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Impact of Agricultural Water Management Interventions on Upstream-downstream Trade-offs in the Upper Cauvery Basin, Southern India: A Modelling Study

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Abstract

The Cauvery basin in Southern India is experiencing transboundary issues due to increasing water demand. This study analysed water balance components and the impact of agricultural water management (AWM) interventions in the Upper Cauvery catchment of the Cauvery basin. Results showed that the study catchment receives an average of 1280 mm of annual rainfall. Of this, 29% (370 mm) flows downstream, 54% (700 mm) contributes to evapotranspiration (ET), and 17% (215 mm) contributes to groundwater recharge and surface storage. Rainfall varies from 700 mm to 5400 mm and the Western Ghats (mountain pass) are the main source of freshwater generation. The estimated ET in different watersheds ranged from 500-900 mm per annum. An increase in the allocation of freshwater supplied by all the three reservoirs (Hemavathi, Harangi and KRS) was observed in the canal command areas, from 1450 Million Cubic Meter (MCM)/year in 1971-1980 to 3800 MCM/year in 2001-2010. AWM interventions harvested 140-160 MCM (13-20 mm) of surface runoff upstream of the Upper Cauvery and reduced inflow into the Krishnaraja Sagar reservoir by 2-6%. The study findings are useful for designing and planning suitable water management interventions at basin scale.

Key words: water balance, surface runoff, watershed treatment, reservoir inflow

1. Introduction

Fresh water availability is essential to ensure food security for an ever increasing population. Agriculture in rainfed areas is characterized by water scarcity, land degradation, low resource inputs and low productivity. India's net sown area of 141 million ha of which 55% is rainfed, has a cropping intensity of 135%. Agricultural productivity, generally, oscillates between 0.5 and 2.0 ton/ha with an average of 1.0 ton/ha (Rockström et al., 2009; Wani et al., 2011; Bhattacharyya et al., 2016; GoI, 2018; Rao et al., 2015; Fischer, 2015; Fischer and Connor, 2018). Irrigated land which constitutes 45% of the total agricultural area, contributes about 55% to the total food requirement and consumes almost 70% of freshwater resources of the country (Green et al., 2020; GoI, 2015).

With limited scope of crop intensification in canal command areas, the focus has shifted towards increasing groundwater (GW) recharge in dryland areas. A number of public welfare programs such as watershed development, The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), and Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) have been initiated since 1980 as drought mitigation measures (Tiwari et al., 2011; Krishnan and Balakrishnan, 2012; NITI Aayog, 2017, 2019). Since 1990, about US$ 14 billion have been invested on drought mitigation measures such as field bunds, farm ponds, check dams, terracing, rejuvenating community ponds, also known as agricultural water management (AWM) interventions (Mondal et al., 2020). *In-situ* water harvesting interventions (e.g., contour/graded bunds) enables improvement in soil moisture availability by enhancing the landscape's infiltration capacity, conserving moisture, and controlling soil erosion (Garg et al., 2011; Singh et. al., 2014). Often, larger fields are divided into relatively smaller plots to reduce runoff velocity and harvest a fraction of the runoff across the field bunds. On the contrary, *ex-situ* interventions harvest a fraction of surface runoff that drains out from agricultural fields. *Ex-situ* interventions such as check dams and farm ponds have a capacity varying from 100-10000 m^3 (Jain et al., 2007; Singh et al., 2014; Garg et al., 2020). Despite concerted efforts and investments India has made in various drought mitigation measures, the impact of AWM interventions on water balance components has not been fully understood (Bouma et al., 2011; Glendenning and Vervoort, 201), with some studies focusing on one or two components of land use change and crop production and others focused on the conceptual framework (Batchelor et al., 2003; Shiferaw et al., 2008).

Studies undertaken in the water sector have mostly focused on multi-purpose, large-scale projects (major reservoirs) to address food security (Goyal and Surampalli, 2018; Bhanja and Mukherjee, 2019); mapping water use efficiency (Garg et al., 2012b); crop intensification (Jayne et al., 2004; Heller et al., 2012; Pellegrini and Fernández 2018); and analyzing socio-economic impacts (Whitehead et al., 2018; Bhave et al., 2018); migration (Tilt et al., 2009; Deshingkar, 2012; Weinthal et al., 2015); and transboundary issues (Sood and Mathukumalli, 2011; UNEP-DHI and UNEP, 2016). To the best of the authors' knowledge, the impact of AWM interventions on hydrological processes at catchment/basin scale have not been investigated thoroughly. However, a few studies have analyzed their impact at micro (<10 km^2) and meso (10-100 km^2) scale watershed hydrology either by comparing paired watersheds (Zégre et al., 2010; Singh et al., 2014; Sultan et al., 2018) or before and after watershed treatment impacts (Huang and Zhang, 2004; Lodha and Gosain, 2007; Nyssen et al., 2009; Garg et al., 2011; Mekonen and Tesfahunegn, 2011). The focus of all these studies was to quantify the impact of watershed interventions on surface runoff, agricultural productivity, and upstream-downstream trade-offs. he knowledge generated from micro and meso-scale watersheds was very important, it may not directly be applicable for catchment or basin-scale decision making due to the difference in scale (Vinogradov et al., 2011; Gentine et al., 2012).

Soil and Water Assessment Tool (SWAT) is a widely used hydrological model that uses a geographic information system (GIS) interface to capture landscape variability and runs on daily time step. SWAT has been used to simulate water resource assessment (Krysanova and White, 2015; Gupta et al., 2020); map agriculture water productivity (Garg et al., 2012b; Thokal et al., 2015; Ahmadzadeh et al., 2016); optimize reservoir operation (Wu and Chen, 2012; Anand et al., 2018); study the impact of land use and management practices (Krysanova and White, 2015; Jodar-Abellan et al., 2019); climate change effect (Narsimlu et al., 2013; Uniyal et al., 2015; Marin et al., 2020); and quantify various ecosystem services (Dile et al., 2016a,b; Lee et al., 2018). It has also been used to analyze upstream-downstream water balance at meso- (Dile et al., 2016 a,b), catchment, and basin scales (Masih et al., 2011).

SWAT can capture hydrological response to AWM interventions and could be customized for a micro-scale community watershed to a large-scale river basin depending on data availability (Glavan and Pintar, 2012). It has been used to evaluate the impact of soil conservation measures on runoff and sediment transport (Berihun et al., 2020; Betrie et al., 2011; Dile et al., 2013, 2016a,b; Worku et al., 2017; Mekonnen et al., 2018; Woldesenbet et al., 2017, 2018; Horan et al., 2021). It also allows the estimation of the integrated impacts of changes in land use-land cover (LULC) and biophysical factors under different land management interventions (Arnold et al., 2012; Berihun et al., 2020).

This study aimed to analyze the impact of various AWM interventions on downstream water availability in the Upper Cauvery sub-basin of southern India. The Cauvery basin experiences severe water scarcity for up to 8 months a year, affecting over 35 million people (Ferdin et al., 2010; Hoekstra et al., 2012). The specific objectives of the study are: (i) to understand the water utilization pattern in major reservoirs of the Upper Cauvery catchment; (ii) to analyze water balance components of the entire catchment; and (iii) to analyze the impact of AWM interventions on reservoir inflow into the Krishnaraja Sagar (KRS).

2. Materials and Methods

2.1 Study Area

The Cauvery river basin is one of the largest basins in southern India with a catchment area of 81,155 km^2. The river flows through the states of Karnataka (42.2%), Tamil Nadu (54%) Kerala (3.5%), and Puducherry (0.2%) (India-WRIS WebGIS, 2014). The basin faces water stress and a number of socio-economic and political challenges. The availability of freshwater in the basin has declined due to increasing population, crop intensification, industrialization, and fast urban growth over last two decades. Competing demands for the water from agriculture, domestic, and industrial sectors have exacerbated the situation. The agriculture sector is one of the largest consumers of freshwater in this basin, with agricultural land being the major land cover type (>50%). The food security and livelihood of millions of farmers mainly depends on freshwater availability (both surface and groundwater resource). The river basin is characterized by large spatial variability in terms of rainfall, land use, topography, soil type, and various land management factors (Sreelash et al., 2020).

The Upper Cauvery catchment was chosen to study the impact of AWM interventions as it is situated in the uppermost part of the basin and relatively independent in terms of hydrological processes. The catchment covers 10619 km^2, ~ 13% of the total basin. The entire Upper Cauvery catchment lies in Karnataka, covering parts of Chikkamagaluru, Kodagu, Hassan, Mandya, and Mysore districts (**Figure 1**). Average annual rainfall in the catchment is 1280 mm with a huge spatial variability of 600 mm to 5400 mm. The catchment includes several tributaries including Hemavathy and Laxmanthirtha, which join the Cauvery river and flow into the KRS dam (outlet of the study basin). The maximum storage capacity of the KRS reservoir is 1275.7 MCM. There are two other major reservoirs in the Upper Cauvery basin, Hemavathy and Harangi, with a maximum storage capacity of 926.8 MCM and 228.6 MCM, respectively (**Figure 1**).

2.2 Data Collection

Figure 2 describes the methodological approach followed based on the study's objectives. The study first analyzed the hydrology of the Hemavathy, Harangi and KRS reservoirs using long-term measured data on inflow, utilization in agriculture (canal command), and release into downstream rivers (*section 3.2*). Water balance components of the Upper Cauvery catchment were estimated using SWAT simulation (refer *sections 3.3 and 3.4*). Using a calibrated model setup, the impact of AWM interventions on the KRS reservoir was analyzed and further projected by describing two future scenarios in 2030 and 2040 (*section 3.5*).

The daily rainfall data of 23 rain gauge stations for the period 1979-2013 (**Figure 1**) was collected along with daily maximum and minimum temperature gridded data at the scale of 0.125° from the India Meteorological Department (IMD). Daily relative humidity, sunshine hours, and wind speed for three climate stations (Bengaluru, Thrissur, and Coimbatore) were collected for the same period. The Digital Elevation Model (DEM) of the study area at 90 m spatial resolution was downloaded from the CGIAR Consortium for Spatial Information (http://srtm.csi.cgiar.org). The land use/land cover (LULC) map of the study area at a 1:250000 scale was collected from the National Remote Sensing Centre (NRSC). Crop statistics data was obtained from the government platform (https://data.gov.in/) and web-based land use statistics (http://aps.dac.gov.in/LUS/Index.htm). The soil map of the study area was acquired from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). The study also used the soil database developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) during 2005 and 2019 for previous studies in Karnataka (Wani et al., 2017; Anantha et al., forthcoming).

The daily discharge data from seven rain gauge locations (Sakelshpur, Akkihebbal MH Halli, Akkihebbal, Kudige, Chuchunkatte, and KM Vadi) was obtained from India-WRIS WebGIS (http://www.india-wris.nrsc.gov.in/). Information on monthly storage, inflows, and outflows of three major reservoirs between 1970 and 2010 were obtained from the Command Area Development Authority (CADA) of Hassan, Kodagu, and Mysore districts. A map of the irrigated area (command area) under these reservoirs was obtained from the National Water Development Agency (NWDA), Bengaluru. Data on the number and type of structures constructed, total treated area along with investments between 2006 and 2012 was sought from watershed development department, Bengaluru.

2.3 Model Description

SWAT is a semi-process based model that operates on a daily time step. The study catchment was divided into nine major land uses/land covers (**Figure 3** and **Table 1a**). In the study area, 51% of the total geographical area is under agriculture, 31% is forest, 11% is fallow/shrubland, and 7% comprises settlement, water bodies and other uses/covers. There are two major soil types, clay (6395 km^2, 58%) and clay loam (4551 km^2, 42%). The entire catchment was further classified into three land slopes: 0-5% covering 6415 km^2 (59%), 5-10% covering 2716 km^2 (25%), and greater than 10% covering 1816 km^2 (16%). With all these combinations, the entire study area was divided into 129 meso-scale watersheds and 4432 Hydrological Response Units (HRUs). The daily rainfall, maximum and minimum temperatures, relative humidity, wind speed, and solar radiation between 1981 and 2013 were provided as inputs to the model.

Table 1a shows the major land use classes in the study area and crop management details provided as inputs to the model. Two major upstream reservoirs (Hemavathy and Harangi) were modeled by creating the reservoir nodes at the respective sites. Their maximum storage capacity, water spread area, and the volume required to fill the emergency spillway were provided from actual records. Delineated watersheds and HRUs belonging to the canal command areas of the respective reservoirs were demarcated and assigned as sources of irrigation. Rice was cultivated during both rainy (*kharif*) and post-rainy (*rabi*) seasons in these HRUs. An auto-irrigation rule was assigned to the model for irrigation management. Initializing auto-irrigation enables the automatic continuation of irrigation during the crop period whenever soil moisture levels are depleted below defined limits (Hao et al., 2015; Vories et al., 2017; Chen et al., 2020).

Sorghum was grown during the rainy season (rice: July to November; sorghum: July to 15 November; and vegetables: July to December) and post-rainy season (rice and vegetables: January to April) as per LULC other than command areas. During the post-rainy period, crops were supported with supplemental irrigation and the groundwater aquifer was mapped as a source of irrigation in the drylands. Details such as date of sowing, harvesting, tillage operations, and fertilizer application were provided based on farmers' interviews.

Table 1b show the input values provided for the model and their parameterization. We found that available water content (field capacity-permanent wilting point) and soil depth are the most sensitive soil physical parameters. Soil biophysical data retrieved from NBSS&LUP and ICRISAT was used as direct input. Sensitive parameters such as Curve number, REVAP_MN, GWQMN, and GW_DELAY that control hydrological processes were used to calibrate the model.

Reservoir nodes were created in different micro-watersheds to represent the AWM interventions. Based on the data collected from the Department of Agriculture, Government of Karnataka, equivalent water harvesting capacities were assigned both for *in-situ* and *ex-situ* interventions. The main differences between *in-situ* and *ex-situ* interventions are the surface area, depth of water harvesting, and infiltration rates. Field bunds are common *in-situ* interventions that harvest runoff water to a maximum height of 0.2-0.4 m, generally across the slope. So the water spread area is relatively greater than in farm ponds that are excavated pits of 2-3 m depth to harvest surface runoff (**Figure 4**). The water spread area to harvest 1 m^3 of runoff water through *in-situ* and *ex-situ* interventions are 5-10 m^2 and 0.5-1.0 m^2, respectively. In addition, water infiltration rates of 4 mm/hr in farm ponds and 12 mm/hour in field bunds were measured (based on 10 locations) at Lakumanahalli micro-watershed in Chikkamagaluru district (**Table 2a**).

The model was run on daily time step between 1981 and 2013. It was calibrated by comparing simulated surface runoff with observed flow data at seven gauging sites and inflows measured at three reservoir locations. odel's performance was evaluated using three statistical indicators: Root Mean Square Error (RMSE), Nash-Sutcliffe efficiency (NSE), and Coefficient of Determination (R^2). A low RMSE value indicates better model performance. The NSE values ranged from $-\infty$ to 1, with values less than or very close to 0 indicating 'unacceptable' or 'poor' model performance and values equal to 1 indicating 'perfect performance'. R^2 ranged from 0 to 1, with a value of 0 indicating no correlation between simulated and observed values.

Scenario generation

Four land management scenarios were developed to analyze the impact of AWM interventions on inflows into the KRS reservoir.

- **No intervention scenario**: This scenario represents the control condition. All the reservoir nodes are removed from the model set up (those that captured *in-situ* and *ex-situ* interventions). This scenario does not exclude the ancient tank system and Hemavathy and Harangi reservoirs as these are integral parts of the catchment.
- **Current stage (2020)**: This is the current SWAT set up calibrated with existing rainwater harvesting interventions. Investments in *in-situ* and *ex-situ* interventions were found to be in the ratio of 70:30 and current AWM density (intervention retention capacity/ha) implemented in drylands was 20-25 m^3/ha.
- **Future scenario 2030:** Current structure density in the study basin is 25 m^3/ha. The Government of Karnataka is emphasizing the construction of farm ponds and similar interventions with a minimum storage capacity of 150 m^3 on smallholder farmers field (less than 2.0 ha of farm land) under the farm pond scheme (GoK, 2014). Such interventions are

likely to lead to an additional 50 m^3/ha retention in one decade, thereby increasing rainwater harvesting capacity to 75 m^3/ha which was considered in the simulation.

- **Future scenario 2040:** Further, it is assumed that harvesting intensity in the study area will reach 125 m^3/ha under this scenario.

Model calibration: The model was calibrated at ten sites (seven runoff gauges and three reservoirs using the periods shown in table 3 . Following the successful calibration, the model was run with the abovementioned scenarios.

Table 2b shows model inputs for developing no intervention, 2030, and 2040 scenarios.

3. Results

3.1 Rainfall Characterization

Variability of measured rainfall from 23 stations between 1979 and 2013 is presented on a yearly time scale in **Figures 5a** and **5b**. Out of the 23 stations, average annual rainfall at 10 stations was less than 1000 mm; at 5 stations between 1000 mm and 2000 mm; at 7 stations between 2000 mm and 3000 mm and at 1 station more than 4000 mm. Bhagamandala in Kodagu district (station no 15) received the highest annual average rainfall (5400 mm) and Channarayapatna in Hassan district (station no 8) received the lowest (720 mm). However, there was huge a variation in the temporal scale as shown in **Figure 5b**. Overall, the average annual rainfall of the study area was 1280 mm.

3.2 Decadal Analysis of Inflow, Water Uses and Downstream Release in Major Reservoirs

Krishnaraja Sagar, Hemavathy, and Harangi reservoirs located in the catchment have been functional since 1934, 1979, and 1982, respectively. A storage capacity of about 1242 MCM was created through the Hemavathy and Harangi reservoirs during 1979-1982. The measured actual inflows and major outflows (canal and river releases) of the three reservoirs were analyzed for four decades: 1971-1980, 1981-1990, 1991-2000, and 2001-2010. The average decadal inflows into the KRS reservoir fell by a third from 5500 MCM/year to 3500 MCM/year during 1981-1990 compared to 1971-1980 due to the construction of two upstream reservoirs (Harangi and Hemavathy). Inflows into the KRS reservoir during 1991-2000 and 2001-2010 were 4200 MCM/year and 4000 MCM/year, respectively. Inflows into the Harangi reservoir over the last three decades were 900-1000 MCM/year, and in the Hemavathy reservoir 2200-2500 MCM/year (**Figure 6a**). Not much inter-decadal variation in inflows was observed as they are located on the most upstream side and receive runoff from the Western Ghats region that has least anthropogenic interference.

The annual average canal releases of KRS, Hemavathy, and Harangi reservoirs for four decades was 47%, 55% and 61% of total inflow in the KRS, Harangi and Hemavaty are presented in **Figure 6b**. The canal command area of Harangi reservoir is located in the Upper Cauvery catchment whereas 85% of the Hemavathy canal command area is located in the study catchment and the rest lies outside the basin. In contrast, the canal command area of the KRS reservoir lies completely outside the Upper Cauvery catchment. An increasing trend towards the release of canal water from all the three reservoirs has been observed. Total surface water utilization (canal water release) for agriculture was 1450 MCM in 1971-1980; 2500 MCM in 1981-1990; 3500 MCM in 1991-2000, and 3800 MCM in 2001-2010. Of the total inflow received into KRS reservoir, water released for the canal command area increased from 27% (of total inflow) in 1971-1980 to 47% in 2001-2010. Similarly, water utilization in agriculture (released to the canal command area) in the Harangi reservoir increased from 30% in 1981-1990 to 55% in 2001-2010, respectively and in the Hemavathy reservoir it increased from 26% in 1981-1990 to 61% in 2001-2010.

Average annual reservoir releases to downstream locations for all the four decades are presented in **Figure 6c**. With reduced inflows and increased canal water release, the downstream release from KRS reservoir declined by over 55%, from 3600 MCM in 1971-1980 to 1950 MCM in 2001-2010. Similarly in both the upstream reservoirs (Harangi and Hemavathy), water release downstream declined from 68-69% (of total inflow) in 1981-1990 to 36-43% in 2001-2010.

3.3 Model Performance

Figure 7 presents the model's performance by comparing simulated flow with observed flow data at four out of seven gauging stations of Kudige, Sakaleshpur, Chuchunkatte, and Akkihebbal and inflows into Hemavathy and KRS reservoirs on a monthly time scale between 1981 and 2013. The flow data for Sakaleshpur, Chuchunkatte, and Akkihebbal was only available for 2002-2014, 2008-2014, and 2002-2014 respectively. In general, the simulated flow at monitoring locations agreed with the observed values as well as matched the peaks. However, at Kudige gauging station (**Figure 1**, **Figure 7a**) and inflow at Hemavathy (**Figure 1**, **Figure 7f**), simulated flow was underestimated. Runoff at upstream locations is generated from the Western Ghats. It is possible that the data from the rain gauges did not capture the entire rainfall variability of the Western Ghats region. There was a steep gradient of rainfall from 2000 mm to 5000 mm within 100 km distance which was not captured fully due to limited rain gauge monitoring. The model's performance in simulating inflows at monthly scale into the KRS reservoir shows that it captured the rising limb, peaks, and recession limb of inflows quite well; however, the peaks were over-predicted for a few events. Model performance was further evaluated by estimating RMSE (174 MCM); NSE (0.85); and R^2 (0.88), indicating that the model was in consonance with observed data. The model performance statistics from all the gauging stations and reservoirs are summarised in **Table 3**. Out of 10 sites, R^2 was found to be more than 0.75 in 8 sites; and NSE was equal or more than 0.5 at 8 sites. Overall, the model was able to capture the catchment hydrology considerably well.

3.4 Water Balance Components

Rainfall is split into major water balance components: evapotranspiration, runoff, and change in water storage. The average annual rainfall of the catchment was 1280 mm and varied from 880 mm to 1880 mm between 1981 and 2013. Of this, 54% (700 mm) of total rainfall was split into ET (590 mm to 800 mm), 29% (370 mm) as catchment outflow (170 mm to 630 mm) and the remainder 17% (215 mm) as change in water storage (**Figure 8a**). In the current case, the inflow to the KSR reservoir is considered as outflow from the catchment as KRS is located at the outlet of the catchment.

Figure 8b shows the water balance components for a wet (2007), normal (2008), and dry (2012) year. The annual rainfall received during wet, normal, and dry years was 1686 mm, 1403 mm, and 1115 mm, respectively. Most of the rainfall went towards ET estimated to be 600-750 mm, which is 40-60% of the total rainfall received. The surface runoff generated was 715 mm (42% of rainfall) in a wet year; 450 mm (34%) in a normal year, and 325 mm (29%) in a dry year. The change in groundwater recharge was in the order of 130-230 MCM, of which 11-14% was generated by the received rainfall. A comparison of dry, normal, and wet years revealed that the most sensitive water balance component is surface runoff, followed by groundwater recharge with changing rainfall conditions from year to year.

Figure 9 shows the spatial variability in major water balance components (rainfall, ET, runoff and change in groundwater storage) for the selected wet (2007), normal (2008), and dry (2012) years across the Upper Cauvery. The Western Ghats received the highest rainfall (> 3000 mm), with rainfall decreases from west to east. Spatial data showed that 40% of the catchment received less than 1000 mm rainfall, 35% between 1000-2000 mm, and 25% above 2000 mm during the normal year. The distribution changed to 40% (<1000 mm), 40% (1000-2000 mm), and 20% (>2000 mm) in a dry year and 45% (<1000 mm), 25% (1000-2000 mm), and 30% (>2000 mm) in a wet year.

ET varied with rainfall distribution. ET in the Western Ghats was higher than in agricultural lands. More number of rainy days and forest cover generated ET as high as 700-900 mm in different rainfall years; however, the extent declined in a dry year compared to a wet year. ET for about 10% of the catchment was less than 500 mm, between 500-900 mm for 80% of the area, and >900 mm for 10% of the area in a dry year. In normal and wet years, ET for about 88-90% area was simulated to range from 500-900 mm and >900 mm for 10-12% of the area of the Upper Cauvery.

Change in groundwater storage was mapped on a spatial scale for selected dry, normal, and wet years. Results from the model showed negative groundwater balance in more than 50% of the area in a dry year, as water withdrawal in these watersheds had been higher than the recharge. Negative groundwater balance was found in 20% of the area in normal years and 3% in wet years.

Runoff, an important source of freshwater, was found to be the most sensitive water balance component with variable rainfall. In a dry year, more than 50% of the catchment produced less than 100 mm of runoff, about 25% between 100 mm and 500 mm, and 25% more than 500 mm. This proportion changed to 25% (< 100 mm), 40% (100-500 mm), and 35% (> 500 mm) in normal and wet years. **Figure 10** shows the spatial variability in simulated runoff coefficients within the catchment. Runoff coefficient in 50% of the area was <0.15, and in 40% of the area 0.15-0.45 during a dry year. The runoff coefficient in 30% of the area was <0.15 and in 60% of the area 0.15-0.45. The remaining 10% of the area had more than 0.45 runoff coefficient during a normal year. Runoff coefficient for 25% of the area was less than 0.15, for 45% of the area 0.15-0.45, and for 30% of the area more than 0.45 in a wet year.

3.5 Impact of AWM Interventions

Figure 11 summarizes the simulated KRS reservoir inflow under the four land management scenarios. Under the no-intervention scenario, the annual inflows during wet, normal, and dry years were 7800 MCM, 4300 MCM, and 3100 MCM, respectively. Under the 2020 scenario, inflows fell by 2-6% due to various water harvesting interventions. Under the 2030 and 2040 scenario, simulation suggested that intensifying AWM interventions would reduce KRS inflow by 6-15%. Simulation suggested greater flow reduction in normal and dry years (by 10-15%) compared to wet years (4-6%).

Figure 12a compares the efficacy of AWM interventions in terms of total water harvested at upstream watersheds during wet, normal, and dry years and under three different land management scenarios (2020, 2030, and 2040). Under the current scenario (2020), about 140-220 MCM/year freshwater was harvested which is equivalent to 13-20 mm at catchment scale. With increased intensity of AWM interventions in 2030 and 2040, simulated results showed 300-440 MCM/year (28-41 mm) and 460-610 MCM/year (43-57 mm) of water harvested in upstream watersheds, respectively. Simulation suggested that AWM interventions filled 8-12 times of the total storage capacity created under the current scenario. The number of fillings fell with increased density of interventions as the number of fillings in future scenarios (i.e., 2030 and 2040) was simulated to be 6-11 and 5-11 times, respectively (**Figure 12b**).

Figure 13 summarizes the water harvested in upstream watersheds under dry, normal, and wet years and also under 2020, 2030, and 2040 AWM scenarios. Currently (in 2020), more than 80-90% of watersheds in the uplands are harvesting less than 25 mm runoff, including during wet years and less than 10% of them are harvesting runoff between 25 mm and 100 mm. With increased intensity of AWM interventions, simulation demonstrated that about 40-50% of the watersheds would harvest runoff less than or equal to 25 mm, 20-30% of them would harvest between 25-75 mm, and 10-20% of them would harvest more than 75 mm in 2030.

3.6 Uncertainties in the Model

Though catchment hydrology is complex to model due to heterogeneity in the topography, soil types, rainfall, land use, and management practices, an effort was made to do so by using secondary data and field measurements to reduce the uncertainty in results. The density of rain gauge stations is low, approximately one rain gauge for every 460 km^2. This low density, especially in the Western Ghats region, may not be able to capture the rainfall's spatial variability adequately. Rainfall in the Western Ghats varies from 1000 mm to 5000 mm within a 50-100 km radius. We also realized that inflow modeled at upstream reservoirs was far lower than the observed data at Harangi. Within the model's set up, we assumed a limited cropping system whereas in reality there is a multiple cropping system and associated land management. Number of AWM interventions were simplified by creating reservoir node either of *in-situ* or *ex-situ* type for each watershed. This may also generate uncertainty as the responses of different AWM interventions depend on their catchment (location), type, and capacity.

4. Discussion

The study showed that a major portion of freshwater in the catchment came from the Western Ghats. The runoff coefficient of the Western Ghats was as high as 60-70%. Thus, rainfall of more than 3000 mm generated over 2000 mm of runoff. Results also showed that freshwater generated from drylands was comparatively low as most of the rainfall was in the form of ET. More than 50% of the catchment, especially in the dry and normal years, generated 100 mm runoff or less with a runoff coefficient of 15-20%.

Under the current scenario (2020), AWM interventions implemented in the drylands as a drought mitigation strategy harvested 25-30 mm of water while the rest was available for downstream users. However, catchment scale water balance showed that flow reduction at the KRS reservoir due to AWM interventions was less than 6% of the total inflow generated. Runoff generated from the Western Ghats is a major contributor to the KRS reservoir (surplus from Harangi and Hemavathy reservoirs). However, the increased density of AWM interventions could be a matter of concern for command area authorities as the inflow at KRS reservoir may decline by 6-15% by 2040.

The results showed that water allocation in canal command areas from all three reservoirs increased at the rate of 60 MCM/year. Water release from the KRS reservoir declined from 3600 MCM in 1971-80 to 1950 MCM in 2001-2010, indicating a 55% reduction in downstream of the

Upper Cauvery basin. Out of this, only 2-6% is due to AWM interventions and the rest due to water allocation in canal command areas. A water balance analysis showed that runoff generated from dryland areas during deficit years was relatively poor. Even under the no-intervention scenario, the runoff generated was far lower than the required demand from the canal command area. AWM interventions have however created a little more deficit against total freshwater demand at KRS but at the same time it might be helpful for alleviating drought at uplands. The amount of water harvested by AWM interventions in a dry year was comparable to that in a wet year. Since AWM interventions harvest a little surface runoff from frequent events, there was not much difference in their efficacy between different rainfall years. These interventions were found to harvest runoff 8-12 times/year of its storage capacity.

AWM interventions in the drylands are meant to alleviate crop water stress by enhancing soil moisture availability, providing life-saving supplemental irrigation through locally harvested runoff; enhancing groundwater recharge and crop intensification. Our analysis showed that water harvested from AWM interventions was equivalent to one or two supplemental irrigations (~25-30 mm) which could be in the form of enhanced soil moisture or blue water availability depending on the local situation and management. However, the resulting gains in crop productivity and crop intensification due to such interventions was beyond the scope of this study. In this basin, there is an apparent trade-off between local benefits and downstream water availability. Upstream development brings regional equity, as the uplands mostly suffer from water scarcity, poor productivity, and land degradation whereas a little reduction in the flow at the KRS reservoir could be compensated by promoting improved water management practices.

Previous studies in the semi-arid tropical central and southern India have reported altered watershed hydrology due to AWM interventions, with a reduction in runoff by 30-50% compared to no-intervention conditions. However, at the same time, these watersheds transformed the landscape. Singh et al. 2014 reported that check dams harvested 8.2 to 9.5 times the total storage capacity developed in one of the degraded landscapes of central India, with rainfall ranging from 750-1050 mm. AWM interventions enhanced groundwater recharge (by 30-50%), crop productivity (by 50-200%), crop intensification (by 30-50%), and controlled soil erosion and land degradation (by 70-90%) compared to the non-intervention stage (Garg et al. 2011, 2012a; Singh et al. 2014). Garg et al. (2011) modeled the impact of various AWM interventions on hydrological processes in the Osman Sagar catchment (736 km^2) of Musi basin in the semi-arid tropics of southern India. The study reported that AWM interventions in the meso-scale watershed reduced inflow into the Osman Sagar reservoir by 40% but improved groundwater recharge and crop intensification by 30% and enhanced crop yields and farm incomes in upstream areas. This also reduced flow intensity and sedimentation in downstream water bodies. In the trade-off between upstream and downstream, there were more upstream benefits and relatively minor negative impacts on downstream flow.

Rainfed areas hold great untapped potential in terms of addressing food security and sustainable development goals that can be unlocked using resource conservation technologies. At the same time, irrigated agriculture has to keep productivity levels high despite reduced resource availability which, historically, used to be met from upstream sources. With developments upstream, downstream irrigated ecosystems need to enhance water use efficiency by adopting conservation measures and demand management strategies. This study's outcomes will help stakeholders design and prioritize development plans for better water management in the basin.

4. Conclusions

An analysis was done of the water balance components of the Upper catchment of Cauvery basin. A Soil and Water Assessment Tool (SWAT) was applied to investigate the basin's hydrology. The model was calibrated at ten sites (seven runoff gauges and three reservoirs). The historical changes in inflow pattern, canal releases, and downstream flow in all the three main reservoirs were analyzed using observation datasets. The model was further parameterized to quantify AWM interventions in the upstream areas. In addition, four land management scenarios representing no-intervention, current status (2020), 2030, and 2040 were generated. Following were the key findings:

- There is increasing water allocation for agriculture in the canal command areas from the three main reservoirs. Surface water utilization for agriculture which was 1450 MCM/year in 1971-1980 increased to 3800 MCM/year in 2001-2010. The average increase in water allocation for agriculture is 60 MCM per year. The increased allocation led to a 55% decline in water released from the KRS reservoir to the downstream river, from 3600 MCM/year in 1971-1980 to 1950 MCM/year in 2001-2010.
- The main source of fresh water in the catchment comes from the Western Ghats region, which receives more than 3000 mm of rainfall. The runoff coefficient of this region was more than 60%. The average annual rainfall in the basin is 1280 mm, 29% of this generated outflow from the catchment; 54% was in the form of ET, and the remaining 17% contributed to change in soil water storage.

- More than 50% of the drylands portion of the catchment receives rainfall ranging from 700 mm to 1200 mm. Most of it is in the form of ET and less than 15-20% generates surface runoff. The change in groundwater storage in the drylands was mostly negative as groundwater withdrawal exceeded recharge most of the time.
- The model suggested that various *in-situ* and *ex-situ* interventions harvested surface runoff of about 140-160 MCM/year under the current implementation status (which is equivalent to 13-15 mm). This has reduced inflow into the KRS reservoir by less than 6%. Increasing the density of AWM interventions in the future (i.e., 2030 and 2040) is expected to harvest 300-440 MCM (28-41 mm) and 460-610 MCM (43-57 mm) of surface runoff in the uplands, respectively. This may reduce inflow into the KRS reservoir by 15% at most.

These findings are useful for stakeholders such as development agencies, water authorities, water companies, reservoir managers, decision makers, local authorities/councils and farmer associations to understand the upstream and downstream trade-offs that will enable them to take informed decisions.

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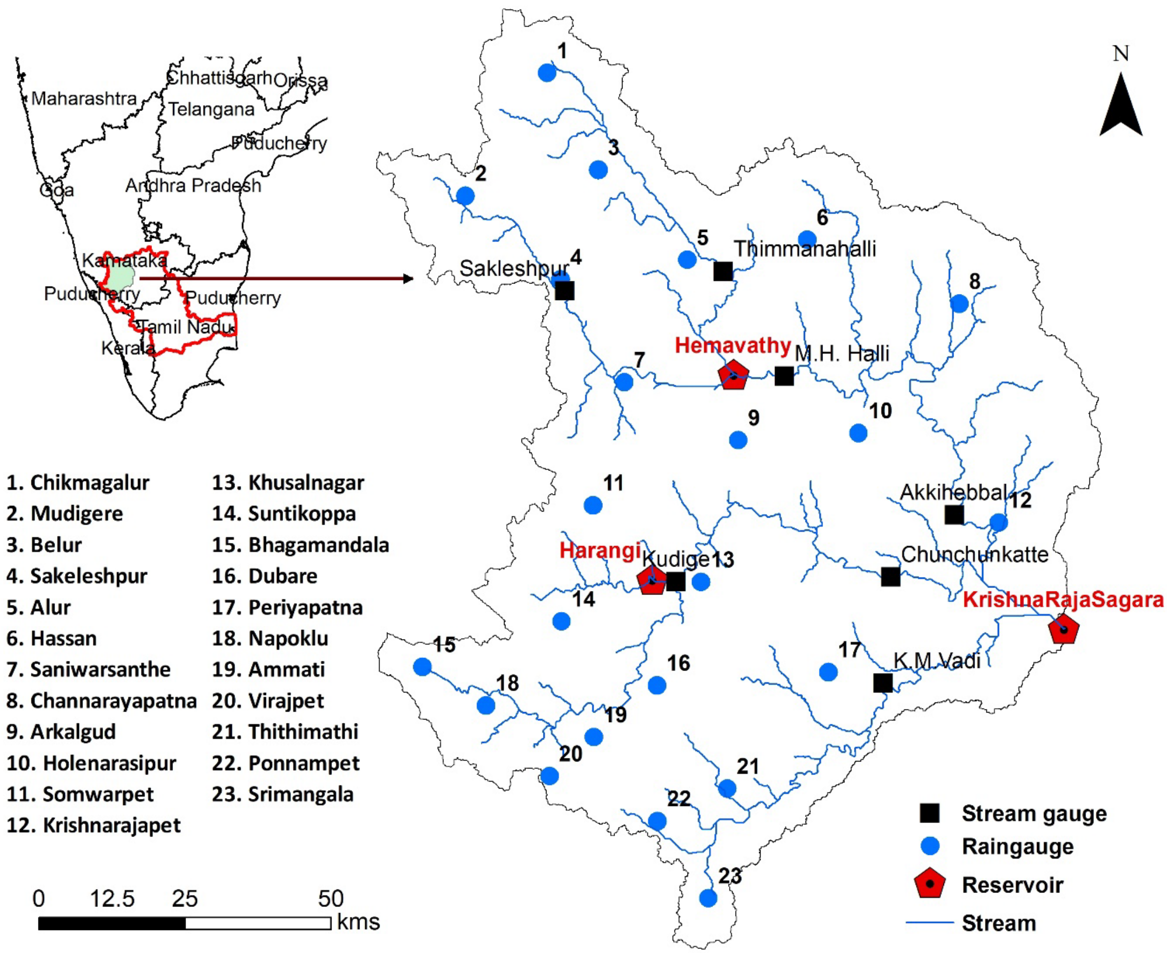

Figure 1: Upper Cauvery sub-basin, major streams, location of rain gauges, stream gauges and major reservoirs in the catchment.

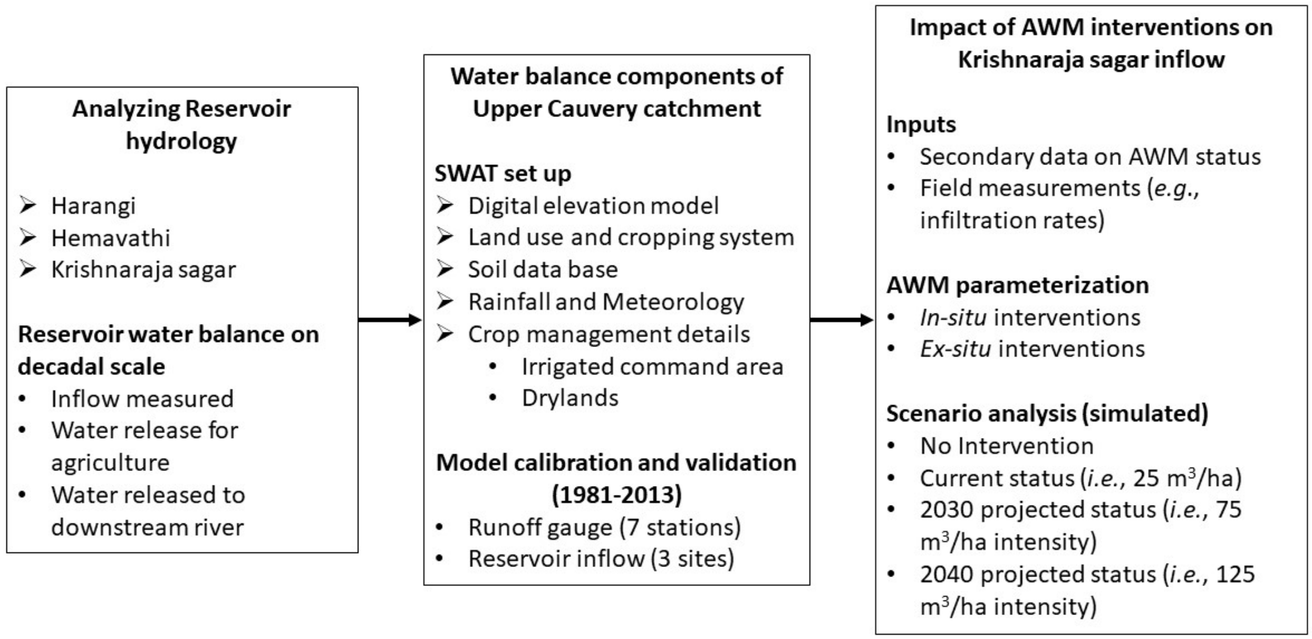

Figure 2: Schema of the methodology adopted.

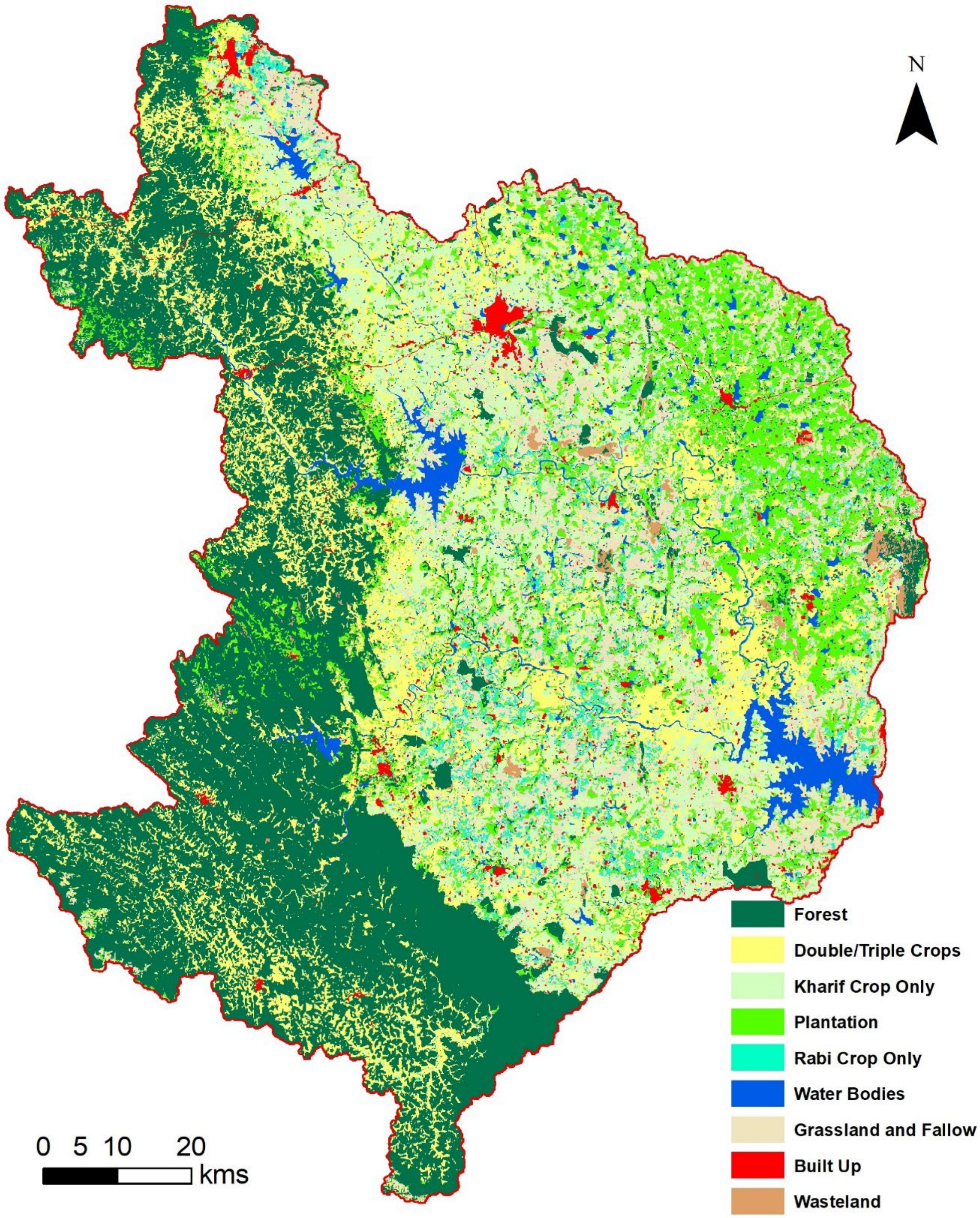

Figure 3: Land Use Land Cover (LULC) map of the Upper Cauvery catchment (2016-2017).

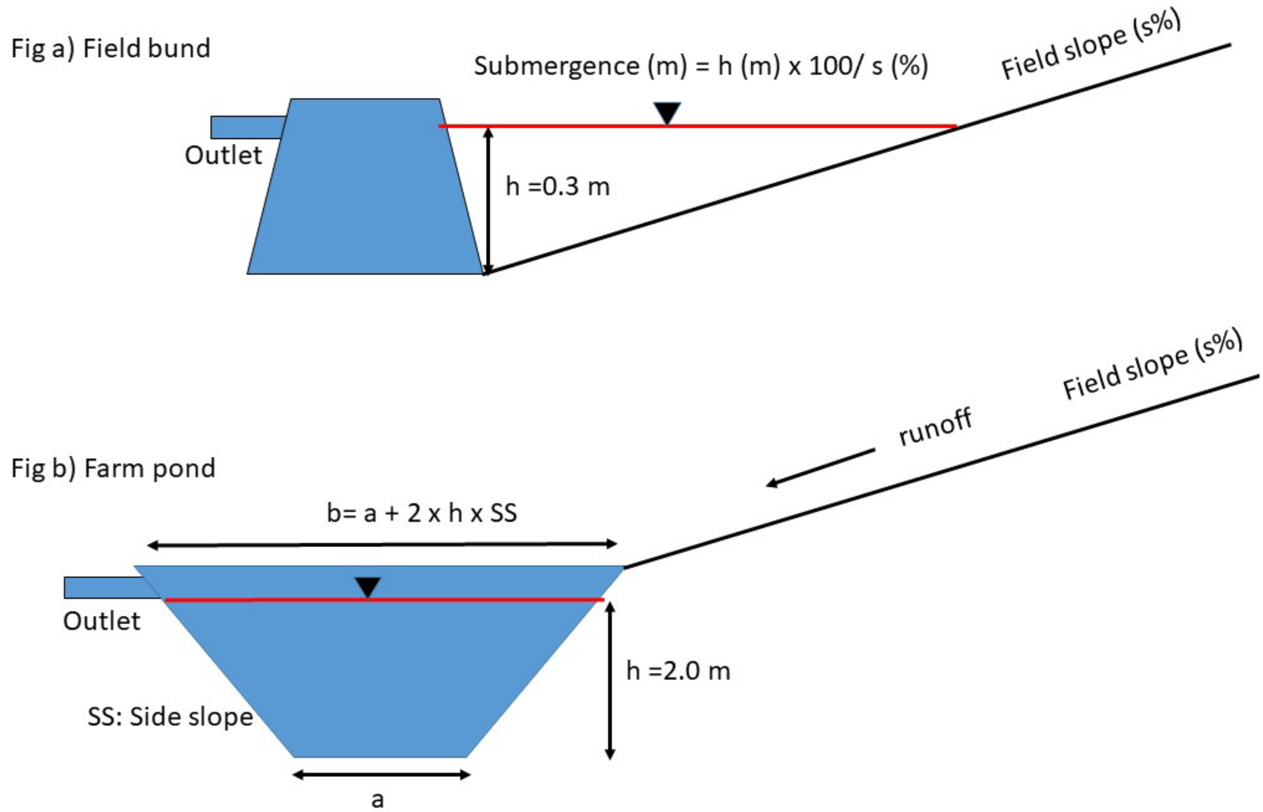

Figure 4: Conceptual diagram of (a) field bund (*in-situ*) and (b) farm pond (*ex-situ*). Figures are not drawn to scale.

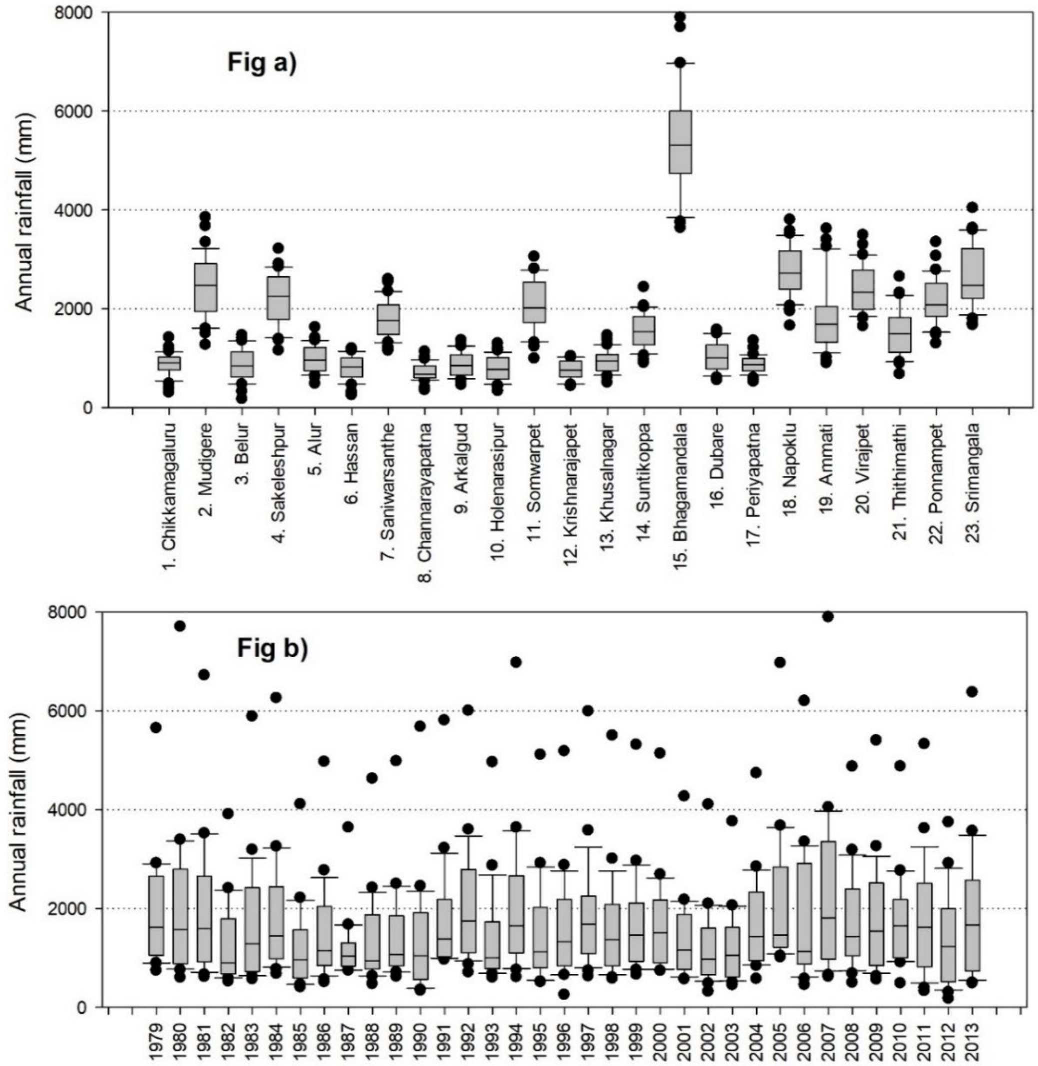

Figure 5. (a) Spatial variation and (b) temporal variation in annual rainfall at 23 rain gauge stations of the Upper Cauvery sub-basin during 35 years (1979-2013).

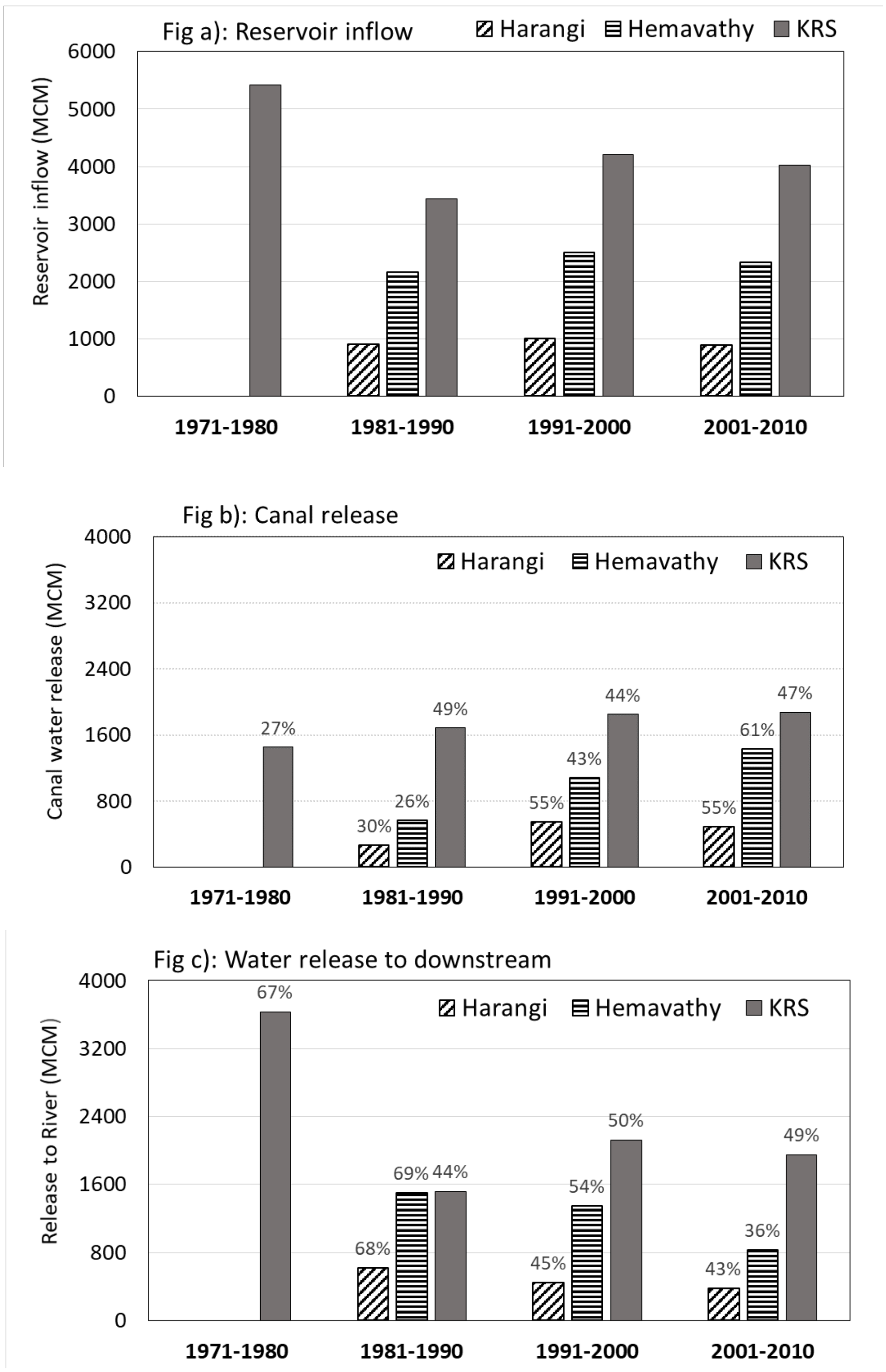

Figure 6: Decade-wise analysis of the measured (a) water inflows into reservoirs, (b) release from reservoirs into canals and (c) release from reservoirs into river, of the Harangi, Hemavathy, and KRS reservoirs. Numbers above bars indicate the percentage of total inflow.

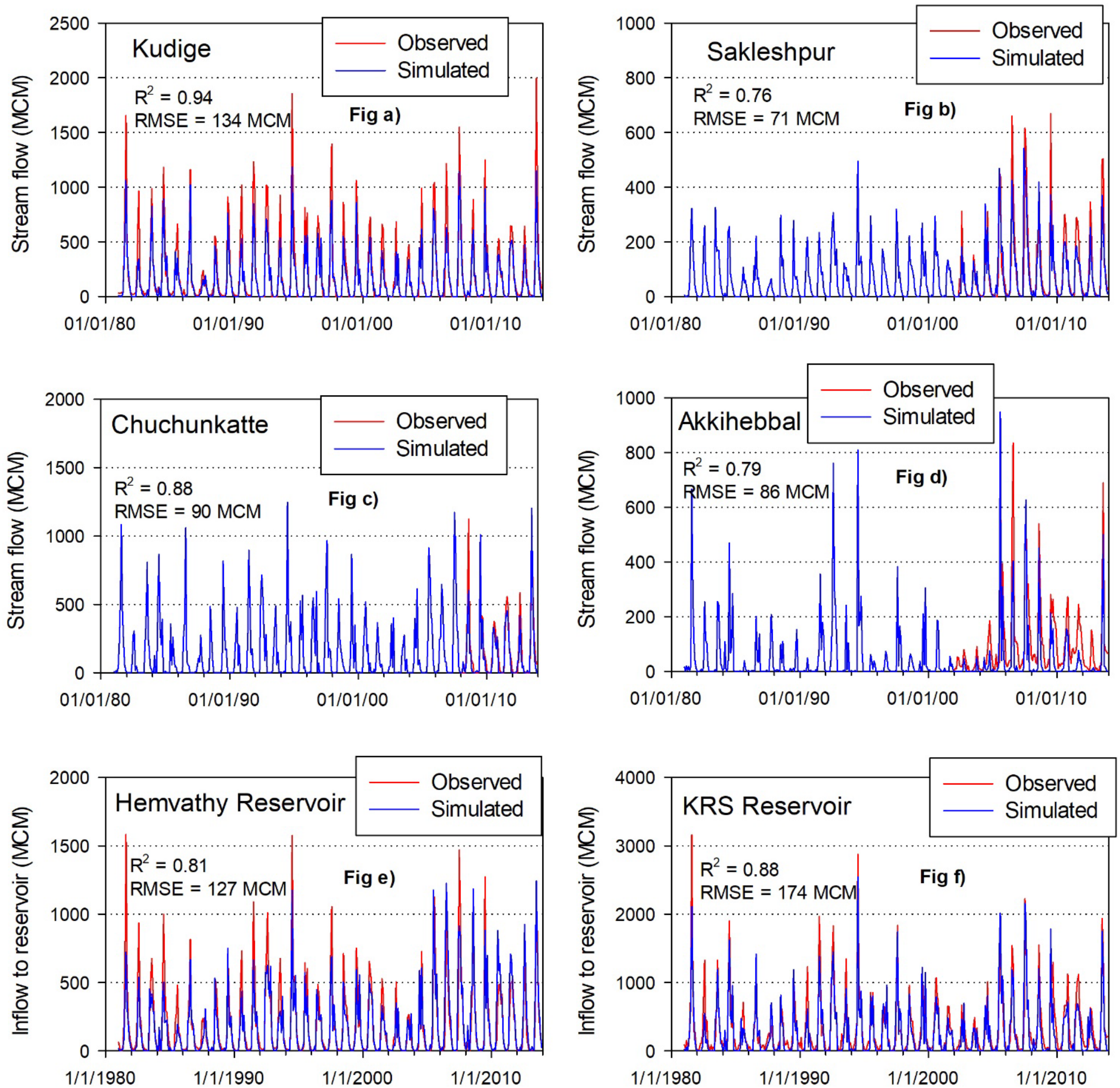

Figure 7: Monthly time series of observed (red) and simulated (blue) streamflow/ reservoir inflows for (a) Kudige, (b) Sakleshpur, (c) Chuchunkatte, (d) Akkihebbal, (e) Hemavathy, and (f) KRS reservoir.

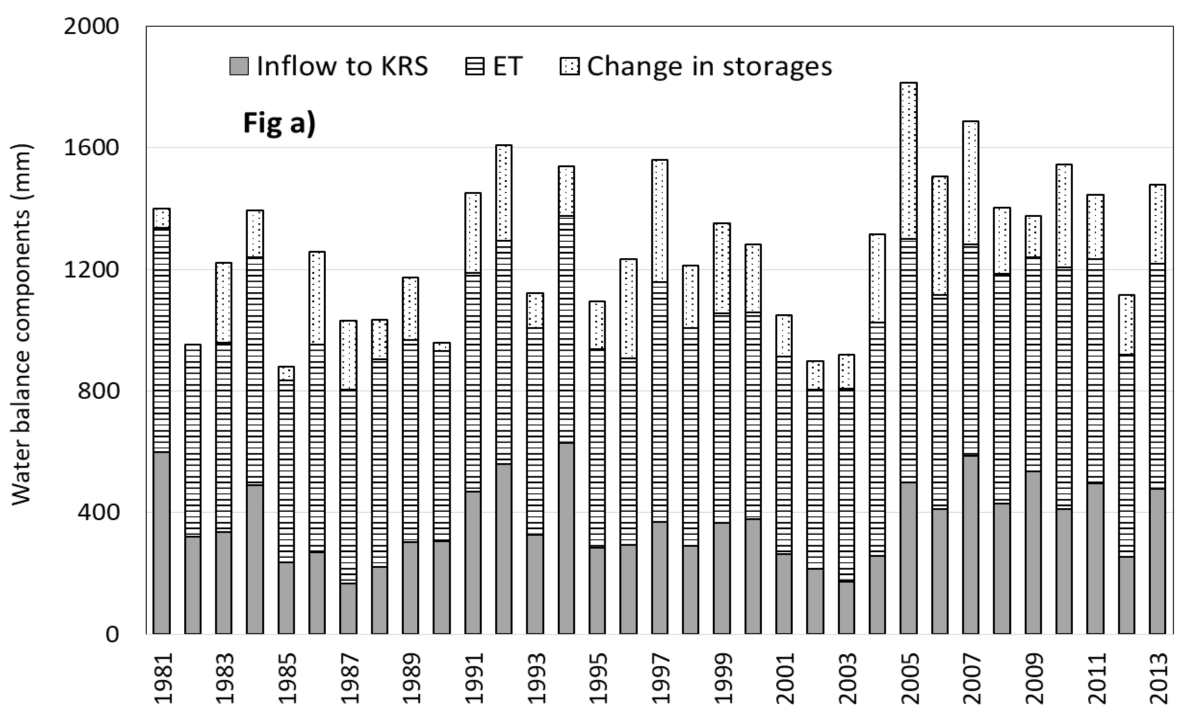

Figure 8a: Major water balance component (rainfall = outflow+ ET + Change in storages) of the Upper Cauvery catchment between 1981 and 2013.The sum of the components is equal to the total rainfall in the respective years.

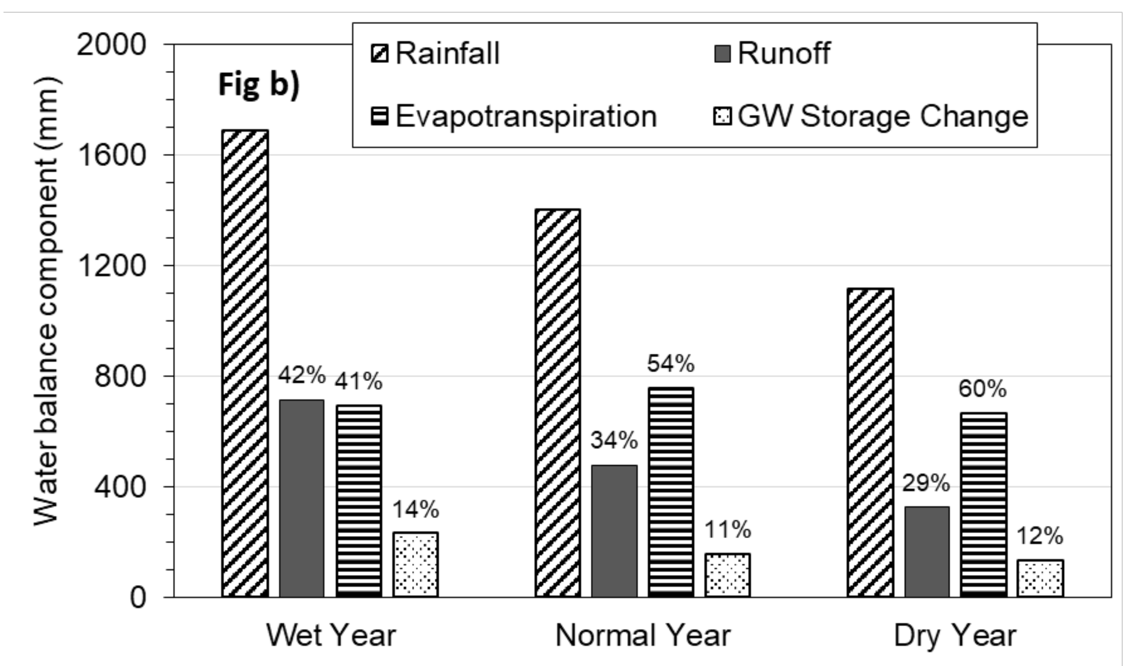

Figure 8b: Water balance in the Upper Cauvery catchment during a wet (2007), normal (2008) and dry (2012) year. Numbers above bars indicate the percentage of rainfall in a particular year.

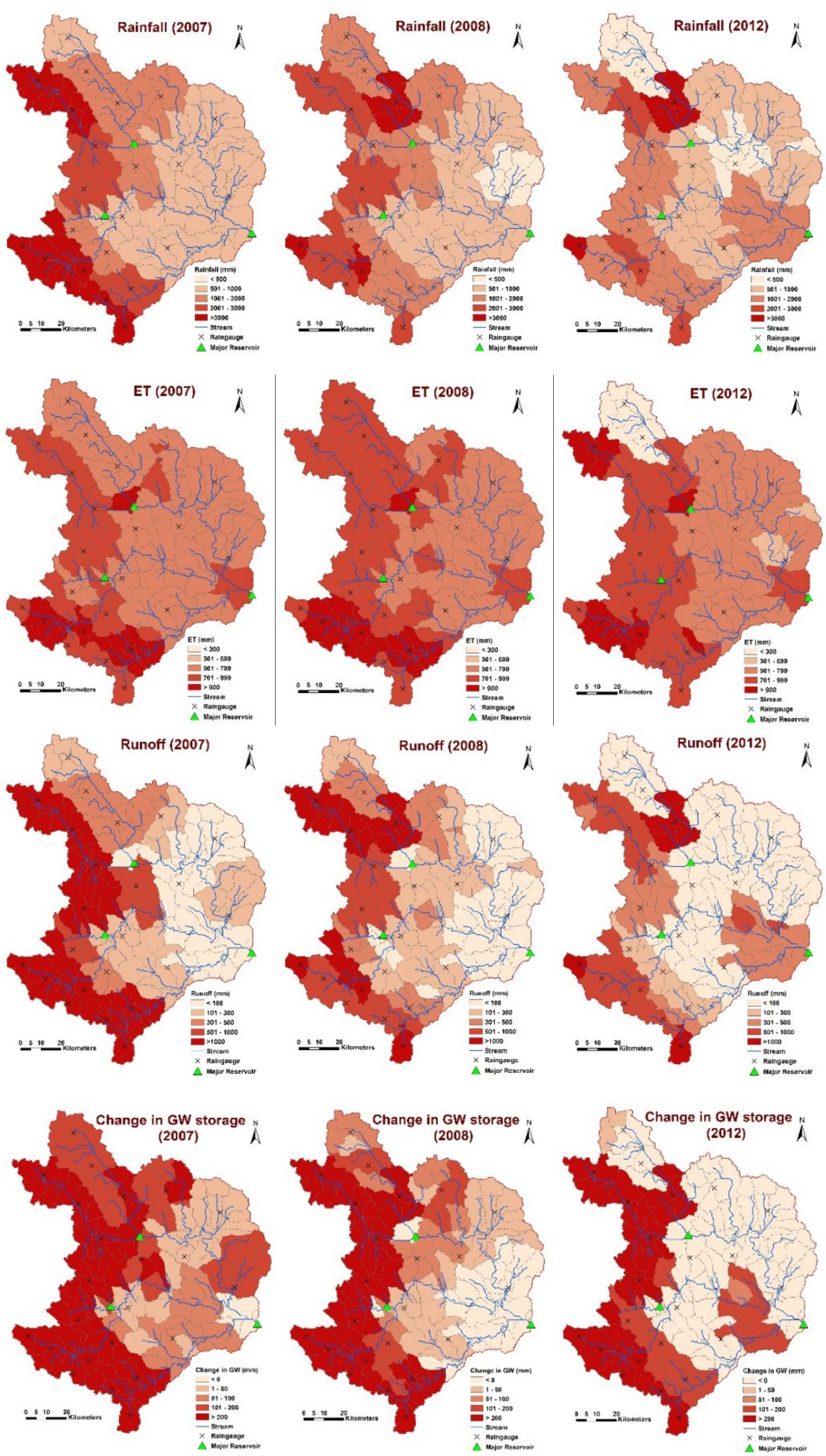

Figure 9: Spatial variability in different water balance components (rainfall, ET, runoff, and change in GW storage) for selected wet (2007), normal (2008) and dry (2012) years.

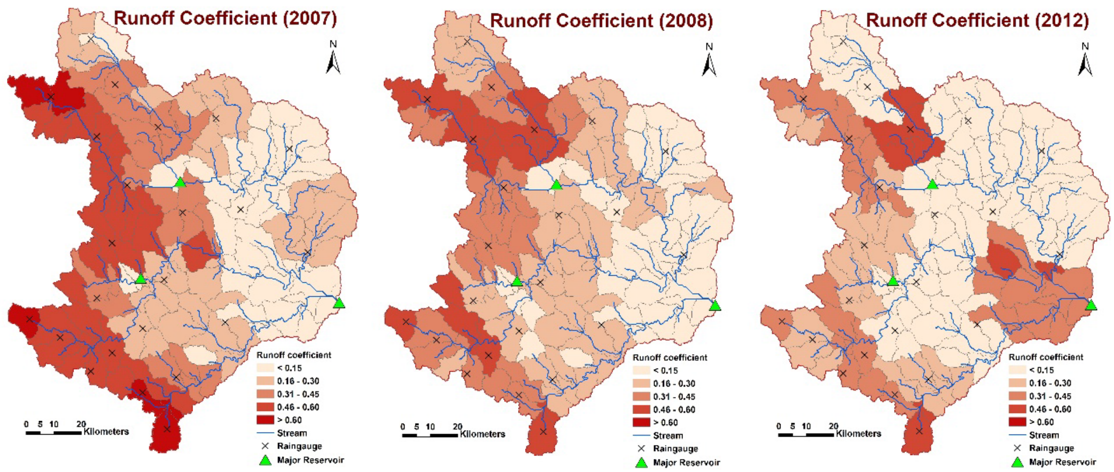

Figure 10: Spatial variability in simulated runoff coefficients in different micro-watersheds of the Upper Cauvery catchment for selected wet (2007), normal (2008), and dry (2012) years.

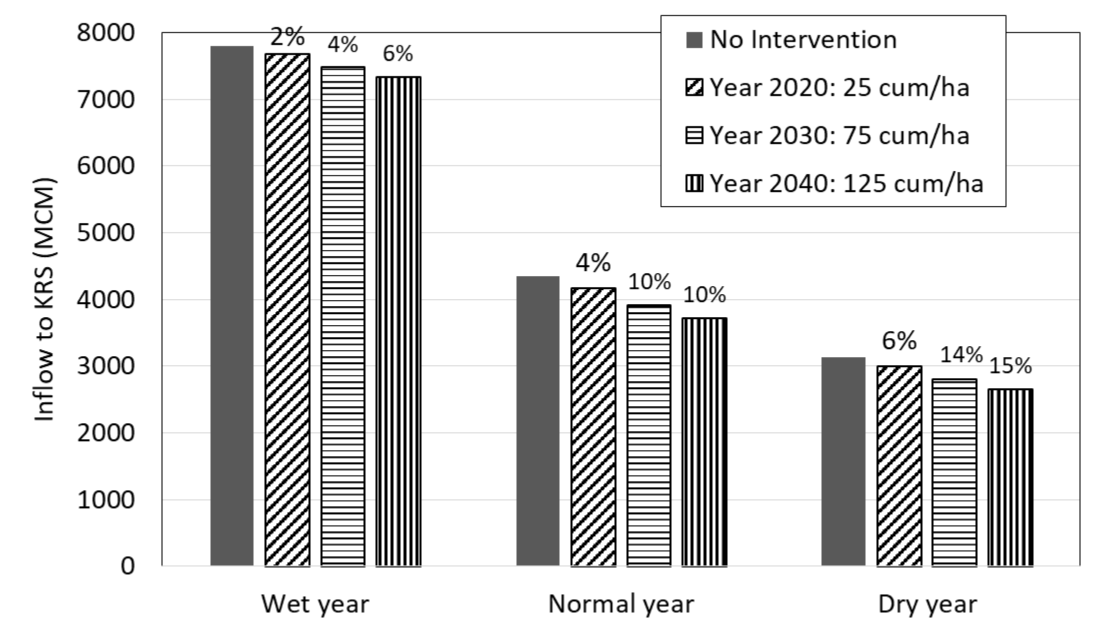

Figure 11. Impact of interventions on inflows into the KRS reservoir. Numbers above bars indicate percentage decrease with respect to the no intervention scenario.

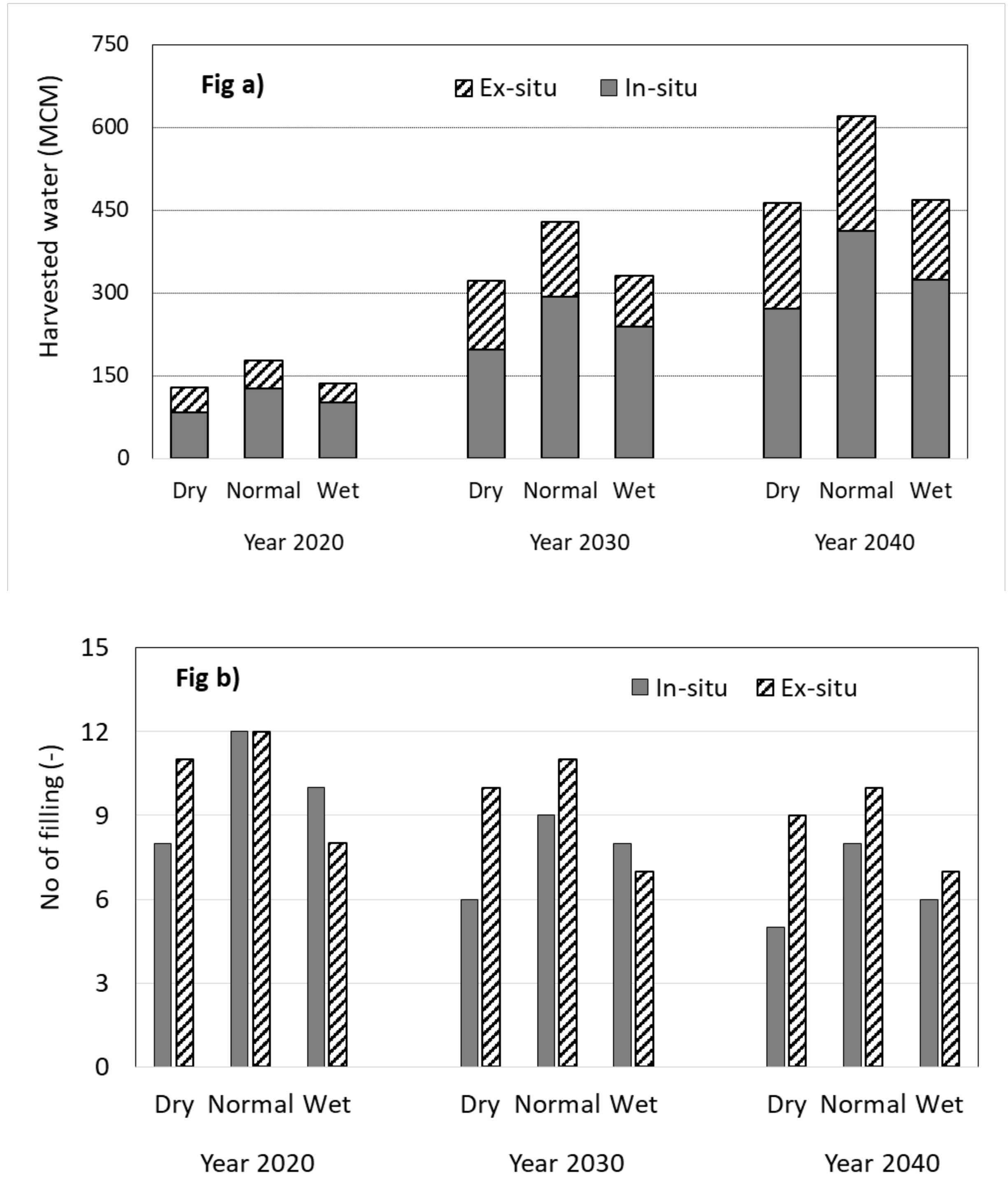

Figure 12: (a) Water harvested by *in-situ* and *ex-situ* interventions and (b) number of fillings during wet, normal and dry years under 2020, 2030 and 2040 land management scenarios.

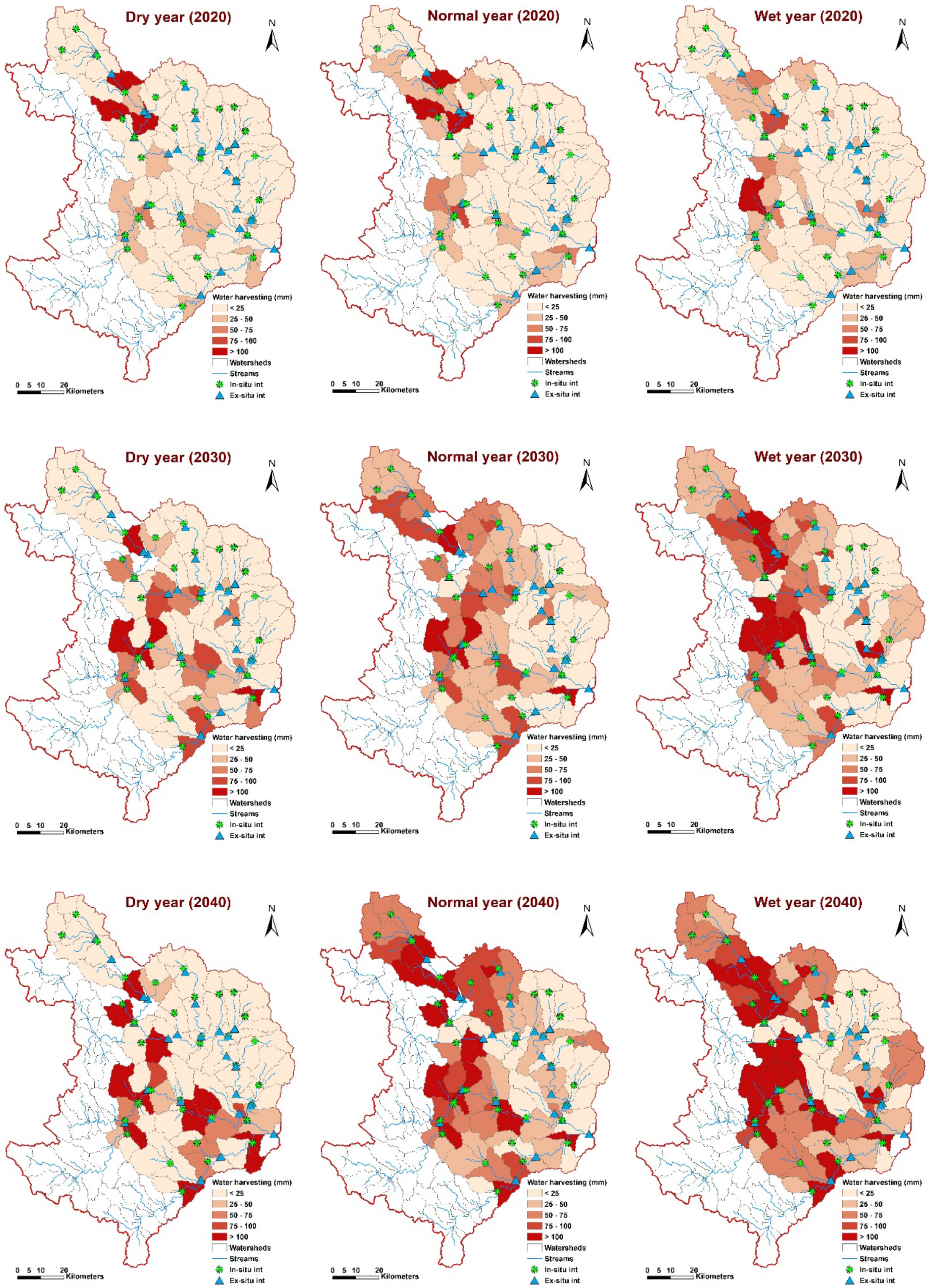

Figure 13: Spatial variability of total harvested water due to various AWM interventions for 2020, 2030 and 2040 scenarios under the wet (2007), normal (2008) and dry (2012) years, respectively.

List of Tables

Table 1a: Land use/ land cover (LULC) statistics and crop season.

Major class	LULC	Area (km^2)	Area (%)	Modeled as	Period
Built up area	Built up	210	2%	Settlement	-
Agriculture	Rainy season crops	1300	12%	Sorghum, rice	15 Jun-15 Oct
Agriculture	Post-rainy season crops	441	4%	Sorghum	15 Nov- 30 Mar
Agriculture	Double/triple crops	2443	23%	Sorghum, rice	15 Jun-15 Oct, 1 Jan- 31 Apr
Wasteland	Current fallow	1151	11%	Rangeland	Perennial
Horticulture	Plantation crops	1286	12%	Coconut	Perennial
Forest	Forest	3391	31%	Forest	Perennial
Wasteland	Wasteland	119	1%	Rangeland	Perennial
Water	Water	427	4%	Water	-

Table 1b: Model inputs and calibration parameters.

Variable (unit)	Parameter name	Parameter value	Source
Sand content (%)	SAND	20 (10-30)	NBSS&LUP*
Silt content (%)	SILT	28 (20-35)	NBSS&LUP
Clay content (%)	CLAY	53 (35-70)	NBSS&LUP
Bulk density (g cm^{-3})	SOL_BD	1.29 (1.24-1.33)	NBSS&LUP
Available water content (mm H_2O/mm soil)	SOL_AWC	0.14	NBSS&LUP
Soil depth (mm)	SOL_Z	750 (300-1200)	NBSS&LUP
Saturated hydraulic conductivity (mm/hr)	SOL_K	6.6 (6.03-7.12)	NBSS&LUP
Curve number	CN2	82 (72-92)	Calibrated
Groundwater revapcoeff (-)	GW_REVAP**	0.02	Default
Threshold depth of water for revap in shallow aquifer (mm H_20)	REVAP_MN***	750	Calibrated
Threshold depth of water in the shallow aquifer required to return flow (mm H_20)	GWQMN	1000	Calibrated
Groundwater delay time (days)	GW_DELAY	31	Calibrated
Surface runoff lag coefficient	SURLAG	4	Default
Base flow alpha factor	ALPHA_BF	0.375	Calibrated

*NBSS&LUP: National Bureau of soil Survey and land use planning

** Groundwater revapcoeff: Water may move from the shallow aquifer into the overlying unsaturated zone. As GW_REVAP approaches 0, movement of water from the shallow aquifer to the root zone is restricted. As GW_REVAP approaches 1, the rate of transfer from the shallow aquifer to the root zone approaches the rate of potential evapotranspiration.

*** REVAP_MN: Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O).

Table 2a: Parameterization of *in-situ* and *ex-situ* AWM interventions

Parameters	Parameter	*Ex-situ* interventions	*In-situ* interventions
Name of structure		Farm pond	Field bunds
Maximum water harvesting depth (m)	Depth of water (h)	2.0	0.3
Cross section (m^2)- Refer Figure 4	AREA	14	2.25*
Hydraulic conductivity of the reservoir bottom (mm h^{-1})	RES_K	4	12
Water harvesting capacity (m^3)	VOL	100 m^3/farm pond	90 m^3/Land holding**

* Land slope= 2%.

** Field bunds of 0.4 ha field (1 acre land holding) = 40 m.

Table 2b: Model inputs to capture Agriculture Water Management scenarios

Scenario/Time period	Unit	No intervention stage	Current stage	Future stage 1	Future stage 2
		Before 2000	2020	In 2030	In 2040
Total treated area with *in-situ* intervention	km^2	0	3350	3350	3350
Total treated area with *ex-situ* intervention	km^2	0	2782	2782	2782
Model parameter (RES_VOL) under *in-situ* intervention	MCM	0	10	31	52
Model parameter (RES_VOL) under *ex-situ* intervention*	MCM	0	4	13	22

* In addition to the major reservoirs (KRS, Harangi, and Hemavathy).

Table 3: Model performance statistics to simulate monthly inflows during calibration

Reservoir /gauge station	Data availability / calibration periods	Observed average monthly flow (MCM)	Simulated average monthly flow (MCM)	RMSE (MCM)	PBIAS	R^2	NSE	RSR
Hemavathy	1981-2013	193	174	127	48.14	0.81	0.79	0.46
Harangi	1981-2013	79	40	88	81.20	0.77	0.49	0.72
KRS	1981-2013	328	265	174	47.46	0.88	0.85	0.39
Akkihebbal	2002-2013	25.97	43.32	86.81	54.63	0.79	0.72	0.59
Chuchunkatte	2008-2013	169	141	90	18.08	0.88	0.86	0.37
KM Vadi	1981-2013	27	71	73	-210.04	0.80	-0.90	1.38
Kudige	1981-2013	207	157	134	33.64	0.94	0.83	0.41
MH Halli	1981-2013	93	74	81	66.95	0.67	0.60	0.64
Sakaleshpur	2002-2013	97	83	71	14.73	0.76	0.75	0.50
Thimmanahalli	2001-2013	4.95	16.44	41.09	-88.11	0.30	-1.16	1.61