Assessment of variability in runoff coefficients and their linkages with physiographic and climatic characteristics of two contrasting catchments
Priyank J. Sharma, Premlal Patel and Vinayakam Jothiprakash

ABSTRACT
In the present study, long-term spatio-temporal variability in runoff coefficient (C) for different drainage areas of Upper Tapi basin, India, is analysed. The Upper Tapi basin is divided into two sub-catchments, Burhanpur and Purna, which are contrasting in nature in terms of their physiographic and climatic characteristics. The digital filter algorithm has been used to separate the base flow from observed streamflow for respective drainage areas. The sensitivity of the parameters involved in base flow separation is assessed by incorporating the hydrological and hydrogeological properties of individual drainage areas. The C values are then computed at different temporal scales, namely, daily, monthly, seasonal and annual, for different drainage areas. The effects of physiographic features such as topography, geology, soil type, and land use; and climatic features such as rainfall, temperature, and evapotranspiration, on the variability of C values are further investigated. The analyses reveal that Burhanpur sub-catchment (C = 0.39) yields higher C value compared to Purna sub-catchment (C = 0.11) at annual time scale. The C values clearly highlight the diversity in response of both sub-catchments, due to their distinct physiographic and climatic characteristics, and enabled us to study the variability in annual water balance of the basin.

Key words | base flow separation, Budyko hypothesis, digital filter algorithm, flow duration curve, runoff coefficient, Upper Tapi basin

INTRODUCTION
The runoff coefficient (C), ratio of direct runoff to the rainfall, is used to describe quick response of the catchment into the surface storage and river systems. It is a useful parameter in describing the runoff dynamics as well as streamflow utilization of watersheds. The runoff coefficients on both a long-term and short-term basis can be computed using rainfall–runoff time series or isolated events, respectively. The event-based C values can be used to study the short-term fluctuations in the systems due to individual flood events or heavy storms, while time series-based C values enable the understanding of total water balance of the catchment on a long-term basis.

The C values have been found to exhibit wide spatial and temporal variability due to varied climatic and physiographic factors of catchments. The spatial and temporal variability of C values mainly depends on precipitation, soil type, basin slope, geology and antecedent soil moisture conditions (Merz & Blöschl 2009; Norbiato et al. 2009). The effects of climatic and physical factors on the water balance of a catchment can be investigated while treating the same as a lumped system. The climatic factors include rainfall seasonality, phase of precipitation, potential evapotranspiration and storminess (Julien & Moglen 1990; Milly 1994), whereas the physical factors include vegetation, soil...
properties, geology and land use. The seasonality of climate exhibits a decreasing effect on streamflow or runoff, when precipitation and evapotranspiration are in phase with each other. The vegetation controls the evapotranspiration by providing water storage for interception and transpiration, and influences the partitioning and shielding of solar radiation. Further, large root zone storage capacity tends to reduce the runoff and promote the evapotranspiration (Milly 1994). Soil properties such as type, texture, permeability, slope, etc. control the infiltration characteristics of rainfall into the earth and, thereby, supply of moisture for evaporation (Yang et al. 2007). The geological settings in a catchment also affect the runoff coefficient as overland flow is predominant in a rocky impervious stratum due to reduction in infiltration and evapotranspiration losses. The land use/land cover changes also affect the surface runoff of catchments due to alteration of macroporosity, hydraulic conductivity, infiltration rate, water storage capacity of the soil and their erosion rates (Giertz et al. 2005).

Previous investigators, including Wainwright & Parsons (2002); Merz et al. (2006); Blume et al. (2007); Norbiato et al. (2009); Merz & Blöschl (2009); Viglione et al. (2009) and Sriwongsitanon & Taesombat (2011), mainly focused on computation of event-based runoff coefficients for describing the rainfall–runoff dynamics during flood events. A few studies also reported the estimation of long-term runoff coefficients while investigating the effects of climatic and catchment characteristics on the response of catchments (Milly 1994; Yang et al. 2007; Zhang et al. 2014; Ali et al. 2015). McCartney et al. (1998) compared the hydrological characteristics of two headwater catchments, namely, ‘dry land’ catchment (Romwe) and ‘wet land’ catchment (grasslands) in Zimbabwe. A distinct dissimilarity in the flow regimes of the said catchments was observed due to dissimilarities in their geological and topographical features. The recession flow was observed to be of longer duration in grasslands compared to Romwe catchment. Berger & Entekhabi (2001) analysed ten basins under diverse climate and terrain conditions to estimate their long-term hydrologic responses using an equilibrium surface water–groundwater model. The variability among the basins was described by deriving relationships between physical characteristics (median slope, relief ratio, drainage density, wetness ratio, infiltration capacity and saturated zone efficiency index) and hydrologic variables (runoff ratio and evaporation efficiency) of respective basins. The study revealed that the model exhibited an improved fit with explained variance of 0.90 while considering all six variables in predicting runoff ratio compared to a combination of fewer variables. The same model, used in predicting evaporation efficiency, yielded a relatively lesser explained variance of 0.79. Sriwongsitanon & Taesombat (2011) assessed the influence of changes in land cover on flood behaviour in Upper Ping River Basin, Thailand from 1988–2005. The study also correlated runoff coefficients with different types of land cover for smaller and larger flood events. The relationships derived between runoff coefficients and types of land cover, for peak flood events of different return periods, showed an increasing trend in runoff coefficient due to intensification of forest area, and proved to be useful in mitigation of smaller flood events. Zhang et al. (2014) studied the effect of catchment properties on the response of 23 catchments in a karst area of southwest China. The Budyko equation was applied to analyse the runoff coefficient and its relationship with drought index and catchment characteristics like slope, vegetation and geology for the period 1961–2000. The sensitivity analysis indicated that catchment characteristics have significant effects on runoff coefficient rather than climatic characteristics.

The Upper Tapi basin, India, has two distinct sub-catchments, namely, Burhanpur and Purna sub-catchments, in terms of their climatic, geologic, topographic and land use settings. The responses of the two sub-catchments are expected to be entirely different for different storm events due to extreme heterogeneity in their physiographic and climatic characteristics. Such expected varied response of two sub-catchments within the same basin is required to be investigated for efficient planning and management of water resources. The present study aims: (i) to study the heterogeneity in characteristics of the two sub-catchments in the Upper Tapi basin and their implications on runoff response; (ii) to estimate the base flow index for different drainage areas using digital filter algorithm for base flow separation technique; (iii) to analyse the spatial and temporal variability in runoff coefficients across the Upper
Tapi basin; and (iv) to attribute the physiographic and climatic characteristics of the catchments with the variability in runoff coefficients.

MATERIALS AND METHODS

Study area

The Tapi River is the second largest westward draining river of the Indian Peninsula, originating at an altitude of 752 m near Multai in Betul district of Madhya Pradesh, and traverses a distance of 724 km before draining into the Arabian Sea. The Tapi basin lies between northern latitudes 20° 05' to 22° 03' and eastern longitudes 72° 38' to 78° 17', covering an area of 65,145 km² (Figure 1). The entire Tapi basin is divided into three sub-basins: (i) Upper Tapi basin – origin (Tapti Kund, Multai) to Hathnur dam (area ≈ 29,430 km²); (ii) Middle Tapi basin – Hathnur dam to Ukai dam (area ≈ 32,925 km²); and (iii) Lower Tapi basin – Ukai dam to the Arabian Sea (area ≈ 2,790 km²). The Upper Tapi basin is further subdivided into two sub-catchments, namely, Purna (area ≈ 18,490 km²) and Burhanpur sub-catchments (area ≈ 10,940 km²). The Burhanpur and Purna sub-catchments exhibit extreme heterogeneity in terms of their physiographic (topography, soil type, land use/land cover, basin slope, geological settings) and hydroclimatic features (rainfall, temperature, evapotranspiration) (Chandra et al. 2016). Figure 1(c) shows the locations of the rain gauge and stream gauging stations, and delineation of drainage areas of respective stream gauging stations, while Figure 1(d) shows the elevation map of the two sub-catchments of the Upper Tapi basin.

Figure 1 | Index map of Upper Tapi basin including locations of rain gauges, stream gauging stations and elevation map.
Physiography of the basin

The Upper Tapi basin comprises Burhanpur (formerly Khandwa) and Betul districts of Madhya Pradesh state; and Akola, Amravati, Buldhana and Jalgaon districts of Maharashtra state in India. The basin is covered by the Satpura mountain ranges in the north, Mahadeo hills in the east, and Ajanta and Satmala hills in the south (Figure 1(c)). The high banks, narrow valleys and gravelly beds are peculiarities of the main Tapi River before it descends down in the plains of Burhanpur. On the other hand, the Purna River (length ≈ 353 km) originates from the Gwalighar hills in Bhainsdehi and travels down mostly through flat plains before it meets the main Tapi River at Changdev village, 14 km upstream of Hathnur dam. The highest point in the basin, named Chikhalda, is located in Amravati district at an elevation of 1,084 m above mean sea level. The hypsometric curves, showing the cumulative distribution of elevations versus percentage area, are plotted for Purna and Burhanpur sub-catchments (Figure 2). It can be clearly seen that despite the elevation range for both the sub-catchments being nearly the same, considerable variation in their respective mean elevations are observed. The mean elevations for Purna and Burhanpur sub-catchments are 372.6 m and 486.5 m, respectively, and 65% and 54% of the respective catchment areas fall below the aforementioned mean contours. The steep nature of the hypsometric curve clearly highlights that Burhanpur sub-catchment has significantly steep slopes compared to the Purna sub-catchment, which has relatively flatter terrain, (Figure 1(d)). Chandra et al. (2016) highlighted the contrasting nature of Burhanpur and Purna sub-catchments in terms of their land use and land cover characteristics – the former has 44.72% and 15.89% of catchment areas covered by forests and range-lands, respectively, while the latter has 74.41% of area under agriculture. The land use–land cover statistics for the present study were taken from Pal (2016), and used in further analyses to correlate their effects on runoff coefficients of the two sub-catchments of the Upper Tapi basin.

Hydrogeology of the basin

The prominent geological units of Burhanpur sub-catchment are Archaen, Gondwana, Deccan traps, laterites and soils. The Deccan trap comprises various types of basaltic lava flows, and occurrence and movement of groundwater flow through them varies accordingly. The groundwater structure varies between 6 and 14 m depth for fractured basalts, 4 and 20 m depth for weathered basalt and 3 and 20 m depth in the case of vesicular type of flows (CGWB 2013). The Purna sub-catchment consists of basaltic lava flows as the major rock formation along with alluvium, Lamenta beds,
Gondwana sediments and some unclassified metamorphic rocks. The major part of Purna sub-catchment is covered with Purna alluvium, where the younger alluvium, which extends down to 70–80 m depth, contains more sand layers and forms good aquifers; while the older alluvium, attaining a depth of about 450 m, is clayey with thin horizons of sand and silt, thereby forming comparatively fewer potential aquifers (CGWB 2013).

**Hydrology of the basin**

The geographical location of the Upper Tapi basin is in proximity to the Western Ghats and the Arabian Sea. The monsoon winds bearing moisture from the Arabian Sea are obstructed by the Satpura and Gwaligarh mountains which bring rainfall in the northern part of the basin. The southern part of the basin falls under the rain shadow zone of the Western Ghats, and thereby, receives low rainfall. Thus, a high variability in rainfall pattern is observed across the basin due to its typical topographic setting and direction of monsoon winds. The basin receives a mean annual rainfall of about 828.6 mm with an average of 57 rainy days during the monsoon (June to September). There are 24 rain gauge stations set up by the India Meteorological Department (IMD) in the Upper Tapi basin, out of which 17 stations fall in Purna sub-catchment (Figure 1(c)). Chikhaldna station receives the highest mean annual rainfall of 1,488.4 mm, while Edalabad station receives the lowest mean annual rainfall of 652.4 mm. The elevation of rain gauge stations and their mean annual rainfall is shown in Figure 3. The stations located in the plains of the Burhanpur sub-catchment (Dharni and Burhanpur) receive more rainfall compared to the stations located in the plains of Purna sub-catchment due to orographic effects of the Satpura and Gwaligarh ranges (Figure 1(d)). Atner station, located at an altitude of 665 m, receives less rainfall (i.e., about 696.0 mm annually), much below the basin average value, due to its location on the leeward side of Gwaligarh mountain range. This clearly highlights the presence of orographic effects on rainfall, thereby resulting in spatial variability across the basin. Moreover, the Burhanpur and Purna sub-catchments, respectively, receive 93.0% and 85.1% of annual rainfall during the monsoon period only, while meagre rainfall is received during the remaining eight months. The basin also experiences a vast difference in observed temperatures, with mean maximum temperature during the month of May being 42.4 °C and mean minimum temperature during December being 10.3 °C. The temperature fluctuations significantly affect the evapotranspiration process in the basin. The high temperature during summer months results in a higher energy supply to plants, which tends to increase their water requirements. As a result, there is rapid loss of moisture from the soil due to the large evapotranspirational requirements of plants. There are five stream gauging stations, established and maintained by the Central Water Commission (CWC), Government of India, in the basin, which are listed in Table 1. The Burhanpur and Dedtalai stations are along the main Tapi River, while Lakhpuri, Gopalkheda and Yerli stations are along the Purna River (see Figure 1). The mean annual runoff during the period of 36 years (1977–2013) at Burhanpur and Yerli stream gauging stations was 4,807 and 2,111 MCM (million cubic metres), respectively. Also, the daily peak discharges observed during this period at Burhanpur and Yerli stream gauging stations were 4,807 and 2,111 MCM, respectively. The above description clearly highlights the variation in catchment response on account of distinct geologic, topographic and climatic settings of Burhanpur and Purna sub-catchments. In the present analyses, Burhanpur and Purna sub-catchments refer to the computations carried out for drainage areas up to Burhanpur and Yerli stream gauging stations, respectively, while Hathnur refers to the entire Upper Tapi basin up to Hathnur dam.
The estimation of base flow and direct runoff is useful in understanding the hydrology of a watershed, including interaction of surface and sub-surface water in the basin. In the present study, an automated Web GIS-based Hydrograph Analysis Tool (WHAT) has been used to separate base flow from observed total streamflow (Lim et al. 2005). In the WHAT program, the digital filter method is used for base flow separation, wherein the high frequency waves can be associated with direct runoff, and low frequency waves with base flow (Eckhardt 2005). The two parameters of the Eckhardt method consist of filter parameter \(a\) and maximum base flow index (BFI\(_{\text{max}}\)). The filter parameter \(a\) describes the rate at which the streamflow decreases with time following a recharge event, and can be derived by recession analysis. The BFI\(_{\text{max}}\) is the maximum base flow index which can be modelled by the recursive digital filter algorithm. The aforesaid algorithm partitions the streamflow into two components, i.e., direct runoff and base flow:

\[ y_k = f_k + b_k \]  

(1)

where, \(y\) = total streamflow, \(f\) = direct runoff, \(b\) = base flow corresponding to \(k\)th time interval.

The general form of the base flow equation, in terms of BFI\(_{\text{max}}\) and \(a\), is expressed as:

\[ b_k = \frac{(1 - \text{BFI}_{\text{max}})ab_{k-1} + (1 - a)\text{BFI}_{\text{max}} y_k}{1 - a\text{BFI}_{\text{max}}} \text{ subject to } b_k \leq y_k \]  

(2)

### Data

In the present study, long-term meteorological and hydrological data pertaining to 24 rain gauge stations, five weather stations and five stream gauging stations located within the Upper Tapi basin for a period of 36 years (i.e., from 1977 to 2013) were collected and analysed. The daily meteorological data, including rainfall depth, maximum and minimum temperatures, average wind speed, sunshine hours, station level pressure, vapour pressure, relative humidity, pan evaporation, etc., were collected from the IMD, Pune and Hydrological Data User Group (HDUG), Nashik, Government of Maharashtra. Also, daily observed streamflows and water levels at five stream gauging stations were collected from the CWC, Surat, India. The daily reservoir levels, inflows, releases and losses from Hathnur dam were collected from the Tapi Irrigation Development Corporation (TIDC) Jalgaon, Maharashtra. The geological maps of each district were collected from the Geological Survey of India (GSI), Nagpur. The lumped rainfall \((P)\) values of respective drainage areas were computed from daily station rainfall data using the Thiessen polygon method (Chow et al. 1988), while the daily potential evapotranspiration \((ET_0)\) was calculated using the Penman–Monteith equation suggested by the Food and Agricultural Organization (FAO) (Allen et al. 1998). The daily streamflow was converted into runoff depth \((R)\) by dividing the streamflow volume with the drainage area of the sub-catchment. The annual actual evapotranspiration \((ET)\) was calculated based on the annual water balance, considering no carry-over of storage from one year to another, i.e., \(ET = P - R\) (Zhang et al. 2013). Table 1 summarizes the mean long-term annual water balances for various drainage areas included under different stream gauging stations in the Upper Tapi basin.

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Eckhardt (2005) found that the filter parameter ‘$a$’ is not very sensitive to the filtered results (Equation (2)), while BFI$_{\text{max}}$ values greatly influence the results. Eckhardt (2005) recommended the use of BFI$_{\text{max}}$ 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 default values of BFI$_{\text{max}}$ and filter parameter ($\alpha$), being used in the WHAT program, are 0.80 and 0.98, respectively, for describing watersheds with perennial streams and porous aquifers.

The runoff coefficient ($C$), defined as the depth of direct runoff generated at the catchment outlet to the depth of rainfall in the same catchment at a given time scale (Chow et al. 1988), can be expressed as:

$$C = \frac{R}{\sum_{m=1}^{M} P_m} \tag{3}$$

where, $P_m$ is the total rainfall depth in the $m$th duration, $R$ corresponds to total depth of direct runoff, and $M$ is the total duration of the storm event.

The Budyko framework (Budyko 1974) is useful in representing the land water balance, wherein mean annual precipitation is partitioned into runoff and evapotranspiration as a function of ratio of atmospheric water supply (precipitation) to water demand (potential evapotranspiration). In the Budyko framework, the mean annual evapotranspiration ratio ($ET/P$) is presumed to be a function of the climatic dryness, and represented as:

$$ET/P = F\left(\frac{ET_0}{P}\right) = F(\phi) \tag{4}$$

where, $\phi$ is the dryness or aridity index defined as $ET_0/P$ and $F(\phi)$ is an empirical function that relates $ET/P$ to $\phi$ based on general water–energy balance in the basin. The proposed relationship by Budyko (1974) for $F(\phi)$, can be expressed as:

$$F(\phi) = \sqrt{\phi \left[1 - \exp(-\phi)\right] \tanh\left(1/\phi\right)} \tag{5}$$

The detailed methodology adopted in the present study for estimation of runoff coefficient at different time scales, and the influence of various physiographic and climatic factors on variability of runoff coefficient, is presented in Figure 4.

**RESULTS AND DISCUSSION**

**Watershed input–response relationship**

Based on the location of streamflow gauging stations, the Upper Tapi basin is sub-divided into six drainage areas: Lakhpuri, Gopalkheda, Yerli, Dedtalai, Burhanpur and Hathnur. The rainfall and flow duration curves for all drainage areas were plotted, using the daily lumped rainfall and streamflow discharges respectively, to visualize input–response relationships of drainage areas in Burhanpur and Purna sub-catchments (Figures 5 and 6). From Figure 5, it is revealed that there are nominal variations in the occurrence of rainfall pattern for different drainage areas. Almost 65–70% of the time, the basin does not receive any rainfall. As per IMD classification, a rainy day is one experiencing a rainfall depth of 2.50 mm or more. Thus, from Figure 5, it can be inferred that the Upper Tapi basin experiences rainy days 20% of the time in a particular water year. On the other hand, from Figure 6, it is seen that 60–90% of the time in a particular year the stream flow duration, which characterizes the peculiarity in flood regimes, can be expressed as:

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of both sub-catchments. The steepness in the upper part of the flow duration curve for Burhanpur sub-catchment indicates the occurrence of high flood events in the past.

**Base flow separation**

From the above discussion, it is clear that base flow plays an important role in the hydrology of the Upper Tapi basin, particularly Burhanpur sub-catchment, and therefore, its estimation was necessary to delineate the contribution of base flow to streamflow before estimation of runoff coefficient. Before carrying out the base flow separation, the parameter sensitivity was carried out in the WHAT program using a digital filter algorithm. The WHAT program specifies default values of BFI_{max}; however, in the present study, weighted BFI_{max} values have been computed based on the hydrological and hydrogeological characteristics using the information derived from district
geological maps; namely, the percentage of alluvium (porous aquifers) and hard rocks (such as basalt, etc.) in each drainage area, as reported in Table 2. The weighted BFImax for a particular drainage area was computed by multiplying the respective weighted areas with corresponding suggested values for porous and hard rock aquifers for perennial streams (i.e., 0.80 and 0.25, respectively). For explanation, the sensitivity of the model parameters pertaining to the recession curve of the observed hydrograph for the rainless period (05/10/1977 to 21/11/1977) at Lakhpuri stream gauging station is graphically shown in Figure 7. It is seen that the default filter parameter value of $a = 0.98$ gives the best results, while lowering its value does not exhibit significant change in the base flow (Figure 7(b)). On the other hand, using the default BFImax value for the porous aquifer as 0.80 sometimes leads to overestimation of base flow compared to the weighted BFImax value (0.52 for Lakhpuri). The parameter sensitivity is assessed with respect to the default parameter values specified by the WHAT computer program, i.e., $a = 0.98$ and BFImax = 0.80 specified for porous aquifer. The variation in the total base flow volume estimated during the period 05/10/1977 to 21/11/1977 at Lakhpuri stream gauging station as well as the percentage change in the base flow volume with respect to default parameter values as specified above, is plotted for different values of filter parameter ($a$) and BFImax in Figure 8. From Figure 8(a), for constant value of filter parameter, $a = 0.98$ and varying values of BFImax (as estimated in Table 2), it is seen that the % change in base flow volume with respect to default parameter values varies from 9.75 to 15.09%. In Figure 8(b), for constant value of BFImax = 0.80 and varying values of filter parameter ‘$a$’ from 0.98 to 0.85, the variation in % change in base flow volume with respect to default parameter values is 0.18 to 1.64%. Thus, from Figure 8(a) and 8(b), it is evident that base flow is more sensitive to

![Figure 5](image)

**Figure 5** | Rainfall duration curves for different drainage areas in the Upper Tapi basin.

![Figure 6](image)

**Figure 6** | Flow duration curves for different drainage areas in the Upper Tapi basin.

<table>
<thead>
<tr>
<th>Drains areas</th>
<th>Total areal extent (km²)</th>
<th>Area covered by alluvium (km²)</th>
<th>Area covered by hard rock (km²)</th>
<th>Weighted BFImax value adopted</th>
<th>Computed BFI using WHAT program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lakhpuri</td>
<td>3,523.3</td>
<td>1,708.3</td>
<td>1,815.1</td>
<td>0.52</td>
<td>0.26</td>
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<tr>
<td>Gopalkheda</td>
<td>8,688.0</td>
<td>4,616.7</td>
<td>4,071.2</td>
<td>0.54</td>
<td>0.27</td>
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<tr>
<td>Yerli</td>
<td>15,884.0</td>
<td>7,276.2</td>
<td>8,607.8</td>
<td>0.50</td>
<td>0.27</td>
</tr>
<tr>
<td>Dedtalai</td>
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<td>0.0</td>
<td>6,769.7</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>Burhanpur</td>
<td>8,994.6</td>
<td>706.7</td>
<td>8,288.0</td>
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<td>0.20</td>
</tr>
<tr>
<td>Hathnur</td>
<td>29,430.0</td>
<td>9,109.5</td>
<td>20,320.5</td>
<td>0.42</td>
<td>0.24</td>
</tr>
</tbody>
</table>
BFImax vis-à-vis filter parameter ‘a’. The parameter sensitivity for other stream gauging stations for different time periods was also assessed, as described above, to derive the robust parameter values for base flow separation in the WHAT program. However, the same could not be reported in the paper due to paucity of space. Accordingly, the weighted parameter value of BFImax for each drainage area (as listed in Table 2) and the default value of filter parameter (a), i.e., 0.98, have been used in separation of base flow from observed streamflow. Eckhardt (2008) showed that tracer measurements to estimate base flow contribution to streamflow and base flow separation by means of digital filter yielded nearly similar results, and can be applied to other catchments as well. The performance of the base flow separation method used in the present study has been validated with observed streamflow during the dry/lean period by presuming that entire streamflow contribution during such periods is due to base flow only. Figure 9 shows the performance of base flow separation algorithm for observed streamflow hydrograph at Dedtalai stream gauging station for both wet (28/08/1983–11/10/1983) and dry (12/10/1983–25/12/1983) periods. The base flow separation for the dry period is enlarged and shown in the inset in Figure 9. During the dry period, the rainfall is very negligible (i.e., of the order of 0.1–0.3 mm) in the Dedtalai drainage area. Rainfall of such magnitude may not be able to generate surface runoff. However, on two occasions, little spikes (i.e., of the order of 10–20 m³/s) are observed in the hydrograph for the dry period, which may be due to possible releases made from minor storage structures for irrigation and
other purposes that later join the streamflow. It is seen that filter algorithm performs satisfactorily in separation of base flow from the total streamflow. The base flow index (BFI), which is the ratio of long-term base flow to total streamflow, is then computed for each sub-catchment, as shown in Table 2. Here, BFI represents the slow and continuous contribution of groundwater to river flow for a given catchment. From Table 2, while observing computed BFI values, it is evident that contribution of groundwater flows at downstream gauging stations is greater than upstream gauging stations due to the natural topographic gradient.

**Temporal variability of runoff coefficient**

The temporal variability of C was analysed by computing the ratio of direct runoff depth to lumped rainfall depth at different temporal scales, namely, daily, monthly, seasonal and annual scales. The daily C values were computed for a period of 36 years (1977–2013) for only those days where
rainfall was recorded. From Table 3, it is clearly seen that $C$ has very low values at all the sites as the time scale is very small, and entire direct runoff contribution may not be available at respective sites, particularly the contribution due to quick interflow. Further, a distinct divide between the values of $C$ for Purna and Burhanpur sub-catchments is seen, which is mainly due to the difference in topography and land use–land cover of both sub-catchments. The monthly runoff coefficients, computed for all the drainage areas, are reported in Table 3. From Table 3, it is seen that $C$ values are higher during the tail end of the monsoon, i.e., August and September, as the detention and retention effects are nullified since most of the storage structures are almost filled, and the flow is not intercepted while contributing towards surface runoff. During pre-monsoon and post-monsoon periods, a consistent decline in $C$ values is observed on account of scanty rainfall leading to low antecedent soil moisture conditions during these periods. The $C$ values were further computed on a seasonal scale, where the seasons were delineated into four different classes: monsoon (June–September); post-monsoon (October–November); winter (December–February); and pre-monsoon (March–May). The $C$ values were estimated to be highest for monsoon months followed by post-monsoon and winter months. The lowest $C$ values during the pre-monsoon period are due to low antecedent moisture conditions in the drier soil and higher rates of evapotranspiration. The relatively higher $C$ values in the winter period vis-à-vis the pre-monsoon period is due to occurrence of rainfall in the former period due to the north-east monsoon.

**Spatial variability of runoff coefficient**

The Purna River originates near Bhainsdehi in Lakhpuri drainage area, where it descends down the hill slope, and then travels on relatively flat ground to the outlet of the sub-catchment. The mountainous topography, presence of rocky strata and fewer minor hydraulic structures up to Lakhpuri results in less infiltration of rain water and, consequently, more overland flow compared to the drainage area up to Gopalkheda. Further, the values of runoff coefficients for drainage areas in Purna sub-catchment (Lakhpuri, Gopalkheda and Yerli stream gauging stations) are consistently lower than those for the drainage areas in Burhanpur sub-catchment (Dedtalai and Burhanpur stream gauging stations). Such consistently higher values of $C$ in Burhanpur sub-catchment are due to: (a) its steep topography and rocky strata and, hence, quick disposal of runoff at outlets of respective drainage areas; (b) presence of fewer storage structures in Burhanpur sub-catchment compared to Purna

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**Figure 9** | Performance of the WHAT program in estimation of base flow at Dedtalai stream gauging station using weighted BFI$_{max}$ values.
sub-catchment; and (c) lower evapotranspiration loss in Burhanpur sub-catchment compared to Purna sub-catchment. The spatial variability in $C$ values across the Upper Tapi basin is clearly evident from Table 3, where it is observed that the runoff coefficient increases as one moves downstream in Burhanpur sub-catchment; i.e., annual $C$ values for drainage areas up to Dedtalai and Burhanpur are 0.32 and 0.39, respectively. However, in Purna sub-catchment, such consistent behaviour of runoff coefficient is not observed, where the annual $C$ values for drainage areas up to Lakhpuri, Gopalkheda and Yerli are 0.12, 0.09 and 0.11, respectively. The Lakhpuri drainage area, having relatively steep topography compared to Gopalkheda and Yerli, serves as a headwater region for the Purna River. Due to its steep topography, presence of rocky strata and smaller catchment area, the runoff generation is comparatively little higher. On the other hand, Gopalkheda and Yerli drainage areas have experienced intensification in agricultural activities due to improvement in irrigation facilities, which has resulted in an increase in evapotranspiration losses and thereby a decrease in surface runoff. The annual $C$ values are estimated to be 0.11 and 0.39 for Purna and Burhanpur sub-catchments, respectively, which exhibit a wide variability in the runoff response of these sub-catchments due to their heterogeneity in physiographic and climatic characteristics. The large area under irrigation in the Purna sub-catchment compared to Burhanpur sub-catchment, where much of the rain water gets stored as soil moisture or inflow into soil, leads to reduced contribution to the streamflow. The heterogeneity in behaviour of both Purna and Burhanpur sub-catchments is marginalized for the entire Upper Tapi basin, which has its outlet at Hathnur dam. The annual $C$ value for Hathnur is around 0.16, which shows the predominance of the areal extent of Purna sub-catchment governing the runoff coefficient at basin scale. The annual time series plots of rainfall depth, direct runoff depth and runoff coefficient are shown in Figure 10. It is clearly seen that Purna sub-catchment, having a semi-arid climate, exhibits significant fluctuations in rainfall. As a result of this, high variability in annual

<table>
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<tr>
<th>Time scale</th>
<th>Lakhpuri</th>
<th>Gopalkheda</th>
<th>Yerli</th>
<th>Dedtalai</th>
<th>Burhanpur</th>
<th>Hathnur</th>
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<td>0.32</td>
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values are observed for Purna sub-catchment ($C_v = 59.6\%$) compared to Burhanpur sub-catchment ($C_v = 36.1\%$). The linear trends for annual $C$ values show a marginal upward slope for Burhanpur sub-catchment (Figure 10(b)), while a steep downward slope is observed for Purna sub-catchment (Figure 10(a)). The decadal variations in rainfall depth, runoff depth and runoff coefficient were analysed and are represented by box-plots in Figure 11. For Purna sub-catchment, rainfall increases during the decade 1988–1998 and then decreases in the next decade 1999–2009. On the other hand, runoff is found to decrease consistently in all three decades with their corresponding lower $C$ values. The steep declining trend of $C$ values with time in Purna sub-catchment is due to intense human intervention in terms of development of storage structures in the sub-catchment. For instance, the surface water storage in the sub-catchment (considering gross storage capacities of the hydraulic structures) prior to 1977 was 270.12 MCM, while the incremental storage during the decades 1977–1987, 1988–1998 and 1999–2009 were 81.44, 140.52 and
163.98 MCM, respectively. Thus, there was a two-fold increase in surface water storage in the decade 1988–1998 vis-à-vis the decade 1977–1987. The steep decline in $C$ values for Purna sub-catchment indicates a reduction in output (runoff) from the sub-catchment, which could have implications for water availability in the region.

**Effect of catchment characteristics on runoff coefficient**

Catchment characteristics such as base flow index, geology and land use–land cover are correlated with average annual runoff coefficient to identify their influence on response of the catchment (see Figure 12). From Figure 12(a), it can be seen that for Burhanpur sub-catchment BFI is less and $C$ is high, thereby indicating a lesser proportion of rainfall is available as base flow contribution in the Tapi River, which implies an increase in direct runoff component. Therefore, in the case of heavy rainfall, the flood discharge is expected to travel at a faster rate in Burhanpur sub-catchment compared to Purna sub-catchment. The presence of hard rock strata (more than 90% of total drainage area) is also responsible for high runoff coefficients for Dedtalai and Burhanpur drainage areas (see Figure 12(b)). The hard rock strata led to less infiltration and thereby generation of higher surface runoff. The Dedtalai and Burhanpur drainage areas, respectively, cover 100% and 92% of hard rocky strata, where the annual $C$ value at Dedtalai ($C = 0.32$) is a little lower than that at Burhanpur ($C = 0.39$). The lower $C$ value at Dedtalai is due to its lesser drainage density and lack of proper channelization of overland flow. On the other hand, the Purna sub-catchment has around 50% of area covered by alluvium, thus forming porous aquifers which serve as major groundwater reservoirs in the region. Due to the presence of such geology in Purna sub-catchment, the infiltration losses are significant, thereby augmenting the base flow and retarding the surface runoff and, subsequently, resulting in low values of $C$.

From the hypsometric curves (Figure 2) and land use–land cover of the Upper Tapi basin, it is observed that Burhanpur sub-catchment has steep sloped forest and rangelands, while the Purna sub-catchment has predominantly flat agricultural fields. The agricultural fields help in retarding the overland flow velocity, thereby allowing ponding of water on the surface and, consequently, helping the infiltration process which contributes to the base flow. On the other hand, the rangelands, supplemented with steeper
slopes, accelerate the overland flow and, thereby, a substantial increase in the direct runoff component is observed in Burhanpur sub-catchment. Figure 13(a) and 13(b) show that, over the past three decades, the agricultural area in the Purna sub-catchment has increased on account of improvement in irrigation facilities; on the other hand, forest cover has been reducing due to industrialization and urbanization activities. The effect of such changes in land use can evidently be seen on the runoff coefficient, wherein the average annual C values for three decades, 1977–87, 1988–1998 and 1999–2009, were estimated to be 0.13, 0.11 and 0.08, respectively. For Burhanpur sub-catchment, it is found that the forest cover is reducing (Figure 13(d)) and the agricultural area is slightly increasing (Figure 13(c)) over the time period. The C values were 0.36, 0.43 and 0.35, respectively, for the three decades, i.e., 1977–1987, 1988–1998 and 1999–2009, as shown in Figure 13. The increase in C value during 1988–1998 for Burhanpur sub-catchment is due to deforestation and urbanization in the region, which is conducive to quick depletion of surface storage at the catchment outlet. The reduction in C value during 1999–2009 is due to development of small storage structures in the sub-catchment for meeting irrigation requirements of agricultural crops in the region. From the above discussion, it can be inferred that distinct and diverse catchment characteristics strongly govern the responses of both sub-catchments, and must be analysed properly by hydrological modellers before envisaging rainfall-runoff or flood modelling in the basin.

Effect of climatic characteristics on runoff coefficient

The effect of climatic characteristics on runoff generation has been studied with the help of the Budyko framework. The Budyko framework enables us to understand the characteristics of annual as well as long-term water balance of a catchment. From the Budyko hypothesis, large values of aridity index, $\phi = \frac{ET_0}{P} (>1)$, indicate that the climate of the catchment is dry or arid, whereas the small values of $\phi (<1)$ indicate a wet or humid climate. Using this framework, the change in behaviour of annual water balance across different time periods, i.e., long-term (1977–2009) as well as on a decadal basis (1977–1987, 1988–1998 and 1999–2009) are studied and shown in Figure 14(a)–14(d). From Figure 14(a), it is observed that, on a long-term basis, Burhanpur sub-catchment has a lower value of aridity index ($\phi$), i.e., between 1 and 1.5, indicating a sub-humid climatic region. On the other hand, higher values of $\phi$ ($>2$) indicate a semi-arid type of climate for the Purna sub-catchment. The Budyko curve provides important inference regarding the water balance of the region based upon water and energy interactions. From the Budyko hypothesis, when the annual evaporation approaches annual precipitation, sufficient energy is available to evaporate annual precipitation and such locations are termed ‘moisture constrained’. Whereas, when the annual evaporation approaches
potential evaporation, the available energy is less than the required energy to evaporate annual precipitation and such locations are termed ‘energy constrained’ (Gerrits et al. 2009). From Figure 14(a), it can be seen that for Purna sub-catchment, moisture constrained conditions are observed where the annual evaporation is observed to be very close to annual rainfall. The heating of dry surfaces would tend to evaporate low intensity rainfall and does not generate surface runoff. From Figure 14(b)–14(d), a distinct shift in the values of $\phi$ and $\epsilon$ towards the lower side is observed for the decade 1988–1998 with reference to other decades, for both Burhanpur and Purna sub-catchments. For other decades, namely 1977–1987 and 1999–2009, the values of $\phi$ and $\epsilon$ were found to be in line with long-term average values (1977–2009). This particular shift in the values of $\phi$ and $\epsilon$ is due to associated changes in the climate regime during the decade 1988–1998, in which significant increase in rainfall and runoff was observed, resulting in subsequent decrease in values of $\phi$ and $\epsilon$. Figure 10 shows the median annual rainfall for Burhanpur sub-catchment for the decades 1977–1987, 1988–1998 and 1999–2009 was 1011.4, 1123.3 and 887.7 mm, respectively, and the corresponding median runoff depth for these decades was 439.2, 648.6 and 352.2 mm, respectively. Whereas the median annual rainfall for Purna sub-catchment for decades 1977–1987, 1988–1998 and 1999–2009 was 795.4, 814.1 and 791.1 mm, respectively, and the corresponding median runoff depth for these decades was 64.8, 109.0 and 65.5 mm, respectively. This clearly highlights that the rainfall variation has considerable effect on the climatic characteristics of these sub-catchments, and thereby, on the values of the runoff coefficient. The Budyko framework also enables us to distinguish human-induced and climate-induced changes on hydrology of the basin; however, this aspect has not been envisaged in the present study.

The impact of climate characteristics on the response of the catchment is further examined by analysing the spatial variability in runoff coefficient (on decadal scale) versus evaporative index for different time periods (see Figure 15). Figure 15 clearly shows that evapotranspiration has a direct effect on response of the catchment. The Purna sub-catchment (Figure 15(a)–15(c)) exhibits very low $C$ values for comparative higher values of $\epsilon$. Contrary to this, for Burhanpur sub-catchment, higher values of $C$ are observed corresponding to relatively lower values of $\epsilon$ (Figure 15(d) and 15(e)). Therefore, the spatial variability observed in Figure 15 indicates the effect of climatic properties on the response of the watersheds. The present study can be helpful in understanding the heterogeneity in the behaviour of the basin; identifying distinctly the roles of physiographic as well as climatic characteristics of the basin in controlling the pattern of runoff at the sub-catchment outlet and ascertaining the changes in long-term water balance of the basin.

**CONCLUSIONS**

The long-term time series of rainfall and runoff, observed in Upper Tapi basin, have been analysed. The observed streamflow was systematically partitioned into direct runoff and base flow to estimate runoff coefficients at different temporal and spatial scales for two contrasting sub-catchments of the basin. The temporal and spatial variations in runoff coefficients have been established with physiographic and climatic characteristics of both sub-catchments of Upper...
The specific findings from the present study are summarized in the following points:

(1) From the rainfall and flow duration curves, it is observed that only 30–35% of the year, rainfall is recorded across Upper Tapi basin, while 60–90% of the year, streamflow is observed at the catchment outlet. Thus, there is significant contribution of base flow to the streamflow during the dry periods.

(2) The base flow separation from observed streamflow was carried out using digital filter algorithm in the WHAT program, where the base flow index is computed to be 0.27 and 0.20 for Purna and Burhanpur sub-catchments, respectively.

(3) The runoff coefficient was found to exhibit wide temporal variability, with lower C values reported at daily and annual time scales. The higher C values are observed for late monsoon months, i.e., August and September, due to high antecedent soil moisture conditions, reduced flow regulation from storage structures and comparatively higher rainfall. For non-monsoon periods, there is a consistent decline in C values due to the lower occurrence of rainfall during these periods.

(4) The spatial variability is clearly highlighted from the fact that C value increases as we move downstream along the river. However, for the Gopalkheda drainage area, a marginal drop in C value was observed compared to Lakhpuri, due to less rainfall and increased evaporation and transpiration losses. The analysis of C values, for the period 1977–2013, exhibited a steep decreasing trend with time due to the development of extensive water storage structures in the Purna sub-catchment. However, such a trend was found to be absent for Burhanpur sub-catchment.

(5) The effect of catchment characteristics such as geology, soil type, topography and land use were found to be significant on the runoff. Higher values of C for Burhanpur sub-catchment (C = 0.39 on annual scale) were reported due to steep topography and the presence of large hard rocky strata in the basin. The lower values of C for Purna sub-catchment (C = 0.11 on annual scale) are due to abundant agricultural land, flat topography and the presence of alluvial soil in the region.

(6) The Budyko framework was applied to assess the effect of climatic parameters on runoff coefficient. It could be seen that Burhanpur sub-catchment had an aridity index
of 1.37 (nearer to 1), which signifies a dry sub-humid climate, while for Purna sub-catchment, the value of aridity index was computed to be 1.96, signifying closer to a semi-arid climate. The semi-arid climatic regime is characterized by a lesser rate of water supply (rainfall), and increased water loss (evapotranspiration) resulting in lower watershed response (runoff).

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