Water Resour Manage (2014) 28:1579–1595
DOI 10.1007/s11269-014-0567-5

Relating Trends in Streamflow to Anthropogenic Influences: A Case Study of Himayat Sagar Catchment, India

Rajesh Nune · Biju A. George · Pardhasaradhi Teluguntla · Andrew W. Western

Received: 18 February 2013 / Accepted: 20 February 2014 /
Published online: 15 March 2014

Abstract Catchment development has been identified as a potentially major cause of streamflow change in many river basins in India. This research aims to understand changes in the Himayat Sagar catchment (HSC), India, where significant reductions in streamflow have been observed. Rainfall and streamflow trend analysis for 1980–2004 shows a decline in streamflow without significant changes in rainfall. A regression model was used to quantify changes in the rainfall-runoff relationship over the study period. We relate these streamflow trends to anthropogenic changes in land use, groundwater abstraction and watershed development that lead to increased ET (Evapotranspiration) in the catchment. Streamflow has declined at a rate of 3.6 mm/y. Various estimates of changes in evapotranspiration/irrigation water use were made. Well inventories suggested an increase of 7.2 mm/y in groundwater extractions whereas typical irrigation practices suggests applied water increased by 9.0 mm/y, while estimates of evapotranspiration using remote sensing data showed an increasing rate of 4.1 mm/y. Surface water storage capacity of various small watershed development structures increased by 2 mm over 7 years. It is concluded that the dominant hydrological process responsible for streamflow reduction is the increase in evapotranspiration associated with irrigation development, however, most of the anthropogenic changes examined are interrelated and occurred simultaneously, making separating out individual impacts very difficult.

Keywords Streamflow trend · Water balance · Groundwater decline · Land use change · Watershed development

1 Introduction

Many regions of the world face increasing water shortages (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 Europe (Stahl et al. 2010), England (Charlton and Arnell 2011), Libya (Whieda and

R. Nune (✉) · B. A. George · P. Teluguntla · A. W. Western
Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia
e-mail: r.nune@cgiar.org

Verhoeven 2007), North China (Xia et al. 2007) and Australia (Chiew and McMahon 2002), among others. These studies emphasize the necessity of understanding different drivers that impact water resources when addressing future water shortages.

The drivers that can 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 (Alemayehu et al. 2007; Ramireddygari et al. 2000). 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 (Garg et al. 2013; 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 or in the meteorological forcing but, in itself, does not provide information on the relative contributions of multiple drivers of change. Various studies have tried to explain observed trends in streamflow with respect to changes in climate, catchment characteristics and anthropogenic activities. For example, 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. Some studies found that streamflow trends are associated with changes in rainfall distribution and land use in the catchment (Rientjes et al. 2011; Zhang et al. 2010; Goncu and Albek 2010). In Tunisia, Chulli et al. (2011), found human induced decreases surface runoff in the upper Merguellil catchment. Similarly Van Kirk and Naman (2008) analysed climatic and non-climatic (irrigation withdrawals) drivers and their effects on base flow. Most of these studies have discussed streamflow trends with respect to changes in land use or climate variability or both within a catchment. Only a few studies have related streamflows to all the changes within the catchment.

This study aims to understand hydrologic change in the Himayat Sagar catchment (HSC), India where a number of small scale changes have occurred including increases in hydrological structures and groundwater extractions. These are challenging to scale up. Since 1987 the Indian Government has promoted small scale watershed development programmes including the Drought Prone Area Programme (DPAP) and the Integrated Wasteland Development Programme (IWDP). From 1994 to 1995, these programmes intensified with 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 rainfed agricultural production, and to control land degradation by conserving rainwater for use during dry periods. 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).

While hydrological structures are beneficial to upstream users, they affect the downstream flows (George et al. 2011; Garg et al. 2012). 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 up to 50 % of their total volume every year to evaporation due to their high surface area to volume ratio (Sakthivadivel et al. 1997). Groundwater utilisation has also expanded in the HSC and it has become a conjunctive resource for agriculture (Sylvain et al. 2013).

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. This has resulted in bringing more water to the Hyderabad City to fulfill the drinking water demand from sources located far away from this catchment. HSC is located in a semi-arid region that is historically among the poorest areas in India and it has been severely affected by droughts (World Bank 2005). Watershed development has included construction of hydrologic structures such as percolation tanks, mini-percolation tanks, check dams, sunken pits, farm pits, and changes in irrigated areas.

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. Potential drivers of hydrologic change in HSC were identified from the literature and our knowledge of the catchment. This included changes in land use, changes in surface water interception by hydrological structures and changes in groundwater extractions. Finally it compares the temporal changes with the aim of investigating which drivers can best explain the trend in streamflow.

2 Study Catchment

The HSC has an area of 1,340 km^2 and is located in the upper part of the Musi River catchment, within the Krishna River Basin in Southern India (Fig. 1a). The catchment partly covers districts in Rangareddy (87 %) and Mahabubnagar (13 %), Andhra Pradesh (Fig. 1b). 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 to 726 m above sea level with slope ranging between 1 and 3 %. The soils are predominantly clayey (>70 % of catchment area), along with loamy and rock formations (Gurunadha Rao et al. 2007). Temperatures reach a maximum of 44 °C during summer and a minimum of 12 °C during winter (George et al. 2007).

The average annual rainfall is 718 mm/y, of which nearly 90 % occurs in the south-west monsoon season (June to October). There are two main cropping seasons, the Kharif or monsoon season (June to November) and the Rabi or dry season (December to March). Agricultural lands are kept fallow during the summer season (April to May). The main stream in the HSC is the Esa River. In 1927, the Himayat Sagar reservoir was constructed on the Esa River near the catchment outlet to control floods and supply drinking water to Hyderabad.

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 do store runoff temporarily. The sunken pits and feeder channels control silt, but

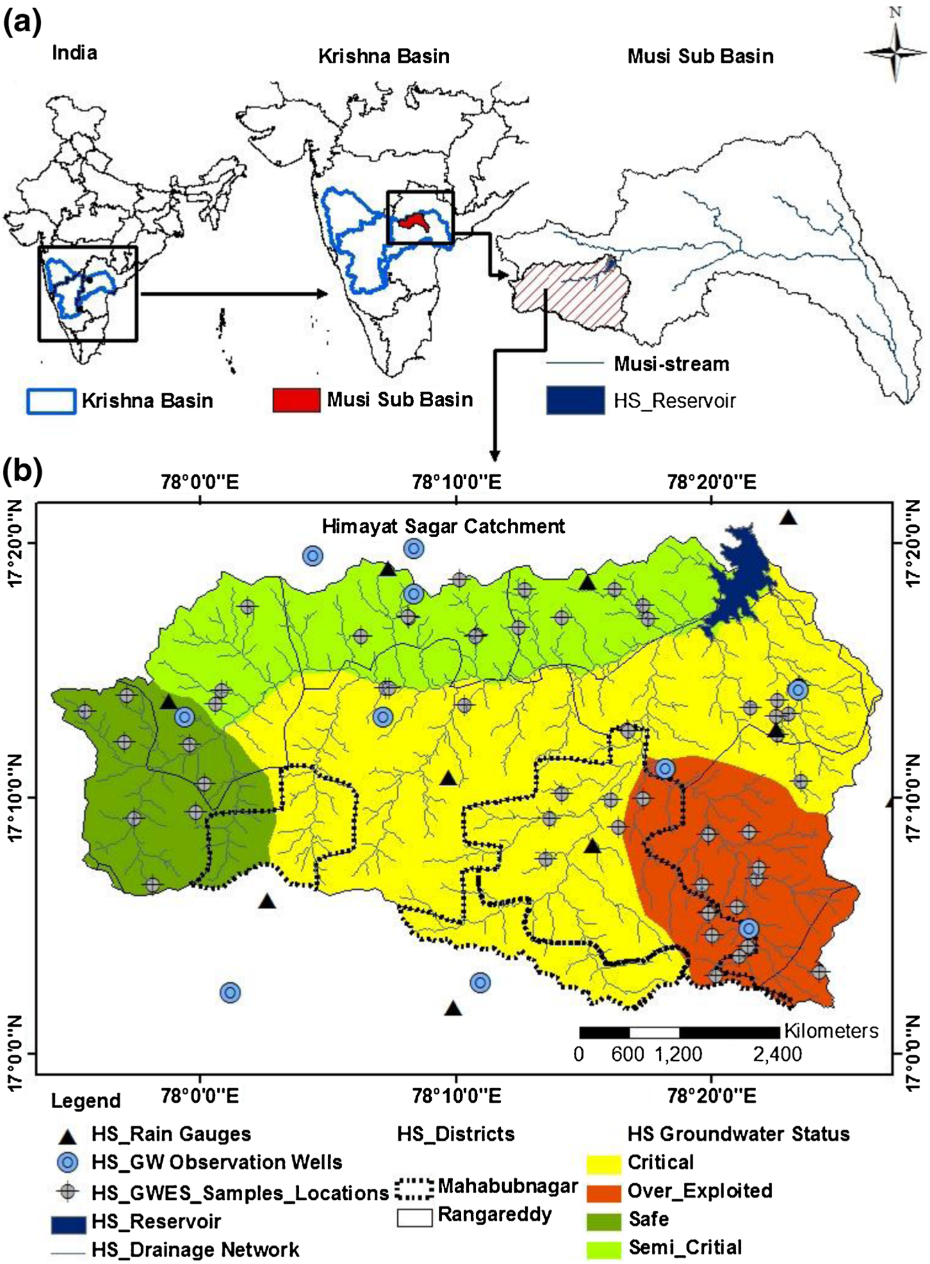

Fig. 1 **a** Location map of Himayat Sagar Catchment (HSC) in southern India. **b** Districts covered by HSC, drainage network, HS reservoir, rain gauge stations, groundwater observation wells, HS groundwater status and HS groundwater extraction survey sample locations

they also hold runoff in the stream bed and recharge the groundwater. The main runoff capturing structures are percolation tanks, mini-percolation tanks, check dams and farm pits, which capture runoff permanently.

3 Data

The data used in this study were collected from three sources: the relevant government departments of Andhra Pradesh, by field survey, and by interpretation of remote sensing images on Google Earth.

3.1 Rainfall and Reservoir Data

Data from 12 daily rainfall gauges (Fig. 1a) were collected from the Directorate of Economics and Statistics (DES). Gauge elevations range from 535 to 720 m. Six stations had records covering 1980 to 2004, while the other six covered 1990 to 2004. Monthly streamflow into HS reservoir was estimated using water storage levels (1980 to 2004), storage-area-capacity tables, surplus discharges (1980–2004) and water supply withdrawals (1980 to 2004) all from the Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB). Evaporation losses were estimated using average monthly evaporation depths from the HMWSSB.

3.2 Land Use Information

Mandal (sub-district, 1985–87, 1991–94 and 1999–2004) and district (1985–2004) level land use information was collected from DES. Data gaps at the mandal level were filled with percentage changes from the corresponding district level information. Areas irrigated during the Kharif (monsoon, June–November) and Rabi (dry, December–March) seasons were obtained from the mandal information. The difference between the net sown area and the irrigated area was considered to be rainfed.

3.3 Groundwater Levels and Extraction Survey

The pre-monsoon and post-monsoon groundwater levels of 11 observation wells, surface elevations range from 570 to 680 m, were collected from Central Ground Water Board (CGWB) (Fig. 1b). District level groundwater production well inventory information (1980–2004) was obtained from the Minor Irrigation Census (MIC), Ministry of Water Resources, India. The groundwater status (Fig. 1b) 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 %). Groundwater status has been evaluated biannually in every watershed by the CGWB. To estimate groundwater extraction rates, we conducted a groundwater extraction survey that was interpreted on the basis of the average groundwater status (Fig. 1b). The information collected in the survey included typical irrigation practices including irrigation application rates, pumping hours and flow rates, the number of wells per hectare, well depth and cropping information in the Kharif and Rabi seasons.

3.4 Watershed Development Structures

The information on watershed development structures (1995 to 2005, Table 1) was extracted from District Water Management Agency (DWMA) data in Rangareddy based on villages within the catchment. The area-volume relationships of each type of structure were collected by field survey (Table 1). Apart from these watershed development structures, large tanks have existed in the catchment for many years.

Table 1 DWMA watershed development structure information and typical geometry

Year	Check dams (A=1,000 m^2; D=1.2 m; V=1,200 m^3)	Perco-lation tanks (A=1,650 m^2; D=3.0 m; V=4,950 m^3)	Mini-percolation tanks (A=750 m^2; D=2.0 m; V=1,500 m^3)	Sunken pits (A=16 m^2; D=1.0 m; V=16 m^3)	Farm pits/ponds (A=28 m^2; D=2.0 m; V=56 m^3)	Feeder channels (A=3 m^2; D=0.5 m; V=1.5 m^3)	Gully control structures (A=30 m^2; D=0.5 m; V=15 m^3)
1995	143	33	–	4	9	7	2,788
1997	109	24	–	355	3	4	1,149
1998	80	29	105	691	6	76	2,190
1999	382	55	2	2,504	29	270	2,553
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

A area, D depth and V volume

4 Methods

This section describes estimation of rainfall, streamflow and their trends, as well as anthropogenic changes, including changes in land use, groundwater extractions and water retention in watershed development structures. Finally water balance reconciliation is considered. Before discussing each analysis, rainfall and streamflow data preparation procedures are described.

4.1 Estimating Streamflows and Catchment Average Rainfall

The consistency of rainfall records was checked using double mass curves. Areal weighted average annual rainfall was then estimated using Thiessen polygons and rainfall data from the 12 rain gauges (1990–2004). In addition to this, weighted annual catchment rainfall was estimated for the whole study period (1980 to 2004) using data from the six stations with long records. This allowed assessment of temporal trends free from any effects of the rain gauge network configuration.

Streamflow is not directly measured in HSC; instead monthly streamflow, R_i, was estimated from monthly reservoir levels and a reservoir water balance using:

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

where, subscript i is the time period (month), ΔRS is the change in reservoir storage volume estimated based on levels and the HS reservoir level-area-volume relationship, W is the water supply withdrawal volume, E the evaporation volume and D is the discharge to the river from the reservoir. Negative streamflow estimates during the non-monsoon period were set to zero. Monthly R_i values were then summed to annual values and converted to runoff depth (mm/month).

4.2 Estimating Streamflow and Rainfall Trends

Non-parametric trend tests (the Mann-Kendall and Spearman's Rho tests) from the TREND tool (Chiew and Siriwardena 2005) were used to detect linear trends in the annual streamflow and rainfall from 1980 to 2004. A 5 % significance level was adopted.

A nonlinear regression model was then fitted to observed rainfall and runoff data, evaluated and then used to quantify the change in streamflow over the study period for different annual rainfall percentiles.

Annual runoff (R) was estimated as:

$$R = \begin{cases} (a \times t + b)(P - P_t) & P \geq P_t \\ 0 & P < P_t \end{cases} \tag{2}$$

where t is time (years since 1980), P is the annual rainfall (mm), a and b are empirical parameters for the trend in rainfall-runoff response and P_t is an annual rainfall threshold below 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 the Generalized Reduced Gradient (GRG2) non-linear optimization tool in Microsoft Excel solver. The model quality was evaluated by plotting residuals against predicted values.

4.3 Analysing Anthropogenic Changes

Here we address three aspects of anthropogenic change: land use and evapotranspiration; groundwater storage and extraction; and interception due to hydrological structures.

First, the DES land use data were grouped into four classes namely forest, range lands (which includes barren lands, non-agricultural use lands, pasture lands, trees, cultivable waste lands and other fallow lands), current fallow 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 and rainfed areas. The area sown more than once was assumed to be a second crop irrigated using groundwater during the Rabi season, as the rainfall in this season is very low (10 % of annual rainfall).

Variations in annual evapotranspiration were derived from groundwater extractions estimated using the inventory of wells and also from irrigated area and typical irrigation application over 1997–2004. In addition, spatially distributed monthly ET estimates HSC derived from Advanced Very High Resolution Radiometer (AVHRR) data and local meteorological stations (1984–2001) were available for comparison (Teluguntla et al. 2012). These estimates used a modified Penman-Monteith model with biome-specific canopy conductance to estimate the AVHRR ET for 8-km pixels.

Second, changes in groundwater storage were obtained by analysing depth-to-water table at 11 observation wells for 1997–2004. The average of the pre and post-monsoon depths was calculated across all wells for each year. The trend in this average depth-to-water table was then found by regression and the rate of change of groundwater storage estimated by multiplying by the specific yield.

Third, changes in interception due to watershed development structures were estimated as follows. The inventory of water retention structures including farm pits/ponds, check dams, percolation and mini-percolation tanks were captured from DWMA data. As the DWMA data only covers the Rangareddy district (87 % of the catchment), Google Earth images were used to count the major structures in the rest of the catchment. To check the DWMA data for small structures (farm pits), we randomly selected 25 villages from the HSC and mapped farm pits using Google Earth images (2003). Due to finding significant discrepancies, we then predicted farm pit density by regression. Finally, the surface areas of the pre-existing large tanks were estimated by classifying Landsat images for 1981, 1989 and 2000 using ERDAS Imagine and unsupervised classification (Chander et al. 2009). The total storage capacity of hydrologic structures was then estimated based on the DWMA data, field survey (for depth, area and volumes) and the extrapolated data discussed above.

4.4 A Mass Balance Framework

The water balance in the HSC was conceptualized using the mass balance equation:

$$dS/dt = P - E - R \tag{3}$$

where the rate of change of catchment storage, S (mm), with time t, is balanced by the rates of input (Rainfall, P) and output (Evaporation, E in mm, and Streamflow, R in mm). Further, it is assumed that changes in unsaturated zone storage were negligible over the study period, in which case S represents the groundwater. This equation implies that an observed trend in runoff must be balanced by trends in one or more of the other components.

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

$$P(t) = P_0 + t.dP/dt \tag{4}$$

$$E(t) = E_0 + t.dE/dt \tag{5}$$

$$R(t) = R_0 + t.dR/dt \tag{6}$$

where P_0, E_0 and R_0 are the precipitation, evapotranspiration and runoff at t=0. Substituting Eqs. (4), (5) and (6) into Eq. (3) and integrating results in an estimate of the change in groundwater storage, ΔS, as:

$$\Delta S = (P_0 - E_0 - R_0)t + 0.5(dP/dt - dE/dt - dR/dt)t^2 \quad (7)$$

Assuming that the catchment is in equilibrium at t=0 implies the first bracket on the right hand side is zero and thus Eq. (7) simplifies to:

$$\Delta S = 0.5(dP/dt - dE/dt - dR/dt)t^2 \quad (8)$$

5 Results

In this section, we firstly test the temporal trends in rainfall and streamflow. We then 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 2 shows the pattern of catchment average annual rainfall during the study period (mean = 718 mm/y, minimum = 471 mm/y (2004) maximum = 996 mm/y (1983), standard deviation = 153 mm/y and coefficient of variation = 0.21). The annual streamflow pattern is also shown (mean = 58 mm/y, minimum = 2 mm/y (2004), maximum = 247 mm/y (1983), standard deviation = 60 mm/y and coefficient of variation = 1.04). The 5-year average streamflows for 1980–84, 1985–89, 1990–94,

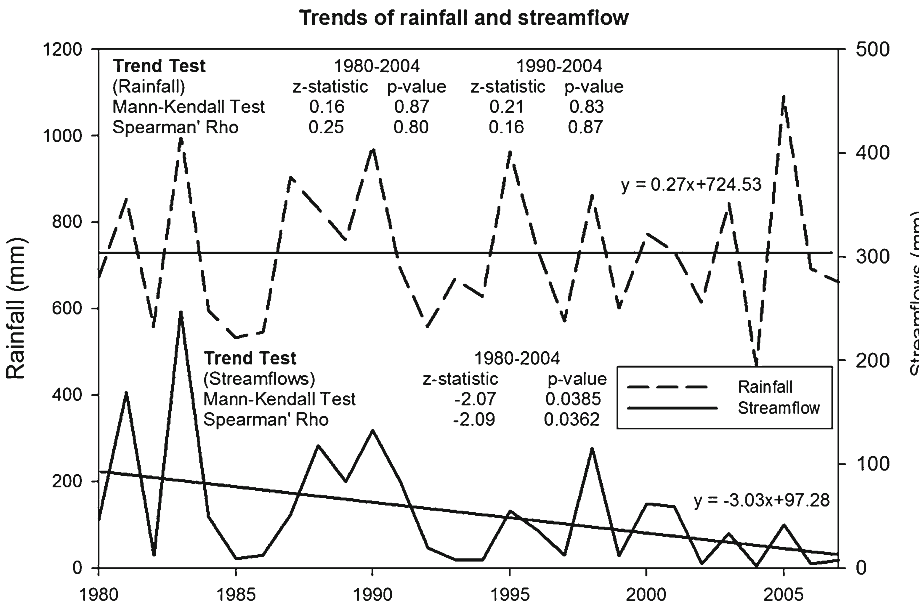

Fig 2 Time series of average annual rainfall and annual streamflows in the Himayat Sagar catchment

1995–99 and 2000–04 were 105, 55, 50, 46 and 32 mm/y respectively for corresponding average rainfalls of 735, 715, 705, 748 and 687 mm/y. The 5-year average runoff coefficient declined from 14 % (1980–84) to less than 5 % (2000–04). The trend test found that the streamflows declined significantly (Fig. 2), 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) changes rather than exogenous (climate) changes.

5.2 Quantification of Change in Magnitude of Streamflows

Figure 3a shows the fit of Eq. 2 to the annual rainfall-runoff data (1980–2004) (R^2=0.76) and Fig. 3b shows the model residuals plotted against predicted values, which indicate that the model fitted the data well. The fitted parameters are a= -0.02y^{-1}, b=0.47 and P_t=518 mm, where t=1 in 1980. The fitted model for 1980, 1990, 2000 and 2004 is shown in Fig. 3c. The predicted runoff for the 25th, 50th and 75th percentile annual rainfalls are given in Fig. 3 for each of these years. 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 percentile rainfall) in streamflow during the study period is a 76 % reduction, from 1980 to 2004.

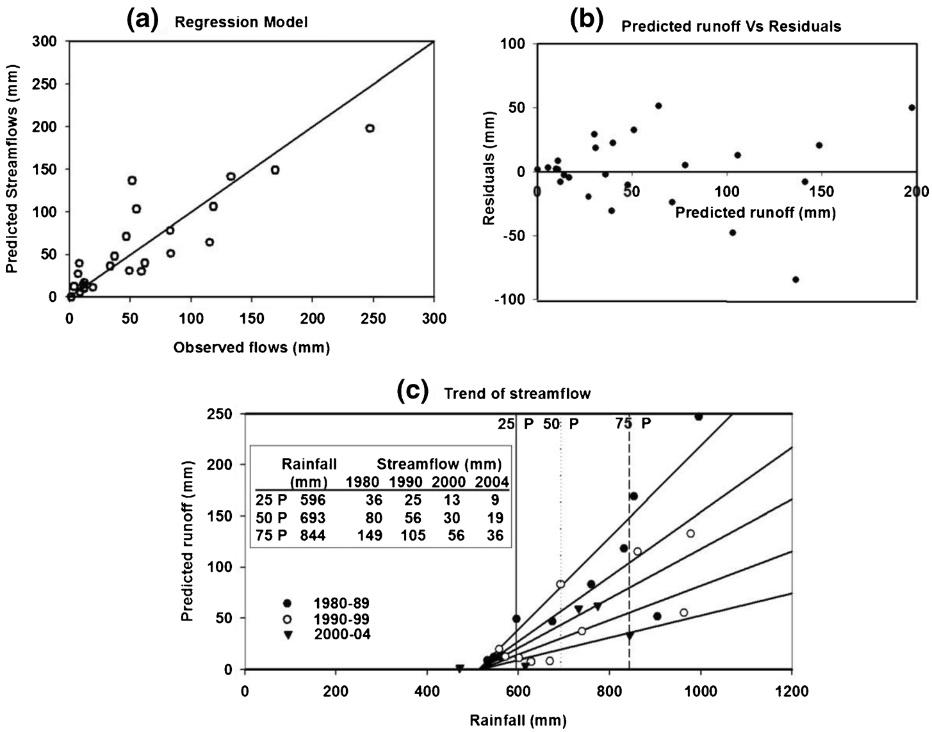

Fig. 3 **a** Linear regression rainfall-runoff model, **b** Residuals against predicted values, **c** Change in magnitude of streamflows at different time periods and rainfall percentiles

5.3 Characterizing Drivers of Streamflow Change

In this section, we first characterise the anthropogenic changes in various catchment characteristics that could influence streamflows including land use, groundwater draft and levels and change in hydrological structures and the volume of water that could be intercepted by these structures.

Figure 4a shows the average land use in the catchment for four periods between 1985 and 2004. Comparison of average land use between the periods 1985–1989 and 2000–04 shows that the Forest (F) area remained at 6 %, Range Lands (RL) reduced slightly from 31 to 28 %, Current Fallow (CF) lands increased from 23 to 33 % and Net Sown Area (NSA) decreased from 40 to 33 %.

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. As a percentage of the NSA, the average net irrigated area has increased from 8 % (1985–89) to 23 % (2000–04) and from 8 % (1985–89) to 16 % (2000–04) in the Kharif and Rabi seasons respectively (Fig. 4b). Furthermore, during the Kharif season the overall percentage area of rice remained constant, but 40 % of the rainfed rice crop was converted into irrigated rice. Thus, it is clear that the most significant land use change in the HSC has been irrigation expansion and intensification.

Second, we examined the groundwater levels and draft during the study period. The groundwater table appears to be declining at a rate of 300 mm/y from 1997 to 2004 (Fig. 5). Available estimates of specific yields are 0.014 (Maréchal et al. 2006) and 0.03 (NINEPlus, EPTRI, NGRI 2005). Assuming a value of 0.02, implies the groundwater storage is declining at a rate of 6 mm/y. Groundwater extractions were estimated using both well inventory land use statistics. The number of groundwater wells in the HSC increased from 13,280 (1993) to 31,600 (2004). To estimate extractions, the number of wells was multiplied by pumping hours and rate of pumping. Information on the average pumping hours per day (7 h) and an average pumping rate were estimated based on field data. The pumping rate was the same as the value estimated by (Maréchal et al. 2006), (8.1 m^3/h) for this region and that is used here. To estimate groundwater draft from land use statistics, average irrigation requirements of 10 mm/day and 15 mm/day for irrigated rice crops during Kharif and Rabi seasons and 7.7 mm/day for dry (Sorghum) and vegetable crops during both seasons were used (Dewandel et al. 2008). Estimated groundwater draft for the catchment based on the land use information increased from 140 mm/y in 1997 to 214 mm/y in 2004. Based on the well inventory, the estimated groundwater draft increased from 102 mm/y (1997) to 149 mm/y (2004). The well based approach leads to lower overall extraction volumes and there are two possible causes of this. It

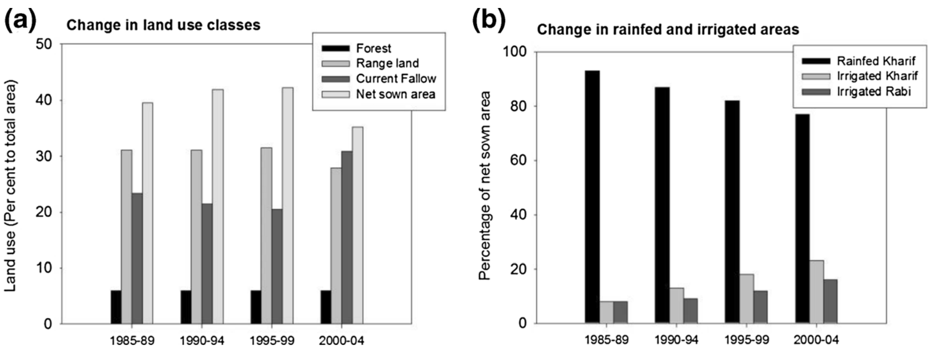

Fig. 4 **a** Major land use classes as a percentage of total catchment area and **b** Change in rainfed and irrigated area, for different time periods

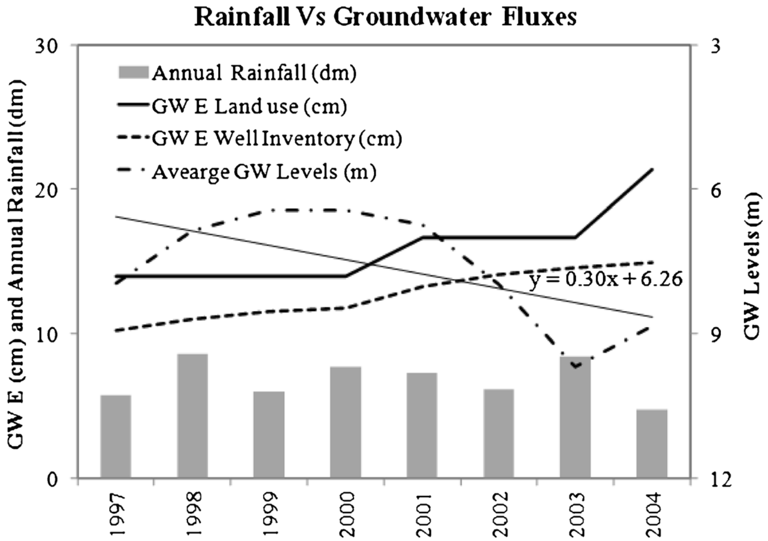

Fig. 5 Annual rainfall, average depth to water table and groundwater extractions (GWE) based on well inventory and land use statistics

is likely that the number of wells in the region is under-reported as farmers make use of private drillers for installing wells which are not recorded. It is also possible that some farmers practice deficit irrigation and the land use based estimates assumed that the crop water demand was fully met. Overall, it appears that significant increases in the groundwater extraction rate have occurred and as a result the groundwater levels have declined in the HSC (Fig. 5).

Third we analysed Watershed Development Structure (WDS) data and estimated the volumes of water captured by these structures. We first compared the village level DWMA statistics for check dams and farm pits with the information extracted from Google Earth images. Results showed no significant difference in the number of check dams for the villages where the information is available in both sets (DWMA & Google Earth images). However, it was also found that there are check dams in many other villages, which are not included in the DWMA data. In the case of farm pond and pit numbers 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 they can be built without any government funding, whereas more costly check dams can only be built by government organisations. Given these discrepancies, 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 the Google Earth image 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 pit numbers. 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/y (1995) to 2.4 mm/y (2004) for each fill. Various tanks existed in the catchment at the start of the study period and their surface area (SA) did not show significant change during study period. Observed surface areas were 1,409 ha (14th Oct–1981, monthly rainfall–79 mm), 680 ha (21st Nov–1989, monthly rainfall–0.0 mm) and 1,486 ha (26th Oct–2000, monthly rainfall–41 mm). The water storage capacity of tanks and WDS increased from 26.4 mm/y (1995) to 28.4 mm/y (2004) of rainfall over the areas of the catchment.

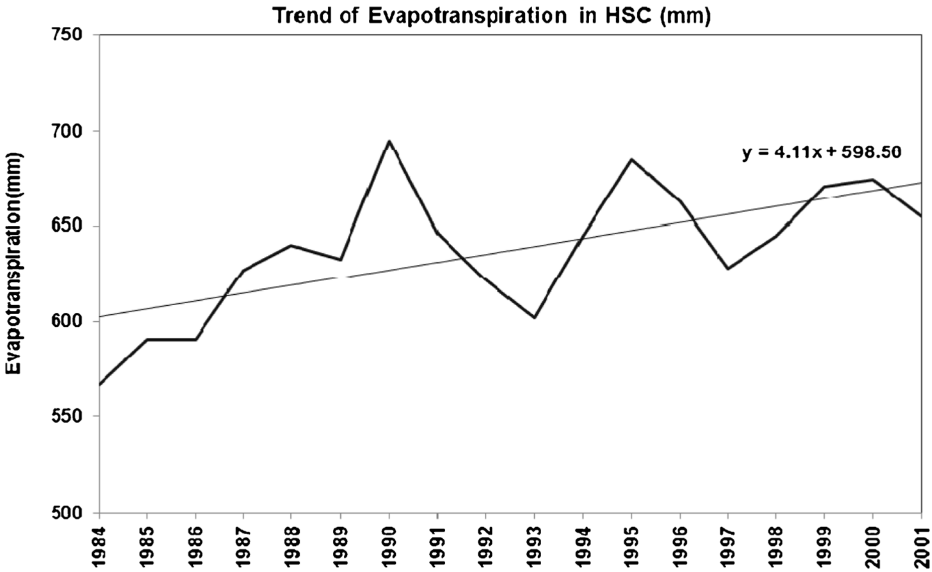

Fig. 6 Temporal change in catchment-scale ET estimated using 8-km AVHRR data in the Himayat Sagar catchment

All these changes clearly indicate that evapotranspiration from the catchment must have increased significantly. The ET estimates obtained from AVHRR show an increasing trend of 4.1±2.6 mm/y from 1984 to 2001 (Fig. 6). 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 test results showed no significant changes in rainfall; however, a significant declining trend was observed in streamflows during the study period. The difference between 5-year average annual streamflows between 1980–84 and 2000–04 shows a decrease of 73 mm from 105 to 32 mm/y. The streamflow estimated by the regression model also suggest that median streamflow reduced by 61 mm from 1980 (80 mm/y) to 2004 (19 mm/y). Overall, the rate of change of observed and model simulated streamflow is −3.6±3.5 mm/y and −3.5± 3.0 mm/y respectively. Given the lack of trend in rainfall, the trend in streamflow 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 the Kharif (8 % to 23 %) and Rabi (8 % to 16 %) seasons. It is also likely that irrigation practice has changed in the past two decades in the catchment. During field survey, it was observed that the farmers were irrigating 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 (Sorgham, vegetables) favoured over wet crops (Rice) in the wet season, and wet crops favoured over dry crops in the dry season now.

Most of this increased irrigation demand was met from groundwater. Groundwater irrigation was originally practiced as supplemental irrigation to satisfy the deficits from rainfall but later become the main source of irrigation because of its availability at low cost.

Based on 11 observation wells, the groundwater levels decreased at a rate of 0.30±0.29 m/y, which is a 6.0±5.9 mm/y decrease in groundwater storage (from 1997 to 2004). These declines are similar to those in the larger Musi catchment during the period 1998–2004 where the water table is declining at a rate of 0.18 m/y (Sylvain et al. 2007).

Estimates of groundwater extractions based on well inventory and land use statistics suggest extraction rates increased at 7.2±1.6 mm/y and 9.0±6.7 mm/y, respectively. There is some evidence (Fig. 5) of increasing rates of groundwater decline over the period for 1997–2004, 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 need further verification. Nevertheless, large changes in groundwater levels have not been observed despite increased pumping. Two effects on the overall groundwater balance could influence this outcome. Recharge might have increased due to increased recharge from irrigation, additional watershed structures and lower groundwater levels. Also, with declining groundwater heads, discharge from the groundwater to the stream may have decreased. Both of these would partially offset the additional pumping from a groundwater balance perspective.

Given that annual groundwater extraction rates have increased by around 47 mm/y to 75 mm/y over 1997 to 2004 and that groundwater storages have declined by an average of only 6 mm/y over this period, it is likely that there was both a decline in base flow and an increase in recharge in the catchment. 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±0.10 mm/filling/y, or 2.0±0.85 mm if it is assumed that the structure fill 8 times in a year. Also the data suggest that the increase in interception was high (0.62±0.37 mm/filling/y or 5.0±3.0 mm/8 fillings/y) from 1995 to 1998 and that there was only limited increase over 1998–2004. From random sampling of Google Earth images, we observed that check dam information in the data obtained from DWMA appears to be incomplete and there could be many additional WDS. This suggests that increased WDS's may have helped to increase the recharge, despite what is suggested by the DWMA data. In addition to the WDS, there are existing tanks which capture 26 mm of runoff over the area of the catchment when they fill. Changes in groundwater levels may have caused some increase in seepage from these large structures.

Turning to the overall catchment water balance, it is possible to jointly examine the trends using Eq. 8. Recall that, 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 streamflow trends are $\mathrm{d}P/\mathrm{d}t = 0$ (1980–2004) and $\mathrm{d}R/\mathrm{d}t = -3.6\pm3.5$ mm/y (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±2.6 mm/y(1984 to 2001);
- Changes in well inventory $\mathrm{d}E/\mathrm{d}t$=7.2±1.1 mm/y(1997 to 2004); and
- Changes in irrigation area $\mathrm{d}E/\mathrm{d}t$=9.0±5.4 mm/y(1997 to 2004).

Using Eq. (8) 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, −949 and −1,900 mm/y respectively, over the period 1997–2004. It should be noted that equating groundwater withdrawals and irrigation volumes to evapotranspiration assumes negligible recharge from irrigation applications, thus these two estimates of dE/dt should be treated as upper bound estimates. Indeed, it is likely that there is significant recharge from irrigation areas and this might explain the differences between the groundwater/irrigation based estimates and the remote sensing estimate.

Each of these terms is uncertain, as are the assumptions underlying Eq. (8). Our judgment is that we have more confidence in the rainfall and runoff trends than 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 1997–2004. 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 any decline since 1980 is $\leq$10 m) also suggests that the remote sensing estimates of evapotranspiration trends are the most plausible of the three.

Finally it is worth summarising the likely relativities between the various changes in the catchment. Increasing evapotranspiration due to land use and water management change has primarily resulted in decreased streamflow, with some of the water coming from mining of groundwater systems. The changes in irrigation/evapotranspiration/groundwater extraction are clearly larger than the impacts of hydrologic structures developed in the catchment, although it is likely those structures do lead to some beneficial increase in groundwater recharge, as well as there being significant evaporative losses as found in other studies (Sakthivadivel et al. 1997; Sylvain et al. 2008).

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 clear declining 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 irrigation and structures such as tanks, check dams and percolation tanks have occurred, together with declining groundwater discharge to streams due to reduced groundwater levels, partially offsetting increased extractions. 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 declining trend in streamflow is due to anthropogenic changes, particularly increasing irrigation and groundwater extractions, as well as some increase in interception by watershed structures 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.

Acknowledgments R Nune received an Australian Centre for International Agricultural Research (ACIAR) John Allwright Fellowship and the Robert Bage Memorial Scholarship from the University of Melbourne to conduct the field work. Sridhar Parupalli (JNTU, IST, Kakinada) assisted with the field survey. The authors thank ACIAR Climate Change Project (LWR/2007/113) for its support. Thanks are due to all the Indian Government departments who provided valuable data. The International Water Management Institute (IWMI), ICRISAT, Hyderabad provided office space during field work. Tim Peterson and Murray Peel (The University of Melbourne) provided valuable suggestions on rainfall and groundwater analysis. The authors thank Dr.K.Dikgola and the anonymous reviewers for valuable comments that improved the paper.

References

Adnan NA, Atkinson PM (2011) Exploring the impact of climate and land use changes on streamflow trends in a monsoon catchment. Int J Climatol 31(6):815–831. doi:10.1002/joc.2112

Alemayehu T, Furi W, Legesse D (2007) Impact of water overexploitation on highland lakes of eastern Ethiopia. Environ Geol 52(1):147–154. doi:10.1007/s00254-006-0468-x

Beavis SG, Zhang L, Evans JP, Jakeman A, Smith DL (1997) Impacts and implications of farm dams on catchment hydrology: methods and application to chaffey catchment. MODSIM 1997 International Congress on Modelling and Simulation Proceedings. Modelling and Simulation Society of Australia and New Zealand, December 1997, pp 282–287. http://www.mssanz.org.au/MODSIM97/Vol%201/Beavis2.pdf. Accessed 21 Sept 2010

Benoit D, Jean-Marie G, Faissal KZ, Shekeel A, Subrahmanyam K (2007) A decision support tool with variable agro-climatic scenarios for sustainable groundwater management in semi-arid hard-rock areas. Curr Sci 92(8):1093–1102

Bouwer LM, Aerts JCJH, Droogers P, Dolman AJ (2006) Detecting the long-term impacts from climate variability and increasing water consumption on runoff in the Krishna river basin (India). Hydrol Earth Syst Sci 10(5):703–713

Cassardo C, Jones JAA (2011) Managing water in a changing world. Water 3(2):618–628. doi:10.3390/w3020618

Chander G, Markham BL, Helder DL (2009) Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. Remote Sens Environ 113(5):893–903

Charlton MB, Arnell NW (2011) Adapting to climate change impacts on water resources in England—an assessment of draft water resources management plans. Glob Environ Chang 21(1):238–248. doi:10.1016/j.gloenvcha.2010.07.012

Chiew F, McMahon TA (2002) Modelling the impacts of climate change on Australian streamflow. Hydrol Process 16(6):1235–1245. doi:10.1002/hyp.1059

Chiew F, Siriwardena L (2005) trend/change detection software: TREND User guide. 1.0.2 edn. CRC for Catchment Hydrology, Australia. http://toolkit.net.au/Tools/TREND/documentation. Accessed 1 Dec 2011

Chulli B, Favreau G, Jebnoun N, Bédir M (2011) Impact of changing climate in the Kairouan Hydrological Basin (Central Tunisia). J Environ Sci Eng 5(6):682–688

Dewandel B, Gandolfi JM, de Condappa D, Ahmed S (2008) An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale. Hydrol Process 22(11):1700–1712. doi:10.1002/hyp.6738

Garg KK, Karlberg L, Barron J, Wani SP, Rockstrom J (2012) Assessing impacts of agricultural water interventions in the Kothapally watershed, South India. Hydrol Process 26(3):387–404

Garg KK, Wani SP, Barron J, Karlberg L, Rockstrom J (2013) Up-scaling potential impacts on water flows from agricultural water interventions: opportunities and trade-offs in the Osman Sagr catchment, Musi sub-basin, India. Hydrol Process 27(26):3905–3921

George BA, Malano MH, Davidson B (2007) Integrated water allocation-economic modelling at a catchment scale. In: MODSIM-2007, Christchurch., Dec 10–14, 2007

George BA, Malano H, Davidson B, Hellegers P, Bharathi L, Sylvain M (2011) An integrated hydro-economic framework to evaluate water allocation strategies I: model development. Agric Water Manag 98(5):733–746

Goncu S, Albek E (2010) Modelling climate change effects on streams and reservoirs with HSPG. Water Resour Manag 24(4):707–726

Gurunadha Rao VVS, Suryanarayana G, Prakash BA, Mahesh Kumar K, Ramesh M (2007) Ecological study of Osmansagar and Himayatsagar Lakes in Greater Hyderabad, Andhra Pradesh, India. In: Taal 2007, 12 th World Lake Conference, Jaipur, India, 28 October to 2 November 2007

Hanumantha Rao T (2006) Innivation participation technologies for water harvesting structures & catchment management in semi arid tropics of India. In: Venkateswara Rao B (ed) 2nd International Conference on Hydrology and Watershed Management, Hyderabad. p 1

Kalpataru Research Foundation (2001) Watershed Development: Andhra and Karnataka (trans: India PCGo). Planning Commission, Government of India. http://planningcommission.nic.in/reports/sereport/index.php?repts=mstudy. Accessed 25 June 2012

Maréchal JC, Dewandel B, Ahmed S, Galeazzi L, Zaidi FK (2006) Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. J Hydrol 329:281–293. doi:10.1016/j.jhydrol.2006.02.022

Masih I, Maskey S, Uhlenbrook S, Smakhtin V (2011) Impact of upstream changes in rain-fed agriculture on downstream flow in a semi-arid basin. Agric Water Manag 100(1):36–45. doi:10.1016/j.agwat.2011.08.013

NINEPlus, EPTRI, NGRI (2005) Ecology of Himayat Sagar and Osman Sagar Lakes-evaluation of permissible developmental activities in the Catchment Areas. Environmental Protection Training & Research Institute

(EPTRI) and National Geophysical Research Institute (NGRI), (trans: Municipal Administration & Urban Development Department), Government of Andhra Pradesh.

Ramireddygari SR, Sophocleous MA, Koelliker JK, Perkins SP, Govindaraju RS (2000) Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and groundwater: the case of Wet Walnut Creek Watershed, Kansas, USA. J Hydrol 236(3–4):223–246

Rientjes THM, Haile AT, Kebede E, Mannaerts CMM, Habib E, Steenhuis TS (2011) Changes in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin–Ethiopia. Hydrol Earth Syst Sci 15(6):1979–1989. doi:10.5194/hess-15-1979-2011

Rockstrom J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resour Res 45:W00A12

Sakthivadivel R, Fernando N, Brewer DJ (1997) Rehabilitation planning for small tanks in cascades: a methodology based on rapid assessment. Research report 13. International Water Management Institute, Colombo

Schreider SY, Jakeman AJ, Letcher RA, Nathan RJ, Neal BP, Beavis SG (2002) Detecting changes in streamflow response to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia. J Hydrol 262(1–4):84–98

Sharma B, Amarasinghe U, Xueliang C, de Condappa D, Shah T, Mukherji A, Bharati L, Ambili G, Qureshi A, Pant D, Xenarios S, Singh R, Smakhtin V (2010) The Indus and the Ganges: river basins under extreme pressure. Water Int 35(5):493–521. doi:10.1080/02508060.2010.512996

Stahl K, Hisdal H, Hannaford J, Tallaksen LM, van Lanen HAJ, Sauquet E, Demuth S, Fendekova M, Jodar J (2010) Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrol Earth Syst Sci 14(12):2367–2382

Sylvain M, George BA, Gaur A, Nune R (2007) Groundwater modelling for sustainable resource management in the Musi Catchment, India. In: MODSIM-2007 "Christchurch" Dec 10–14, 2007. pp 1429–1435

Sylvain M, Jérome P, Cédric M, Mohamed W, Subash C, Benoit D (2008) Percolation efficiency of an artificial tank in semi-arid hard rock aquifer context, South India. International Water Resources Association, 13th World Water Congress

Sylvain M, George BA, Venot JP, Bharati L, Acharya S (2013) Improving assessment of groundwater-resource sustainability with deterministic modelling: a case study of the semi-arid Musi sub-basin, South India. Hydrogeol J 21(7):1567–1580

Teluguntla P, Ryu D, George BA, Walker JP (2012) Multi-decadal trend of basin-scale evapotranspiration estimation using AVHRR data in the Krishna River Basin, India. Vadose Zone J. doi:10.2136/vzj2012.0118

Van Kirk RW, Naman SW (2008) Relative effects of climate and water use on base-flow trends in the Lower Klamath Basin. J Am Water Resour Assoc 44(4):1035–1052. doi:10.1111/j.1752-1688.2008.00212.x

Whieda E, Verhoeven R (2007) An alternative solution of the water shortage problem in Libya. Water Resour Manag 21(6):961–982. doi:10.1007/s11269-006-9067-6

World Bank (2005) Drought in Andhra Pradesh: long term impacts and adaptation strategies. Final Report. South Asia Environment and Social Development Department

Xia J, Zhang L, Liu C, Yu J (2007) Towards better water security in North China. Water Resour Manag 21(1): 233–247

Zhang Z, Dehoff A, Pody R, Balay J (2010) Detection of streamflow change in the Susquehanna River Basin. Water Resour Manag 24(10):1947–1964