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Climate Change Impact on Water Resources of Tank Cascade Systems in the Godavari Sub-Basin, India

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Abstract
The availability of water at the regional and river basin scales in the future will be significantly impacted by climate change. Effective water management in the sub-basin is essential for ensuring long-term sustainability in the face of changing climatic conditions. The Maner River basin is a significant contributor to the Godavari River, and agriculture serves as the primary source of income for the majority of individuals residing in the sub-basin. Nearly 50–65% of irrigational fields in the Maner basin are cultivated using local Tank Cascade Systems (TCS) and reservoirs that are managed by monsoon precipitation. The regional level climate change impact on the water resources of these tank cascade systems is important for sustainable management of water resources. In this study, The NEX-GDDP RCM models of CCSM4, MPI-ESM-LR and MIROC-ESM-CHEM were utilized to examine climate patterns during historical and future periods under RCP 4.5 and RCP 8.5 scenarios. The Maner sub-basin and KTCS (Katakshapur Tank Cascade System) were modeled using the SWAT hydrological model to simulate runoff and water availability. The average monsoon (July-October) streamflow increase in the Maner basin during the near, mid, and far futures is projected to be 47%, 66%, and 114% under the RCP 4.5 scenario, and 53%, 72%, and 69% under the RCP 8.5 scenario, respectively. Excess flow may overflow from Ramchandrapur, Mallampalli, and Dharmaraopalli tanks to the downstream Katakshapur tank since it can accommodate the up to 18.91 Mm3. To enhance water management in response to climate change, one potential adaptation strategy is to utilize the surplus inflow to refill downstream artificial ponds, which can aid in the replenishment of groundwater and the provision of water supply to tail end tanks.

Keywords Tank Cascade System · Water management · Climate change · NEX-GDDP · SWAT

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1 Introduction

The change in the global climate will have a substantial influence on the hydrological patterns at the local and regional levels (Sridhar et al. 2018; Hillard et al. 2003; Dibike, 2005). According to the climate projection, there will be more precipitation over the Indian peninsula and coastal regions, while no increase or decrease is anticipated in the inland areas (Kumar et al. 2013). India is projected to experience an average temperature increase of 1.5 °C by the year 2050, based on ensemble means (IPCC 2021). The monsoon precipitation dominates the Indian climate, though it erratic and highly seasonal in nature, any changes in climate variability are likely to have a significant impact on water availability within the basin (Maurya et al. 2023; Satish Kumar et al. 2020; Venkata Rao et al. 2020). Climate change is likely to have a significant impact on the availability of streamflow in basin (Sharannya et al. 2018) and water availability in the tank (Alehu and Bitana 2023). Tanks and a series of tanks connected by a single watercourse as Tank Cascade Systems (TCS) were built in ancient times to store rainfall and surface runoff in order to alleviate the local region's water scarcity (VonOppen and Subba Rao, 1987). In India's southern state of the Telangana is enriched of TCS (mostly falling in the Krishna River Basin (KRB) and Godavari River basin (GRB)) in the basin has a substantial influence on surface energy, hydrological water balance, and regional climate (Thiery 2015; Ramabrahmam et al. 2021). The direct climate impact on tank hydrology also influenced by basin hydrology (Alejo and Alejandro 2022), therefore, it is important to consider climate change impact on both river basins and tank systems.

The key literature on the effects of climate change on basins and tanks around the world and in India was discussed below. In Dau et al.'s (2021) found that the hydrology of the Huong River Basin in Vietnam is expected to withstand the most severe climate projections, ensuring sufficient water supply for agricultural and domestic purposes in the future. Nandi and Manne 2020 investigated on Sina basin, India, and found that, the water balance components would be adversely affected by climate change in the near future. The projected hydrological changes caused by climate change are an important input in defining water resource policies (Hengade et al. 2018). Climate change projections using HadCM3 resulted an increase in future runoff of more than 36% in the upper Godavari basin (Saraf et al. 2018). In the Wardha watershed of the GRB, the future streamflow is reduced, and the intra- and inter-annual streamflow variability is less variable than the observed streamflow (Sowjanya et al. 2020). The spatial pattern in the Wainganga River basin of GRB remained unchanged despite an increase in rainfall, evapotranspiration, and runoff (Das and Umamahesh 2018; Hengade et al. 2018). Similarly, In the latter half of the 21st century, there will be an upward trend in precipitation in the Warangal basins, specifically during the months of July and August (Chanapathi et al. 2020).

The hydrology of the watershed will change as a result of climate change's impact (Dessie et al. 2015; Alejo and Alejandro 2022,). The climate impact of the Great African Lakes revealed that the largest lake cools during the day (Thiery et al. 2015). The future inflow into the Mediterranean basin's Beysehir lake is reduced, and land-use scenarios had no significant impact on hydrology (Bucak et al. 2017), some important global studies are (Hassan et al. 2022; Alehu and Bitana 2023) on lakes and (He et al. 2020) on cascade reservoir. The impacts of climate change on Phakal Lake located in KRB, India, analysed with SWAT model results to a decrease of up to 57% in tank inflows in the future (Jayanthi and Keesara 2021). Therefore, the water harvesting structures can absorb the rainfall variability and improve the of agricultural productivity under future climate projections (Vema et al. 2022).

Tank systems are crucial water management and storage systems in semi-arid regions, and changes in the basin's hydrology and climate can have an impact on their water balance (Kumar 2016). Therefore, it is critical in this case to analyse how climate change affects the management of cascade tank irrigation. However, majority of climate change research has focused on projected precipitation and streamflow variations in basins rather than tank systems. To date, the climate impact analysis on reservoirs and large tanks at the regional scale has been addressed, but the climate impact on medium irrigation TCS and the relationship with the basin have not been addressed. In light of climate variability, it is essential to conduct a comprehensive investigation to formulate enduring water management strategies that support agricultural production sustainability. As per the literature, the Godavari River basin and Maner watershed needs the climate change impact analysis and some adaptation strategies to tanks and TCS. The SWAT model was used in the majority of the studies for basin-scale analyses, with only a few studies using it for climate change effect analysis on reservoirs and lakes. The novel aspect of our study was to perform interlinked modeling and analysis using rescaled climate projections, the SWAT model, and storage infrastructure in the Maner River in peninsular India as the importance of place-based assessment, particularly for the Godavari river basin was urgently needed. Hence, the future projected streamflow in the Maner basin, inflows to TCS using SWAT model and development of adaptable strategies for sustainable water management policies at the local scale were the focus of this study. The following sections provide detailed information about the study area, methodology, results, and discussions.

2 Study Area

The Maner watershed is the sub-basin of the Godavari basin, India (Fig. 1a). The basin is located between latitudes 17°41'20 N to 18°40'N and longitudes 78°13'E to 79°59'40E. The Maner river is a right-bank tributary of the Godavari River covering an area of 13,106 Square Kilometers. The entire Maner catchment area is located in the state of Telangana. Maner river has Upper Maner, Middle Maner and Lower Maner dams are the main water resource projects for providing drinking and irrigation water to the Karimnagar district as well as water to the Ramagundam NTPC plant. The average annual rainfall of the catchment is 932 mm (1951–2005) and the southwest monsoon (JJASO) is the only primary rainy season. The Pedda bodaru Vagu (stream), a 13 km long stream, is a tributary of the Salivagu River, flowing from the topmost Ramchandrapur tank to the lowest Katakshapur tank in the KTCS (Fig. 1b). The Maner river is fed by the Salivagu river, which has numerous small to medium-sized tanks and TCS within its watershed, most of which are ungauged.

3 Data and Methodology

3.1 Data

The digital elevation model (DEM) data obtained through the Shuttle Radar Topography Mission (SRTM) has a spatial resolution of 30 m. The basin has medium topographic relief, with elevations ranging from 106 to 669 m (Fig. 2b). It has been utilized for the automated demarcation of the watershed limits and stream network.

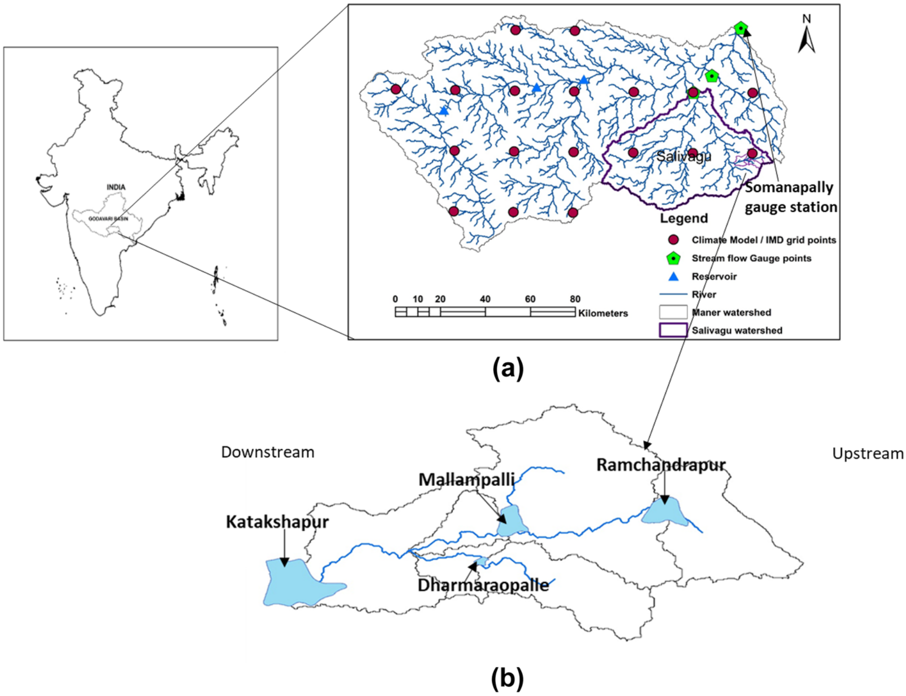

Fig. 1 Study area of **a** Maner river basin and **b** KTCS (Katakshapur Tank Cascade System)

The Land Use-Land Cover (LULC) maps for the base period and subsequent periods were provided by the National Remote Sensing Center (NRSC). Based on these maps, the Maner sub-basin was found to contain 65% and 67% of agricultural (AGRL) land, 17% and 14% of barren area (BARR), 7% of water (WATR) and forest land (FRST), and 4% and 5% of urban area (URBN) in 2005-06 and 2017-18, respectively. (Fig. 2a).

The study utilized the soil map from the ISRIC (International Soil Reference and Information Centre) world soil data, which had a resolution of 1 km (Fig. 2c). The predominant soils in the Maner basin are clay loam and sand clay loam. Paddy is the crop that is most frequently grown during the Kharif season due to improvements in surface and groundwater usage in the area, which is composed of a mixture of red and black soil. Depending on water availability and crop cycle, cotton, chili, and maize are also grown in the basin.

According to data collected from India WRIS (IWRID 2022), the Maner river experiences seasonal flow, with 80% of the total streamflow occurring between July and October and the peak flow is observed in August. Gridded data with a spatial resolution of 0.25° x 0.25° from the Indian Meteorological Department (IMD) Pune (IMD 2021, Pai et al. 2014; Srivastava et al. 2009), covering the period of 1980 to 2020, was utilized to analyze the daily precipitation, maximum, and minimum temperatures.

The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) are simulations that have been downscaled statistically. They are based on runs of General Circulation Models (GCM) conducted as part of the Coupled Model Intercomparison Project Phase 5 (CMIP-5). These simulations cover two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs), specifically RCP 4.5

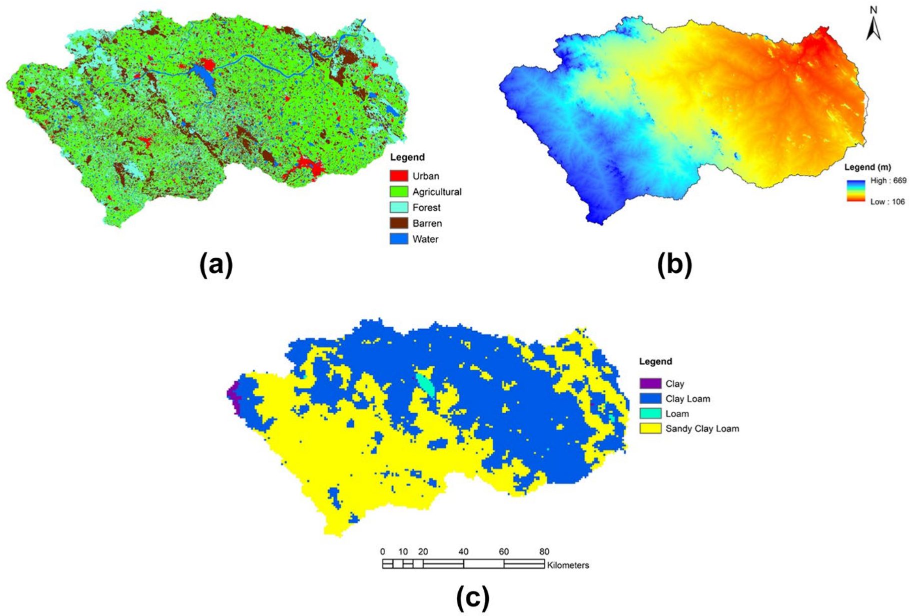

Fig. 2 **a** Land use-land cover map (2017-18), **b** Digital elevation model and **c** soil map of the Maner watershed

and 8.5 (Taylor et al. 2012). These datasets, with a spatial resolution of 0.25° × 0.25° are available at the Indian Institute of Tropical Meteorology (IITM 2022), Pune. The climate models including MIROC-ESM-CHEM, CCSM4, and MPI-ESM-LR were used in this study and details are provided in Table 1. These datasets were used to hydrological processes under RCP 4.5 and 8.5 scenarios for historic (1980–2005) and future (2006–2099) climatic conditions.

3.2 Methodology

Initially, the SWAT hydrological simulation was performed in the Maner river basin using IMD gridded precipitation (1980–2020), LULC, and soil data. The simulated streamflow was calibrated (1980–2010) and validated (2011–2020) in SWAT-CUP using observed discharge at the Somanapalli gauge station to evaluate the model performance. Secondly, the best SWAT parameters were used to perform the future climate change impact in the Maner basin and Katakshapur Tank Cascade System (KTCS) using an ensemble of CCSM4,

Table 1 The details of RCM models used in the study

RCM-Name	Institute name
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (University of Tokyo) and others (Japan)
CCSM4	National Center for Atmospheric Research (NCAR), USA
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), Germany

MPI-ESM-LR and MIROC-ESM-CHEM RCM model data under RCP 4.5 and 8.5 future projected scenarios. As a result, the tank inflow volumes are estimated for the future period from 2022 to 2099. The details methodology followed in this study is given in Fig. 3.

3.2.1 RCM Model Selection

The NEX-GDDP climate models were sorted based on the correlation of mean monthly IMD precipitation during 1951–2005. MIROC-ESM, MIROC-ESM-CHEM, CCSM4, INM-CM4, BNU-ESM and MPI-ESM-LR RCM models were selected from among all 21 climate models with coefficient of correlations of 0.7 and determination 0.5 or higher were chosen. The other statistics of MAE is 25.64–38.2% and RMSE is 26–35% were selected for the basin average annual precipitation. The chosen models aligned with studies on the effects of climate change on the Godavari River basin and reservoirs (Jayanti and Keesara 2021; Dubey and Sharma 2018) using GCMs (Sharmila et al. 2015; Hengade and Eldho 2019) and RCMs (Das and Umamahesh 2018).

3.2.2 Hydrological Modelling

The physically-based SWAT model is a spatially distributed continuous-time simulation model designed to simulate the quantity and quality of surface and subsurface water on a daily basis. Its purpose is to forecast the environmental impacts of climate change and land use and management practices (Srinivasan et al. 1998; Neitsch et al. 2001). The watershed is subdivided into subbasins, which are then divided further into Hydrological Response Units (HRUs). Using the water balance Eq. 1 (Neitsch et al. 2005), the model computes surface and subsurface flow by simulating hydrological processes.

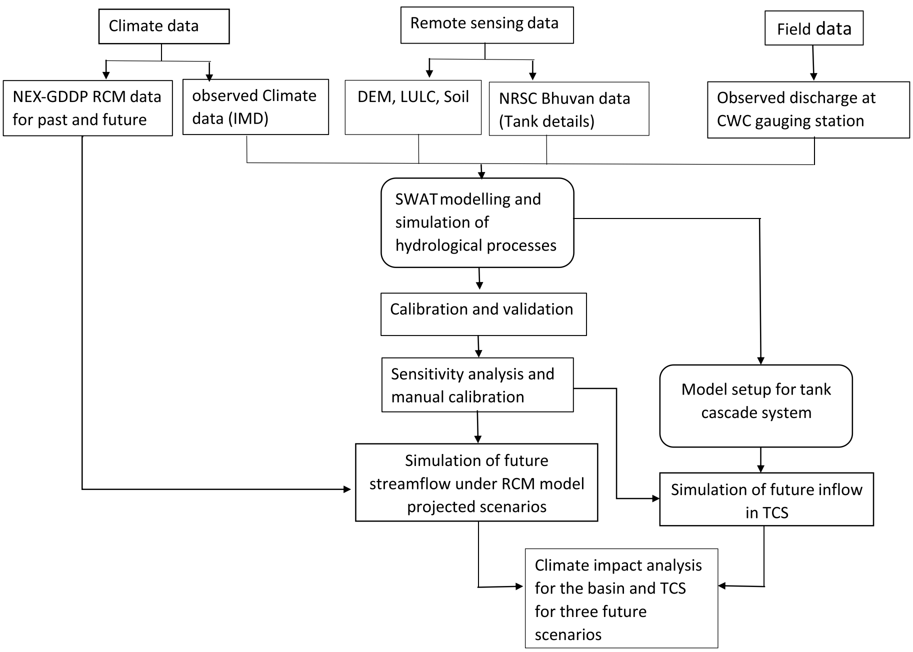

Fig. 3 The methodology used in the present study

$$SW_t = SW_0 + \epsilon_{i=1}^{t}(R_{day} - Q_{sur} - E_a - W_{Seep} - Q_{gw}) \tag{1}$$

where SW_t is the soil water content at time 't', SW_0 is initial soil water content, R_{day} is precipitation on day (i), Q_{sur} is the surface runoff on day (i), E_a is the evapotranspiration on day (i), W_{Seep} is the amount of the water seep to the vadose zone from soil profile on day (i), Q_{gw} is the amount of return flow on day (i). R_{day}, E_a, W_{Seep} are the vertical flow and $Q_{gw,}$ Q_{sur} are the horizontal flow water budget components respectively. The Penman-Monteith method is used to estimate the E_a fluxes based on potential evapotranspiration. Seepage from the soil surface is regulated by infiltration and is dependent on the permeability of the soil layer.

3.2.3 Evaluation of Model Performance

The streamflow simulated by SWAT is calibrated (1980–2010) and validated (2011–2020) by comparing it with observed discharge at Somanapalli gauge station, using the Sequential Uncertainty Fitting (SUFI-2) algorithm of SWAT-CUP (SWAT Calibration and Uncertainty Program). The Nash-Sutcliffe (NS) index, expressed in Eq. 2, is employed as the primary objective function for the model's calibration and validation, as it determines the residual variance between the simulated and observed data. Additionally, the coefficient of determination (R2), calculated using Eq. 3, is used to determine the correlation between the simulated and observed streamflow. Finally, the average tendency of the simulated flow compared to the field data is evaluated using P-BIAS, which employs Eq. 4.

$$NS = 1 - \frac{\sum_{i=1}^{n} (Q_m - Q_S)i^2}{\sum_{i=1}^{n}\left(Q_{m,i} - \overline{Q}_m\right)^2} \tag{2}$$

$$R2 = \frac{\sum_{i=1}^{n}\left[\left(Q_{m,i} - \overline{Q}_m\right)\left(Q_{s,i} - \overline{Q}_s\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{m,i} - \overline{Q}_m\right)^2 \sum_{i=1}^{n}\left(Q_{s,i} - \overline{Q}_s\right)^2} \tag{3}$$

$$PBIAS = 100 \times \frac{\Sigma_{i=1}^{n}(Q_m - Q_s)_i}{\Sigma_{i=1}^{n} Q_{m,i}} \tag{4}$$

where, Q_m is observed discharge, $\overline{Q}_m$ is mean of observed discharge, Q_s is simulated discharge, $\overline{Q}_s$= mean of simulated discharge, i is the ith measured and simulated variable, n is the total number of observations.

4 Results and Discussion

4.1 Precipitation and Temperature Analysis for Historic and Future Periods

Among six selected models, the CCSM4, MPI-ESM-LR, and MIROC-ESM-CHEM models precipitation have a moderate bias of -15 to + 38% in monsoon months (JJASO) during the base period (Fig. 4b). For better results, these three models ensembled (ENS3) mean

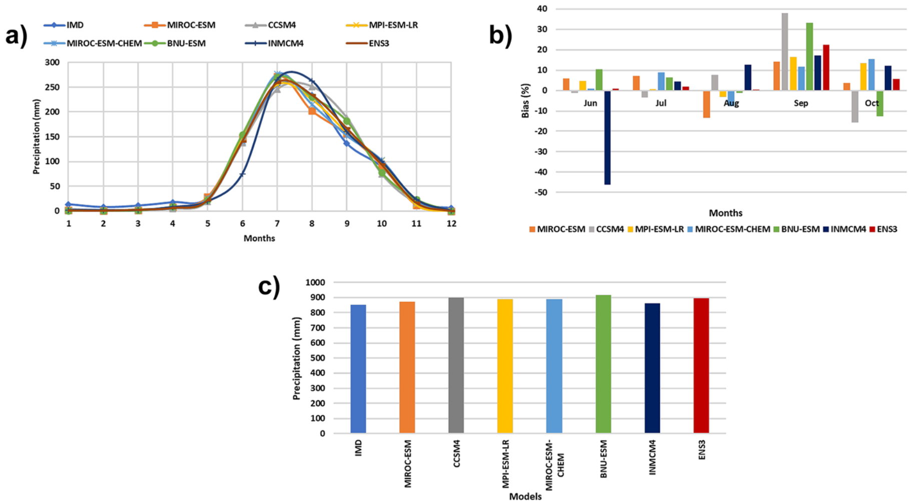

Fig. 4 **a** Observed and RCM models average mean monthly precipitation and **b** percentage bias **c** Average monsoon precipitation in the Maner basin during base period of 1980 to 2005

used for historical and future climate impact analyses. The ensembled modeled (ENS3) precipitation has a lower percentage bias, ranging from 0.96 to 22.3. The mean monsoon precipitation is 895.09 mm, which is similar to the observed precipitation (852.4 mm), with a bias of +5% due to higher precipitation in September.

All future scenarios (Fig. 5a) show an increase in mean monthly precipitation for ENS3 when compared to the historical base period. The ENS3 mean monthly future predicted precipitation increases by up to 20% in the near future, 40% in the mid-future, and 51% in far future under RCP 4.5 and 8.5 scenarios (Fig. 5b). The maximum percentage increase is

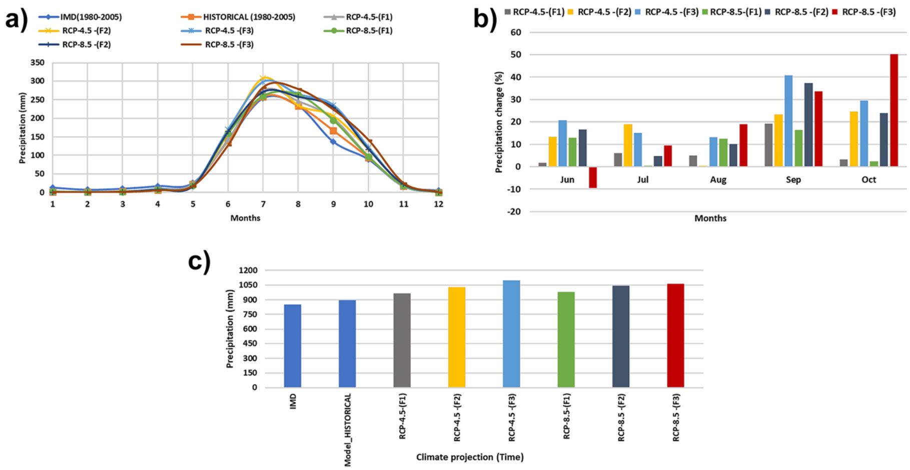

Fig. 5 **a** Ensembled model (ENS3) mean monthly precipitation, **b** percentage change and **c** Average monsoon precipitation in the Maner basin for future projected RCP 4.5 and 8.5 scenarios (F1 = 2006–2039, F2 = 2040–2069, F3 = 2070–2099)

40% and 51% in far future months of September and October under the RCP4.5 and RCP 8.5 scenarios, respectively (Fig. 5b). Monsoon (JJASO) precipitation in near, mid, and far future periods is 964.19, 1029.75, and 1097.45 mm under RCP 4.5, and 979.71, 1042.97, and 1064.23 mm under RCP 8.5 (Fig. 5c).

The average annual minimum temperature is 22.37 °C, 23.12 °C, 23.61 °C and 22.63 °C, 24.01 °C, 25.95 °C during near, mid, far futures under RCP 4.5 and 8.5 scenarios, respectively. The average annual maximum temperature is 32.99 °C, 34.87 °C, 36.22 °C and 34.01 °C, 34.9 °C, 35.34 °C during near, mid, far futures under RCP 4.5 and 8.5 scenarios, respectively. The increase in maximum and minimum temperature is 3.23 °C and 1.88 °C under RCP 4.5 scenario, 1.33 and 3.32 °C under RCP 8.5 scenario, respectively.

4.2 Calibration and Validation of SWAT Model

Using the SWAT model, we simulated the streamflow in the Maner basin and identified the sensitive parameters and their best fitted values, as presented in Table 2. The observed discharge of the CWC gauge station at Somanapally was used to calibrate the mean monthly streamflow from 1980 to 2010 and validate it from 2011 to 2020 with the SUFI-2 algorithm in SWAT-CUP, as shown in Fig. 6. The model performance statistics for NS and R2 were 0.8 and 0.84 during calibration, and 0.87 and 0.87 during validation, respectively, as presented in Table 3.

The p-factor and r-factor model uncertainty parameters were found to be 0.51 and 0.89, respectively, during calibration, and 0.49 and 0.54, respectively, during validation. The performance statistics indicate that the SWAT model has been reasonably well-calibrated and validated for the Maner basin. During high flows, the simulated flow is greater than the observed flow and underestimated during baseflows. The model P-Bias was underpredicted during calibration due to streamflow being captured

Table 2 The list of SWAT model calibrated parameters

S.no	Parameter Name	Minimum values	Maximum values	Fitted Value
1	R__CN2.mgt	-0.08	0.020	-0.043
2	V__ALPHA_BF.gw	0.47	0.833	0.730
3	A__GW_DELAY.gw	-30	10	-29.24
4	A__GWQMN.gw	-729	-48	-361.941
5	V__GW_REVAP.gw	0.13	0.2	0.193
6	V__ESCO.hru	0.32	0.53	0.390
7	R__SOL_AWC(.).sol	-0.05	0.016	0.001
8	A__RCHRG_DP.gw	-0.035	0.022	0.001
9	A__REVAPMN.gw	-517	-250	-367.213
10	V__CH_N2.rte	0.026	0.06	0.027
11	V__CH_K2.rte	15	25	18.21
12	V__CH_K1.sub	23	32	30.335
13	V__CH_N1.sub	0.008	0.09	0.020
14	V__LAT_TTIME.hru	15	41	35.566
15	V__ALPHA_BF_D.gw	0	1	0.535

R-Relative, V- Replace, A-Absolute methods to change existing value

Table 3 The SWAT-CUP statistical results of SWAT simulated flow of the Maner basin during 1980–2020

Process	P-factor	R-factor	R^2	NS	P-Bias
Calibration (1980–2010)	0.51	0.89	0.84	0.8	9.1
Validation (2011–2020)	0.49	0.54	0.87	0.87	-14.1

by the upper Maner dam and overpredicted during validation due to the presence of mid-Maner dams as balancing reservoirs on the Maner river. Most of peak flows are observed in August and September, with an average peak flow of 547 m^3/s observed between 1980 and 2020. The first wet year was recorded in 1983, with a flow of 1048 m^3/s, and they occurred every three years until 1990. The streamflow was reduced due to the construction of the lower Maner dam in 1985, and the first dry year was noticed in 2014. The mid-Maner dam was built in 2017 and acted as a balancing reservoir, there after the flooding condition was observed in 2020. As per above results and actual condition, it is apparent that the three big dams (Upper, Middle and Lower Maner) have complete control over the Maner River.

During the base period (1980–2005), Fig. 7a shows that the ENS3 model reasonably simulated streamflow, which was consistent with the amount of precipitation. The average peak flow during this period was 406 m3/s, but there were ten occasions when the peak flow exceeded this value. The ensemble model predicted that in 1989 and 2005, there would be high and low peak flows of 734 m3/s and 235.4 m3/s respectively.

4.3 Climate Change Impact on Future Streamflow

The impact of climate change on streamflow is studied over three time periods i.e., 2006–2039 (F1) near future, 2040–2069 (F2) mid future, and 2070–2099 (F3) far future.

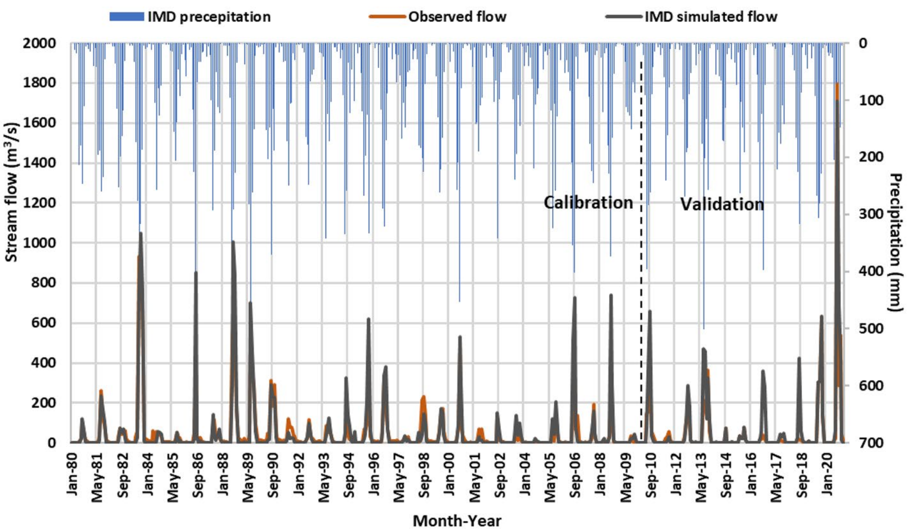

Fig. 6 The SWAT simulated streamflow in the Maner basin at Somanapalli gauge station during 1980–2020 period

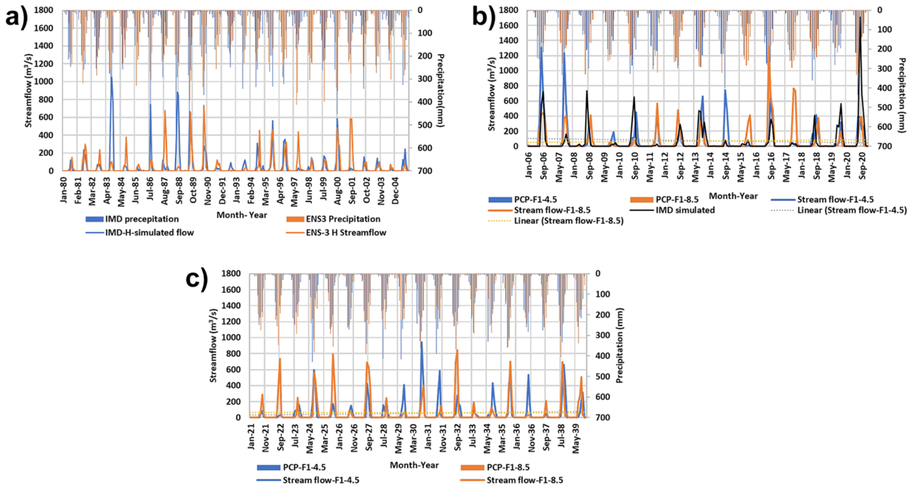

Fig. 7 The ensemble model (ENS-3) precipitation and SWAT Simulated streamflow **a** during base period (1980–2005), **b** during historic (2006–2020) and **c** current near future (2021–2039) of the Maner river basin

The near future (2006–2039) is divided into two parts one is historic (2006–2020) and the current near future (2021–2039) for the purpose of understanding climate models predictions. In the historical period, the streamflow trend with the simulated IMD showed a decrease in the RCP 8.5 scenario and an increase in the RCP 4.5 scenario (Fig. 7b). The historical low and medium streamflow magnitudes under the RCP 4.5 scenario match the IMD simulated flows, with the exception of a few peak flows.

The Peak flows are typically observed in August, September, and October. According to RCP4.5 scenario, the average peak flow is 605.9 m^3/s, while the maximum and minimum peak flows in August 2006 and 2013 were 1310 m^3/s and 331.6 m^3/s, respectively. The average peak flow under RCP8.5 scenarios is 523.74 m^3/s, the maximum and minimum peak flows were 1332 m^3/s and 335 m^3/s in August 2016 and 2013, respectively. The average simulated peak flow by IMD is 516.85 m^3/s, with the maximum and minimum flows occurring in August 2020 and September 2019, respectively, with values of 1711 m^3/s and 257.30 m^3/s. Both scenarios peak flows do not match the IMD simulated flow, but the RCP 4.5 scenario flows are close to the IMD's average peak flow.

In the current near future period (2021–2039), the streamflow has shown an increasing trend in the RCP 4.5 scenario, but a declining trend in the RCP 8.5 scenario (Fig. 7c), which is the opposite of the historical period. The average peak flow in RCP4.5 scenarios is 503 m^3/s, and six events exceeded the average peak flows during this time period, with maximum and minimum peak flows of 943 m^3/s and 315.5 m^3/s, respectively. The average peak flow under RCP8.5 scenarios is 564.3 m^3/s, with seven events exceeding the average peak flow, 847.8 m^3/s and 341.6 m^3/s being the maximum and minimum peak flows, respectively.

The streamflow of near future period (2006–2039) under RCP 4.5 and 8.5 scenarios has shown a decreasing trend, which is different with historic and near future periods. The average peak flow under RCP 4.5 is 579.45 m^3/s, with eleven events exceeding this magnitude; the maximum and minimum peak flows in this duration are 1310 m^3/s and 377 m^3/s, respectively (Fig. 8a). Under RCP8.5 scenario, the average peak flow is 544 m^3/s, with fourteen events exceeding the average peak flows; the maximum and minimum peak flow are 1332 m^3/s and 334 m^3/s, respectively. The ensemble model predicted that average streamflow peaks would be higher in the near future than in the baseline period.

The average peak flows in the mid-future (2040–2069) are 550.92 m^3/s and 720.28 m^3/s, respectively, and eleven and twelve events are exceeded under RCP 4.5 and 8.5 scenarios (Fig. 8b). Under RCP 4.5 and 8.5 scenarios, the maximum and minimum peak flows are 1175, 1237 and 335, 453.6 m^3/s, respectively. The mid-future simulated streamflow's under the RCP 8.5 projected scenario had higher peak flows than the RCP 4.5 scenarios.

Under RCP 4.5 and 8.5 scenarios, average peak flows of 726.68 m^3/s and 586.14 m^3/s, and ten and eleven events are exceeded the flow respectively in the far future (2070–2099) (Fig. 8c). Under RCP 4.5 and 8.5 scenarios, the maximum and minimum peak flows are 1271, 1125, and 442, 357.1 m^3/s respectively. The far future simulated streamflow's under the RCP 4.5 projected scenario had higher peak flows than the RCP 8.5 scenarios.

4.4 Mean Monthly Streamflow in the Maner Basin

The average annual monthly streamflows of the CCSM4, MIROC-ESM climate models during the base period are shown in Fig. 9a, with a bias of 9.83, 6.31, and 25.51, 63.58 in the months of August and September, respectively. The remaining four models, MPI-ESM-LR, MIROC-ESM-CHEM, BNU-ESM, INMCM4, and ensemble model (ENS3), have low streamflow than other models due to less precipitation therefore the corresponding biases of -25.27, -28.46, -43.94, -45.45, and -32.56 in the month of August during the base period, respectively (Fig. 9b). The CCSM4 model has an ideal percentage bias and is close to the IMD predicted flow during the base period. Similarly, the ensemble model (ENS3) has a reasonable bias percentage of -32.56, 3.63 and +36.85% in the months of August, September, and October respectively. As a result, additional analysis is performed on the ensemble ENS3 model findings.

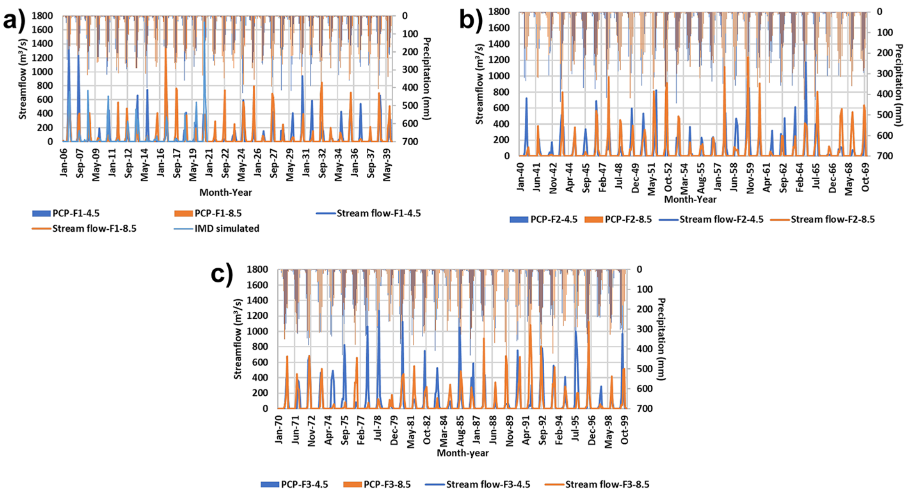

Fig. 8 The ensemble model (ENS-3) precipitation and SWAT-simulated streamflow **a** during near future (2006–2039), **b** during mid future (2040–2069) and **c** far future (2070–2099) of the Maner river basin

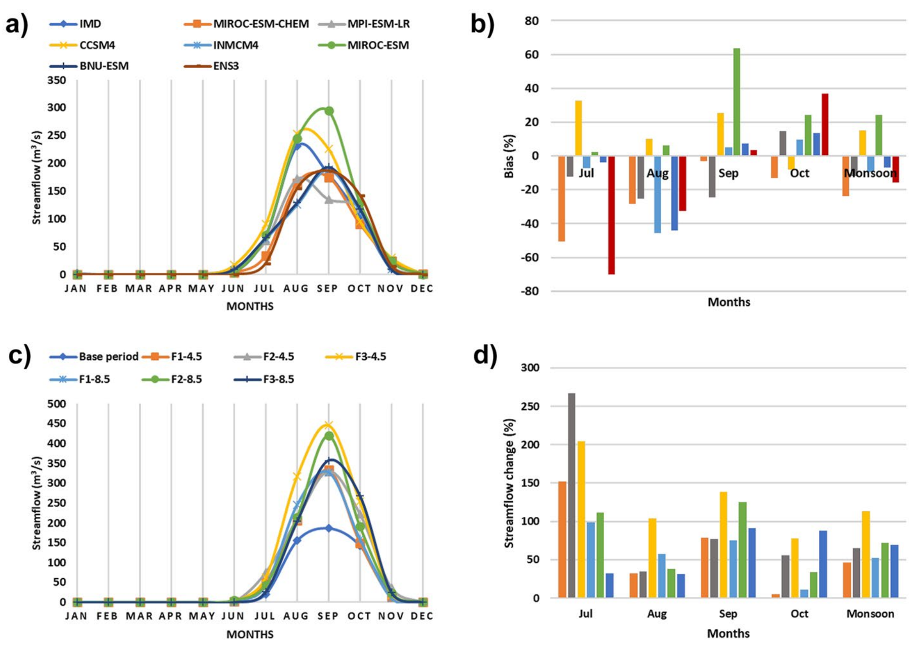

Fig. 9 **a** The mean monthly streamflow of IMD and RCM models, **b** the corresponding percentage bias during base period (1980–2005), **c** the ENS3 future projected streamflow under RCP 4.5 and 8.5 scenarios and **d** percentage change during near(F1-2006-2039), mid (F2-2040-2069) and far (F3-2070-2099) future periods in the Maner basin

Because climate models predict high precipitation, the ensemble model future mean monthly streamflows are higher than base period flows in August, September, and October (Fig. 9c). Under RCP 8.5 and 4.5 scenarios, the mean monthly monsoon streamflow increased in the near, mid, and long term. Due to more bias in base period flow, the percentage increase in July is greater, i.e., 250%. Under RCP 4.5 and 8.5 scenarios, the percentage increase in monsoon streamflow is 46.73, 65.48, 113.528, and 52.77, 71.96, 69.34 in the near, mid, and far future, respectively (Fig. 9d). The streamflow percentage increase is more in the month of September i.e., 78.89, 76.55, 138.74 and 75.3, 125, 91.3 in the near, mid, and far future under RCP 4.5 and RCP 8.5 scenarios, respectively because these ensembled models predicted 40 and 33% more precipitation.

4.5 Climate Change Impact on KTCS

In the cascade arrangement, the inflows to the tanks have increased proportionally with the tank size. During the base period in August, the IMD and ensemble model simulated tank inflows of 1.2, 3.5, 0.9, 5.94 Mm^3 and 0.83, 2.54, 0.63, 4.26 Mm^3 in Ramchandrapur, Mallampalli, Dharmaraopalli, Katakshapur tanks (Fig. 10a-d). The corresponding bias is -32.61, -27.33, -30.58, -28.54% in August, -2.7, -8.96, -11.08, -12.2% in September and 51.38, 31.71, 29.97, 35.02% in October months of Ramchandrapur, Mallampalli, Dharmaraopalli, Katakshapur tanks respectively (Fig. 10a-d). The highest negative and positive biases are observed in August and October months in Ramchandrapur and Dharmaraopalli tanks as these are small and staring tanks in the cascade. The average monsoon tank inflows are 2.32, 6.98, 1.77

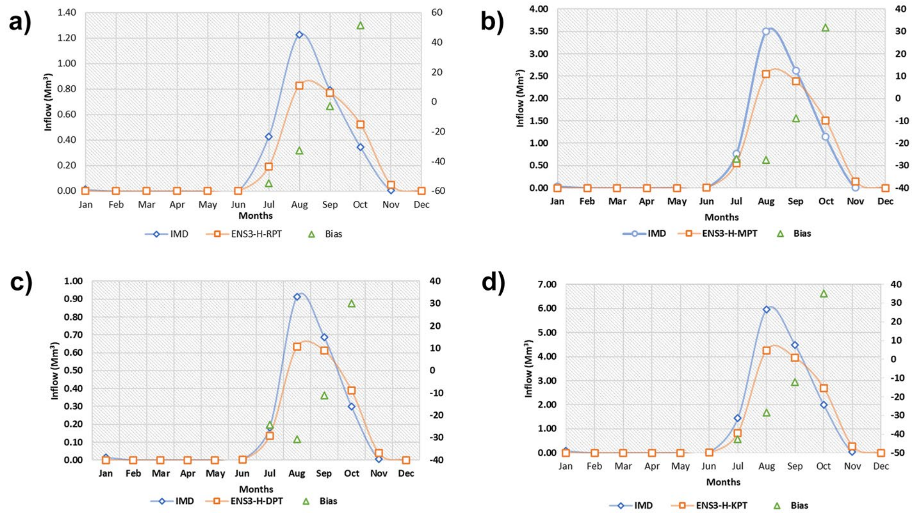

Fig. 10 The IMD and Ensemble (ENS3) model tank inflows and corresponding bias of **a** Ramchandrapur tank (RPT) **b** Mallampalli tank (MPT) **c** Dharmaraopalli (DPT) and **d** Katakshapur (KPT) tanks during base period (1980–2005)

and 11.74 Mm^3 during base period and respective biases are -17.1, -12.87, -14.87 and -15.58 in Ramchandrapur, Mallampalli, Dharmaraopalli and Katakshapur tanks (Fig. 10a-d). These tank monsoon inflow results are similar to streamflow and the negative bias is due to RCM models being underpredicted and precipitation shifting during the base period.

All tank inflows in KTCS are increased in the near, mid, and far futures compared to the base period, but the percentage increase is minimal in the mid-future compared to the near future under RCP 4.5 and 8.5 scenarios (Fig. 11a-d).

In comparison to model historical flows, the ensemble model results under RCP 8.5 scenario projected less inflow than RCP 4.5 scenario in the near, mid, and long term. Under the RCP 4.5 projected scenario, the RPT collects less inflow, 2.8 Mm^3 (Fig. 11a), and the KPT collects more inflow, 15 Mm^3 (Fig. 11d), in the September month among the KTCS tanks. In the future period, peak inflows will be observed in September, whereas in the base period, they were observed in August. According to the RCP 4.5 scenario, the inflow of tanks in September will increase by 200% and 250% during the near, mid, and far future periods, respectively (Fig. 11a-d). The cascade tanks receive nearly 150, 180 and 220% increase of inflow during the monsoon (July to October) in near, mid and far future respectively, similar results were noticed in Das and Umamahesh, 2018 study. In all the tanks of the cascade the maximum increase is nearly 300% observed in the month of July in mid future under RCP 4.5 scenario, though it is maximum percentage but the magnitude is less.

4.6 Water Balance of the Maner Basin and KTCS

Table 4 shows the water balancing components of the Maner river basin. As Precipitation increases the surface runoff and evapotranspiration is also increased in the future under RCP 4.5 and 8.5 scenarios. Under RCP4.5, the precipitation contribution to surface runoff

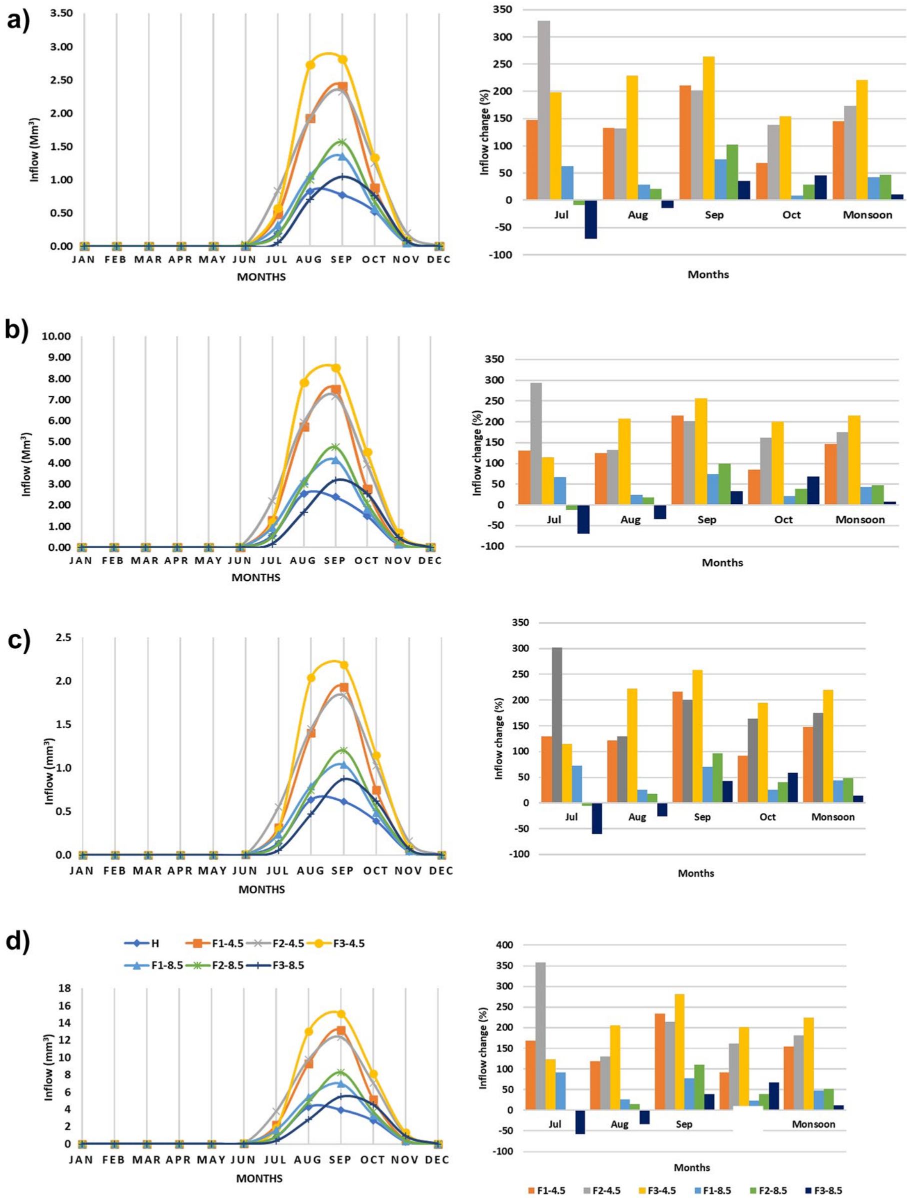

Fig. 11 The ensemble model mean monthly tank inflows and percentage change of **a** Ramchandrapur **b** Mallampalli **c** Dharmaraopalli **d** Katakshapur tanks for future projected scenarios during 2022–2099

is 12% in the base period, 14 to 18% and 14 to 17% under RCP8.5 in the near, mid, and far future periods. Evapotranspiration is the largest contributor to precipitation, accounting for 61.31% during the base period. Similarly, 61 to 56% and 61 to 60% in near, mid, far future periods under RCP 4.5 and 8.5 respectively, these results are similar with Nandi and Manne (2020). In far future the contribution of surface runoff and evapotranspiration is

Table 4 The average annual water balance components of the Maner basin

Period	Precipitation (mm)	Surface Q (m^3/s)	ET (mm)	Total aquifer recharge (mm)
ENS3-Base period (H-1980-2005)	935.6	112.5	573.6	349.57
ENS3-RCP4.5-F1	1017.4	149.02	623.3	358.45
ENS3-RCP4.5-F2	1084.6	178.39	640.3	387.13
ENS3-RCP4.5-F3	1145.6	201.73	644.9	433.8
ENS3-RCP8.5-F1	1025.2	150.97	622.1	366.51
ENS3-RCP8.5-F2	1092.7	175.45	647.9	392.82
ENS3-RCP8.5-F3	1107.4	187.25	660.8	388.97

increased with respect to base period and near future period in RCP 4.5 and 8.5 scenarios. The increase is majorly due to increase in the future precipitation as well increase in the urban and agricultural area in the future period.

The water balancing components of KTCS are shown in Table 5, and the precipitation, surface runoff, and evapotranspiration are expected to increase in the future, similar to the Maner basin. In the base period, the precipitation contribution to surface runoff and evapotranspiration is 12.51 and 64.55%, respectively. Surface runoff and evapotranspiration contributions are 15 to 17% and 59 to 56% in the near, mid, long term under RCP 4.5, and 14 to 16% and 59 to 61% under RCP 8.5. Surface runoff contribution increases and evapotranspiration decreases in the far future under RCP 4.5 scenario due to decrease in projected precipitation and increase in temperature.

The main difference between the Maner basin and the KTCS is in total aquifer recharge, which is 349.57 and 286.46 mm during the base period, respectively. Under RCP 4.5 and 8.5 scenarios, the total aquifer recharge percentage increase in the Maner basin is 2 to 24% and 5 to 11% in the near, mid, far future. Similarly, the total aquifer recharge percentage increase in KTCS is 22 to 41%, and 25 to 21% in the near, mid, long term under RCP 4.5 and 8.5 scenarios. Because of the tanks, the percentage of aquifer recharge is higher in the KTCS than in the Maner basin in all future periods.

Table 5 The average annual water balance components of KTCS

Period	Precipitation (mm)	Surface Q (m^3/s)	ET (mm)	Total aquifer recharge (mm)
ENS3-Base period (H-1980-2005)	933.2	116.71	602.4	286.46
ENS3-RCP4.5-F1	1037.5	155.92	614.2	350.89
ENS3-RCP4.5-F2	1097.7	183.94	631.6	370.31
ENS3-RCP4.5-F3	1145.1	198.37	638.5	405.24
ENS3-RCP8.5-F1	1039.2	150.34	614.2	359.46
ENS3-RCP8.5-F2	1092.4	172.56	642.4	365.82
ENS3-RCP8.5-F3	1081.4	166.92	658.1	345.03

4.7 Sustainable Adaptation Methods in KTCS

Due to the impact of climate change, the KTCS expect to receive more inflow in far future time periods compared to base period. Consequently, the Ramchandrapur and Dharmaraopalli tanks are small and not able to accommodate the excess flow. As result the downstream tank of Katakshapur receiving more inflow as it is evident from the Hydrograph of Katakshapur given in Fig. 12. According to the hydrograph, there will be an additional inflow of 10 Mm3 of water during month of September. However, the Katakshapur tank has already receiving significant inflow in previous months and its maximum capacity is only 18.91 Mm3. As a result, the overflow would go to the Salivagu project, which is further downstream and can handle these overflows. If the tank capacity is increased by removing silt and mud that has settled at the bottom of the tank and by installing suitable control structures (Sluice gate), the excess flow may be retained in the Katakshapur tank. To effectively utilize these excess inflows, supply and demand side adaptation methods can be used. The supply side adaptation is construction of a storage pond-1 and pond 2 at downstream of the Katakshapur tank overflow section and near the tail end of the command area, where the flow typically does not reach the end of command area (Fig. 12). To maximize the number of farmers who can benefit, it is essential to both increase the number of borewells in the uplands of the tank command area and maintain an optimal level of pumping from the wells (Palanisami et al. 2010). To make use the most of excess tank inflow in the future, several demand-side adaptations are possible. One option is to provide additional drinking water to the nearby habitats of the near villages. Another option is to switch to different crops in the command area. Additionally, open wells can be dug in the fields of the command area to store excess water and use it for percolation and irrigation during the next crop season. In the far future, these adaptation techniques may be help to maximize the utilization of surplus inflow received by Katakshapur tank and to increase the agriculture production.

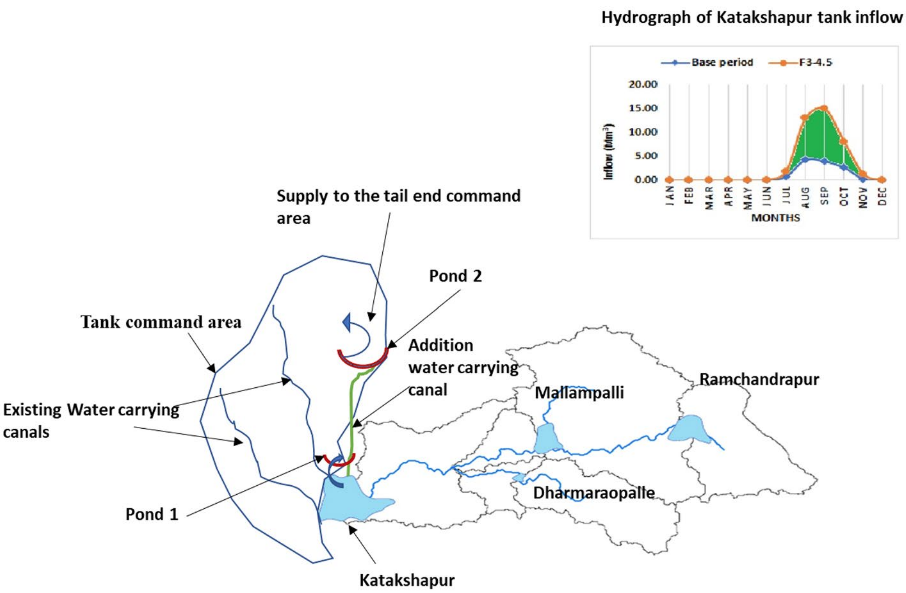

Fig. 12 The schematic diagram of adaptation strategies to sustain the future tank inflow

5 Conclusion

Using the SWAT hydrological model, streamflow and tank inflows were analysed for the Maner basin and KTCS under future climate change scenarios of RCP4.5 and 8.5. The ensemble of MPI-ESM-LR, MIROC-ESM-CHEM, and CCSM4 models simulated flow is close to base period streamflow in all climate model combinations. Among the three models, the CCSM4 is the closer to the simulated flow.

Under RCP 4.5, the ensemble model monsoon precipitation percentage increase in the near, mid, and long term is 13.11, 20.81, and 28.75, respectively, and 14.93, 22.36, and 24.85 under RCP 8.5. Under the RCP4.5 and RCP8.5 scenarios, the maximum monthly precipitation percentage increase is 40 and 51 in September and October of the far future period, respectively. With respect to the base period, the increase in maximum and minimum temperature is 1.88 °C under RCP 4.5, 3.23 °C and 3.18 °C under RCP 8.5.

The simulated flows from IMD closely match the low and medium streamflow magnitudes under the RCP 8.5 scenario during the historical period from 2006 to 2020 in the ensemble model. The Maner basin average monsoon (July-October) streamflow percentage increase is 46.73, 65.48, and 113.53 in the near, mid, and long term under RCP 4.5 scenarios, and 52.77, 71.96, and 69.35 under RCP 8.5 scenarios.

Future streamflow peaks in the Maner basin occur in September, with maximum and minimum peak flows of 1271 m^3/s and 335.2 m^3/s in September 2078 and 2045, respectively, under the RCP 4.5 scenario. The upper, middle, and lower Maner dams have the greatest influence on the Maner river flow and water balance.

In KTCS, the inflow into the Ramchandrapur, Mallampalli, Dharmaraopalli, and Katakshapur tanks increased by 200% in the near, mid, and far future periods under the RCP 4.5 scenario. Similarly, inflows will increase by 150, 180, and 220% during the monsoon season (July to October) in the near, mid, and long term, respectively. The increase is primarily due to the high precipitation in September.

The surface runoff of Maner and KTCS tank inflows increases over time, with the maximum observed in the far future RCP 4.5 scenario. Katakshapur tank receives the most future inflow because it is the lowest and largest tank in the KTCS.

The contribution of surface runoff and evapotranspiration in the far future is increased in comparison to the base and near future periods in Maner and KTCS water balances due to increases in precipitation, urban area, and agricultural area. Because of the presence of tank systems, the percentage of aquifer recharge in KTCS is greater than the overall Maner basin in all future periods.

The storage capacity of the tanks must be increased with appropriate controlling structures to capture more water and dissipate flooding conditions as adaption strategy. Other adaptation methods, such as building an artificial recharge pond downstream of the overflow section and in the fields of command area will improve groundwater recharge. Alternatively, the percolation ponds can be the strategies outlined in this study can be used to develop policies for sustainable water management in this region.

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Data Availability Datasets will be made available upon request to the authors.

Declarations

Ethical Approval All authors accept all ethical approvals.

Consent to Participate The authors agree to participate in any survey or feedback task.

Consent to Publish All authors agree to provide manuscript for publication.

Conflict of Interest The authors declare no conflict of interest.

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