchment responses during periods without rain [7]; [21]; [22]. The model of linear reservoir is applied in this study for describing base flow changes following end of a precipitation period. The issue of whether storages can be represented by linear reservoirs or require to be treated as non-linear reservoirs has also been widely discussed in the hydrological literature (in the case of recession analysis by [23], [24] [25] and [26]. [25] identified three different storage behaviours in the three catchments they studied. Linear reservoirs only require one parameter each and are more tractable mathematically. They are widely used in rainfall–runoff models. Non-linearity can be approximately accommodated by using two or more linear reservoirs in parallel, but more parameters are required (three in the case of two reservoirs).

2. Methodology

The little available record was only the 1979-1988 discharge data of Otamiri River (at Nekede gauging station) as the gauging equipment was reportedly faulty. The data was obtained from the Anambra-Imo river basin in Imo State of Nigeria, which is one of the twelve river basin development authorities, (RBDAs) in Nigeria. The mean monthly discharge was computed as presented in Table 1.

2.1 Study Area

The Otamiri River itself starts as a first-order stream at its source at Egbu, Owerri North L.G.A. and captures Nworie river and flows for about 30 km to confluence with the Oramiriukwa River at Emeabiam, Owerri West L.G.A. in Imo State, Nigeria. The catchment area measures about 100 square kilometer. The source of the river is located on latitude 05`26`N and on longitude 07`02`E [27] reported that the Otamiri River has maximum average flow of 10.7m^3/s in the rainy season (September - October) and a minimum average flow of about 3.4 m^3/s in the dry season (November-

February). The total annual discharge of the Otamiri is about 1.7 x 10^8 m^3, and 22 percent of this (3.74 x $l0^7$ m^3) comes from direct runoff from rainwater and constitutes the safe yield of the river.

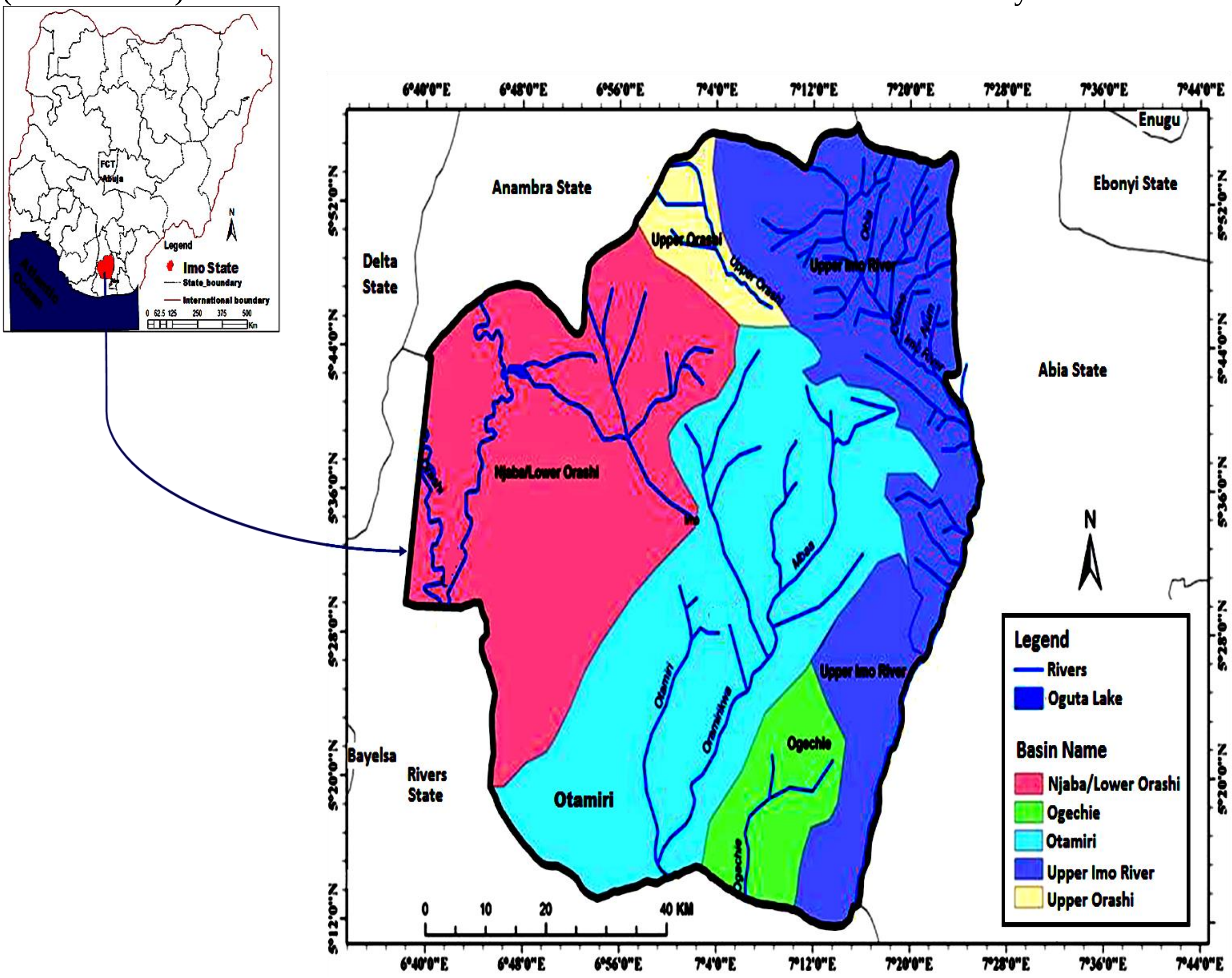

Figure 1: Otamiri sub-basin showing the location of River Otamiri (modified from [27])

2.2. Baseflow separation

One widely used empirical method for baseflow separation in small catchments proposed by [17] was used in the study. [17] argued that “since an arbitrary separation must be made in any case, why not base the classification on a single arbitrary decision, such as a fixed, universal method for separating hydrographs on all small watersheds?” The hydrograph was separated into “quickflow” and “delayed flow” components by arbitrarily projecting a line of constant slope from the beginning of any stream rise until it intersected the falling side of the hydrograph. The steady rise was described by the equations.

$$B_t = B_{t-1} + k \; for \; Q_t > B_{t-1} + k \tag{6}$$

$$B_t = Q_t \; for \; Q_t \leq B_{t-1} + k \tag{7}$$

where k is the slope of the dividing line. The slope they chose was 0.05ft^3 s^{-1} $mile^{-2}$ h^{-1} (0.000546m^3 s^{-1} km^{-2} h^{-1} or 0.0472$mmday^{-1}$ h^{-1}).

This universal slope gives a firm basis for comparison of BFIs between catchments.

Table 1: 10-year Mean Monthly Discharge (m^3/s) of Otamiri River

YEAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR
1978/79	3.85	3.65	3.54	3.77	4.09	5.35	7.48	6.56	5.79	4.64	4.07	2.61
1979/80	5.36	4.97	4.87	4.68	5.62	8.46	10.1	7.87	6.88	6.12	4.59	3.77
1980/81	2.49	2.23	3.22	3.85	4.33	5.45	6.14	6.14	5.7	5.55	4.66	4.49
1981/82	4.11	4.23	4.59	4.97	6.15	8.2	8.61	7.64	7.28	7.39	7.16	6.88
1982/83	6.67	6.97	6.93	7.01	6.97	6.97	7.99	8.42	8.68	7.67	7.11	7.33
1983/84	7.32	8.46	10.16	9.83	9.81	11.16	11.84	11.34	11.19	11.15	10.33	9.33
1984/85	6.06	6.35	6.81	7.33	7.87	7.55	8.1	8.53	8.48	7.82	7.47	7.82
1985/86	7.39	7.14	7.24	7.79	8.88	9.25	9.2	8.15	7.95	7.91	7.71	7.73
1986/87	7.84	8.77	8.19	8.01	8.08	8.67	9.23	9.21	9.13	9.08	8.69	8.96
1987/88	8.6	8.81	8.71	8.68	8.63	9.13	9.15	9.28	8.8	8.43	8.09	7.91

2.3 Recession analysis

Once baseflow separation has been achieved, recession analysis via the recession plot was applied to the separated quickflow and baseflow components, in addition to the streamflow. According to [22], it was assumed that water flow (Q) from a basin, following end of a precipitation period, is in direct proportion with then quantity of water in the reservoir (S). This can be expressed with the following equation:

$$S = kQ \tag{8}$$

where k stands for the retention constant which represents the retarding time of the system. The depletion of such a linear reservoir can be described by an exponential recession:

$$Q_t = Q_0 e^{-(t-t_0)/k} \tag{9}$$

where Q_t stands for the outflow at any time t in m^3s^{-1}; Q_o stands for the outflow at time t_0 in m^3s^{-1}, and k for the retention constant with the dimension of time.

Though there are number of equations to describe the recession curve but the following equation according to [13] was used:

$$\mathrm{Q_t = Q_0 K_r^{(t-t_0)}} \tag{10}$$

where $\mathrm{Q_o}$and $\mathrm{Q_t}$are the flows at time t_o and t and $\mathrm{k_r}$ is a recession constant with a value of less than unity. Equation (10) was expressed in a different form as:

$$\mathrm{Q_t = Q_0 e^{-a(t-t_0)}} \tag{11}$$

where $\mathrm{a = -In(k_r)}$. The value of the recession constant $\mathrm{k_r}$ depends on the time unit selected.

Equation (11) was plotted on a semi logarithmic paper with Q plotted on logarithmic scale and the slope represented the recession constant, $\mathrm{k_r}$. Base flow, Q_b was computed for each stream flow discharge, Q while the runoff component, Q_r was obtained by subtracting the base flow from the stream discharge. The percentage contribution of base flow and runoff to the discharge were respectively calculated. The contribution of base flow to the discharge was determined by dividing the total annual base flow ΣQ_b, by the total discharge Q_T, ($\Sigma Q_b/Q_T$) and the contribution of runoff to the total discharge was obtained by dividing the total runoff ΣQ_r by total discharge Q_T, ($\Sigma Q_r/Q_T$).

3. Results and Discussion

The average monthly discharge data were plotted on the same axis to reveal the various features of the hydrographs for each year. This is presented in Figure 2. The hydrograph for 1979/80 showed the characteristic feature of a hydrograph and was the only hydrograph amenable to baseflow separation by recession curve method. It cut across all other hydrographs in such a manner that it appeared to be the mean hydrograph for the ten year data. This hydrograph, 1979/80 shown in Figure 3 was then selected on this basis as representative of all hydrographs for baseflow separation.

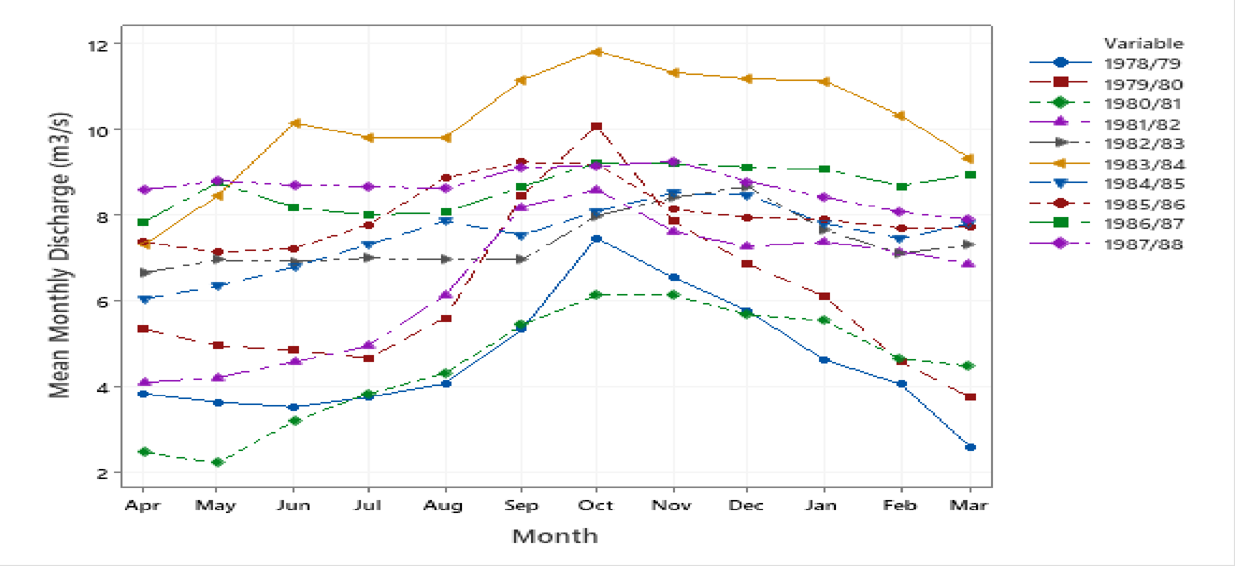

Figure 2: 1979/80 to 1987/88 Mean Monthly Discharge Hydrograph of Otamiri River

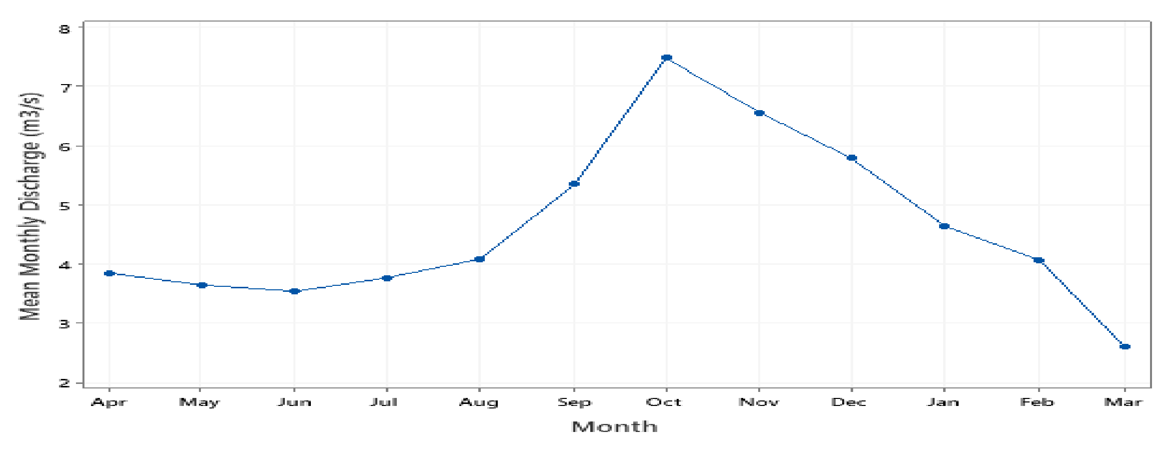

Figure 3: 1979/80 Mean Monthly Discharge Hydrograph of Otamiri River

3.1 Recession Analysis

From the 1979/80 hydrograph (Figure 3), for $Q_o = 5.36m^3/s$, $t_0 = 1$ month and for $Q_4 = 4.68m^3/s$, $t_4 = 4$ months. Substituting these values into Equation 10 gives:

$$K_r^3 = {}^{4.68}/_{5.36} = 0.873 \equiv K_r = \sqrt[3]{0.873} = 0.95 \qquad (12)$$

Then substituting Q_t from Equation 10 for Q in Equation 8 gives the expression for computing the groundwater storage S as:

$$S = KQ_0 K_r^{(t-t_0)} \qquad (13)$$

And, substituting K= 0.95 and t_0= 1into Equation 13 gives

$$S = (0.95)(5.36)K_r^{(t-1)} \equiv \qquad S = 5.09K_r^{(t-1)} \qquad (14)$$

3.2. Baseflow Separation

Equation 14 was used to compute the baseflow for the various time intervals and is tabulated in Table 2 as Q_b. The runoff component Q_r was obtained by subtracting the baseflow from the stream discharge (Q-Q_b) and also is shown in Table 2. The baseflow is plotted on the same axis as the discharge hydrograph as shown in Figure 4. It can be observed that the baseflow progressively declined from the rainy season (April to October) to the dry season (November to March). However, baseflow was observed to be sustained with the peak of rainy season (July to October).

Table 2: Computation of Direct Runoff for 1979/80 Hydrograph

Month	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
1979/80 Mean monthly average discharge Q (m^3/s)	5.36	4.97	4.87	4.68	5.62	8.46	10.10	7.87	6.88	6.12	4.59	3.77
Base flow Q_b (m^3/S)	5.36	5.09	4.84	4.59	4.36	4.14	3.94	3.74	3.55	3.38	3.2	3.05
Direct Runoff Q_r (m^3/s)	-	-0.12	0.03	0.09	1.26	4.32	6.16	4.13	3.33	2.74	1.39	0.72

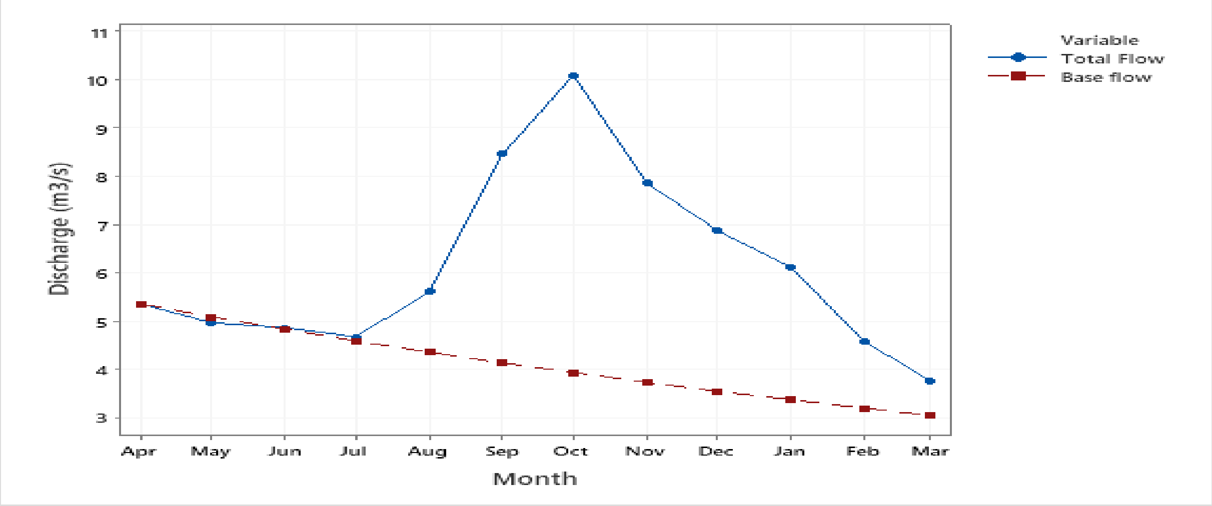

Figure 4: Baseflow Separation from Total Flow

The percentage of baseflow to the total discharge was computed as 67. 19% while the percentage of runoff to total discharge was estimated as 32. 81%. The above analysis revealed that the contribution of the baseflows to the total discharge for Otamiri River is about 67% which is substantial while the contribution of the runoff is about 33%. Therefore Otamiri River is greatly sustained by the underground flow and runoff does not have significant effect on the river discharge. High baseflow yield in the basin is likely due to the combination of land use and high elevation settings. This may be explained by the presence of forest supported by high elevations of the area, high precipitation, and low temperature [21]. Soil permeability, underlying aquifers, and hydrologic landscape regions also play a major role in baseflow distribution in the basin [9]. Overall, baseflow was a large proportion of total streamflow in Otamiri River during the period examined.

4. Conclusion

Baseflow is an important ecological factor in river basin. It is important to analyze baseflow to optimize the arrangement of water resources in river basin. The base flows of the Otamiri River catchment is evaluated in this study using the measured data of streamflow discharge at the catchment outlet point. The investigation revealed that base flow contributes about 67.19% to the total flow of Otamiri catchment. Based on the described analysis of separation of total flow into base flow and direct flow, it can be concluded that Otamiri River is greatly sustained by the underground flow and runoff does not have significant effect on the river discharge. The outcome of this study provides water managers with information that can be used to develop improved water management strategies.

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