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Baseflow Estimation for Tropical Wet and Dry Climate Region Using Recursive Digital Filters

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A region with tropical wet and dry climate is characterised by two major seasons of wet and dry. Baseflow could be a good predictor of drought by representing the low flow conditions in this region. Hence, having knowledge regarding baseflow is important for the drought preparedness. Based on this aspect, the study aims to separate the baseflow of Baitarani River, India in a tropical wet and dry climate region using the Eckhardt filter and to compare that with Lyne and Hollick (L&H) filter. The baseflow separated using two filters were further used for the estimation of Baseflow Index (BFI) values for the wet and dry seasons. Throughout both the seasons, Eckhardt filter generates almost same BFI values and shows a high level of agreement with each other, whereas the L&H filter generates a wide range of BFI values. Further, sensitivity analyses performed to analyse the relative importance of Eckhardt filter parameters exhibited that recession parameter is having a significant effect on baseflow only during the dry season, but the BFI has a notable effect on baseflow throughout the season. Hence, being a two parameter filter, Eckhardt filter gives good estimates of baseflow compared to the L&H filter.

Key Words: *tropical wet and dry climate region, baseflow separation, recursive digital filter, Lyne and Hollick filter, Eckhardt filter*

1. INTRODUCTION

Regions with tropical wet and dry climate are one of the prevailing climate regions characterised by two major seasons of wet and dry. The prevailing climate is dry and the drought occurrence will be higher in those regions during the dry season. Over the past decades, the persistence of drought is remarkable in this region. Hence, drought needs to be predicted because it is a creeping disaster and it is not visible due to its slow accumulation process[1)]. Baseflow could be a predictor of drought by representing the low flow conditions. Baseflow is the portion of streamflow that contributed from groundwater storage and baseflow separation involves partitioning of the streamflow into the baseflow and quick flow. International Glossary of hydrology[2)] defines the baseflow as the ‘flow of water in a stream during prolonged dry weather’. This prolonged low flow during dry weather does not constitute a drought, but sometimes can be defined as an annual drought[3)]. Separation of baseflow from the quick flow, resultant of excess rainfall, is essential and useful to get an idea about this annual drought and groundwater exploitation levels and further rejuvenation required.

The baseflow can vary with variations in groundwater abstraction, changes in land use and land cover patterns, climate change, etc. from time to time[4)]. Hence it is very important to have clear knowledge about the baseflow as it is the key factor for the drought prediction and the baseflow separation techniques having prime importance in the field of hydrology and water resources management. Further, baseflow forecasting is important for the study of climate fluctuations and for the survival of ecosystem components. The information of baseflow forecasted from the predicted stream discharge can be used to allocate water for drinking and irrigation needs under drought conditions.

Enormous baseflow separation techniques are currently in use such as the primitive graphical method to the most advanced isotope tracer technology. The other common prevailing methods are flow duration curves, frequency curve analysis, streamflow recession for gauged basins and regional regression, digital filters, and physically based models for ungauged basins[5)]. For the long term analysis of baseflow in an ungauged basin, digital filters are being used which separates the direct runoff from the streamflow with limited data. It has an added advantage of easy handling and capability to produce results similar to graphical method[5)].

The one parameter digital filter has been proposed by Lyne and Hollick[6)]. Although recognised as lacking a physical basis, it is easy to automate and repeatable. The filter parameter enables the shape of the hydrograph after separation by controlling the degree of attenuation[7)]. The Lyne and Hollick (L&H) filter have been used by Nathan and McMahon[7)] and they generalised the value of the filter parameter by comparing the results of baseflow separation using three parameter values of 0.9, 0.925 and 0.95 against two other methods of manual separation and the smoothed minima. They found that satisfactory results were provided by all three values, but recommended a value of 0.925 which gave similar results to manual baseflow separation for 122 catchments in New South Wales and Victoria[8, 9)]. Later, Chapman[10)] pointed out that the L& H filter provides a constant baseflow. Hence, Chapman modified the L & H filter and developed a new algorithm and simplified it later[11)] by adding a recession constant. Boughton introduced a two-parameter filter which is used in the hydrologic model AWBM as a single pass filter[12)]. Further, Jakeman and Hornberger established a three parameter filter which was the extension of Boughton two-parameter algorithm[13)]. Later Furey and Gupta developed a physically based filter using the mass balance equation for baseflow through a hillside[14)]. Subsequently, Eckhardt generalised the L&H filter algorithm and developed Eckhardt's two-parameter recursive digital filter[15)] based on recession analysis under the assumption that the outflow from an aquifer is linearly proportional to its storage. Eckhardt added another parameter called Baseflow Index (BFI) for the estimation of baseflow from the stream hydrograph.

Among the above-mentioned filters, the L&H filter has been widely used in many parts of the world. It forms the basis of Australian Rainfall and Runoff Revision Project 7, which uses the baseflow as flood flow predictors[16, 17)]. Another application of L&H filter includes its implementation in parts of Eastern Africa and North-Western parts of Singapore[18, 19)]. However, the Eckhardt filter is a newly developed filter and is mainly applied on North American Catchments and Germany[15, 20)]. None of the studies have been conducted in the wet and dry climate regions to evaluate the effects of the two major climates on baseflow using Eckhardt filter. Hence, application of Eckhardt filter in these regions will provide useful information on baseflow variation. Being the widely used filter in different parts of the world, the results obtained from the Eckhardt filter can be compared with L&H filter. Due to the prevalence of long dry season and large area contribution, baseflow estimation has very much importance in tropical wet and dry climate regions.

Based on the light of the above discussions, the present study was undertaken to apply the Eckhardt filter to separate the baseflow and to compare the results with the baseflow estimated by most widely used L&H filter of an ephemeral river in tropical wet and dry climate region. The study also evaluates the effects of two major seasons on baseflow in which the characteristics of the BFI are also studied.

2. MATERIALS AND METHODS

(1) Study area and data used

The catchment area of the Baitarani River at Anandapur, Odisha is about 8,580 km^2, which lies in Eastern India between the longitudes of 85°10' E to 87°03' E and latitudes of 20°35' N to 22°15' N and is shown in **Fig.1**[21)]. The annual rainfall in this river basin varies from 642 mm to 3,094 mm with an average of 1,187 mm (1980-2010). There is no regular trend in the rainfall pattern. The maximum temperature in the watershed was 48.5°C (21/04/2009), recorded at Keonjhar station and the minimum was 6°C (15/01/1995)[22)]. The drainage pattern of the basin is dendritic or semi-dendritic in nature and it has the forest, vegetation, and hard rocks as major land covers. The basin is overlain by well-drained loamy soil and it has an important role in the groundwater storage of the basin. The basin showed the occurrence of thick sand and gravel layers in its sedimentary piles forming prolific aquifers[23)]. Baitarani River is an ephemeral river with porous aquifer having short period flow. The basin lies in the

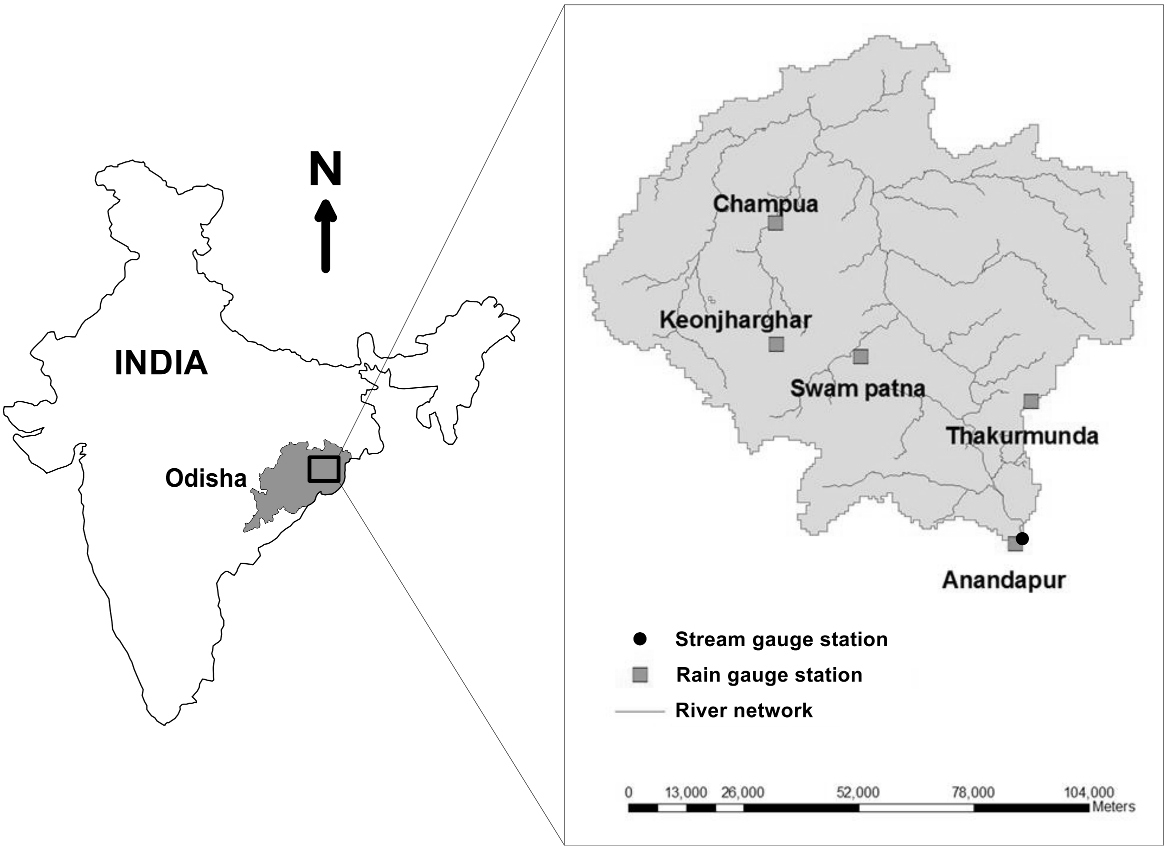

Fig.1 Index map of study area.

tropical wet and dry climate region where wet and dry seasons are profound. The wet season is prolonged only for five months from June to October whereas the remaining months constitute the dry season. The runoff and water stage data at daily scale was collected from the Central Water Commission (CWC), Bhubaneswar for the Anandapur gauging station from 1996-2008.

(2) Baseflow separation methods

a) L & H recursive digital filter

The L&H filter[6)] is given by the following equation:

$$b_k = \alpha \cdot b_{k-1} + \frac{1-\alpha}{2}(Q_k + Q_{k-1}) \qquad (1)$$

subject to $b_k \leq Q_k$, where $b_k =$ baseflow at kth time step, $b_{k-1} =$ baseflow at k-1th time step, $Q_k =$ streamflow at kth time step, $Q_{k-1} =$ streamflow at k-1th time step, and $\alpha =$ filter parameter. The value of filter parameter has been chosen as recommended by Nathan and McMahon[7)]. The initial estimate of baseflow, b_0 was set as the initial value of streamflow, Q_0 subject to criteria $b_0 \leq Q_0$. The stream flow Q_0 was estimated as the ratio of Q_1 to the filter parameter α when the quick runoff has ceased. Then the river flow is maintained only by groundwater recharge and that outflow from the aquifer is linearly proportional to its storage. Under this condition, the streamflow is,

$$Q_k = \alpha \cdot Q_{k-1} \qquad (2)$$

A two pass filtering is applied to separate out the baseflow from streamflow. Once the baseflow had been separated, the BFI, which is the long term ratio of baseflow to streamflow, is given by the following equation:

$$BFI = \frac{\sum_{k=1}^{t} b_k}{\sum_{k=1}^{t} Q_k} \qquad (3)$$

where $t =$ total time period under consideration. However, there is no exact definition of this time period and it varies between four months to several years[15, 24)] in different studies. Hence, we have calculated the BFI for the wet and dry seasons in each year.

b) Eckhardt recursive digital filter

Eckhardt filter serves the partition of the streamflow into two main components, direct runoff and baseflow[15)] by low pass filtering. The two parameter filter can be represented by the following equation:

$$b_k = \frac{(1-BFI_{max})a \cdot b_{k-1} + (1-a)BFI_{max} \cdot Q_k}{1-(a \cdot BFI_{max})} \qquad (4)$$

subject to $b_k \leq Q_k$, where $a =$ recession constant, and $BFI_{max} =$ maximum value of BFI. The filter parameter BFI_{max} is defined based on the hydrological and hydrogeological characteristics of the basin. Eckhardt[15)] suggested setting $BFI_{max} =$

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. The recession constant a can be determined by recession analysis. The recession analysis for the selection of recession period was undertaken according to the correlation method described by Eckhardt[20, 25]. The condition of the streamflow candidate to be selected for the recession period is that it should follow the recession criteria at least for five days continuously[20]. If the above recession were long enough that the streamflow Q_k and Q_{k+1} consisted entirely of baseflow, and there were no groundwater recharge during the time steps k and k + 1, then the assumption that the aquifer is a linear reservoir were correct, and the following relation would hold: [20]

$$Q_{k+1} = a \cdot Q_k \tag{5}$$

Then construct the scatter plot of Q_{k+1} against Q_k and the slope of the line passing through the origin, which forms the upper bound of the scatter plot is chosen as recession constant[20]. With these two estimated filter parameters, the baseflow separation was carried out using Eckhardt filter. The initial value of baseflow has been set in the same way as that of L&H filter. However, Eckhardt filter uses its recession constant instead of L&H filter parameter α. Once the baseflow has been separated, the BFI was calculated in a similar way as that of L&H filter.

(3) Autocorrelation analysis

Autocorrelation analysis is a measure of the correlation of a variable with its lagged copy. The correlation is measured in terms of correlation coefficient, which is given as:

$$r_m = \frac{\sum_{t=m+1}^{\tau}(x_t-\bar{x})(x_{t-m}-\bar{x})}{\sum_{t=1}^{\tau}(x_t-\bar{x})^2} \tag{6}$$

where m is the lag time and τ is the sample size.

(4) Sensitivity analysis

Sensitivity analysis is performed to check the influence of parameters involved in the estimations. For this purpose, BFI_{max} is changed while keeping the filter parameter constant and vice versa. Sensitivity index (SI) is a measure of sensitivity analysis and is given by:

$$SI = \frac{b_i-b_j/b_i}{p_i-p_j/p_i} \tag{7}$$

where b_i= baseflow with parameter p_i, b_j= baseflow with parameter p_j , p_i =parameter at ith iteration, p_j=parameter at jth iteration.

3. RESULTS AND DISCUSSIONS

The baseflow was separated from the observed streamflow using the L & H filter for the wet and dry seasons in which the filter parameter was kept as 0.925. Two filter passes were applied over the streamflow which resulted in the baseflow. The estimated baseflow varies with the streamflow and become high when the streamflow reaches its peak values during the wet season. It is obvious that the filter generates higher baseflow under peak flows, which may be consistent with the actual conditions of the basin during the rainfall. Hence, it can be envisaged that the L&H filter not only accounts for the baseflow contributed from groundwater storage, but also from the delayed interflow during the wet season. However, during the dry season, accounted baseflow was low compared to that of the wet season and the major portion was contributed from groundwater storage.

In the case of Eckhardt filter, two filter parameters need to be defined. The first parameter, BFI was initially approximated using Eckhardt's pre-defined basin specific BFI_{max} values. The value of BFI_{max} was chosen as 0.5 because the study area is an ephemeral stream with porous aquifer. The second parameter, recession constant a, was estimated by performing the autocorrelation analysis of recession flow. Hence, the correlation of streamflow was analysed for various seasons and recession period with different lag times. 13 year data was used for the analysis from 1996-2008. A time lag of 85 days was considered in the analysis, after which the correlation coefficient becomes zero or negative. **Fig.2** shows the correlogram of streamflow for total, wet and dry seasons, and recession periods. It shows that the correlation varies with time and high correlations are found at short lags.

Variations in the value of correlation coefficient observed in daily series may be due to the changes in the precipitation pattern, water storage, and drainage characteristics of the basin. The comparison of discharge autocorrelations of different seasons (wet and dry) indicates that discharge autocorrelation is very high for the dry season. During the dry season, the flow is mainly contributed from baseflow and rainfall contribution is insignificant. Hence a uniform flow is maintained during the dry season, which produces a high autocorrelation. A high variability in discharge occurs during the wet season due to high rainfall, which significantly contributes to total streamflow. Thus, the discharge autocorrelations for the wet season are lower than those for the dry season. The correlogram for recession periods lasts up to 30 days, after which the correlation coefficient becomes insignificant. With an increase in the time lag, the

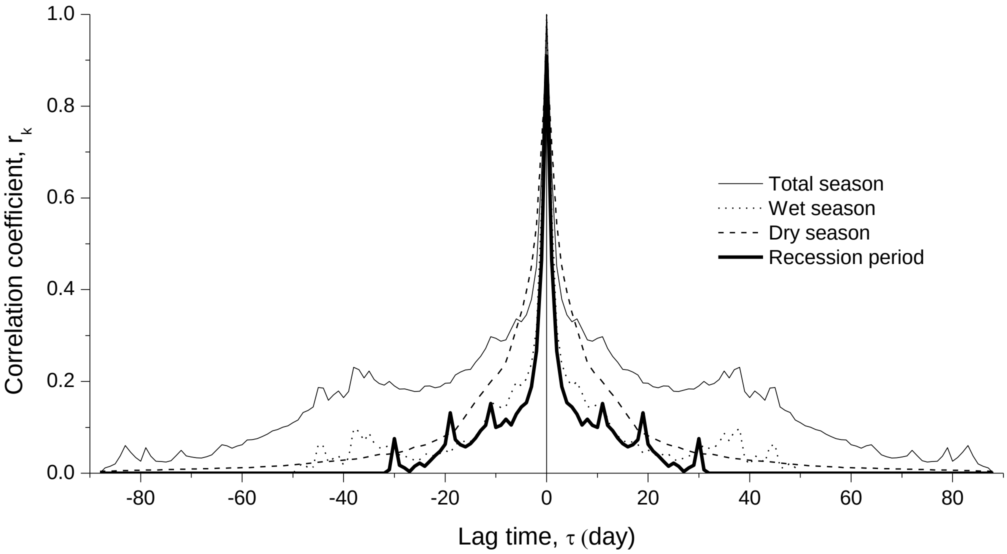

Fig.2 Correlogram of daily discharge for the total, wet, dry seasons and for recession periods.

correlation coefficient becomes small which indicates the fast recession characteristics of the basin. Hence, for the filter parameter estimation, discharge correlations during recession period with a lag time of one day was considered. **Fig.3** shows the scatter plot of Q_{k+1} against Q_k during the recession periods. It is clear from **Fig.3** that most of the points are clustered near to the origin and having fast recessions. Hypothetically, all points must lie on a line which passes through the origin with slope a. Hence, in the actual case, Q_{k+1} and Q_k having a different level of recessions. These differences in streamflow recession at the kth and k+1th time steps are may be because the streamflow contains direct runoff instead of baseflow alone. Consequently, it recesses faster than it assumes. For the present study, the recession constant is the slope of the line passing through the origin, which forms the upper bound of scatter plot as shown in **Fig.3,** and is 0.8595.

Using these two parameters (recession constant andBFI_{max}), the baseflow separation was carried out in the wet and dry seasons. The baseflow separated using both the filters are shown in **Fig.4**. The dry season is represented by the rising and recession limb of **Fig.4** and the rest segment constitutes the wet season. The Eckhardt filter predicts a higher baseflow during the wet season when compared to the dry season. During the wet season, a significant amount of precipitation will be stored in the basin as groundwater and this will contribute to the streamflow in the form of baseflow. However, through the dry season, due to the absence of rainfall, the baseflow contribution will be low. It can be seen from **Fig.4** that during the wet season, high baseflow peaks were observed along with the streamflow peaks by both the filters. At this stage, both the filters

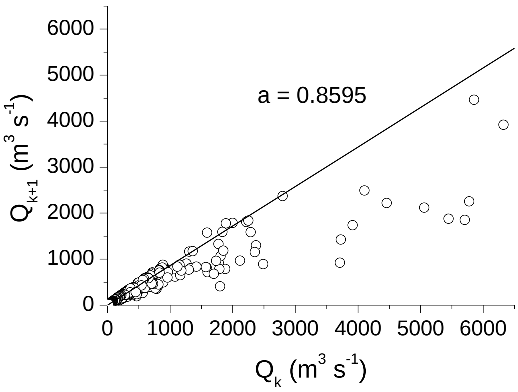

Fig.3 Scatter plot of Q_{k+1} against Q_k during recession periods.

account almost same baseflow. However, the L&H filter quantifies slightly higher baseflow compared with the Eckhardt filter during both the seasons. The reason for that difference may be the L&H filter is a fixed one parameter filter compared with Eckhardt filter. It does not consider the hydrological characteristics of the basin and slightly over predicts the baseflow. Since the Eckhardt filter involves a recession parameter which shows the recession characteristics of the particular basin and a BFI_{max} parameter which predicts the maximum value of BFI, the basin can generate based on the hydrological and hydrogeological characteristics. The BFI_{max} controls the amount of baseflow to be separated from streamflow.

Using this estimated baseflow by both the filters, BFI values was calculated for the wet and dry seasons of each year as the ratio of baseflow to streamflow of that particular season and is shown in **Fig.5**. It varies from year to year for both wet and dry seasons.

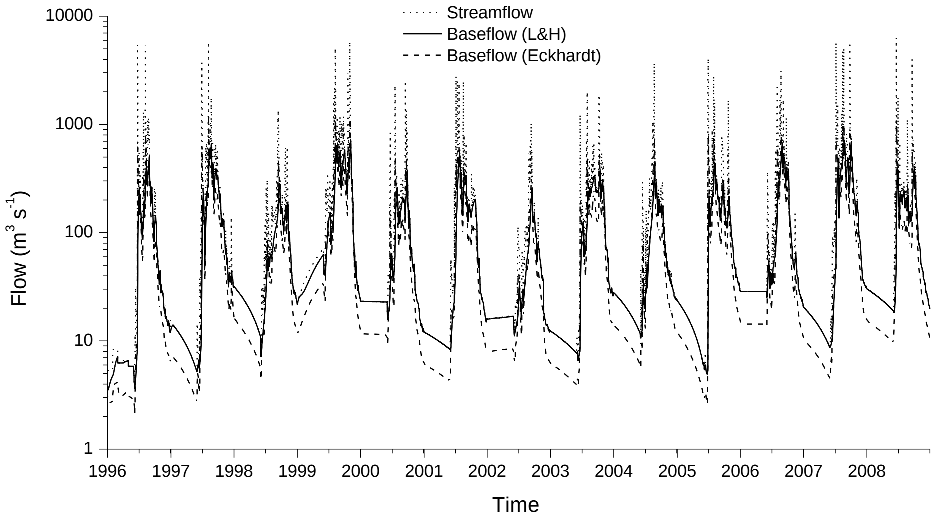

Fig.4 Daily baseflow separation using Eckhardt and L&H filters.

Fig.5a) shows the BFI box plot for the dry season calculated using the two filters. The box plot for the Eckhardt filter is comparatively short and having a high level of agreement with each other. The maximum and minimum BFI values obtained was 0.57 and 0.51 respectively, excluding the outliers with an average value of 0.54. At the same time, the box plot of L&H filter is quite long and is skewed towards the bottom, which shows a range of values with a maximum value of 0.98 and a minimum of 0.78 which averages at 0.94. This indicates that the BFI values calculated using the L&H filter for each year are different and very high compared with BFI values calculated using Eckhardt filter. This reveals that, during the dry season, L&H filter not only predicts baseflow from groundwater storage but also from delayed interflow. Hence, the Eckhardt filter generates baseflow which is usually associated with water discharged from groundwater storage.

The box plots for the wet season is shown in **Fig.5b)**. As like in the dry season, box plot for the Eckhardt filter is small with a maximum, minimum, and average BFI values of 0.49, 0.45, and 0.48 respectively. Most of the observations are on the lower end of the scale, so the distribution is skewed towards the bottom. Concurrently, the box plot of L&H filter is skewed towards the top with a maximum, minimum, and average values of 0.57, 0.45, and 0.51 respectively. During the wet season, both the filters are capable of predicting almost same

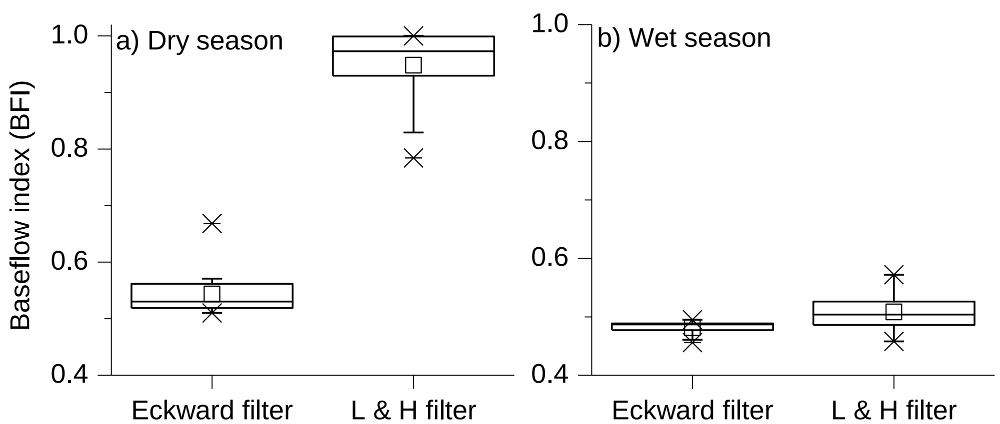

Fig.5 The box plot of calculated BFI values for the dry and wet season. The bottom and the top lines of the boxes show the lower and upper quartiles, respectively. The line passing through the box and the square within the box represent median and mean respectively. The whiskers extend to the highest and lowest observation unless they are more than 1.5 box-lengths long; observations outside this range are plotted as asterisks. The x-axis shows the two types of filter used for the BFI value estimation.

Table 1 Results of sensitivity analysis of Eckhardt filter parameters.

		Wet season		Dry season	
a	BFI_{max}	calculated mean baseflow	SI	calculated mean baseflow	SI
0.8595	0.5	171.33		17.74	
0.7595	0.5	172.57	-0.06	16.86	0.42
0.8095	0.5	172.09	-0.07	17.20	0.52
0.9095	0.5	169.82	-0.15	18.83	1.05
0.9595	0.5	164.11	-0.36	22.91	2.50
0.8595	0.4	136.68	1.011	14.47	0.92
0.8595	0.45	153.98	1.012	16.12	0.91
0.8595	0.55	188.74	1.015	19.32	0.89
0.8595	0.6	206.19	1.017	20.87	0.88

BFI value. The BFI values calculated using Eckhardt filter is lower than 0.5 during the wet season, which is equal to the BFI_{max} suggested by Eckhardt for ephemeral streams. When it comes into play with the dry season, slight deviations from the pre-defined value was observed. However, the L&H filter generates BFI values greater than 0.5 during both wet and dry seasons. Both the filters estimate a higher BFI value during the dry season compared with the wet season. This can be interpreted as the absence of rainfall. Through the dry season, the effect of rainfall become insignificant and streamflow is mainly contributed by baseflow. However, the wet season is characterised by rainfall variability and the streamflow is mainly composed of direct runoff.

The standard deviation of BFI values generated by L&H and Eckhardt filters during the dry season is 0.06 and 0.04 respectively, and the same for the wet season is 0.03 and 0.01 respectively. Hence, the Eckhardt filter gives good estimates of baseflow and BFI values compared to the L&H filter because it is a two parameter filter. Further, to analyse the comparative effect of two parameters of Eckhardt filter, the sensitivity analysis was performed using the SI. The filter parameter BFI_{max} was changed from 0.5 by ± 0.05 by keeping the recession constant, a as 0.8595 and the recession constant a was changed from 0.8595 by ± 0.05 by keeping the BFI_{max} as 0.5. The results of sensitivity analysis are shown in **Table 1**. For the wet season, the SI slightly increases with increase in BFI_{max} value. Concurrently, the SI values are negative and decrease with an increase in the value of recession parameter. From **Table 1**, we can see that the SI during the dry season have the opposite trend with respect to the relative changes in parameter a and BFI_{max} . However, BFI_{max} having an influence on estimated baseflow for both the seasons. During the dry season, recession characteristics are more pronounced and recession parameter exerts higher influence on baseflow. Simultaneously, the effect of recession parameter is insignificant during the wet season due to prevailing rainfall and BFI_{max} exerts high influence on baseflow during the wet season. This shows that the BFI_{max} have a higher influence on estimated baseflow and recession parameter exerts a comparatively weak influence on baseflow.

4. CONCLUSIONS

The use of Eckhardt recursive digital filter in tropical wet and dry climate region with pre-defined BFI_{max} value and recession parameter obtained as a result of correlation analysis with a lag time of one day will give a first approximation of the baseflow. This baseflow separated using the Eckhardt filter were compared with L&H filter baseflow. The baseflow separated by using two digital filters were further used for the estimation of BFI values for the wet and dry seasons. Throughout both the seasons, Eckhardt filter generated almost same BFI values which satisfy the condition of BFI_{max} =0.5 and shows a high level of agreement with each other. However, the L&H filter generates a wide range of BFI values for both the seasons and over predicts the BFI value for the dry season. Hence, the Eckhardt filter gives good estimates of baseflow compared to the L&H filter.

Further, the sensitivity analysis was performed to analyse the comparative effects of the parameters of Eckhardt filter. The results exhibited that even though the recession parameter is insignificant during the wet season, it can considerably affect the baseflow during the dry season. However, the BFI_{max} having notable effects on baseflow separation throughout the season. The higher proportion of baseflow predicted during the dry season by both the filters can be interpreted as the release of groundwater storage in the absence of rain. Comparative low BFI values during the wet season are explained by the prevailing rainfall.

During the wet season, the groundwater table will rise due to high characterised rainfall and recharge. Consequently, throughout the dry season groundwater table will fall. Hence, having knowledge regarding baseflow during the dry season is important. The baseflow contribution to streamflow from groundwater storage will be higher during the dry season and is mainly composed of baseflow compared to the wet season. Delayed interflow will also contribute baseflow. However, during the wet season, the controlling flow is quick flow, the resultant of rainfall. The baseflow can be further affected by the size of the catchment. The larger basins will cause to increase the baseflow due to its longer time of travel to reach the catchment outlet. The results obtained from this study can be further used for drought prediction and for estimating the groundwater exploitation levels in the tropical wet and dry climate regions.

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