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Simulating the Impact of Forest Cover Change on Annual Stream Flow from a Forested Watershed

[1]B. Venkatesh, [1]B.K. Purandara and [2]S. Varadaraju
[1]National Institute of Hydrology, Hanuman Nagar, Belgaum, Karnataka.
[2]College of Fisheries, Hoige Bazar, Mangalore, Karnataka

Abstract : The present study aims at understanding the impact of changing land cover on the stream flow. In order to simulate the impact of land cover changes, a mathematical model has been used with the observed data such as rainfall, discharge and evaporation from a forested watershed in Western Ghats, namely Barchinala catchment.

The simulations were done by hypothetically assuming the rate of deforestation in the catchment (i.e, by altering the forest cover). The simulated discharges are quantified using the flow duration curves. A comparison of simulated and observed flow data indicate that, there is a significant change in flow as the forest cover reduces to 40% in the catchment.

INTRODUCTION

Water and forests both cover large portions of the earth and both are crucial to sustenance of life and environment. As the world population increases exponentially with time, so does the pressure on the extent of utilization of these natural resources. Water and forest are not two independent natural resources; a close linkage exists between the two. Forest ecosystems generate multiple benefits to society through a wide range of products for consumption and use. In addition, forests on account of interactions with the water cycle, also provide hydrological regulation through groundwater recharge, low-flow augmentation and flood control processes. The rapidly increasing population pressure in many areas of developing countries has often led to changes in forest, mostly in terms of deforestation aimed at increasing agricultural production and providing additional land for human activities. It is generally accepted that deforestation can dramatically alter the water regime with respect to its quantity and quality.

In India too, significant reduction in all types of forest covers has taken place during the post-Independence period. Recently, Bhat et al. (2001) made an assessment of land cover changes in the country and reported an annual decrease in forest cover by 1.2% and the coverage of dense forest has marginally increased, whereas a major reduction in the scrub forest cover (-25.5%) has taken place during that decade. A similar attempt has been made by Jha et al. 2000; Bhat et al. 2002 to assess the land cover changes in the Western Ghats of India. These authors have reported that, over a period of 22 years (1973 – 1995), the Western Ghats have undergone substantial changes in land use/land cover both in terms of deforestation and afforestation.

Given that the Western Ghats mountain ranges form the headwater catchments of all major rivers of Peninsular India, there is a growing cause for concern regarding the hydrological impacts of such land cover changes. In view of this, an attempt has been made to assess the impact of the land cover changes on the water yield of a small catchment, namely Barchinala sub-catchment situated in the headwater catchment of River Kali in Karnataka. The objective of the study is twofold, firstly, the proposed model is calibrated to the observed data from the catchment and the model parameters of the flow duration curve were estimated. Secondly, the calibrated model has been used to assess responses of catchment due to changing forest cover on the water yield from the catchment.

STUDY AREA

Barchinala River originates from Thavaragatti village, which falls on the leeward side of Western ghat, at an altitude of about 734m, and 20 Km north of Dandeli in the Uttara Kannada district of Karnataka state (Figure.1). The catchment is relatively short in width and the river flows in a southerly direction and joins the main stream of Kali river near Dandeli. The total catchment area is about 14.5 Sq. Kms. The location of the catchment area lies between 75^0 35' E and 75^0 40' E longitude and between 15^0 18' N and 15^0 24' N latitude. Most part of the catchment is covered with dense dry deciduous (prominently teak trees) forest.

The predominant soil found in the catchment is silty clay soil and the red gravelly soil. These soil layers are underlined by granite rocks. The soil depth varies between 1.0 m to 1.5 m over the entire catchment. It has been reported that the saturated hydraulic conductivity of the soils vary from 2.51 mm/hr to 5.30 mm/hr in the catchment. The depthwise saturated hydraulic conductivity varies between 2.8 mm/hr at 10cm depth to 4.1 mm/hr at 150cm depth. The maximum value 5.8 mm/hr was observed at a depth of 45-60 cm (Venkatesh, et.al. 2004). A study of rainfall disposition through the various soil layers show that, the possible runoff generation mechanisms are Hortonian-type of overland flow and sub-surface flow (Venkatesh. et.al. 2005).

The Barchinala catchment is being monitored for discharge and weather parameters by Water Resources Development Organization, Govt. of Karnataka. The data for a period of 1980-2003 has been collected. From the rainfall records it is observed that the average annual rainfall over the catchment is 1500 mm and the evaporation is 1300 mm.

Discharge records for the Barchinala catchment for the period of 1980 to 2003 shows that mean annual flow is 64.97 cumecs. During July to October period mean flow is 112.5 cumec which is greater than the annual mean flow. The flows during July to October amount about 94.9% of the annual flow. These statistics imply that the runoff occurs only during the rainy season. Another 5.1% are distributed over other 8 months, with the major contribution from delayed (base) flow. The floods occur generally during monsoon season when catchment is under high antecedent moisture conditions with low evapotranspiration. The major events recorded between 1994 and 1998 have occurred during this season. In summer, occasional very high intensity rainfall were recorded, with out generating the flows in the stream. This gives an indication that, the catchment mostly generates the quick overland flow only when catchment is fully saturated (i.e., during the monsoon season). This is in agreement with the observations made by Venkatesh, et.al., (2005),

In the present study, the daily data of rainfall, runoff and pan evaporation observation for a period of 10 years (1994-2003) has been used to analyse the effect of change in the forest cover on the flow.

MODEL DESCRIPTION

The algorithm used to simulate the impact of changing land-use on flow is based on the framework developed using a global dataset by Zhang et al., (2001). This framework simulates average annual change in ET as a function of area weighted forest cover for an area. It does this by assuming that on an average annual time step there are not significant changes of soil moisture stores and that precipitation is either partitioned into ET

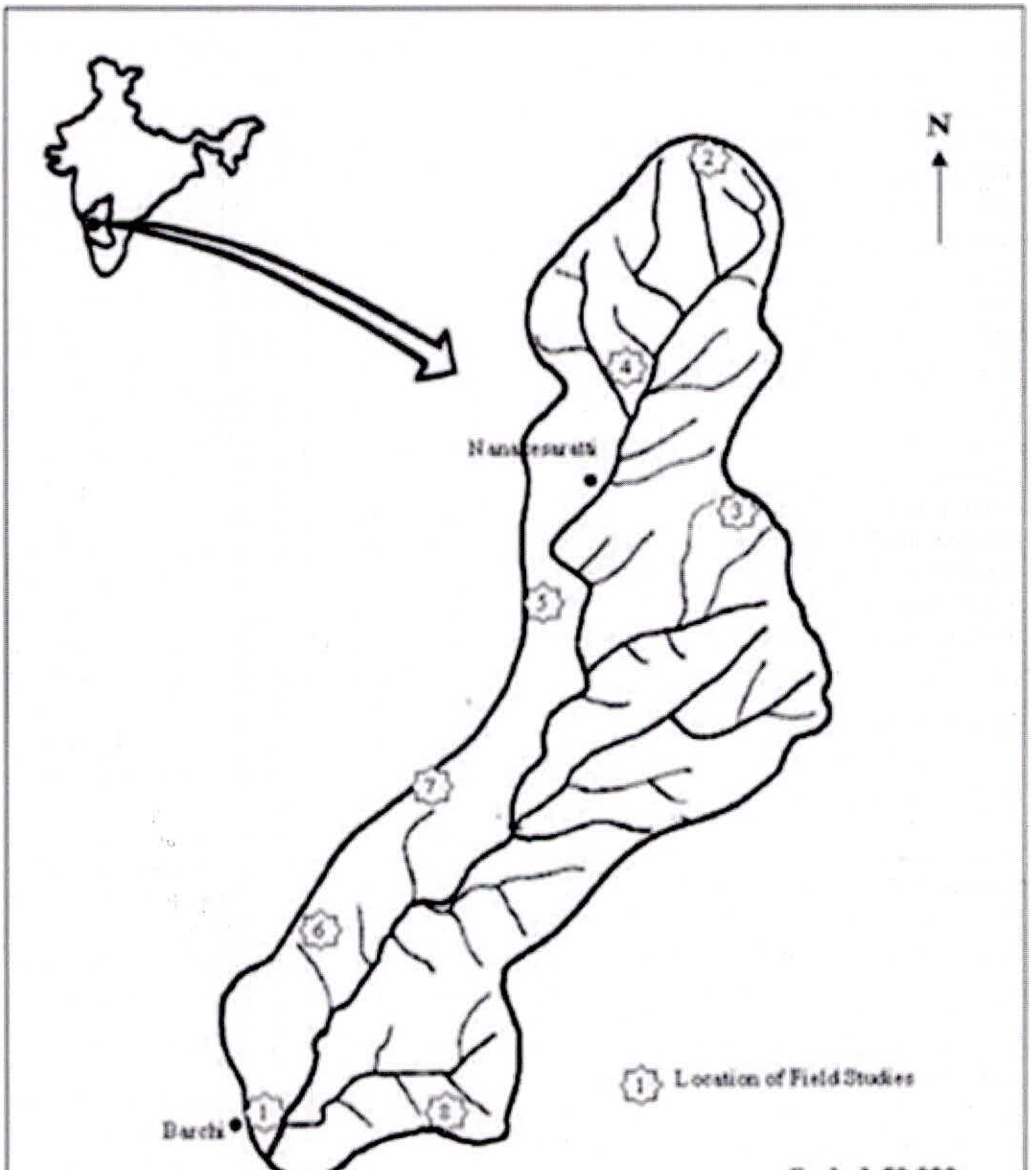


Fig.1. Barchinala catchment and location of rain gauges and stream flow gauge

or runoff. Hence, as a result of increasing forest area in a catchment, a modeled increase in ET results in an equal reduction of streamflow on an average annual time step for a given area. The model is a regional steady state mode suitable for a broad area scenario simulation. It requires only a limited dataset to parameterize, and was deemed suitable for the purpose of raising the awareness of the impact of land-use change on regional hydrology of an area. It does not dynamically model the growth of forest and does not allow for changes in precipitation and/or evaporative demand due to either climate variability or climate change

$$ET = P\left(f\frac{1+2*_{(1410/_{P})}}{1+2*\left(1410/_{P}\right)+\left(P/_{1410}\right)}+\right.$$
$$\left.(1-f)\frac{1+0.5*\left(1100/_{P}\right)}{1+0.5*\left(1100/_{P}\right)+\left(P/_{1100}\right)}\right) \quad \text{Eq.}(1)$$

Where ET us actual evapotranspiration, P is precipitation, f is the fractional forest cover.

The changes observed in the flow due to changes in the forest cover in the catchment is quantified using the flow duration curve. The daily annual flow duration curve is defined as the flow duration curve for a complete year constructed from daily flow data from that year. In this application, a water year has been adopted as the annual time unit. This is to minimize the difference between the soil water storage at the beginning of each year. In determining the water years, it was decided not to split either the wet or the dry flow periods. Therefore, the start of the water year was defined as being the first day of the month following the driest three months period. In the present case, 1st June to 30th May as considered as the water year. Once the start of the water year is determined, the observed flow data was divided into water years, the observed FDCs are then calculated and the FDC model parameters were determined for each water year. The most controlling parameter of the FDC is that of Cease to flow percentile.

In this study, it is assumed that, stream flow in a river ceases when the soil water storage is below the stream invert. The simplest conceptualization of this system is a single bucket model where the relationship between precipitation (P), evapotranspiration (ET) and stream flow (Q) is mediated by the soil water storage. The bucket model has been conceptualized as shown in Figure 2. The maximum soil water storage S_{max} represents the maximum soil water possible above the baseflow threshold (S_{base}). The threshold for evapotranspiration is given by S_{ET}, while the soil water storage at which stream flow ceases is given by S_{base}. While the soil water storage (S) is greater than S_{base} flow occurs in the stream, if S is below S_{base} flow in the stream ceases.

The Figure (2b & 2c) above show the possible configurations of the bucket model. In Figure (2b) threshold for ET is greater than threshold for baseflow, while in Figure (2c), the threshold for ET is less than the threshold for baseflow. The shaded regions in these two diagrams refer to the range in which the soil water storage needs to be in order for ET to occur. To adjusting the bucket model for the predicted range in water yield or ET it is assumed that S_{max} and S_{base} values are not impacted by change in vegetation. Therefore, the only S_{ET} can be altered to achieve a change in water yield, this should simulate the change in the rooting depth of the vegetation when going from a short rooted annual pasture or grass to deeper rooted vegetation such as tress. Under conditions, where a stream goes from being perennial to ephemeral, it is anticipated that the S_{ET} would change from being above S_{base} to below S_{base}. S_{base} therefore provides a point of reference for both S_{base} and S_{ET}. In order to account for the different rates of interception between grasses for forest, an interception storage has been added to the model. The interception store takes off the first 1 mm of rainfall for a 100% grass catchments and the first 3 mm of rainfall for a 100% forested catchment, with a liner function to allow for the partial forestation of a catchment.

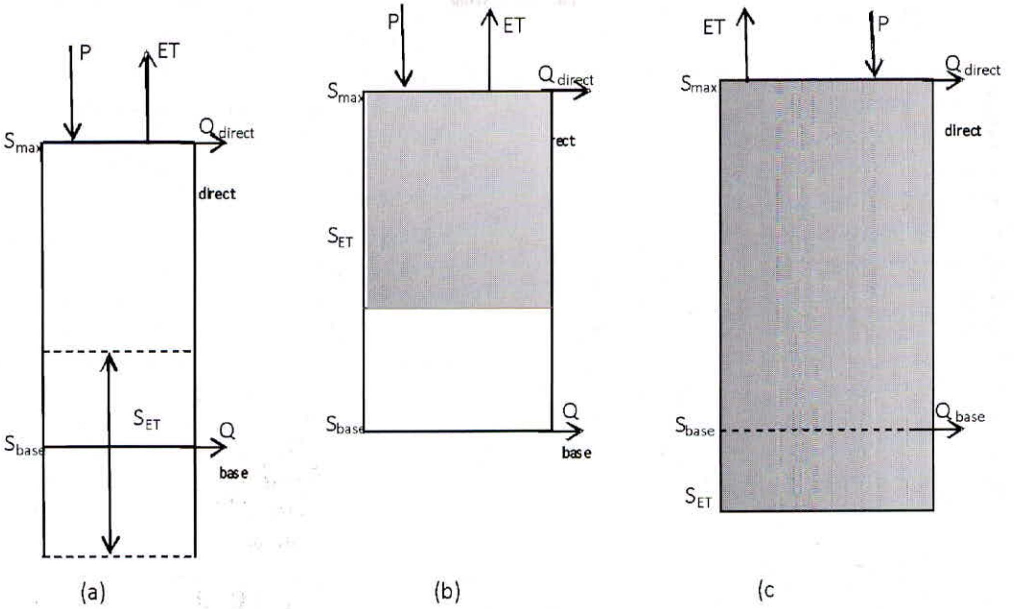


Fig. 2. Single bucket model used to model the percentage of time the flow occurs in a given catchment.

The water balance of the bucket is given by

$$S_t = S_{t-1} + P_t - I_t - ET_t - Q_{direct(t)} - Q_{base(t)} \quad \text{Eq. (2)}$$

Where

S_{t-1} is the storage of the previous time step
P_t is the rainfall
I_t is the interception
ET_t is the evapotranspiration from the catchment
Q_{direct} is the direct runoff and
Q_{base} is the basef low from the catchment

$$Q_{Direct} = \begin{cases} 0 & S_{t-1}+P_t-I_t \le S_{max} \\ S_{t-1}+P_t-ET_t-S_{max} & S_{t-1}+P_t-I_t \ge S_{max} \end{cases} \quad \text{Eq. (3)}$$

The ET used by the vegetation is a function of soil water storage in the root zone, leaf area index and the relative ET rate of the vegetation type. A number of functions are available for relating the soil water storage and potential evapotranspiration to different vegetation types. Farmer et al. (2003) used a function relating the percentage saturation of the soil profile to the ratio of potential ET to actual ET. The difference between grass and forest were achieved using two relationships as shown in Figure 3. The relative proportion of forest and grass is multiplied by each of these functions and added to get the actual ET for the catchment.

$$ET_{forest} = \begin{cases} PET & RSWS > 0.4 \\ \dfrac{RSWS}{0.4 * PET} & 0.4 \ge RSWS \ge 0 \\ 0 & RSWS < 0 \end{cases} \quad \text{Eq. (4)}$$

$$ET_{Grass} = PET * RSWS \quad \text{Eq. (5)}$$

Where

$$RSWS = \frac{S_t - S_{Max}}{S_{Max} - S_{Min}}$$

$$ET_t = f\,ET_{Forest} + (1-f)\,ET_{Grass} \quad \text{Eq. (6)}$$

Where

ET_{Forest} is the ET for a 100% forested catchment
ET_{Grass} is the ET for 100% Degraded /Grass land catchment
ET_t is the ET for the catchment at time t; and
f is the percentage of forest cover in the catchment

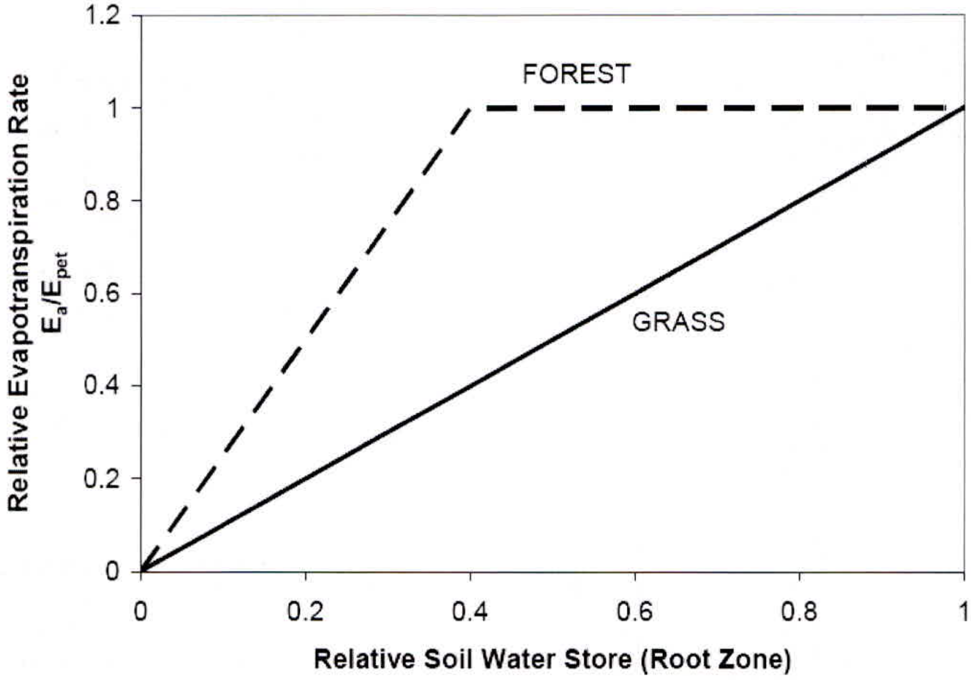


Fig. 3. ET function proposed by Farmer et al., 2003 and adopted in the single bucket model

$$Q_{Base} = \begin{cases} 0 & S_{t-1} \le S_{base} \\ [(S_{t-1} + P_t - I_t - ET_t - Q_{Direct}) - S_{Max}] * (-\ln(k) & S_{t-1} \ge S_{base} \end{cases} \quad \text{Eq. (7)}$$

Where k is the recession constant

The order in which water is added and subtracted from the bucket to achieve the storage at the end of any day is important and should represent the order in which the processes occur. Therefore, the interception loss is removed from the rainfall and the remaining rainfall is added to the storage in the bucket. If the storage exceeds S_{max} then direct runoff occurs and is calculated as shown in equation (3). Once Q_{direct} has been determined the ET_a can be calculated based on the equations 3 & 4, and removed from the storage. Once the ET has been removed the Q_{base} can be calculated as shown in equation (7). Thus the storage of the end of each time step can be calculated. Here in the present case, base flow has been calculated assuming a simple linear storage. This requires an estimation of the recession constant. As the bucket model is to be calibrated to observed flow, the recession constant can be estimated from the observed time series.

ESTIMATION OF PARAMETERS OF THE FLOW DURATION CURVE

The present model is aimed at quantifying the impact of land cover changes on the flow. The changes thus caused by the land cover changes are quantified using flow duration curve. Here in this case, a methodology proposed by Burt and Swank, 1992 has been used. In this method, firstly, the cease to flow percentile (CTF) is established. The CTF can be defined as the ratio of the number of non-zero flow days to the total number of days. A non-zero flow day is defined as any day on which flow is greater than or equal to a specified threshold value (0.001 mm/day). A FDC is then constructed for only the days on which flow occurs. The FDC for the days of flow is then normalized by dividing all flow values by the conditional median. The conditional median is defined as the median flow of the days on which flow occurs. Finally, the FDC is plotted in log-normal space to produce a normalized flow duration curve(NFDC). This normalization procedure results in all of the NFDCs intersecting the origin. This model uses five parameters to describe NFDC. The model involves fitting slope and exponential cure to the upper and lower section of the NFDC as described below

$$\dot{y} = \begin{cases} \left(10^{\frac{a}{b_1}*exp\left(F^{-1}\left(\frac{x}{CTF}\right)c_1\right)-a/c_1}\right)P_{50}, & x \le \frac{CTF}{2} \\ \left(10^{\frac{a}{b_2}*exp\left(F^{-1}\left(\frac{x}{CTF}\right)\right)^{-a/c_2}}\right)P_{50}, & \frac{CTF}{2} \le x \le CTF \\ 0, & x \ge CTF \end{cases} \quad \text{Eq. (8)}$$

Where

$\dot{y}$ is the predicted flow,

F^{-1} is the inverse of the standard normal cumulative distribution

P_{50} is the median of the non-zero flow days

CTF is the cease to flow percentile (expressed as a percentage)

X is a probability value (0-100%) and

a, b_1,b_2, c_1,c_2 are the curve fitting parameters

The method described above was applied to predict FDCs for changed land-use conditions. Firstly, mean annual water yield under changed land-use was calculated using the water balance model. Then the method was used to redistribute the total water yield reduction to reflect seasonal changes in flow. This is described in the following steps:

1. Quantify the effect of reducing the forest cover on percentile flows using data of the calibrated model
2. Create a typical normalized FDC by averaging the normalized FDCs from sub-catchment. This involves ranking the stream flow data and normalizing the flow by median flow.
3. Convert the typical normalized FDC into dimensional form (mm) using average flow (*Qcurrent*).
4. Estimate mean annual average flow under changed land-use (*Qnew*) using the relationships as obtained from the proposed bucket model.
5. Optimize the model parameter 'a' so that the calculated average flow for the new FDC equals the mean annual average flow under changed land-use (*Qnew*).

RESULTS AND DISCUSSION

The data required to run the model are the daily rainfall, evaporation and the observed flows. The required data for Barchinala catchment has been compiled for a period of 10 years from 1994 to 2003. Initially, the model was run with the base line condition (i.e., for the existing land use condition) such as 85% forested land and 15% grass land. The optimised model parameters obtained for this run is tabulated in the Table.1

Table 1, depicts that, the maximum soil moisture storage (S_{max}) is 487.4 mm, which represent the moisture holding capacity of the soils in the catchment. The soil found in the catchment is predominantly the black soil with higher silt and clay content. The higher value of S_{max}, will give rise the more evapotranspiration as the catchment is covered by 85% of forest. In an another study, Venkatesh and Purandara (2009) applied a conceptual rainfall-runoff model namely TOPMODEL to simulate the daily flows in the sub-basin. The optimized value of the maximum soil moisture storage is 450mm, which is much closer to the values obtained in the present study. The authors have also reported that, about 75% of the total daily flow is contributed by the delayed flow and rest by the quick flow. This may be the

Table. 1. Optimized Model parameters

Sl No	Model Parameters	Units	Optimised Value
1	Maximum Soil Moisture Storage S_{max}	mm	487.40
2	Minimum Soil Moisture Storage S_{min}	mm	0
3	Soil Moisture Threshold for base flow occurrence S_{base}	mm	470.40
4	Recession Coefficient for base flow K_{base}	mm/d	0.05

possible reason for obtaining the higher values for both Smax and Sbase. The optimized value for the soil moisture threshold for base flow (S_{base}) occurrence is 470.40 mm, which is an indication of the catchment wetness over the year. In the earlier studies carried out in the Barchinala indicate that, the soils in the catchment are deeper and have higher rate of percolation. The measured percolation rates are as high as 4.68 mm/hr.

The model employs the Flow duration curves technique to quantify the effect of changing land use on the annual yield of the catchment. As a first step, the model estimate the FDC parameters for all the time period which is considered for the analysis. In the present case, the model estimated the parameters of the FDC for all the hydrological years with their statistics. The results obtained are tabulated in Table.2.

From the table above, it is noticed that, the cease to flow (CTF) expressed as percentile and has been decreasing over the study period, for ex. 2.2 percentile indicate the three are about 2% of values are below this value, which have no flow. This may be true as reported elsewhere that, the higher forest cover influence for higher release of flow during the non-rainy period. Other statistics of the NFDC such as slope parameter (a) is conceptualized as the ratio of mean to median flow. The empirical relationship that is determined for mean and median relationship can be used to predict the slope. These values show a decreasing trend as that of the CTF indicating that the FDC is not fitted to the very high flows. Similarly other two model parameters such as c_1 is primarily linked to rainfall and rainfall intensity and c_2 to the geo-morphology of the catchment along with CTF percentiles.

The parameter c_1 and c_2 are present the response of the FDC to vegetation changes appears to occur in two ways depending on the rainfall. In the high rainfall areas it is anticipated that the proportional reductions in all flow percentiles are similar, while for catchments in lower rainfall areas the higher percentiles are reduced by a greater proportion than the higher flows. This hypothesis proves to be correct of the present study area as it is classified as the high rainfall area with an average annual rainfall of over 1500mm.

Simulating the Flow for Different Forest Cover

The main objective of the present analysis, is understand the effect of changing forest cover on the flow in the catchment. In order to achieve the objective, it is envisaged to assess the impact by altering the forest cover in the catchment. The flow duration curves obtained for different % of forest cover are shown in the Figure.4, and the respective FDC parameters are tabulate in Table.3. From the Figure 4, it is noticed that, as the % of forest cover changes, the flow duration curve changes its shape giving rise to more flow in the flow range of 1 to 10 m^3/sec (normalized by dividing

Table. 2. Yearly flow duration curve shape parameters and statistics

Year	Conditional Median	CTF (Percentile)	Slope (Par a)	Upper (Par c_1)	Lower (Par c_2)	Mean	Conditional Mean	CE
1994-95	4.262	32.1	-0.577	-0.137	0.065	3.688	11.504	0.971
1995-96	0.806	9.6	-1.205	0.351	-1.533	0.402	4.202	0.935
1996-97	1.613	7.1	-0.165	-1.503	2.263	0.284	3.981	0.986
1997-98	3.024	14.8	-0.885	0.02	-0.257	2.107	14.24	0.969
1998-99	1.066	8.2	-0.641	0.143	-0.115	0.169	2.05	0.964
1999-00	4.55	9	-0.726	-0.089	0.837	1.328	14.73	0.991
2000-01	4.14	4.7	-0.451	-0.115	1.709	0.283	6.07	0.971
2001-02	0.547	2.7	-2.172	1.069	-3.226	0.105	3.84	0.969
2002-03	17.05	2.2	-0.863	-0.439	1.698	0.801	36.52	0.989

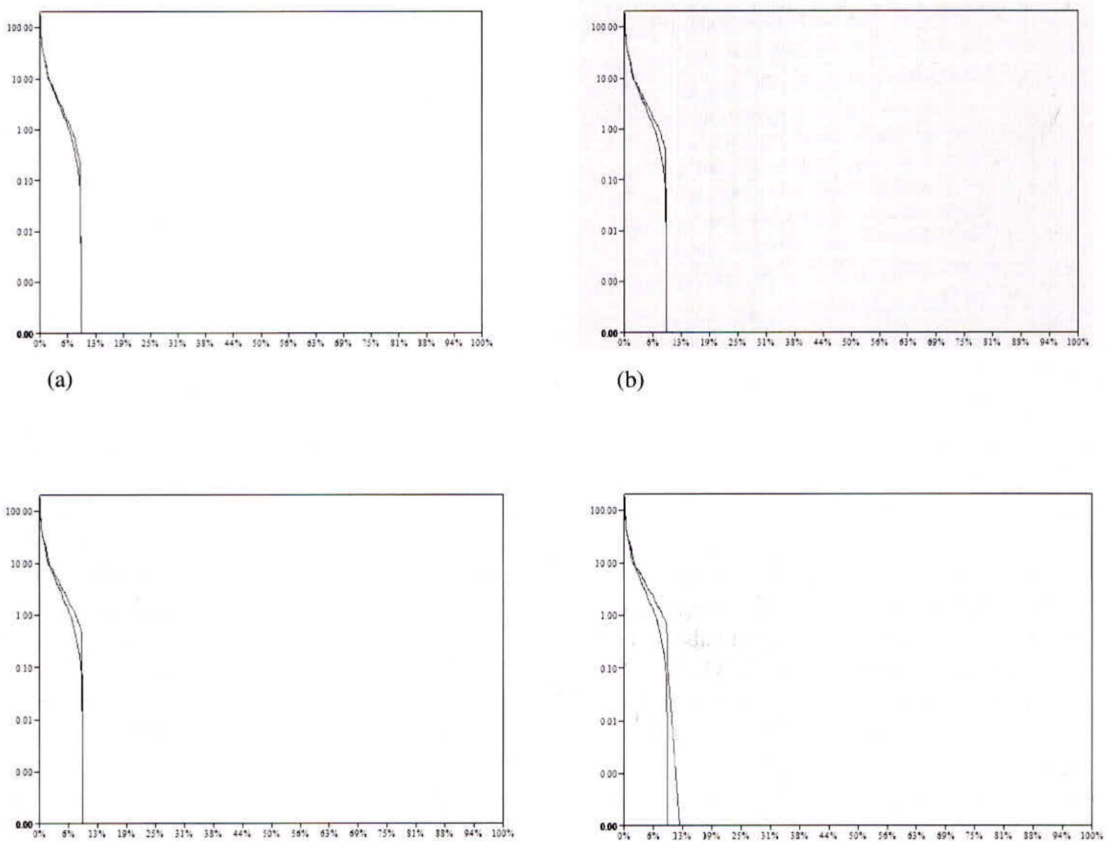
the conditional median value). However, the entire ranges of flows have registered changes when the forest cover reaches to its lowest value of 40% (as one of the scenario in the study). Similarly CFT values show an increasing trend as the forest cover decreases. Whereas the other shape parameters such as c_1 and c_2 show varied response to the forest cover changes.

As it is mentioned earlier that the parameters c_1 is related to rainfall and its intensity, the effect of the rainfall and its intensity in the catchment is clearly seen on the shape of FDC. As it is observed from the Figure 4, the lesser forest cover with the increase in the rainfall intensity can give rise to an increased flow (due to the generation of overland flow). This could be due to the possibility of occurrences of Infiltration excess overland flow in the catchment (Venkatesh et al., 2003). Similarly the parameter c_2 is showing the higher values for the lower forest cover. This is also possible that, higher flows generally occurr when the soils are completely saturated. As observed by Scott et al (2005), under the saturated condition, even the forested catchment can produce the flow equivalent to that of the degraded catchment. This statement may be true to some extent in the present case also, as observed deviation in the FDC is in the higher flow range in all the cases.

SUMMARY

Our understanding of the deforestation impact on annual flow regime is limited. However, it is possible to draw some general conclusions about the impact of deforestation on high flow or storm flow and low flow or dry-season flow. Deforestation is expected to decrease storm flow volumes and increase the magnitude of peak flows by removing a proportion of the storm rainfall and accumulating soil water storage. However, there are no specific, robust and readily available tools to assess the impact. In this analysis, a conceptual model developed by Zhang et al, (2001) is used to assess the impact of land cover change on the flow. The model was applied to Barchinala catchment and results were analyzed and discussed.

From the above discussion, it can be concluded that, a simple model like the one used in this analysis can be effectively be used to assess the impact of land cover changes on the water yield of the catchment. Following are some of the important points emerged out of the discussion,



(a) (b)

(c) (d)

Fig. 4. Showing the Normalised Flow Duration Curve (NFDC) for different scenarios of forest cover in the catchment; (a) 70%, (b) 60%, (c) 50% and (d) 40%

Table 3. The FDC parameters obtained for different forest covers

% forest Cover	CTF (Percentile)	Slope (Par a)	Upper (Par c_1)	Lower (Par c_2)
85	9.255	-0.0979	0.044	-0.025
70	10.32	-0.126	0.122	-0.058
60	11.09	-0.137	0.268	-0.125
50	11.41	-0.298	-1.023	0.024
40	12.24	-1.010	1.253	0.136

1. The results obtained clearly show a reduction in stream flow (through FDC) due to the changes in forest cover. The observed changes in the flow are mainly related either to the rainfall amount or its intensity.
2. Reductions in annual flow can due to the higher evapotranspiration as induced by the growth of the plants in the catchment.

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