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Relating trends in streamflow to anthropogenic influences: a case study of Himayat Sagar catchment, India

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Abstract

Catchment development has been identified as potentially causing major changes in streamflow in India. This paper tests for trends in rainfall and streamflow in Himayat Sagar catchment and shows major declines in streamflow without significant changes in precipitation. It then relates the streamflow trends to anthropogenic influences in Himayat Sagar catchment. A simple rainfall-runoff regression model was used to quantify the change in magnitude of rainfall-runoff relationship over the study period. Then, the anthropogenic changes in the catchment including land use, watershed development, groundwater abstractions and storages, and evapotranspiration were quantified. The changes in the components of the water balance were then compared. Streamflows were found to decline at a rate of 3.6 mm yr^{-1}. The main land use change was found to be a conversion from rainfed to irrigated agriculture, fed by groundwater extractions. Irrigated area increased from 8 % to 23 % of the cropping area during the monsoon (Kharif) season (June–November) and from 8 % to 16 % of cropping area during the dry (Rabi) season (December–March). Various estimates of changes in evapotranspiration/irrigation water use were made. Well inventories suggest groundwater extractions increase of 7.2 mm yr^{-1}, typical irrigation practices suggests applied water increased by 10.8 mm yr^{-1}, while estimates of evapotranspirations using AVHRR images showed an increasing rate of 4.1 mm yr^{-1}. Surface water storage capacity for various small watershed development structures increased 2 mm over 7 yr. Taken together, the streamflow trends and groundwater information suggest the most plausible estimates of evapotranspiration changes comes from the AVHRR imagery.

1 Introduction

Many regions of the world face water shortages that are increasing and may become severe in the future (Rockstrom et al., 2009). A range of studies have discussed water shortages in regions and river basins including the Indus, Ganges and Krishna basins in south Asia (Bouwer et al., 2006; Sharma et al., 2010) , southern and eastern European countries (Stahl et al., 2010) , many regions in England (Charlton and Arnell, 2011) and in Australia (Chiew and McMahon, 2002) , among others. These studies emphasised the necessity of understanding different drivers that impact water resources for addressing future water shortages.

The drivers that could affect water availability, in particular streamflow and groundwater include climate change, water resource development and water use at a variety of scales, and a wide range of anthropogenic changes in catchment characteristics. Specific examples include construction of water retention structures (Beavis et al., 1997; Ramireddygari et al., 2000; Schreider et al., 2002) , increased and/or changing agricultural land use (Masih et al., 2011) and increased groundwater extraction and artificial water storages for groundwater recharge (Ramireddygari et al., 2000; Alemayehu et al., 2007). In some cases, these variations may change evapotranspiration and the surface energy balance, thereby also affecting the local climate (Cassardo and Jones, 2011). While development activities may provide benefits in agricultural production, they can also have adverse effects on streamflow and groundwater availability that may lead to both human and ecological impacts downstream (Schreider et al., 2002). In rapidly developing catchments, there are often a number of changes occurring simultaneously with significant potential to impact on the hydrology.

The most visible sign of hydrologic change in a catchment is from the trend of streamflow, which indicates that changes have occurred within the catchment but, in itself, does not provide information on the relative contributions of multiple drivers of change. Such information is critical for developing evidence based policies to manage such changes into the future. A number of studies have tried to explain observed trends in streamflow with respect to changes in climate, catchment characteristics and anthropogenic activities. For e.g. Adnan and Atkinson (2011) observed that the trend in streamflows of the Kelantan catchment, Malaysia resulted from changes in precipitation and land use in the catchment. Rientjes et al. (2011) evaluated the streamflow trend in the upper Gilgel Abbay catchment and found it to be associated with rainfall

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distribution and land use changes. In Tunisia, Chulli et al. (2011) , found that the decrease in surface runoff in the upper Merguellil catchment is due to consequences of human activities. Similarly Van Kirk and Naman (2008), analysed climatic and non-climatic (irrigation withdrawals) drivers and their affects on base flow trends. Most of the studies have discussed streamflow trends with respect to changes in land use or climate variability or both within a catchment; whereas only a few studies have related streamflows to all the changes within the catchment.

This study aims to understand a variety of changes in the Himayat Sagar catchment (HSC), India where there has been a number of changes at small scales including increased hydrological structures and groundwater extractions that are challenging to scale up. Since 1987, in drought prone areas of India, small scale water resource developments under various watershed development programmes were introduced by the Government of India, including the Drought Prone Area Programme (DPAP) and Integrated Wasteland Development Programme (IWDP). From 1994–1995, these programmes have intensified after the launch of detailed new guidelines on organizational aspects, finance, training and stakeholder participation (Kalpataru Research Foundation, 2001; Hanumantha Rao, 2006). In many arid and semi-arid regions of India, these programmes aimed to improve socio economic conditions through increased agricultural production in rain fed areas, and to control land degradation by conserving rainwater for use during dry periods. The study area (HSC) is located in a semi-arid region. This region is historically among the poorest areas in India and it has previously been severely affected by droughts (World Bank, 2005). Therefore, Water Development Structures (WDS, Fig. 1) such as percolation tanks, mini-percolation tanks, check dams, sunken pits, and farm pits, have been developed in the study area (HSC).

While these structures are beneficial to upstream users, they affect the downstream flows. A case-study on percolation efficiency of artificial tanks found that only 35 % of stored water recharges the groundwater (Sylvain et al., 2008). Another study on small water storage structures reported that these structures can lose 50 % of their total volume every year to evaporation due to their high surface area to volume ratio

(Sakthivadivel et al., 1997). Due to rapid development of these structures, groundwater utilisation has expanded and it has become a conjunctive resource for agriculture in semi-arid areas. Overall, the use of water resources for irrigation has accelerated and currently in India 78 % of irrigated land is supplied through groundwater resources (Benoit et al., 2007). Coinciding with all these changes, there have been significant reductions in downstream flows (Schreider et al., 2002).

This paper examines these issues in the HSC, which has undergone a suite of changes due to watershed development over the past two decades and has exhibited declining streamflows. The paper first addresses the question of whether streamflow trends are exogenous (climate forced) or endogenous (due to changes in the catchment) by characterising the trends in climate and streamflows. It then examines changes in catchment characteristics due to anthropogenic activities in detail. Finally it compares the changes with the aim of investigating which drivers could best explain the trend in streamflow.

2 Study catchment

The HSC has an area of 1340 km^2 and is an upper part of the Musi River catchment, within the Krishna River Basin in Southern India. The catchment partly covers two districts of the state of Andhra Pradesh, namely Rangareddy (87 %) and Mahabubnagar (13 %) as shown in Fig. 2. There are 12 Mandals (a combination of a few villages) and 217 villages either partially or fully covered by the catchment. The elevation varies from 527 m to 726 m above sea level with flat topography ranging between 1 % and 3 % slope. The soils are predominantly clayey (> 70 % of catchment area), along with loamy and rock formations making up the remainder (Gurunadha Rao et al., 2007). The extreme temperature reaches a maximum of 44 °C during summer and a minimum of 12 °C during winter (George et al., 2007).

The average annual rainfall observed in the catchment is 718 mm yr^{-1}, of which nearly 90 % occurs in the south-west monsoon season (June–October). The monsoon

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typically starts by early June, gradually recedes from early September and finishes by mid October. There are two main crop seasons in this catchment, the Kharif or monsoon season (June–November) and the Rabi or dry season (December–March). Agricultural lands are kept fallow during the summer season (April–May) in preparation for the next Kharif season.

The main stream in the HSC is the Esa River, which has a dendritic stream network of density 0.4 km km^{-2}. In 1927, the Himayat Sagar reservoir was constructed on Esa River near the catchment outlet and 9.6 km upstream of Hyderabad city to control floods and supply drinking water to the city. The Esa River flows into the Himayat Sagar (HS) reservoir and then joins the Musi River downstream of the reservoir.

In this study, the term watershed development structures implies particular structures which play an important role in improving local access to water resources, including percolation tanks, mini-percolation tanks, check dams, sunken pits, gully control structures, feeder channels and farm pits/ponds. The main purpose of gully control structures is erosion control, though they store some runoff temporarily, which passes downstream slowly. The sunken pits and feeder channels are also silt controlling structures, but they hold runoff permanently in the stream bed. Therefore, the main runoff capturing structures are percolation tanks, mini-percolation tanks, check dams and farm pits, which hold runoff permanently in the catchment.

3 Data

The data used in this study was collected from three sources: the relevant Government departments in Andhra Pradesh, India; field survey; and interpretation of remote sensing images on Google Earth. The following sources of Government data were used and are described in more detail in this section, with the other data described in the methods section. Data collected included: daily rainfall data of 12 rainfall stations distributed in and around the study area from the Directorate of Economics and Statistics (DES); HS reservoir data from the Hyderabad Metropolitan Water Supply

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and Sewerage Board (HMWSSB); Land use statistics from the Directorate of Economics and Statistics (DES); Groundwater levels (pre-monsoon (end of May) and post-monsoon (end of November)) of 10 observation wells from the Central Groundwater Board (CGWB); and the time series of WDSs sanctioned in Rangareddy district from the District Water Management Agency (DWMA), Rangareddy district.

3.1 Rainfall

The 12 rainfall stations and their locations are shown in Fig. 2, and their detailed properties are given in Table 1. The elevation of rainfall stations ranges from 535 m to 720 m above sea level. Among these stations, six had longer records covering 1980–2004, while the other six had shorter records covering 1990–2004.

3.2 Reservoir data

Monthly streamflow into HS reservoir has been estimated using water storage levels (1980 to 2004), storage-area-capacity tables, surplus discharges (1980–2004) and water supply withdrawals (1980 to 2004). Evaporation losses are estimated using monthly evaporation depths estimated by HMWSSB and were assumed to be constant for all the years during the study period.

3.3 Land use information

The mandal (sub-district area, 1985–1987, 1991–1994 and 1999–2004) and district (1985–2004) wise land use information of the study area was collected from DES. Data gaps (1988 and 1990) found in the mandal level were filled with the corresponding percentage changes observed in the district level information. Area irrigated during the Kharif (monsoon, June–November) and Rabi (dry, December–March) seasons in the catchment were obtained from the mandal wise information under area irrigated by the groundwater sources. The difference between the net sown area and the irrigated area was considered as rain fed area.

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3.4 Groundwater levels

The locations and other details of the observation wells are given in Fig. 2 and Table 2, respectively. The surface elevations of observation wells above mean sea level range from 570 m to 680 m. The district wise groundwater production wells inventory information (1980–2004) was obtained from the Minor Irrigation Census, (MIC, Ministry of Water Resources), India. The number of groundwater wells within the catchment was obtained from the district level information and the percent of area covered by each district.

3.5 Groundwater extractions survey

The groundwater extraction survey has been taken place based on groundwater status in the catchment. The groundwater status is defined using four categories based on the ratio of groundwater usage to rainfall recharge. The categories are Over-Exploited (> 100 %), Critical (90–100 %), Semi-Critical (75–90 %) and Safe (< 75 %). The groundwater status has been evaluated in every watershed by CGWB for every two years. The groundwater status (2004–2005) was taken as the average status for all villages within the watershed (Fig. 3). The information needed to estimate the groundwater extractions including typical pumping hours and flow rates, the number of wells per hectare used during the cropping seasons, were collected through field survey in representative villages of every category.

3.6 Watershed development structures

The information of watershed development structures (1995–2005, Table 3) was extracted from the data collected at DWMA, Rangareddy district based on the village locations covered within the catchment. The function of these structures is either silt control (sunken pits, feeder channels and gully control structures) or groundwater recharge (check dams, percolation tanks, mini-percolation tanks and farm pits). Although the silt

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control structures occupy a major part in total number, the volume of water that they could capture is relatively small. There are fewer recharge structures but they can capture a significant amount of runoff from the catchment. The area-volume relationships of each type of structures were collected during field work and are in Table 4. Apart from these watershed development structures, tanks are existed historically in the catchment. The surface areas of these tanks were obtained by analysing the Land Sat images taken during the monsoon seasons of the years 1985, 1989 and 2002.

4 Methods

This section describes the study conceptualization, estimation of streamflows and their trend, and analysis of anthropogenic changes. In this paper, anthropogenic changes include changes in land use, groundwater extractions and water retention in watershed development structures. The analysis presented in this section consists of three parts. First, we examined the streamflow and rainfall data for statistically significant trends. Second, we quantified the variations in streamflows over the study period. Third, we compared the trend in streamflow to various anthropogenic changes that have taken place during study period. Before discussing each of these steps we describe rainfall and streamflow data preparation procedures.

4.1 Estimating streamflows and catchment average rainfall

The consistency of rainfall records was checked using the double mass curve method. Areally weighted average annual rainfall was then estimated using the Thiessen polygon method (ArcGIS) using rainfall data (estimated from the available records) from the 12 rainfall stations. In addition to this, weighted annual catchment rainfall was estimated for the whole study period (1980–2004) using continuous data from the 6 rainfall stations with long records.

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Streamflow is not directly observed in HSC; instead it was estimated by applying a water balance to the HS reservoir. Monthly streamflows, R_i, into HS reservoir for the study period were then estimated using Eq. (1).

$$R_{\bar{i}} = \Delta RS_i + W_i + E_i + D_i \tag{1}$$

In Eq. (1), subscript i is the time period (month), ΔRS is the change in reservoir storage volume (GL), W is the water supply withdrawal volume (GL), E the evaporation volume (GL) and D is the discharge/spill volume (GL) from the reservoir. Negative streamflow estimates during the non-monsoon period were set to zero. R_i were then summed to annual values and converted to runoff depth (mm) by dividing by catchment area.

4.2 Estimating trends of streamflow and rainfall

Non-parametric trend analysis tests (the Mann-Kendall test and Spearman's Rho test) from the TREND tool (Chiew and Siriwardena, 2005) were used for detecting linear trends in the time series data of the annual streamflow and rainfall during study period (1980–2004). A 5 % significance level was adopted for this test.

4.3 Quantification of change in magnitude of streamflows

This analysis involved fitting and evaluating a regression model to observed rainfall and runoff data in the HSC and then quantifying the change in streamflow over the study period for different annual rainfall percentiles.

First, we fitted a non-linear regression rainfall-runoff model (Eq. 2) to simulate streamflows (R) into the reservoir:

$$R = \begin{cases} (at+b)\,(P-P_{\mathrm{t}}) & P \geq P_{\mathrm{t}} \\ 0 & P < P_{\mathrm{t}} \end{cases} \tag{2}$$

Where t is time (years since 1980), P is the annual rainfall (mm), a and b empirical parameters for the trend in rainfall-runoff response and P_{t} is a rainfall threshold below

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which no runoff occurs. The parameters a, b and P_t were obtained by minimising the sum of squared errors between observed and simulated annual runoff values using Microsoft Excel solver. The model quality was evaluated by plotting residuals against predicted values.

Second, we quantified the variations in magnitude of rainfall-runoff relationship at different time steps (1980, 1990, 2000 and 2004) for different annual rainfall percentiles.

4.4 Analysing anthropogenic changes

In this section, we address three aspects of anthropogenic change: land use and evapotranspiration; groundwater storage and extraction; and interception due to hydrological structures. These changes can influence the hydrological components and alter the entire catchment water balance.

The hydrologic components in the HSC was conceptualised using a simple mass balance method (Eq. 3). That is, input (rainfall, P) to the catchment equals the sum of outputs (evaporation, E, and streamflow, R) from the catchment plus the change in (groundwater) storage, ΔS, within the catchment. Equation (3) is applied for the period 1998–2004 as the data required to evaluate the changes in all components are available. It is assumed that changes in unsaturated zone storage are negligible over this period. This equation implies that a trend observed in runoff must be balanced by trends in one or more of the other components.

$$P = \Delta S + E + R \quad (3)$$

Units of mm yr^{-1} are used throughout.

First, land use was classified into four classes namely forest, range land (which includes barren lands, non-agricultural use lands, pasture lands, trees, cultivable waste lands and other fallow lands), current fallow land and net sown (i.e. first crop) areas. Then, to examine the detailed changes in land use associated with significant water resource usage, the net sown area (first crop) was partitioned into irrigated area and rainfed area. Area sown more than once was assumed to be the second crop irrigated

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using groundwater during the Rabi season, as the rainfall contribution in this season is very low (10 % of average annual rainfall).

Second, changes in groundwater storages were obtained and their trends were analysed. The change in groundwater storage was estimated using average pre and post monsoon groundwater heads and using Water Table Fluctuation (WTF) method as given in Eq. (4). The Digital Elevation Model (DEM) was used to obtain the average groundwater head of the catchment. For this, the pre and post monsoon groundwater heads for each grid cell was obtained by applying the correlation between observed groundwater heads and elevations at 11 observation wells every year (1997–2004). The groundwater heads of 1997 (pre and post monsoon) were considered as datum to evaluate the change in heads of remaining period (1998–2004) as given in Eq. (5). Then, the mean heads of all grid cells was considered as the average head of the season. The average of pre and post monsoon heads was taken as average change in groundwater storage of the year.

$$R_{\text{chg},t} = S_{\text{y}} \Delta H_t \tag{4}$$

$$\Delta H_t = \frac{\sum_{j=1}^{n} \left(H_{i_{(t)}} - H_{1997} \right)}{N} \tag{5}$$

Where t is the time period (annual), j is the number of grid cell, R_{chg} the recharge (mm), S_{y} the specific yield and ΔH the average of change in water head (mm, post monsoon and pre monsoon).

Third, the change in interception due to watershed development structures over the study period was estimated as follows. The inventory of water retention such as farm pits/pond, check dams, percolation and mini-percolation tanks were captured from DWMA data. As the data collected from DWMA covers 87 % of the study area (only Ranga reddy district), Google Earth images were used to count the major structures in the missing area (13 % of study area) of the catchment. Among the retention structures, the small structures such as farm pits are often constructed by individual farmers

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with no Government funding and these are missing from the information collected. To capture this information we randomly selected 25 villages in the entire catchment and mapped the structures using Google Earth images. The mean densities of farm pits were grouped as per groundwater status of the village, total village area and irrigated area and the means of these groups were compared using ANOVA test to analyse the significance among them. The best correlation was taken into consideration to extrapolate the information for the entire catchment. The surface area of already existing tanks were estimated by classifying Land Sat images for the years 1985, 1989 and 2002 using the ERDAS Imagine software (Chander et al., 2009). Overall, the total volume of interceptions by these structures was estimated based on the data collected (DWMA), field data and extrapolated data.

5 Results

In this section, we firstly test the temporal trends in rainfall and streamflow. Secondly, we quantify the changes in streamflows before we examine the drivers that have impacted the streamflows in the HSC.

5.1 Estimation of trends in rainfall and streamflow

Figure 4 shows the pattern of annual average rainfall during the study period. The weighted average annual rainfall is estimated as 718 mm yr^{-1} and it ranges between 471 mm yr^{-1} (2004) and 996 mm yr^{-1} (1983) with a standard deviation of 153 mm yr^{-1} and coefficient of variation of 0.21. The trend tests performed on two sets (1980–2004, 6 rainfall stations; 1990–2004, 12 rainfall stations) of catchment average annual rainfall shows no significant temporal trend (Table 5). The annual streamflow pattern into HS reservoir is also shown in Fig. 4. The average annual streamflow into the HS reservoir is estimated as 58 mm yr^{-1}, ranging between 2 mm yr^{-1} (2004) and 247 mm yr^{-1} (1983), with a standard deviation of 60 mm yr^{-1} and coefficient of variation of 1.04. The 5-yr

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average streamflows for the periods 1980–1984, 1985–1989, 1990–1994, 1995–1999 and 2000–2004 were declined as 105, 55, 50, 46 and 32 mm yr^{-1} respectively for the corresponding average rainfall of 735, 715, 705, 748 and 687 mm yr^{-1}. It is observed that the average runoff coefficient has declined from 14 % (1980–1984) to less than 5 % (2000–2004). Also the trend test on annual streamflows suggests that the streamflows were declined significantly (Table 5). Overall, the streamflows showed a declining trend, while no trend was observed in rainfall over the study period, at a 5 % significance level. This strongly suggests that observed changes in streamflow are due to endogenous (i.e. internal to the catchment, anthropogenic) rather than exogenous (due to climate) changes in the catchment.

5.2 Quantification of change in magnitude of streamflows

Figure 5a shows the model (Eq. 2) fit to the annual rainfall-runoff data (1980–2004), for which the coefficient of determination, R^2 was 0.76. Figure 5b shows the model residuals plotted over predicted values, which indicated that the model fitted well to the data. It is observed that the parameters resulting from the model fit are $a = -0.02$, $b = 0.47$ and $P_t = 518$ mm, where $t = 1$ in 1980. Using these parameters, the model for 1980, 1990, 2000 and 2004 is shown in Fig. 5c. The predicted runoff for these years and the 25th, 50th and 75th percentile annual rainfall are given in Table 6. From 1980 to 2004, the predicted streamflows declined by 27, 61 and 113 mm respectively for the 25th, 50th and 75th rainfall percentiles. The median change (i.e. 50th rainfall percentile) in streamflow during the study period is a 76 % reduction, from 1980 to 2004.

5.3 Characterizing drivers of streamflow change

In this section, we first characterise the changes in various catchment characteristics that could influence streamflows. These are endogenous changes due to anthropogenic activities. First, we examined the changes in land use; second we examined the groundwater levels and groundwater draft; and third, we examined the trend in time series of hydrological structures during study period and the volume of water that could be intercepted by these structures.

First, Fig. 6a shows the average land use variations in the catchment between 1985–1989 and 2000–2004. The comparison of land use changes from 1985–1989 to 2000–2004 shows that the Forest (F) area has not changed and remained at 6 %, Range Lands (RL) has reduced slightly from 31 % to 28 %, Current Fallow (CF) lands have increased from 23 % to 33 % and Net Sown Area (NSA) has decreased from 40 % to 33 %. However, it is unclear whether these changes reflect the inter-annual variability or whether the changes will be sustained.

A detailed analysis of NSA over the last two decades indicates that the irrigated crop area (and the area sown more than once) has at least doubled (Fig. 6b). As a percentage of the net sown area, the average net irrigated area has increased from 7 % (1985–1989) to 23 % (2000–2004) and from 8 % (1985–1989) to 17 % (2000–2004) in the Kharif and Rabi seasons respectively (Table 7). It is also observed that during the Kharif season the overall percentage of rice remained constant, but 40 % of the rain fed rice crop area was converted to irrigate. Thus, it is clear that the most significant land use change in the HSC has been due to irrigation expansion and intensification.

Second, we examined the groundwater heads and draft during study period. The average groundwater heads from 1998 to 2004 appeared to be declining at a rate of 0.30 m yr^{-1}, while the groundwater storage is declining at a rate of 6.1 mm yr^{-1} (assuming a specific yield of 0.014, Maréchal et al., 2006) as shown in Fig. 7. Groundwater extractions were estimated using two methods: based on inventory of bore wells and land use statistics. The number of groundwater wells in the HSC has increased from 13 280 (1993) to 31 600 (2004). Information on the average number of pumping hours per day (7 h) was collected during the field survey (Table 8) and an average pumping rate of 8.1 $m^3 h^{-1}$ was used (Maréchal et al., 2006) in this analysis. To estimate groundwater draft from irrigation practice, average irrigation requirements of 10 mm day^{-1} and 15 mm day^{-1} for rice crops during Kharif and Rabi seasons and 7.7 mm day^{-1} for dry and vegetable crop during both seasons were assumed (Dewandel et al., 2008). The

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results indicate that the groundwater draft estimates in the catchment based on the land use information has increased from 140 mm yr^{-1} (1998) to 214 mm yr^{-1} (2004), and based on an inventory of wells it has increased from 110 mm yr^{-1} (1998) to 149 mm yr^{-1} (2004). Overall, it appears that significant increases in groundwater extraction rate have occurred and as a result the groundwater levels have declined in the HSC.

Third we analysed Watershed Development Structures (WDS) data and estimated the volumes of water captured by these structures during the study period. For this, first we compared the statistics of check dams and farm pits collected from the DWMA (Village level data) with the information extracted from Google Earth images (2003 image, Table 9). Results showed no significant difference in the number of check dams among the villages where the information is available in both sets (DWMA & Google Earth Survey). However, it was also found that there had been check dams in many other villages, which may have constructed by other Government departments. For farm pond and pit numbers; however, it was observed that there were significant differences between these two data sets. This difference is likely to arise because the construction cost of a farm pit is low and it can be built without any Government funding, whereas check dams can only be built by Government organisations. As there is significant discrepancy between the farm pit numbers observed from Google Earth data and the Government data, it was concluded that the statistical data for farm ponds and pits are unreliable. Therefore we attempted to predict the density of farm pits based on Google Earth data and village characteristics including village area, irrigated area and cultivable area. The highest correlation was observed between the density of farm pits and the total village area, which was then used to estimate the farm pits number. The estimated total number of farm pits in the HSC was 1950 (in 2004).

Finally the total storage volume of WDS was estimated from the depth-area-volume relationship developed from field survey. This shows that the water interception by these structures has increased from 0.4 mm yr^{-1} (1995) to 2.4 mm yr^{-1} (2004) per each fill. Various tanks existed in the catchment at the start of the study period and their surface area (WSA) did not show any significant change during the study period

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(Table 10). The Surface water storage capacity of tanks and WDS has increased from 26.4 mm yr^{-1} (1995) to 28.4 mm yr^{-1} (2004).

The above all changes indicate that evapotranspiration from the catchment must be have increased significantly. The ET estimates obtained using AVHRR remote sensing images show a continuous increasing trend of 4.1 ± 2.6 mm yr^{-1} from 1984 to 2001 (Teluguntla et al., 2011) (Fig. 8). This increase in ET is mainly due to increase in Leaf Area Index (as indicated by NDVI) which is directly linked to irrigation as there are no other significant changes in land use in the study area.

6 Discussion

The trend tests results showed no significant changes within the rainfall; however, significant declining trend was observed in streamflows during the study period. The difference between 5-yr average annual streamflows of 1980–1984 and 2000–2004 shows a decrease of 73 mm from 105 mm yr^{-1} to 32 mm yr^{-1}. The streamflow simulated by the regression model also show that median streamflows reduced by 61 mm from 1980 (80 mm yr^{-1}) to 2004 (19 mm yr^{-1}). Overall, the rate of change of observed and model simulated streamflows is -3.6 ± 3.5 mm yr^{-1} and -3.5 ± 3.0 mm yr^{-1} respectively. Given the lack of trend in rainfall, the trend observed in the streamflows is likely to be due to internal changes within the catchment, not due to changes in rainfall.

Our analysis of catchment characteristics shows changes in land use, particularly within cropping areas; changes in groundwater extraction; and changes in the number of hydrological structures in the catchment. The major change in land use was in the irrigated area, which increased in both Kharif (from 8 % to 23 %) and Rabi (from 8 % to 16 %) cropping seasons. Most of this irrigation demand was met from groundwater and is reflected in the groundwater storage which is decreasing at a rate of 6.1 mm yr^{-1}. Groundwater irrigation was originally practised as supplemental irrigation to satisfy the deficits from rainfall but later become the main water resource for irrigation because of its availability at low cost.

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It is also likely that irrigation practice has changed in the past two decades in the catchment. During field survey, it is observed that the farmers are irrigating the crops without considering the crop water demand. This is mainly because of the availability of free electricity to utilise groundwater. The statistical data on the evolution of the total number of wells in use also demonstrates this. The mix of irrigated crops has also changed with dry crops favoured over wet crops in the wet season, and wet crops favoured over dry crops in the dry season now.

The change in irrigated area has affected groundwater level and storage in the catchment. We examined 11 observation wells for the period from 1998 to 2004. It was observed that the groundwater levels decreased at a rate of $0.30 \pm 0.29\,\mathrm{m\,yr^{-1}}$, which is $6.1 \pm 5.9\,\mathrm{mm\,yr^{-1}}$ of decrease in groundwater storage. A study carried out in the Musi catchment during the period 1998–2004 concluded that the water table is declining at a rate of $0.18\,\mathrm{m\,yr^{-1}}$ (Sylvain et al., 2007).

Estimates of groundwater extractions based on inventory of wells and land use statistics show increased rates of $7.2 \pm 1.6\,\mathrm{mm\,yr^{-1}}$ and $10.8 \pm 6.7\,\mathrm{mm\,yr^{-1}}$, respectively. There is some evidence (Fig. 7) of increasing rates of groundwater decline over the period 1998–2004, although it is likely that inter-annual variability influences these patterns, so it is hard to draw firm conclusions. There is also some uncertainty in the specific yield values used in this analysis which needs some verification in the future. Large changes in groundwater levels are not observed in spite of increased pumping, which may be because overall recharge might has increased due to increased recharge from irrigation and WDSs and also due to reducing base flows in streams.

Given that annual groundwater extraction rates have increase by around $40\,\mathrm{mm\,yr^{-1}}$ to $75\,\mathrm{mm\,yr^{-1}}$ over 1998–2004 and that groundwater storages are only declining by an average of $6\,\mathrm{mm\,yr^{-1}}$ over this period, it is likely that there was both a decline in base flow and an increase in recharge in the catchment over this period. The WDS information collected suggest only a limited increase in recharge. The WDS data (1995–2005) show that the runoff capture increased at the rate of $0.24 \pm 0.10\,\mathrm{mm\,filling{-}1\,yr^{-1}}$, or $2.0 \pm 0.85\,\mathrm{mm}$ 8 $\mathrm{fillings^{-1}\,yr^{-1}}$ (i.e., assumed that the

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structure fills 8 times in a year). Also the data suggest that the increase in interception was high (0.62 ± 0.37 mm filling^{-1} yr^{-1} or 5.0 ± 3.0 mm 8 fillings^{-1} yr^{-1}) from 1995 to 1998 and that there was only limited increases from 1998 to 2004. However, from the random sampling of Google Earth images, we observed that check dams information in the data obtained from DWMA appears to be incomplete and that there could be many WDS situated within the catchment developed by other departments than DWMA. This suggests that increased WDSs within the catchment may have helped increase the recharge, despite what is suggested by the DWMA. In addition to the WDS, there are existing tanks which capture 26 mm of rainfall when they fill to full capacity. Change in groundwater levels is likely to have reduced base flow discharge to streams and may also have caused some increase in seepage from these large structures.

In an attempt to reconcile the trends in water balance, we rearranged the simple water balance Eq. (3) into Eq. (6), where the rate of change of groundwater storage, S, is balanced by the net input to the catchment from rainfall, P, evapotranspiration, E, and runoff, R; where it is assumed that changes in soil moisture storage are negligible (Eq. 6).

$$\mathrm{d}S/\mathrm{d}t = P - E - R \quad (6)$$

Approximating the fluxes by linear trends allows them to be written as

$$P(t) = P_0 + t\mathrm{d}P/\mathrm{d}t \quad (7)$$

$$E(t) = E_0 + t\mathrm{d}E/\mathrm{d}t \quad (8)$$

$$R(t) = R_0 + t\mathrm{d}R/\mathrm{d}t \quad (9)$$

Where P_0, E_0 and R_0 are the precipitation, evapotranspiration and runoff at $t = 0$ substituting Eqs. (7), (8) and (9) into Eq. (6) and integrating results in an estimate of the change in groundwater storage as:

$$\Delta S = (P_0 - E_0 - R_0)t + 0.5(\mathrm{d}P/\mathrm{d}t - \mathrm{d}E/\mathrm{d}t - \mathrm{d}R/\mathrm{d}t)t^2 \quad (10)$$

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Assuming that the catchment is in equilibrium at $t = 0$ implies the first bracket on the right hand side is zero and thus Eq. (10) simplifies to:

$$\Delta S = 0.5(\mathrm{d}P/\mathrm{d}t - \mathrm{d}E/\mathrm{d}t - \mathrm{d}R/\mathrm{d}t)t^2 \tag{11}$$

Given that significant water resource development began around 1980 and the low level of water resource development in 1980, we assume that this represents equilibrium conditions at the start of the subsequent development phase.

Our estimates of the rainfall and runoff trends are $\mathrm{d}P/\mathrm{d}t = 0$ (1980–2004) and $\mathrm{d}R/d\mathrm{t} = -3.6 \pm 3.5\,\mathrm{mm\,yr^{-1}}$ (1980–2004). We have several estimates of rates of change of evapotranspiration as follows:

- remote sensing estimate $\mathrm{d}E/\mathrm{d}t = 4.1 \pm 2.6\,\mathrm{mm\,yr^{-1}}$ (1984 to 2001);
- changes in well inventory $\mathrm{d}E/\mathrm{d}t = 7.2 \pm 1.57\,\mathrm{mm\,yr^{-1}}$ (1998 to 2004); and
- changes in irrigation area $\mathrm{d}E/\mathrm{d}t = 10.8 \pm 6.7\,\mathrm{mm\,yr^{-1}}$ (1998 to 2004).

Using Eq. (11) with $\mathrm{d}R/\mathrm{d}t = -3.6$, $\mathrm{d}P/\mathrm{d}t = 0$, and each of these estimates of $\mathrm{d}E/\mathrm{d}t$ in turn implies groundwater storage changes of $-63\,\mathrm{mm\,yr^{-1}}$, $-949\,\mathrm{mm\,yr^{-1}}$ and $-1900\,\mathrm{mm\,yr^{-1}}$ respectively, over the period 1998–2004. It should be noted that equating groundwater withdrawals and irrigation volumes to evapotranspiration assumes negligible recharge from irrigation applications, thus these two estimates of $\mathrm{d}E/\mathrm{d}t$ should be treated as upper bound estimates. The groundwater data that suggests groundwater storage falls by $6.1 \pm 5.9\,\mathrm{mm\,yr^{-1}}$ or from 41 mm to 6 mm (around 35 mm) over 1998–2004.

Each of these terms is uncertain, as are the assumptions underlying Eq. (11). Our judgement is that we have more confidence in the rainfall and runoff trends and less confidence in the evapotranspiration and groundwater trends. The remote sensing estimates of evapotranspiration trends appear to lead to a reasonable reconciliation of the combination of rainfall, runoff and groundwater trends over the period 1998–2004. Another plausibility check is to estimate the total groundwater level decline since 1980.

Using a specific yield of 0.02 as above, the declines would be 7, 29 and 104 m respectively. Given that depth to water table is currently around 10 m (implying the decline since 1980 is ≤ 10 m), also suggests that the remote sensing estimates of evapotranspiration trends are the most plausible of the three.

7 Conclusions

This paper considers hydrologic trends and compares anthropogenic changes in different aspects of the water balance of the Himayat Sagar Catchment in India. It is demonstrated that there are no statistically significant trends in annual rainfall, whereas there are clearly trends over time in catchment streamflows. These are associated with trends in land use and water management. Increases in irrigated area have occurred and groundwater levels are declining. It is likely that increases in recharge from structures such as tanks, check dams and percolation tanks have occurred, together with declining groundwater discharge. Irrigation water use per unit of irrigated area seems to be increasing. By examining water flux and storage trends within a simple water balance framework, it was possible to approximately reconcile the changes in the various fluxes with groundwater storage declines, although significant uncertainty exists in these estimates.

Overall, it is clear that the trend in streamflow is due to anthropogenic changes, particularly increasing irrigation and groundwater extractions, as well as some increase in interception by WDSs in the HSC. Water usage in this catchment now exceeds total sustainable resource availability, which suggests water shortages will continue to increase into the future unless water management practices change.

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Table 1. Details of rainfall stations distributed in and around HS catchment.

Station code	Rainfall station name	Latitude (°)	Longitude (°)	Data period	Elevation (m)	Average annual rainfall (mm)
1411122	Kondurg	17.01	78.04	1990–2004	639	645
1412120	Farooqnagar	17.03	78.17	1980–2004	634	700
1413123	Kothur	17.14	78.26	1990–2004	598	625
1414121	Keshampet	16.98	78.33	1990–2004	566	590
1516113	Rajendranagar	17.39	78.40	1980–2004	535	775
1517121	Moinabad	17.31	78.25	1990–2004	607	707
1518117	Chevella	17.32	78.12	1980–2004	627	793
1529122	Pargi	17.12	77.94	1980-2004	720	911
1530128	Pudur	17.23	77.98	1990–2004	677	893
1531119	Shabad	17.18	78.16	1980–2004	646	623
1532116	Shamshabad	17.21	78.38	1980–2004	585	780
1533111	Maheswaram	17.19	78.41	1990–2004	593	744

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Table 2. The location details of observation wells in HS catchment.

District name	Mandal name	Village name	Lat (°)	Long (°)	Elevation (m)
Rangareddy	Chevella	Alur	17.33	78.07	631
Rangareddy	Chevella	Chevella	17.13	78.07	642
Rangareddy	Shabad	Shabad	17.33	78.14	644
Rangareddy	Pudur	Kandlapally	17.04	78.02	643
Rangareddy	Pudur	Pudur	17.22	78.99	680
Rangareddy	Pudur	Peddamrthial	17.22	77.99	636
Rangareddy	Pargi	Kuduvantapur	17.15	77.90	666
Rangareddy	Shamshabad	Palmakole	17.19	78.30	572
Rangareddy	Shamshabad	Peddagollaapally	17.24	78.39	581
Rangareddy	Rajendranagar	Katedan	17.32	78.44	535
Rangareddy	Rajendranagar	Sivarampalli	17.33	78.44	530

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Table 3. The watershed development structures within HS catchment extracted from collected data (DWMA).

Year	Check dams	Percolation tanks	Mini-percolation tanks	Sunken pits	Farm pits/ponds	Feeder channels	Gully control structures
1995	143	33	–	4	9	7	2788
1997	109	24	–	355	3	4	1149
1998	80	29	105	691	6	76	2190
1999	382	55	2	2504	29	270	2553
2000	8	1	–	3	–	–	–
2001	5	8	9	178	–	12	–
2002	40	11	27	303	4	3	424
2003	28	–	1	65	20	2	133
2004	4	–	–	–	–	–	40

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Table 4. Area-Volume particulars of different watershed development structures collected from the field survey.

Structure	Average surface area (m^2)	Average depth (m)	Average volume (m^3)
Check Dams	1000	1.2	1200
Percolation Tanks	1650	3.0	4950
Mini-Percolation Tanks	750	2.0	1500
Sunken Pits	16	1.0	16
Farm Pits/Ponds	28	2.0	56
Feeder Channels	3	0.5	1.5
Gully Control Structures	30	0.5	15

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Table 5. Results of trend test on rainfall and streamflows.

	Test	1980–2004		1990–2004	
		Z-statistic	p-value	Z-statistic	p-value
Rainfall	Mann-Kendall	0.16	0.87	0.21	0.83
	Spearman's rho	0.25	0.80	0.16	0.87
Streamflows	Mann-Kendall	–2.07	0.03		
	Spearman's rho	–2.07	0.03		

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Table 6. Change in magnitude of streamflows at different time steps.

Percentile	Rainfall (mm)	Streamflow (mm)			
		1980	1990	2000	2004
25th	596	36	25	13	9
50th	693	80	56	30	19
75th	844	149	105	56	36

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Table 7. Average variations in net sown area at different time periods.

Year	Average rainfed area (% of NSA) (Kharif season)	Average irrigated area (% of NSA) (Kharif season)	Average irrigated area (% of NSA) (Rabi season)
1985–1990	93	7	8
1991–1996	87	13	9
1997–2001	81	19	13
2001–2004	77	23	17

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Table 8. Groundwater extraction survey particulars during field survey.

GW_Status	No. of samples	Average number of pumping days (Rabi Season)	Average number of pumping hours per day	Number of Wells used	Number of Wells used (Kharif Season) (Rabi Season)
Safe	10	115	7	All	70 %
Semi-Critical	15	120	7	All	50 %
Critical	15	120	7	All	50 %
Over-Exploited	15	120	7	All	40 %

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Table 9. Data comparison between DWMA and Google Earth for 25 villages, where GW_S is the Groundwater status, S_CD & S_FP are Google Earth survey check dams, and farm pits, R_CD & R_FP are records available on check dams and farm pits with DWMA, Irrig. Area and T_Cul Area are Irrigated area and Total cultivable area in the village.

S No.	Village Name	Soils	GW_S	S_CD	S_FP	R_CD	R_FP	Village area (ha)	Irrig. area (ha)	T_Cul area (ha)
1	Ammapalle	C	Cri	0	50	NA	NA	313	81	178
2	Devarampalle	C	Cri	7	43	NA	NA	381	52	297
3	Komerabanda	C	Cri	2	41	NA	NA	231	0	142
4	Ganisimiyaguda	C	Cri	4	31	1	NA	287	12	54
5	Farooqnagar	C	Cri	3	50	NA	NA	NA	NA	NA
6	Golkonda Kurd	GC	Cri	0	40	NA	NA	195	82	165
7	Gandiguda	GC	Cri	0	28	1	NA	280	43	69
8	Nagaram	GC	Cri	0	45	3	NA	577	103	103
9	Sriramnagar	L	Cri	14	41	NA	NA	940	280	871
10	Chegur	R	Cri	30	64	NA	NA	3136	298	2923
11	Ibrahimpalle	C	OE	18	42	11	NA	384	27	241
12	Kothur	C	OE	11	105	NA	NA	1962	221	803
13	Chevella	C	OE	30	75	15	NA	1205	59	456
14	Akhanpalle	C	OE	5	45	0	NA	556	67	397
15	Shubanpur	L	OE	6	50	0	NA	645	78	618
16	Yabajiguda	C	Safe	5	40	5	NA	335	19	267
17	Peddamunthal	C	Safe	19	51	18	NA	1318	49	950
18	Niz-Medipalle	C	Safe	6	37	11	NA	718	33	400
19	Anantharam	GC	Safe	16	55	12	NA	733	17	223
20	Khandlapalle	GC	Safe	11	66	9	NA	688	29	288
21	Bangaliguda	C	S-Cri	0	37	NA	NA	43	22	31
22	Kothwalguda	C	S-Cri	3	30	2	NA	1109	167	234
23	Narkhuda	C	S-Cri	10	74	10	NA	1063	180	180
24	Nagireddyguda	C	S-Cri	0	65	NA	NA	455	245	375
25	Sajjanpalli	GL	S-Cri	24	52	NA	NA	205	124	169

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Table 10. Details of water surface area by tanks existed in HS catchment.

Year	Date of image	Rainfall during the month (mm)	Annual rainfall (mm)	Surface area of tanks (ha)
1981	14 October	79.20	854	1409
1989	21 November	0.00	760	680
2000	26 October 2012	41.10	774	1486

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Fig. 1. Pictures of tank and Watershed Development Structures in HSC.

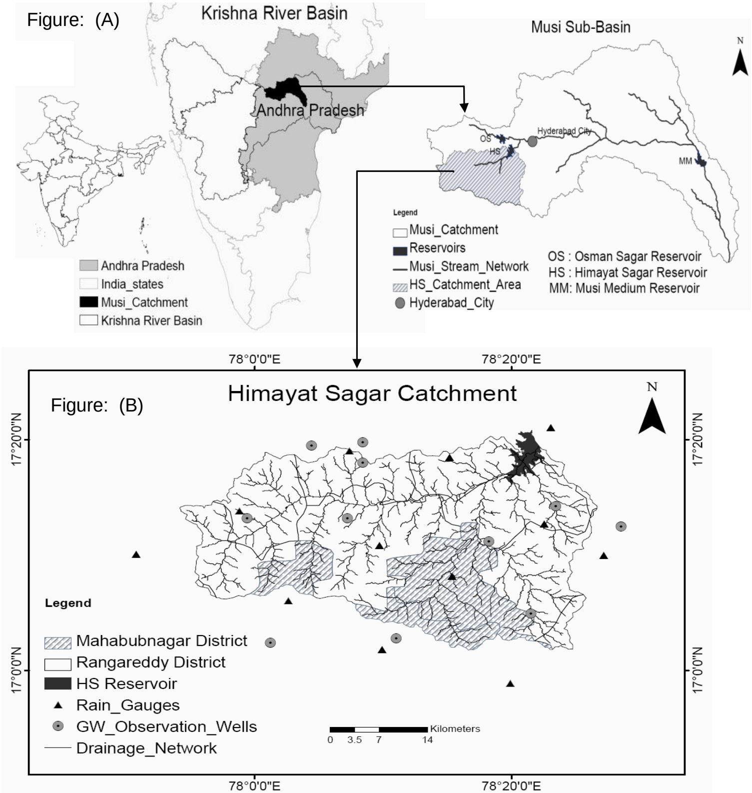

Fig. 2. (A) location of Himayat Sagar Catchment (HSC) in Musi Sub-basin of Krishna river basin. **(B)** districts covered by HSC, drainage network, locations of HS reservoir, rain gauge stations and ground water observation wells.

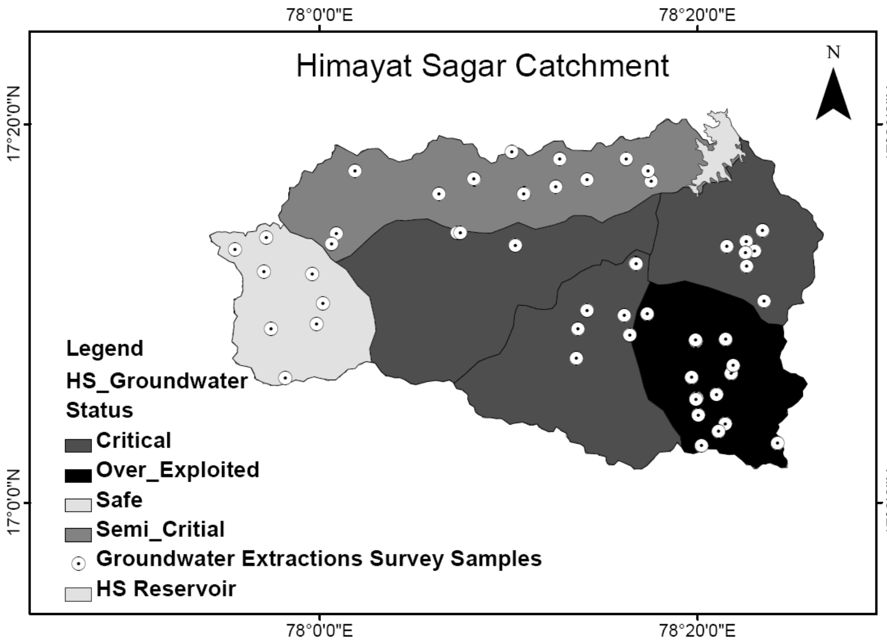

Fig. 3. Location map of groundwater extraction survey samples.

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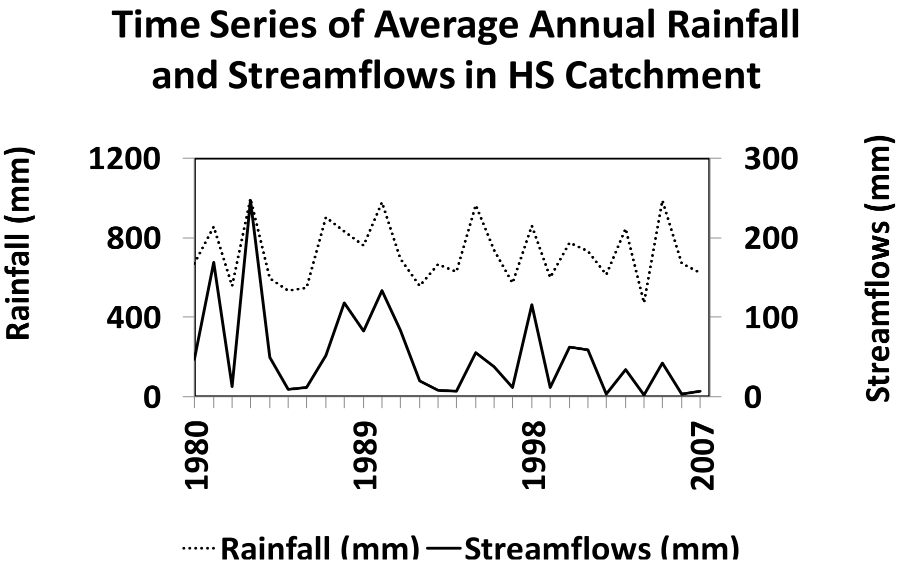

Fig. 4. Times series of average annual rainfall and streamflows of HS catchment.

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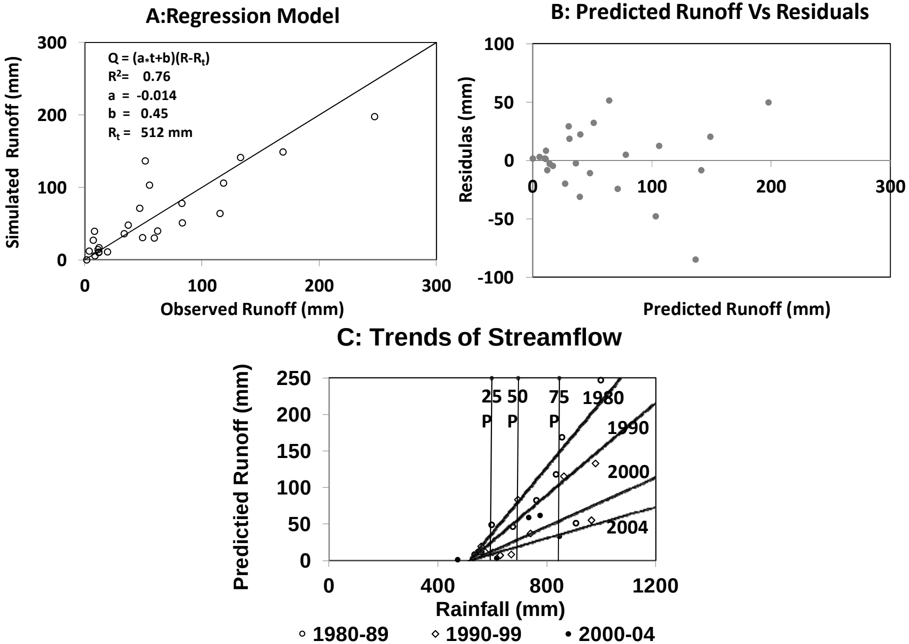

Fig. 5. (A) linear regression model of rainfall-runoff, **(B)** plot shows the residuals against predicted values, **(C)** change in magnitude of streamflows at different time trends and rainfall percentiles.

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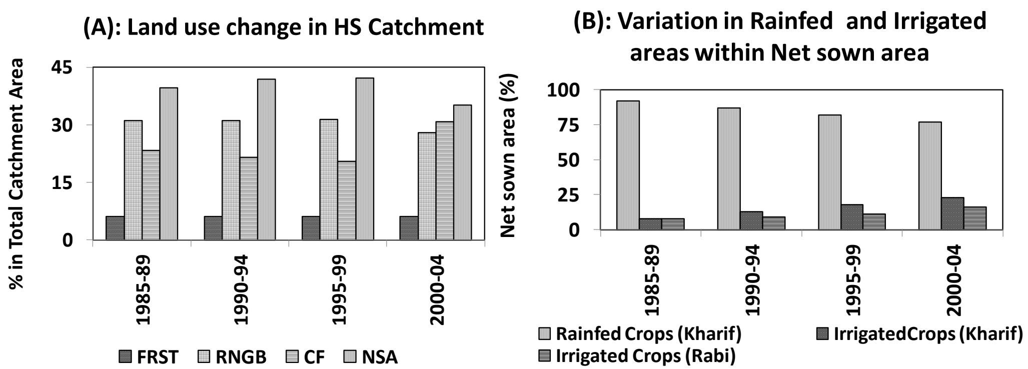

Fig. 6. (A) over all land use details of major classes such as Forest (FRST), Range lands (RNGB) Current Fallow lands (CF), Net sown area (NSA), and in HS catchment for last two decades, **(B)** the change in rainfed and irrigated crops within Net sown area of the catchment from 1985–2004.

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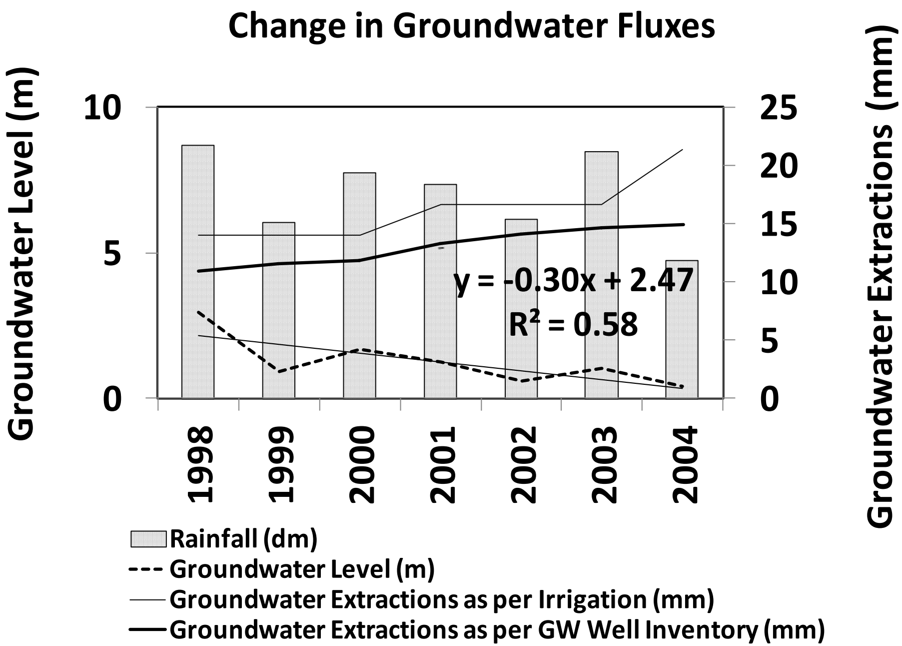

Fig. 7. The Trend of groundwater levels and extractions in HS catchment.

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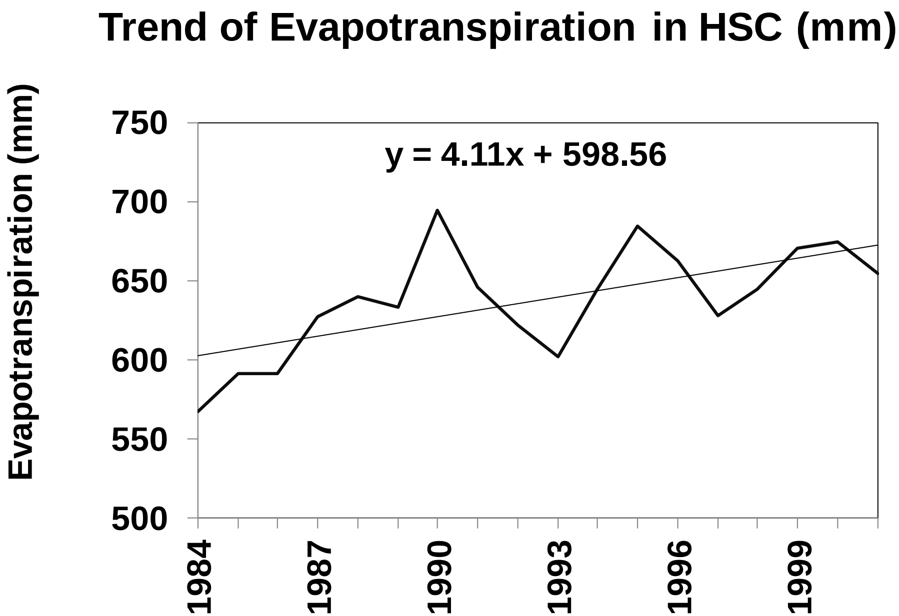

Fig. 8. Change in Evapotranspirations in the HS catchment estimated using AVHRR data and remote sensing techniques.

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