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Changes in streamflow regime as indicator of upstream urbanization in a humid tropical river basin

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ABSTRACT: Changes in streamflow in the Meenachil river basin, Kerala, are assessed at two upstream gauging stations located at Palai and Cheripad and one downstream gauging station at Peroor to understand changes in flows due to upstream urbanization. An increase of 14% in the population and 46% in the number of housing units have been observed in the entire study area during the last two decades, indicating increase in urbanization. Time series analysis of 29 years data shows an increasing trend at Peroor at 2.8% *per* year for total flow and 5.2% for peak flow, which indicates the effect of urban land use. There has been a decreasing trend in the flows at 2% at the upstream gauging stations of the river basin. The frequency of occurrence of flows are observed to be increasing at Peroor due to urbanization which brings down vegetation, enhances the impervious area and contributes to fast draining of stormwater. The decrease in both the flow and its frequency of occurrence at the upstream stations are due to the increase in area under plantation crops and also the soil and water conservation works attempted in the area.

KEY WORDS streamflow; urbanization; population density; time series analysis; frequency of occurrence

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1. Introduction

Urbanization has a significant effect on many of the processes that control streamflow (McCuen, 1998). Urbanization has a considerable hydrological impact in terms of influencing the nature of runoff and other hydrological characteristics, delivering pollutants to rivers and controlling rates of erosion. There is reasonably good literature on urbanization impacts on water quantity and quality (Geiger *et al*., 1987; Hall, 1988; Warren *et al*., 2008). This includes peak flow enhancement, non-stationary discharge signals, decrease in travel time, increase in total runoff, base flow changes and sewage overflows. The prime physical cause of these impacts is an increase in impervious area within the watershed. Impervious areas can be defined as areas in which all rainfall is converted to surface runoff and are categorized by buildings (e.g., roof surfaces) and transportation infrastructure (e.g., roads, drive ways, parking lots). Impervious areas related to transportation often have more impact than rooftops, especially in highly automobile-dependent areas. Several studies have shown imperviousness to be directly related to urban runoff and pollutant loading, with effects being evident at levels as low as 10% impervious coverage (Cowden *et al*., 2006). Land use change can be considered as the main reason for increased runoff and sediment in tropical regions where the change in rainfall amount can be neglected (Alansi *et al*., 2009). Urbanization and changes in urban-related land use – land cover could affect the streamflow behaviour or characteristics (Noorazuan *et al*., 2003). A study conducted in the Paochiao watershed in Taiwan by Yu-Pin *et al*. (2008) revealed the variability and magnitude of hydrological components based on the historical and predicted land use pattern, cumulatively affecting urban sprawl in the watershed, specifically, increasing surface runoff and decreasing baseflow for the historical and predicted periods, 1990–2025. To detect the effects of human induced shifts from those of precipitation on the hydrologic responses, a paired watershed approach was undertaken by Stanley *et al*. (1996). On comparing watersheds in rural and urban areas, the urban watersheds showed a high magnitude increase in mean and peak flows. Stanley *et al*. also emphasized the need for careful analysis of natural basin characteristics (soils and basin shape), land use and drainage changes and of various precipitation conditions if the influence of shifting precipitation on hydrological conditions is to be detected, accurately measured and correctly interpreted. For such studies the paired basin comparison techniques appear to be a valuable approach.

The effects of urbanization upon hydrology have become a subject of worldwide concern. A first step towards the assessment of the effects of urbanization upon hydrology of a basin is the examination of the available streamflow data to ascertain whether there are detectable changes that may be attributed to urbanization.

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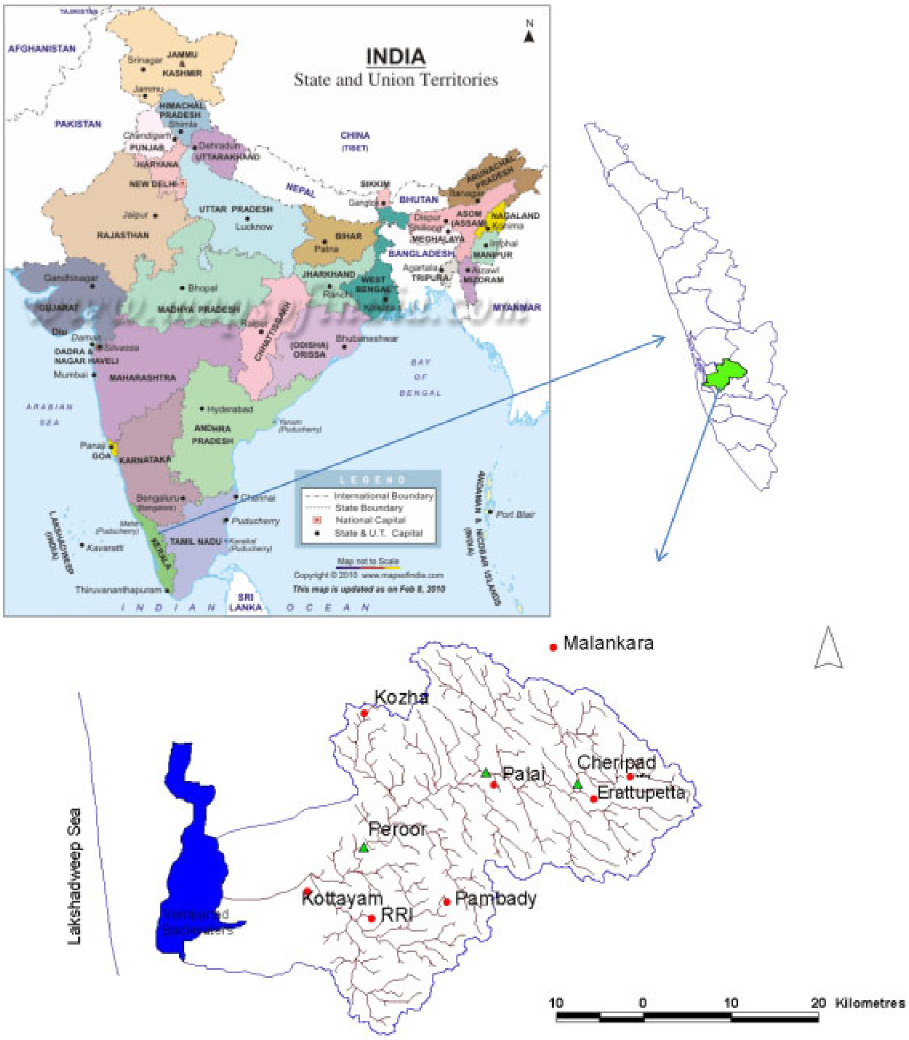

Figure 1. Drainage map of Meenachil river basin. ● Rainguage stations, ▲ Discharge stations, Streams, Meenachill river basin. This figure is available in colour online at wileyonlinelibrary.com/journal/met

The objective of this paper is to analyse the streamflow records of Meenachil river basin in the humid tropics of Kerala to determine the effects of urbanization. Exploratory data analysis techniques are used in this study. Results are not generalized as they do not incorporate all climate, soil and vegetal properties. This study is intended as an initial step in examining the effects of land use change using more generalized water balance models.

2. Study area

The area taken up for the study is Meenachil river basin in Kerala, which encompasses approximately 1272 km^2 of drainage area, extending from Vagamon in the east at an elevation of 1195 m above mean sea level and Vembanad lake on the southwest coast of India. It lies between 09°26′24″ and 09°51′00″N and 76°22′12″ and 76°55′12″ E. Average annual rainfall in the river basin is 3510 mm. Figure 1 shows the drainage map of the Meenachil river basin with the locations of rain gauge and streamflow stations. The streamflow data at Peroor, Palai and Cheripad are used in the present study; areas of the sub basins covered by these stations are 768, 438 and 147 km^2 respectively.

3. Methodology

3.1. Data availability

Streamflow data for the period 1979–2007 at Peroor, Palai and Cheripad stations are collected from the Water Resources Department of Kerala State. Streamflow is estimated using the data from stage-discharge stations. Stage-discharge curves are calibrated using current meter readings. Gauge readings are taken three times a day. Rainfall data, from gauges installed as *per* the specifications of Indian Meteorological Department, for the same period are available from there gauging stations at Teekoy, Erattupetta and Kozha falling within the sub-basins represented by the streamflow stations. Data on population and the number of housing units for 1981 and 2001 are based on the census data collected from the Department of Economics and Statistics, Government of Kerala.

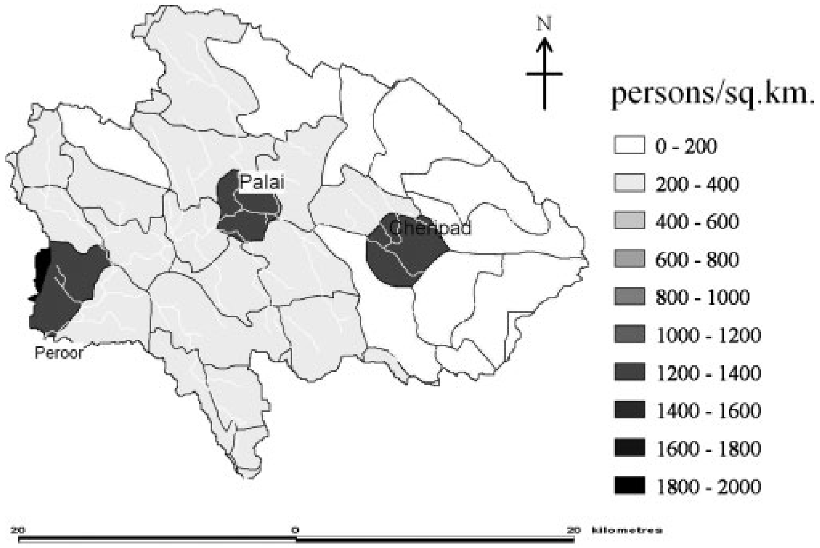

Figure 2. Population density – 1981.

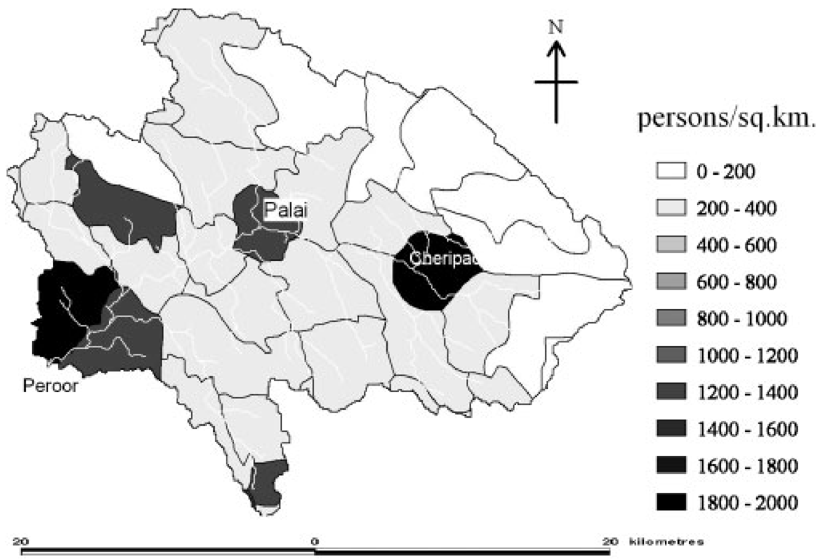

Figure 3. Population density – 2001.

Urban hydrological studies generally focus on the effect of land use change on the quantity or quality of water. In order to detect these changes, three basic approaches are used (Hall, 1988): (1) 'upstream-downstream', (2) 'before and after', or, (3) 'paired watershed'. In the 'upstream-downstream' approach, the data collected from a section of river upstream of the urban area are compared to those from downstream along the same river. This method produces evidence of the urban land use change on the stream. In the 'before and after' method the data collected from an urban area prior to the land use change are compared to the data collected after the land use change. In this method the effects of rainstorms in one period is to be separated from those in the other periods. This is a cumbersome exercise. Hence, application of non-parametric statistics to eliminate the effects of precipitation may be considered. In the 'paired watershed' method, data from concurrent time periods from an urban watershed are compared with that from a rural (controlled) watershed. Any change in these data is taken as indicative of land use change. The basins compared must be in proximity (for climatic purposes): the geology should be the same and land use must be stable over the study period in the rural basin. This method, if applied properly, produces a sound argument. The time period of change in land use may be determined by observing data on vegetation, population shifts, road network, residential or other constructions.

To arrive at estimates of the population contained in the study area, the political/census demarcated area i.e., village/panchayat boundaries (around 30 km^2), are considered. In this study the panchayat-wise census data have been collected from the report of Department of Economics and Statistics based on the census for 1981 and 2001. Since the entire study area lies in the Kottayam district, the panchayat-wise map of Kottayam district has

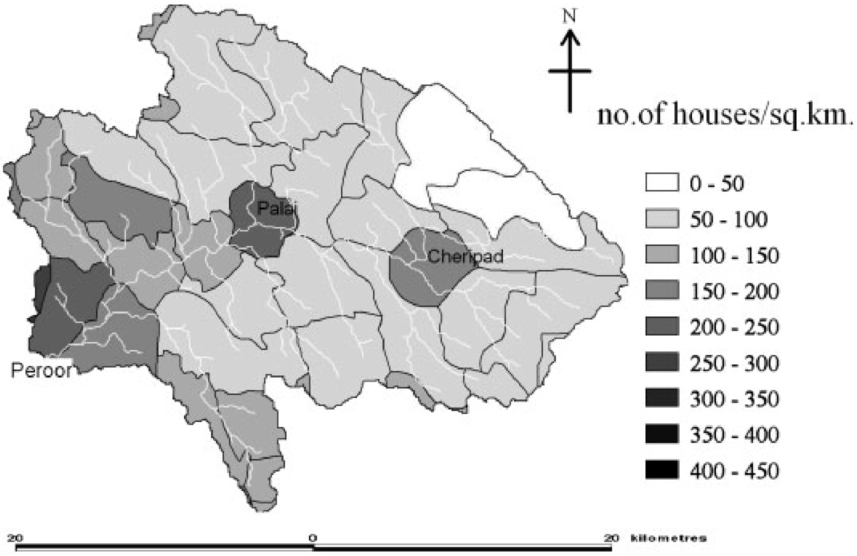

Figure 4. Density of housing units – 1981.

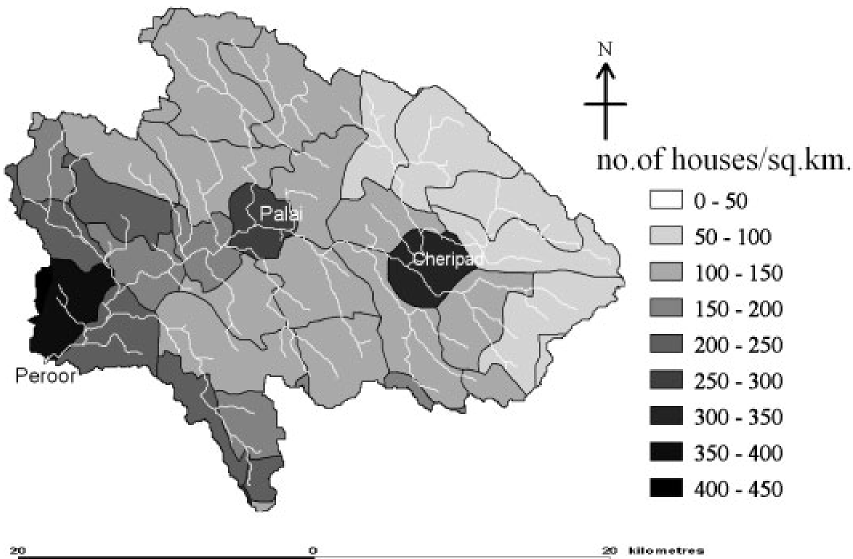

Figure 5. Density of housing units – 2001.

been collected and digitized. The drainage map is then superimposed over the district map to get the panchayats within the study area. This map is used to represent the population density and gross density of housing units in the study area. To assess the area lying beneath forests, vegetation and that covered by roads and buildings two satellite imageries of two different periods are used for the study. Landsat TM data acquired on 24 January 1990 (P144/R53) and IRS P6 LISS III data acquired on 13 February 2005 (P100/R67) are registered to the Survey of India toposheets 58C/9, 58C/10, 58C/13 and 58C/14. The digital image processing of these satellite data are carried out using ERDAS IMAGINE 8.5 software. Visual interpretation technique has been followed for the on-screen interpretation. Ground truth verification has been done and changes incorporated in the final map. The different land use classes delineated include

Table I. Percentage area covered under different landuses.

Landuse	% area covered					
	For u/s area			For d/s area		
	1990	2005	% change	1990	2005	% change
Paddy field	5.25	5.25	–	17.30	9.59	−7.71
Barren rocks	7.32	7.31	–	0.20	0.21	–
Mixed crops	35.50	19.34	−16.16	56.30	30.65	−25.65
Plantation	19.27	43.69	+24.42	6.76	33.63	+26.87
Grass	17.39	14.10	−3.29	3.53	7.87	+4.34
Water body	2.76	1.04	−1.72	1.94	0.70	−1.24
Urban/city area	1.50	2.48	+0.98	3.87	5.14	+1.27
Cleared area	11.01	6.82	−4.19	10.10	12.21	+2.11

u/s area: drainage area upto Palai gauging station; d/s area: drainage area below Palai gauging station

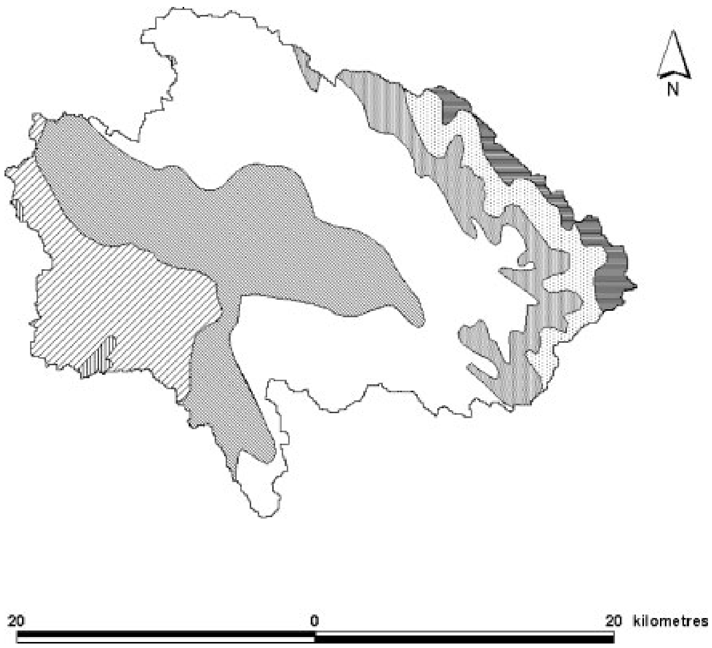

Figure 6. Major solis of Meenachil river basin upto Peroor. nellappara, muthur, mavady, kooroppada, koduman, arpookkara, lakkathoor.

Table II. Major soil characteristics in the Meenachil river basin.

Major soils	Type	Drainage type	Texture
Muthur	Fine, mixed, isohyperthermic, aquic humitropepts	Very deep, imperfectly drained, hydromorphic soils	Silty clay to clay texture
Arpookara	Clayey-skeletal, mixed, isohyperthermic, plinthohumults	Very deep, well drained laterite soils	Gravelly clay loam to gravelly clay
Kooropada	Clayey-skeletal, mixed, isohyperthermic, typic dystropepts	Deep, well drained soils underlain by hard laterite	Gravelly clay loam
Lakkattoor	Clayey, mixed, typic hapludults isohyperthermic,	Very deep, well drained soils developed from gneissic rocks	Gravelly loam to gravelly clay loam
Koduman	Clayey-skeletal, isohyperthermic, oxic humitropepts	Very deep, well drained hill soils developed from gneissic material	Sandy clay loam to gravelly clay texture
Nellappara	Fine-loamy, mixed, isohyperthermic, lithic humitropepts	Moderately deep to deep, well drained soils developed from gneissic rocks	Sandy clay loam to clay loam
Mavady	Fine-loamy, mixed, isohyperthermic, typic paleudults	Very deep, excessively drained soils developed from gneissic rocks	Gravelly sandy loam to gravelly clay loam

grass, plantation, mixed crops, barren rocks, cleared area, urban/city area, water body and paddy field. Details regarding watershed development programmes carried out by the panchayat/local authorities are collected. Details on water table fluctuations are not available. The soil characteristics for the entire river basin are collected from the Soil Survey Organisation under the Department of Agriculture, Government of Kerala, which organization has conducted detailed surveys in the study area.

3.2. Annual hydrological statistics

Total annual flows and annual peak flows in the study area are compared at three gauging stations, at Peroor downstream and at Palai and Cheripad on the upstream for the period from 1979 to 2007. Temporal trends in the rainfall and streamflow values for the three gauging stations are estimated using the MAKESENS (Mann–Kendall test for trend and Sens's slope estimates) excel template (Timo, 2002).

The Mann–Kendall test is applicable in cases where the data values x_i of a time series can be assumed to obey the model

$$x_i = f(t_i) + \varepsilon_i \quad (1)$$

where $f(t)$ is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean.

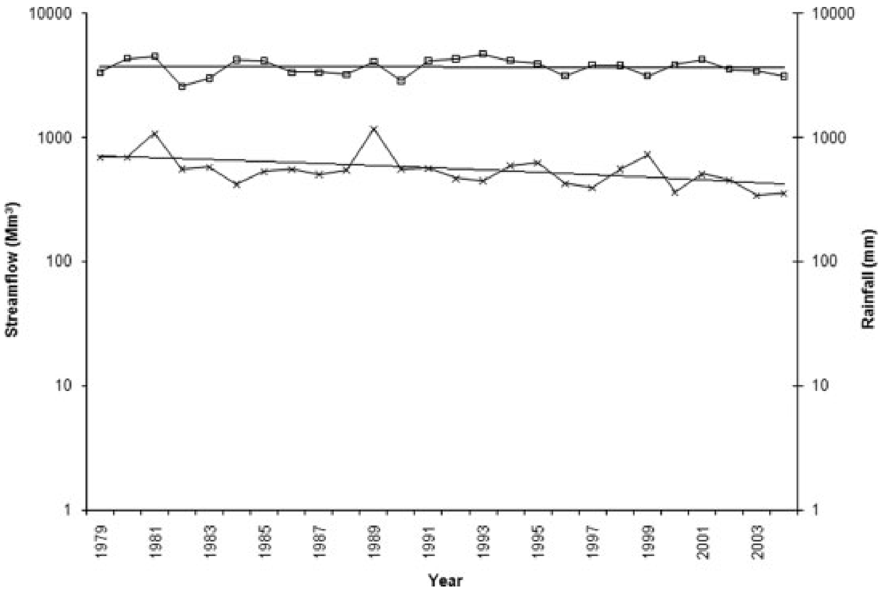

Figure 7. Total annual flow/rainfall recorded at Cheripad (1979–2004). Line with square markers represent rainfall and line with cross markers represent flow.

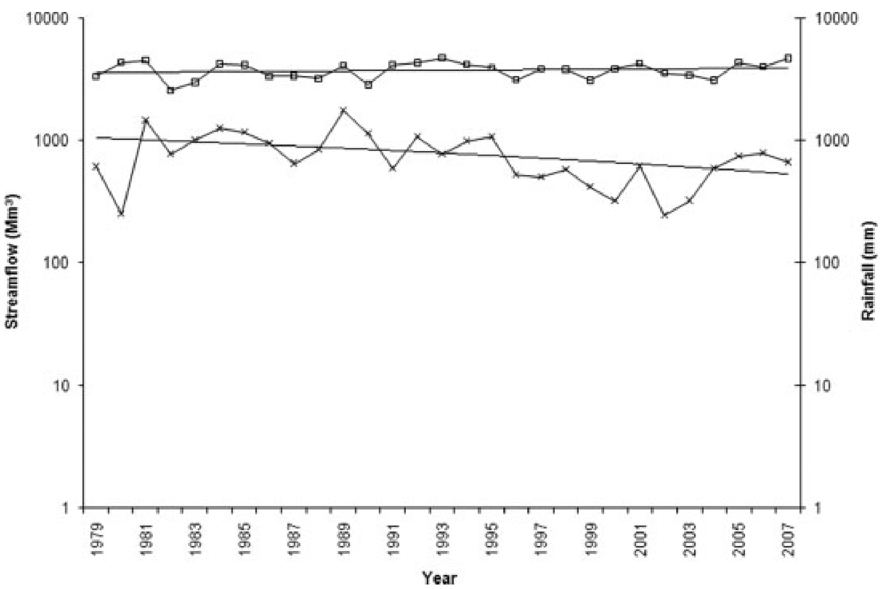

Figure 8. Total annual flow/rainfall recorded at Palai (1979–2007). Line with square markers represent rainfall and line with cross markers represent flow.

For time series with less than 10 data points the S test is used and for time series with 10 or more data points the normal approximation (Z statistic) is used. A positive value of Z indicates an upward trend and a negative value of Z indicates a downward trend. In MAKESENS the tested significance levels α are 0.001, 0.01, 0.05 and 0.1. For the four tested significance levels the symbols used in the trend statistics worksheet are:

- *** if trend at $\alpha = 0.001$ level of significance;
- ** if trend at $\alpha = 0.010$ level of significance;
- * if trend at $\alpha = 0.050$ level of significance, and,
- + if trend at $\alpha = 0.100$ level of significance.

If the cell is blank, the significance level is greater than 0.1.

Chow (1988) pointed out that one of the most important problems in hydrology deals with interpreting past record of hydrologic events in terms of future probabilities of occurrence. Most of the science of hydrology is based on historical data and the probabilistic methods have found wide application. This is especially true in the study of floods. Among the several methods which can be used to compute the recurrence interval, the California method and the Weibull method are the most common ones used because of their soundness (Timothy, 1979). Recurrence interval (T) is the reciprocal of probability given

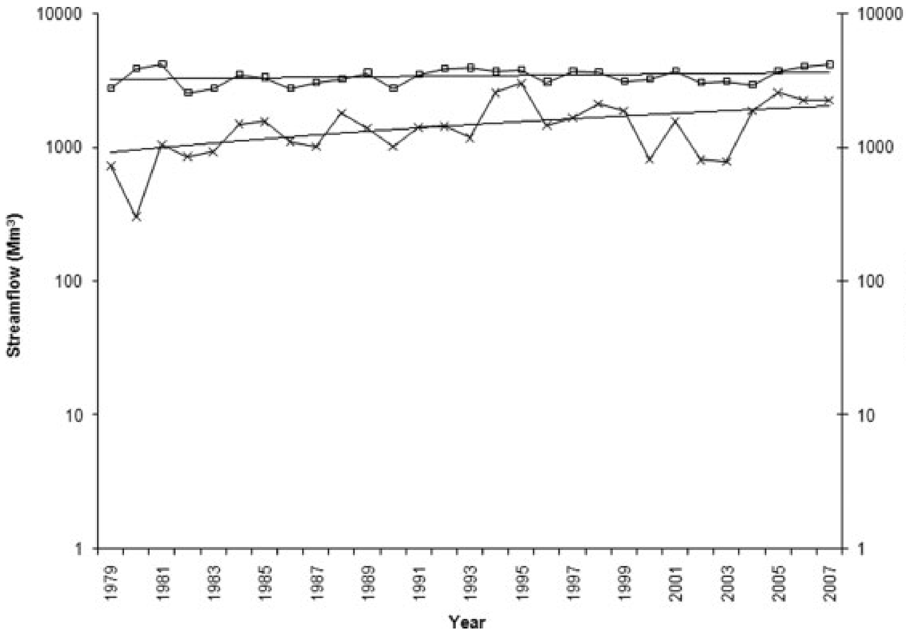

Figure 9. Total annual flow/rainfall recorded at Peroor (1979–2007). Line with square markers represent rainfall and line with cross markers represent flow.

by:

$$T = \frac{1}{P} \tag{2}$$

To determine recurrence intervals, streamflow values for each station during the period under study are ranked from highest to lowest (i.e., the highest flow with rank (1) using the Weibull method. Recurrence interval (T) of each flow is calculated as:

$$T = \frac{n+1}{m} \tag{3}$$

where n is the number of streamflow values ranked and m the rank number of each streamflow value. Recurrence intervals are calculated separately for streamflows at each station. Streamflow values and recurrence intervals are plotted with recurrence interval on a logarithmic scale and streamflow on a linear scale. Streamflow values are estimated from linear regression equations obtained from the transformed data.

4. Results and discussions

Figures 2 and 3 show the population density variations for the years 1981 and 2001 respectively. There is a 14% increase in population during the 20 year period (1981–2001) in the entire sub-basin of Peroor, whereas there is only an 11% increase in the upstream sub basins. Figures 4 and 5 give the variation of gross density of housing units in the study area for 1981 and 2001 respectively. It is seen that during the 20 year period there is 46% increase in the number of housing units in the downstream sub basin and 44% in the upstream sub-basins.

Table I gives the percentage area covered under different land uses and the change that has occurred for the two selected periods i.e., for the years 1990 and 2005.

Figure 6 shows the major soils in the entire river basin with more details given in Table II. According to the characteristics of soils, upstream sub-basins are well drained.

Figures 7–9 show the variations of streamflow and rainfall at the three gauging stations. Total annual streamflow shows inter-annual variations at the three gauging stations for the study period (1979–2007). The trend statistics computed for Mann–Kendall test is given in Tables III(a) and III(b).

Table III(a). Trend analysis for streamflow at the three stations.

Time series	First year	Last year	n	Test Z	Significant
Dis-Per	1979	2007	29	2.95	**
Dis-Pala	1979	2007	29	−2.27	*
Dis-Cheri	1979	2007	29	−2.73	**

Dis-Per: Streamflow at Peroor, Dis-Pala: Streamflow at Palai; Dis-Cheri: Streamflow at Cheripad, *: 0.05 significant level, **: 0.01 significant level.

Table III(b). Trend analysis for rainfall at the three streamflow stations.

Time series	First year	Last year	n	Test Z	Significant
Rf-Pa/Ch	1979	2007	29	0.39	–
Rf-Per	1979	2007	29	1.56	–

Rf-Pa/Ch: Rainfall at Palai and Cheripad; Rf-Per: Rainfall at Peroor; - : significant level >0.1.

The analysis predicts a decreasing trend in the total streamflow at the 0.01 significance level at Cheripad, at the 0.05 significance level at Palai, whereas an increasing trend is observed at Peroor gauging station at a significance level of 0.01. No significant trend in the total annual rainfall is observed (Table III(b)). The back-transformed regression coefficient of the trend line predicts a decrease of 2% *per* year in the annual streamflow at Palai and Cheripad, whereas a 2.8% *per* year increase is observed at Peroor. Though the population is increasing in all the sub-basins, the density of population is less upstream to have an effect on streamflow as compared to downstream (Figure 3).

Figures 10–12 give the variations of annual peak flow at the three gauging stations under consideration. The trend statistics computed are given in Table IV. An increasing trend at the 0.001 significance level is observed at Peroor, whereas there is a decreasing trend at the 0.1 significance level at Palai. The back-transformed regression coefficient of the trend line predicts a 2% decrease in the peak flow for the two upstream gauging stations whereas a 5.2% increase *per* year is observed for the downstream gauging station at Peroor. The total annual streamflow and the annual peak flow at the downstream station of Peroor have increased by 2.8 and 5.2% *per* year due to urbanization. The cleared area, urban/city area and rice field converted area contribute to the increase in streamflow downstream. The increase in the plantation area and decrease in the cleared area reduces the streamflow upstream. In addition, soil conservation works were initiated from 1997 in the Western Ghat region of the state under the watershed programmes of the Western Ghat Cell of State Planning and Economic Affairs Department. Rain pits, contour trenches and bunds were attempted mainly in the highland region. Now with the introduction of Hariyali projects, more and

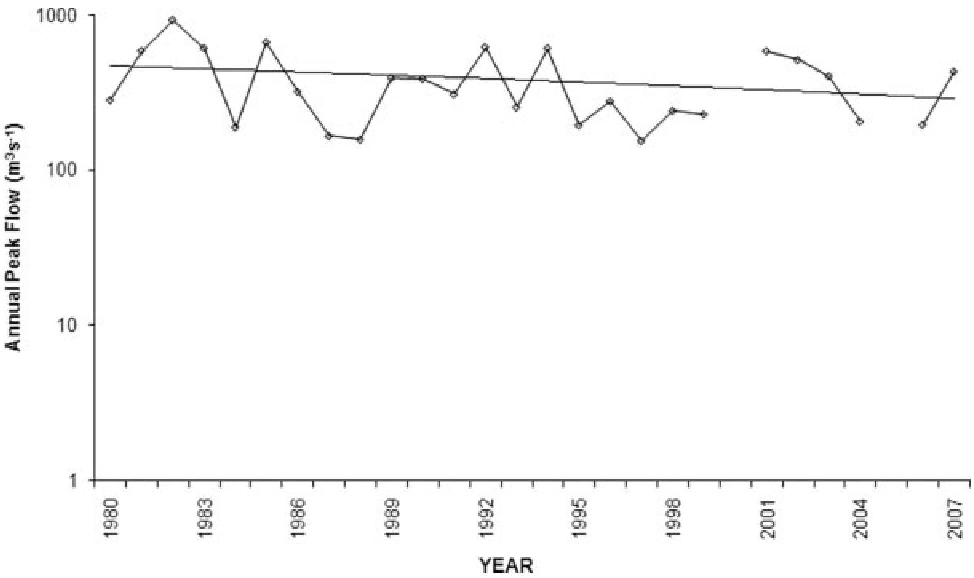

Figure 10. Annual peak flow at Cheripad (1980–2007).

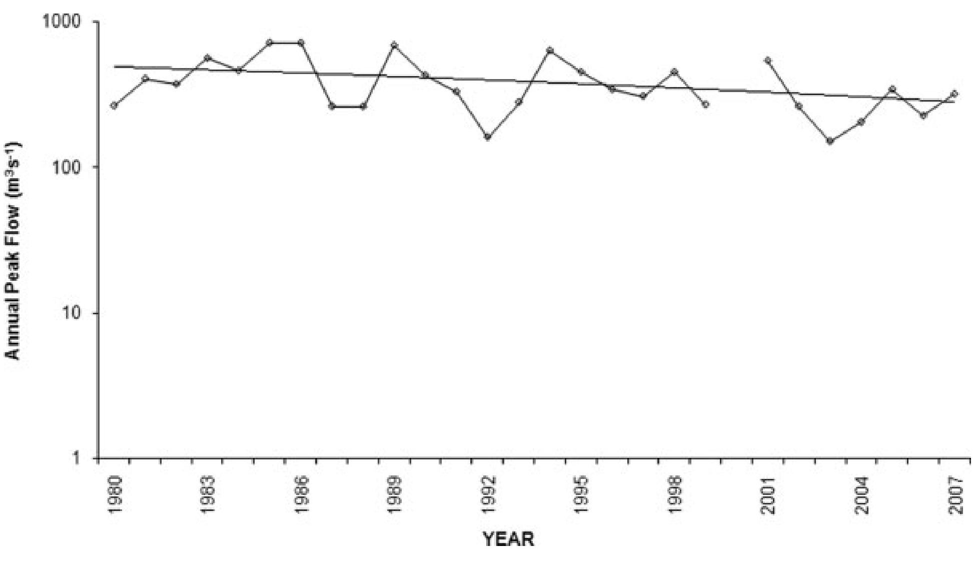

Figure 11. Annual peak flow at Palai (1980–2007).

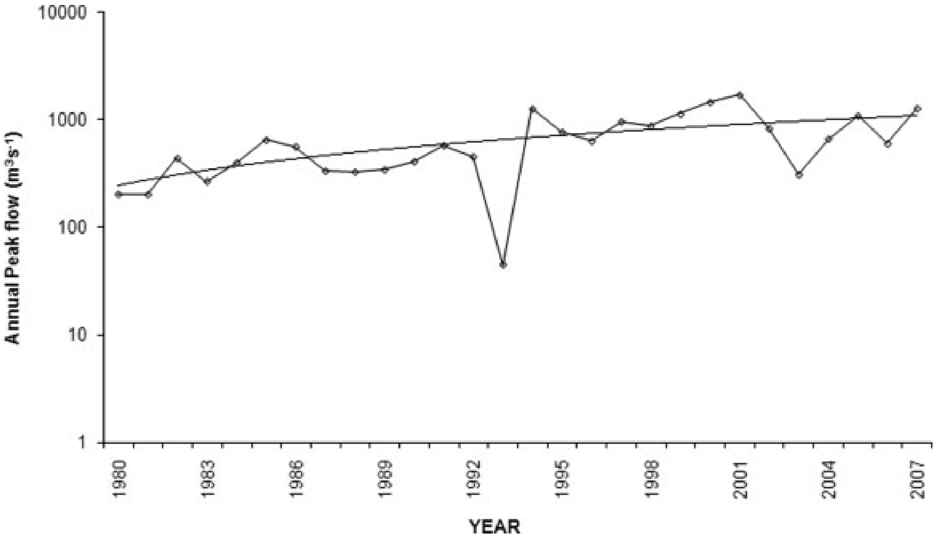

Figure 12. Annual peak flow at Peroor (1980–2007).

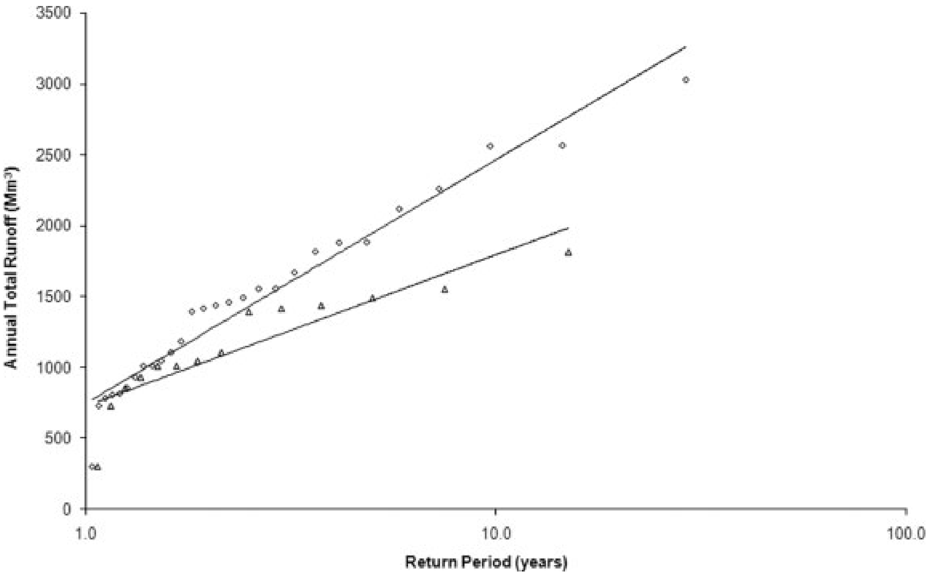

Figure 13. Annual stream flow – return period at Peroor. Line with diamond markers represent 28 year period curve A – ($y = 743.8 \ln(x) + 752.9$, $R^2 = 0.955$) and line with triangular markers represent first half 14 year period curve B – ($y = 461.1 \ln(x) + 732.0$, $R^2 = 0.816$).

more conservation works including rain water harvesting structures are attempted in the highland and midland regions. Also, the humus soil in the highland contributes to more infiltration, thereby reducing the surface flow.

For obtaining return periods of flow, two curves – curve A computed using the entire period of record and curve B for first half period of the record are plotted using Equation (3). In Figure 13, curve A represents the return periods computed using the entire 28 year data for Peroor, the downstream station, curve B represents the return period for the first half period (14 years) and projected with the hypothesis that if urbanization had not occurred in the sub basin; the 28 year curve would more closely approximate the slope of this projection. A runoff of 1500 Mm^3 can be expected to occur on an average once in 2.7 years as seen from curve A, whereas curve B predicts for once in 5.3 years. It is seen from Figure 16 that a peak flow of 500 $m^3 s^{-1}$ can be expected to occur once in every 1.8 years on curve A, whereas on curve B it would occur once in 4.8 years. So, curve A demonstrates the influence of urban land use change on annual streamflow and annual peak flow as evidenced from the recurrence intervals.

Table IV. Trend statistics for peak flows at the three stations.

Time series	First year	Last year	n	Test Z	Significant
Dis-Per	1980	2007	28	3.65	***
Dis-Pala	1980	2007	28	−1.96	+
Dis-Cheri	1980	2007	28	−1.15	–

Dis-Per, Streamflow at Peroor; Dis-Pala, Streamflow at Palai; Dis-Cheri, Streamflow at Cheripad.

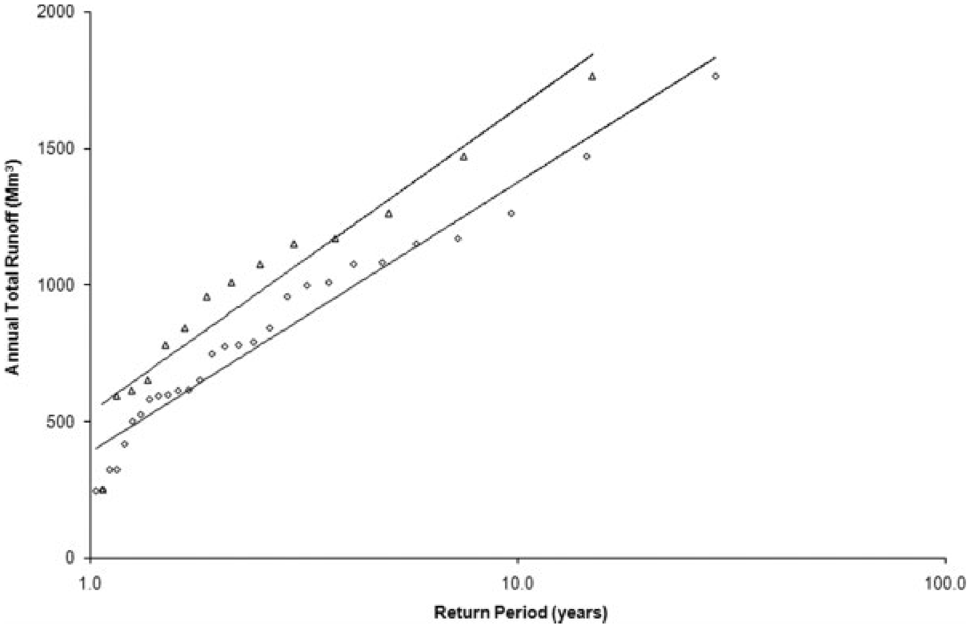

Figure 14. Annual stream flow – return period at Palai. Line with diamond markers represent 28 year period curve A – ($y = 492.2$ ln(x) + 385.1, $R^2 = 0.955$) and line with triangular markers represent first half 14 year period curve B – ($y = 484.7$ ln(x) + 530.0, $R^2 = 0.918$).

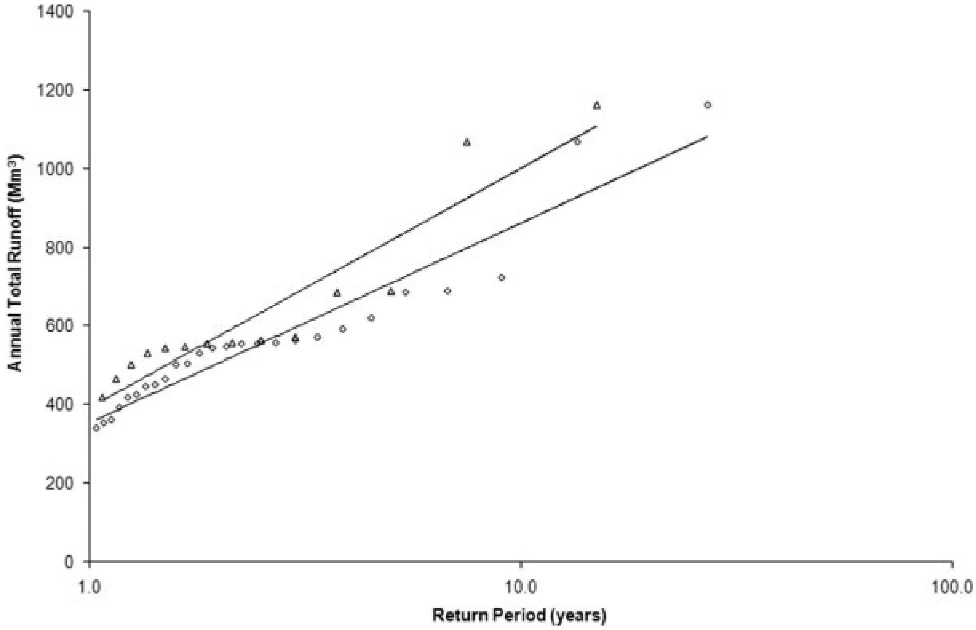

Figure 15. Annual stream flow – return period at Cheripad. Line with diamond markers represent 28 year period curve A – ($y = 220.0$ ln(x) + 355.7, $R^2 = 0.921$) and line with triangular markers represent first half 14 year period curve B – ($y = 263.6$ ln(x) + 393.3, $R^2 = 0.883$).

This observation may be strengthened by comparing similar data from two upstream sub basins with less density of population, small households, less density of road network and with dense vegetation. Figures 14 and 15 show the plots of streamflow data from Palai and Cheripad gauging stations, which are much upstream of Peroor in the same river. Here, curve A represents the total period series and curve B a plot of first 14 years. The annual flow for any year gives a lesser value from curve A than that from curve B in both the cases. Figures 17 and 18 show the plots of annual peak flow from Palai and Cheripad. Also, the annual peak flow for any year gives a lesser value from curve A than that from curve B. By a comparison of Figures 13–18, it is observed that over the study period the streamflows have increased in the more urbanized part of the study area, whereas the annual total streamflow and annual peak flow for any given year have decreased in the less urbanized part of the river basin.

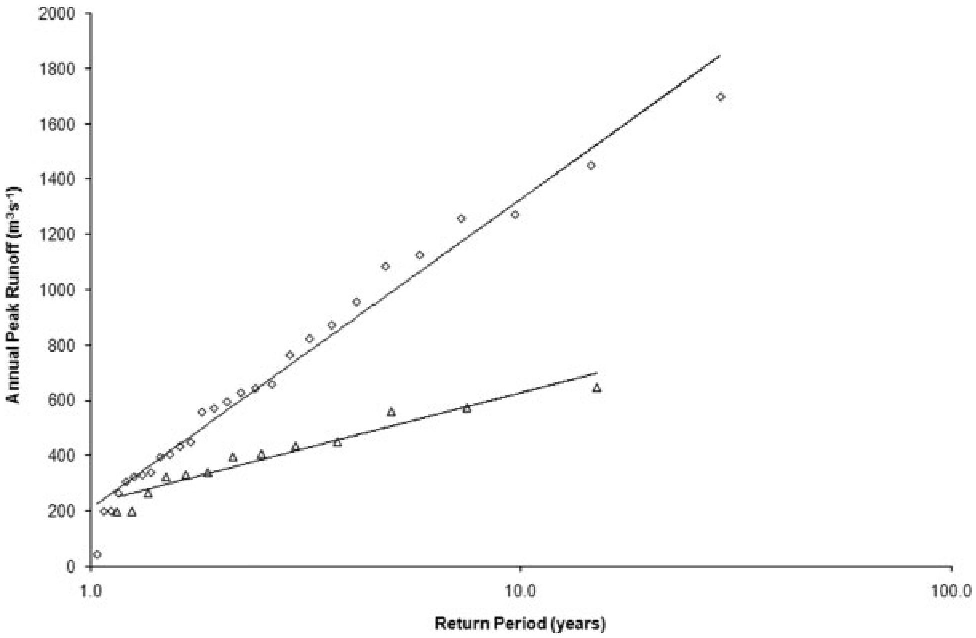

Figure 16. Annual peak flow – return period at Peroor. Line with diamond markers represent 28 year period curve A – ($y = 486.9$ ln(x) + 208.5, $R^2 = 0.977$) and line with triangular markers represent first half 14 year period curve B – ($y = 174.7$ ln(x) + 224.5, $R^2 = 0.932$).

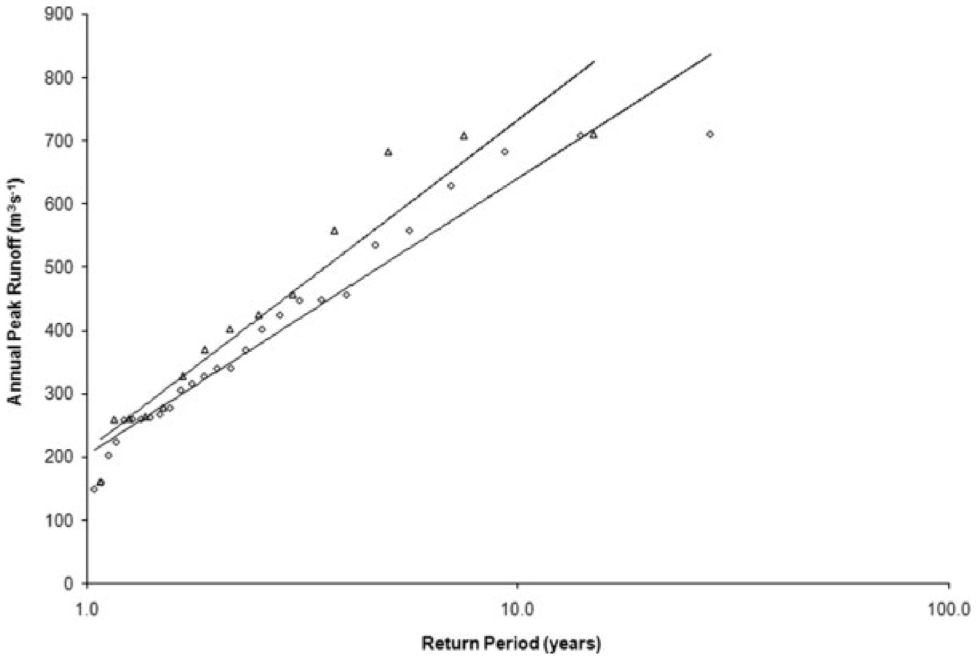

Figure 17. Annual peak flow – return period at Palai. Line with diamond markers represent 28 year period curve A – ($y = 189.5$ ln(x) + 204.0, $R^2 = 0.949$) and line with triangular markers represent first half 14 year period curve B – ($y = 225.7$ ln(x) + 213.4, $R^2 = 0.919$).

5. Conclusions

This study documents urbanization-induced changes on the streamflow records of Meenachil river basin in the humid tropical zone of Kerala State. The population and housing density variation plots give an indirect measure of imperviousness in the study area. Total annual streamflow and annual peak flow exhibited a significant rising trend at Peroor, representing large urbanized area, whereas at Palai and Cheripad, representing less urbanized area, significant decreasing trends are observed. A regression analysis of the streamflow data at Peroor showed an increase in total streamflow of 2.8% *per* year and an increase of 5.2% *per* year in annual peak flow. During the same period, there was no significant change in the trend of rainfall pattern. Thus, urbanization has resulted in increased streamflow and peak flow for a given

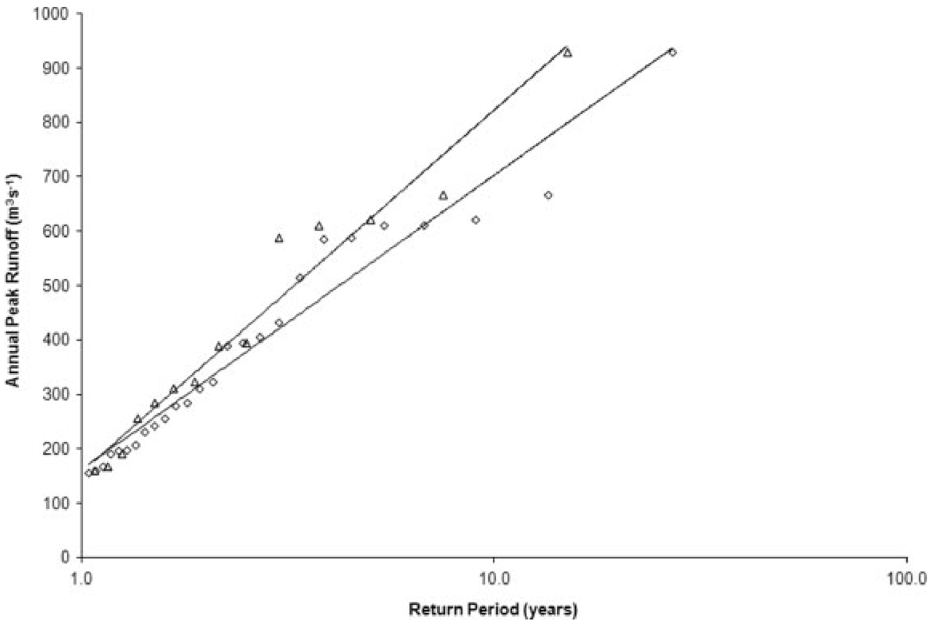

Figure 18. Annual peak flow – return period at Cheripad. Line with diamond markers represent 28 year period curve A − ($y = 235.1$ ln(x) + 161.1, $R^2 = 0.956$) and line with triangular markers represent first half 14 year period curve B − ($y = 288.7$ ln(x) + 157.7, $R^2 = 0.960$).

return interval, particularly with higher return intervals. The study shows that streamflow can serve as an indicator of the degree of urbanization.

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