

Assessment of Water Availability in Chennai Basin under Present and Future Climate Scenarios

J. Anushiya and A. Ramachandran

Abstract Climate change may significantly impact the hydrological processes of a watershed system and lead to water scarcity or increased flooding. It may also cause serious problems to humans including loss of biodiversity and risks to the ecosystem. Quantifying and understanding the hydrological response to a changing climate are necessary for water resource management and formulation of adaptive strategies. In this study, changes in water balance components of the Chennai Basin under present and future climate scenarios had been assessed using Soil and Water Assessment Tool (SWAT). High resolution climate outputs ($0.25^\circ \times 0.25^\circ$) from PRECIS regional climate model for present (1961–1990 BL), mid-century (2041–2070 MC) and end-century (2071–2098 EC) under the IPCC SRES A1B emission scenario were used to assess the hydrological changes in the Chennai Basin. The study had determined the present and future water availability in space and time without incorporating any man-made changes like dams, diversions etc. The results indicated a decrease of precipitation in future scenarios as a result decrease of total water yield and ground water flow component in mid-century and end-century. Though both of these scenarios showed decreases in water balance components, the decrease in end-century would be lesser than the mid-century. In the season-wise analysis, the ET would be increased in winter and post monsoon seasons. Water yield had shown decrease in all the seasons of the mid-century scenario and increase during the EC winter and summer seasons.

Keywords Hydrological response · Chennai Basin · SRES · PRECIS · SWAT

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1 Introduction

According to the Fourth Assessment Report of the IPCC, the climate change will affect water resources through its impact on the quantity, variability, timing, form and intensity of precipitation. The report has also highlighted the imminent intensification of the global hydrological cycle affecting both ground and surface waters. The IPCC report concluded that it is highly likely that “the negative impacts of climate change on freshwater systems outweigh its benefits’ with runoff declining in most streams and river (IPCC 2007). In recent times, several studies show that the climatic change is likely to impact significantly freshwater resource availability. It is expected to have several impacts on water resources, including the diminishing of snow pack and increase in evaporation, which affect the seasonal availability of water (Field et al. 2007). A warmer climate will accelerate the hydrological cycle, altering rainfall, magnitude and timing of runoff. Changes in precipitation intensity and duration will probably be the main factors altering the hydrological cycle leading to more floods and droughts (Gleick 2010). Climate-change-induced changes of the seasonal runoff regime and inter annual runoff variability can be as important for water availability as changes in the long-term average annual runoff amount if water is not withdrawn from large groundwater bodies or reservoirs (US Global Change Research Program 2000).

Availability or scarcity of water will vary greatly depending on the region. A number of global-scale (Alcamo and Henrichs 2002; Arnell 2004), national-scale (Thomson et al. 2005), and basin-scale assessments (Barnett et al. 2004) show that the semi-arid and arid basins are most vulnerable. Among these two types of basins, the semi-arid river basins located in the developing countries are more vulnerable to climate change than those basins located in the developed countries, as population, and thus water demand, is expected to grow rapidly in the future and the coping capacity is low (Millennium Ecosystem Assessment 2005).

It is a complex task to assess the impacts of climate change on future availability of fresh water resources, given the uncertainty in predicting climate change (Boorman and Sefton 1997). The uncertainties in climate projection can be examined with the range of available SRES scenarios. These SRES scenarios are developed by the Intergovernmental Panel on Climate Change (IPCC) to capture a wide range of potential changes in future emissions due to demographic, socio-economic, and technological changes (IPCC SRES 2000). These scenarios are plausible representations of the future that are consistent with assumptions about future emissions of GHGs and their effects on global climate and defined as A1, A2, B1, and B2 scenarios (Fig. 1).

A1 scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. A2 scenario describes a very heterogeneous world with continually increasing global population and regionally oriented economic growth that is more fragmented and slower. B1 scenario describes a convergent world with the same global population as in the A1, but with rapid changes

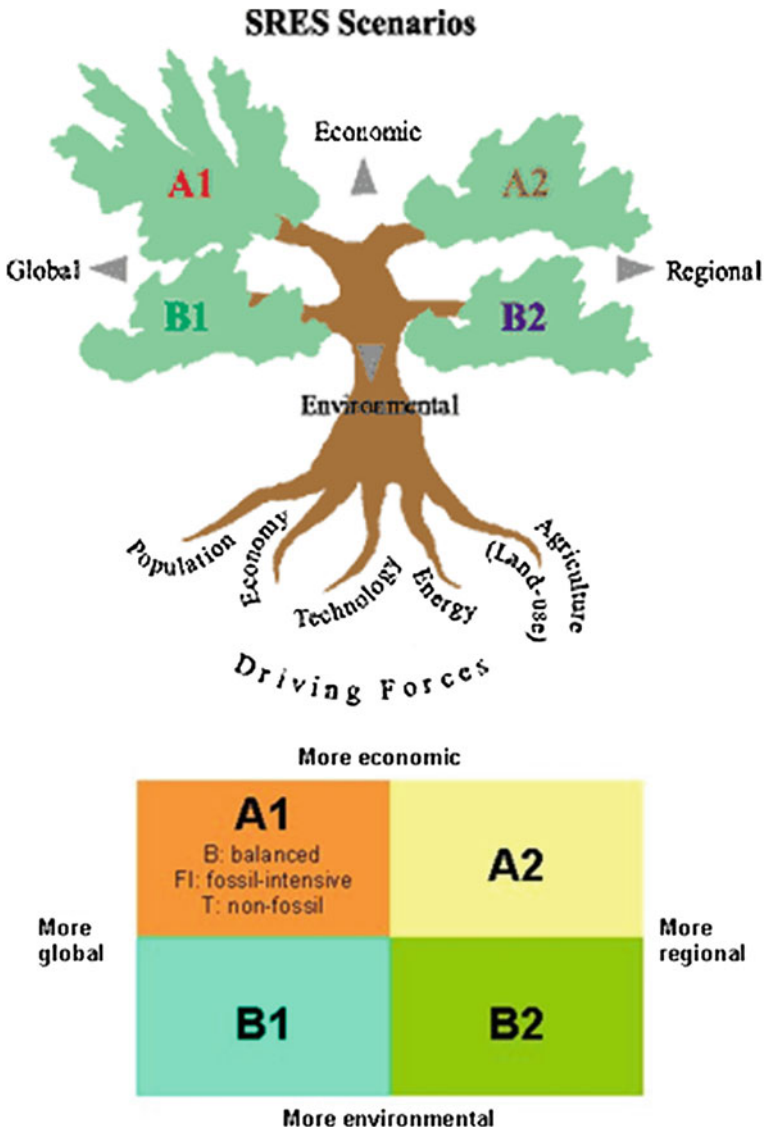


Fig. 1 IPCC SRES scenarios

in economic structures towards a service and information economy with reductions in material intensity and the introduction of clean and resource-efficient technologies. B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability, with continuously increasing population (lower than A2) and intermediate levels of economic development and less rapid and more diverse technological change than in the B1 and A1 Scenarios.

This scenario is also oriented towards environmental protection and social equity and it focuses on local and regional levels.

In 2050s, differences in the population projections of the four SRES scenarios would have a greater impact on the number of people living in the water-stressed river basins (defined as basins with per capita water resources of less than 1,000 m³/year) than the differences in the emissions scenarios. Globally, the number of people living in the severely stressed river basins would increase significantly. The population at risk of increasing water stress for the full range of SRES scenarios is projected to be: 0.4–1.7 billion, 1.0–2.0 billion and 1.1–3.2 billion, in the 2020s, 2050s, and 2080s, respectively. In the 2050s (SRES A2 scenario), 262–983 million people would move into the water-stressed category (Arnell 2004).

In India, the pressure on the water resources has greatly increased, leading to severe competition for available water since 1970s (Gulati et al. 2009). According to the Government of India Statistics (GoI 2010), the per capita surface availability (based on census 1991 and 2001) are about 2,309 and 1,902 m³ for the populations of 1991 census and 2001 census respectively. The demand for water has already increased manifold over the years due to the expansions of urbanization, agriculture, population, industrialization and economic development. The river basins in south Asia are marred with complexities and fractured; the problems identified by Janakarajan (2006) in this regard are listed herein:

- Lack of information flow
- Lack of scientific data generation
- Myopic policies, competitive populism of successive government and lack of political will for the good governance
- Disintegrated/uncoordinated/fractured institutional structures
- Inadequate and unscientific planning resulting in chronic upstream and downstream conflicts, mismatch between groundwater recharge and extraction and water logging and salinity problems
- Growing population and increasing demand for water for attaining food security
- Rapid urbanization process resulting in the increase in drinking water needs and sanitation, industrial expansion which demands more water, and competing demands for scarce water across sectors and emerging conflicts.

Water resource development and management in large areas require an understanding on the basic hydrologic processes and simulation capabilities at the river basin scale. Wide varieties of hydrological models as well as applications of them have been developed over the past decades. Important among them include, but not limited to, the continuous stream flow simulation model, tank model, Hydrologic Simulation Program-Fortran (HSPF) and European Hydrologic system (SHE) model (Maidment 1993). While few models describe the processes by differential equations based on simplified hydraulic laws while other few attempt describing the processes by empirical algebraic equations (Arnold et al. 1998). Two types of hydrological models are in most of the applications, namely, the lumped conceptual models and physically based models. A lumped model is generally applied in a single point or a region for the simulation of various hydrological processes.

The parameters used in the lumped model represent spatially averaged characteristics in a hydrological system and are often unable to be directly compared with the field measurements (Yu 2002). The major drawback of lumped models is the incapability to account for spatial variability (Dhar and Majumdar 2009).

The Physically based hydrological models represent the hydrological processes and spatially distributed data. The need for the research on the better representation of physical processes in space and time is evident given the availability of digital products (e.g., distributions of elevation, soil, vegetation) and remotely sensed data (e.g., soil moisture, vegetation), along with new technologies for measuring temporal and spatial variability in precipitation (Yu 2002). The common feature of these models is that they can incorporate the spatial distribution of various inputs and boundary conditions, such as topography, vegetation, land use, soil characteristics, rainfall and evaporation, and produce spatially detailed outputs such as soil moisture fields, water table positions, groundwater fluxes and surface saturation patterns (Troch et al. 2003). In these models, difference is approximated by spatial variation of precipitation, catchment parameters and hydrologic responses. Temporal variations of hydrologic responses are modeled by introducing threshold values for different processes. Representation of the catchments by individual sub-basins or grids of individual elements are used to integrate the spatial variability of the parameters with the model. One of such model is SWAT.

1.1 Description of SWAT (Soil and Water Assessment Tool) Model

The Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998; Neitsch et al. 2005) is a distributed parameter and continuous simulation model. SWAT is a public domain model actively supported by the Grassland, Soil and Water Research laboratory of the USDA Agriculture Research Service (<http://swat.tamu.edu/>). It is physically based and computationally efficient. Unlike the other conventional conceptual simulation model, it does not require much calibration. Therefore it can be used on ungauged watersheds

In SWAT, a watershed is divided into multiple sub watersheds which are then further subdivided into unique soil/land use characteristics called Hydrologic Response Unit (HRU). Flow generation, sediment yield, and non point—source loadings from each HRU in a sub watershed are summed and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlets. Hydrological processes are estimated with the following water balance equation:

$$SW_t = SW + \sum (R_t - Q_t - ET_t - P_t - QR_t)$$

where SW is the soil water content, minus the wilting point water content and R, Q, ET, P and QR are the daily amounts (in mm) of precipitation, runoff,

evapotranspiration, percolation and ground water flow respectively. The soil profile is subdivided into multiple layers that support soil water processes, including infiltration, evaporation, plant uptake, lateral flow and percolation to the lateral layers. The soil percolation component of SWAT uses a storage routing technique to predict the flow through each soil layer in root zone. Downward flow occurs when the field capacity of the soil is exceeded, and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. The percolation is not allowed from the layer, if the temperature in a particular layer is 0 °C or below. Lateral subsurface flow in the soil profile is calculated simultaneously with percolation. The contribution of ground water flow to the total stream flow is simulated by routing a shallow aquifer storage component to the stream (Gosain and Sandhya 2012).

The SWAT model has been used extensively as a useful tool to evaluate the hydrologic process impacts, with various soil, land use, agricultural management, and weather conditions over long periods (Neitsch et al. 2005; Gassman et al. 2007; Srinivasan et al. 2010). The SWAT is physically based model and uses readily available inputs facilitated by the GIS interface and it is suitable for the study of watersheds from small to very large sizes. Advantages of SWAT model include, ungauged watersheds with no monitoring data (e.g. stream gauge data) can be successfully modeled, the relative impact of alternative input data (e.g. changes in management practices, climate, vegetation etc..) on water quantity, quality or other variables of interest can be quantified, the model uses readily available inputs and computationally efficient, simulation of large basins or a variety of management strategies can be performed without excessive investment of time and money, the model is also capable of incorporating climate change conditions to quantify the impacts of climate change. Based on these traits, it has gained wide global acceptability.

2 Study Area

The Chennai basin is situated between latitudes 12° 3' 00"–13° 35' 00" N and longitudes 79°15'00"–80°22'30"E and is located in the northern part of Tamil Nadu State (Fig. 2). It comprises 8 sub basins and covers Chennai, Kancheepuram, Thiruvallur and Vellore districts. The Chennai basin is bordered in the north by Andhra Pradesh and Pulicat lake, southern and western sides by the Palar river basin and eastern side by the Bay of Bengal.

The total geographical area of the Chennai basin within Tamil Nadu State is 6118.34 km². Four major rivers namely, Araniar, Kosasthalaiyar, Cooum and Adyar are draining in this basin. In addition to numerous small-scale freshwater ponds and tanks, the Chennai Basin is home to the major freshwater supply tanks namely, the Poondi reservoir, Cholavaram lake, Redhills lake and Chembarambakkam tank and brackish waterbodies namely, the Pulicat lake, Ennore estuary, Cooum estuary, Adayar estuary and Covelong estuary. Typically, the ground water

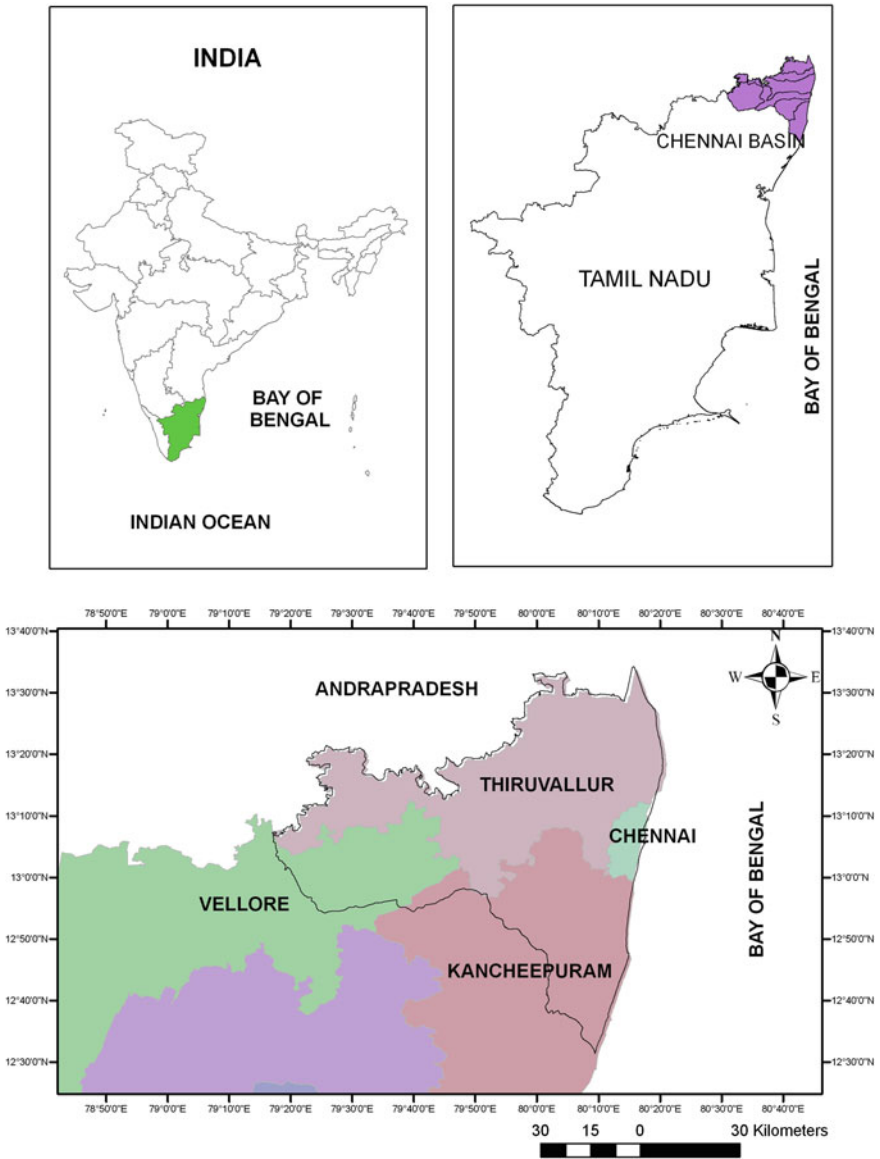


Fig. 2 Administrative map of Chennai Basin

distribution in this basin is not uniform and is subjected to wide spatio-temporal variations, depending on the underlying rock formation, their structural fabric, geometry, surface expression, etc. Thus, hydro-geomorphology controls the groundwater potential of the Chennai Basin.

Major land use categories of the Chennai basin include, agriculture and waste land which accounts nearly 79 % of the total rainfall. The area that other land use categories cover are: Build up 291.13 km², Forest 397.14 km², Water bodies 430.75 km² and Mining and industries 112.78 km² (Micro Level Study 2007). There are about 652 large, medium industries and 92,381 small scale industries in the basin. The major crops grown in the basin are rice, food grains, and oilseed.

Chennai basin lies in a tropical monsoon zone and experiences four seasons namely, winter (January–February), summer (March–May), monsoon (June–September) and post monsoon (October–December). The monsoon season is also known as southwest monsoon and the post-monsoon is known as the northeast monsoon. The post-monsoon months account approximately 50 % of the total annual rainfall. Monsoon precipitation helps to improve the recharging of groundwater as well as storage of surface water.

3 Materials and Methods

A distributed hydrological model SWAT (ArcSWAT 2009.93.7b compatible with Arc GIS 9.3 version) has used in this study. The daily weather data from high resolution regional climate model are used to carry out the future simulations. The potential impacts of the climate change on water availability are quantified using the SWAT outputs with current and future climates.

3.1 Data Used

SWAT requires spatially distributed information on elevation, soil, slope and land use (Arnold et al. 1998). In addition to these, SWAT requires daily weather data which includes maximum and minimum temperature, rainfall, solar radiation, relative humidity. Types of data and their sources used in this study include;

- Digital Elevation Model—SRTM 90 m resolution, Shuttle Radar Topography mission (<http://srtm.csi.cgiar.org/>)
- Drainage network and Land Use maps—Institute of Remote Sensing, Anna University
- Soil map and associated soil characteristics map—Tamil Nadu Agriculture University
- Meteorological data—daily rainfall, maximum and minimum temperature, solar radiation, relative humidity and wind speed
 - High resolution IMD gridded data (1971–2000)—IMD Pune
 - Baseline (1961–1990), Mid-century (2041–2070) and End-century (2071–2098) climate scenario data—PRECIS

3.2 PRECIS (Providing Regional Climate Scenarios for Impact Studies)

PRECIS is an atmospheric and land surface model developed by Hadley Centre, UK Met office (<http://www.metoffice.gov.uk/precis/>). It runs on Linux based PC in the area of interest. The Centre for Climate Change and Adaptation Research, Anna University is the licensed user of PRECIS. For the first time in India, Centre for Climate Change and Adaptation Research, Anna University has developed high resolution (25 km resolution) future climate projections with PRECIS (<http://www.annauniv.edu/CCAR/precis.html>). UK Met office has provided the boundary data (HADCM3Q0-Q16) for 17 member perturbed physics ensemble 'QUMP' (McSweeney and Jones 2010). The selection of subsets of the 17 available QUMP members for India have been done based on their performance ability to project reasonable present day climate. The selected members were simulated under A1B scenario (a mid range emission scenario) for a continuous run till 2100. A1B scenario is characterized by a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies with the development of balanced across energy sources.

The outputs have been post processed and used for impact studies. The PRECIS grid points which cover the Chennai basin have been considered and processed for SWAT hydrological assessment (Fig. 3). PRECIS model outputs for three periods namely Base line (1961–1990 BL), mid-century (2040–2070, MC) and end-century (2071–2098, EC) were further processed with WGN Excel Macro to create weather input files readable by SWAT (<http://swat.tamu.edu/media/41586/wgen-excel.pdf>).

3.3 Hydrological Assessment and Simulation of Chennai Basin

Automatic delineation of the basin was done using SRTM 90 m DEM (Fig. 4). The sub basin threshold area was set to 532,745 h. Table 1 shows the land use categories and the area covered under each category.

The agriculture and settlements cover approximately 11 % of the total area (Fig. 5). Predomination of sandy loam, followed by lesser coverage by sandy clay; sandy clay loam, clay, sand and clay loam are observable in the basin. The Chennai Basin has moderate to gentle slope and nearly 88 % of the basin exhibit slope of 1 %. Nearly 10 % of the area has slope of 1–5 %.

The basin has been subdivided into 60 sub-basins for spatial aggregation (Fig. 6). Each sub-basin was further divided into hydrological response units (HRUs) which have unique combination of soil, slope, and land use. Then, the model was simulated to run a for control period to assess the present water availability in space and time without incorporating any man-made changes like dams,

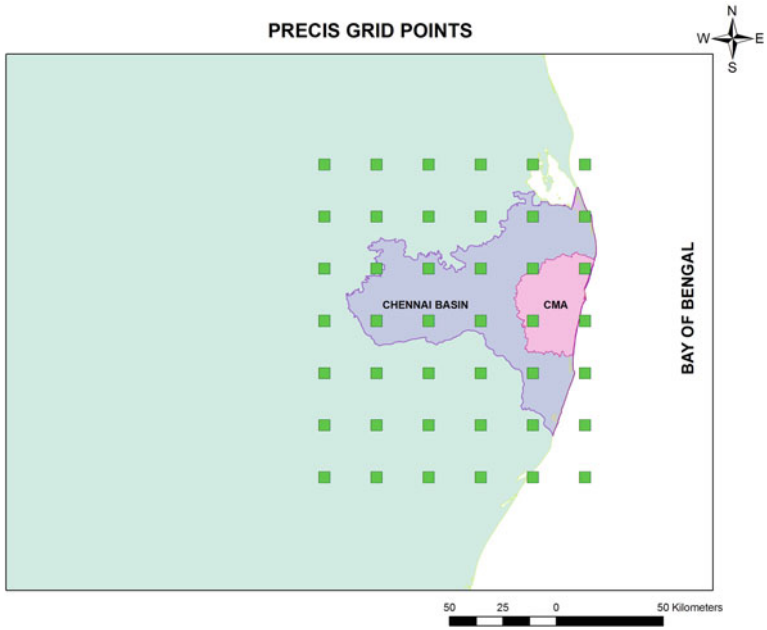


Fig. 3 PRECIS grid points covering Chennai Basin

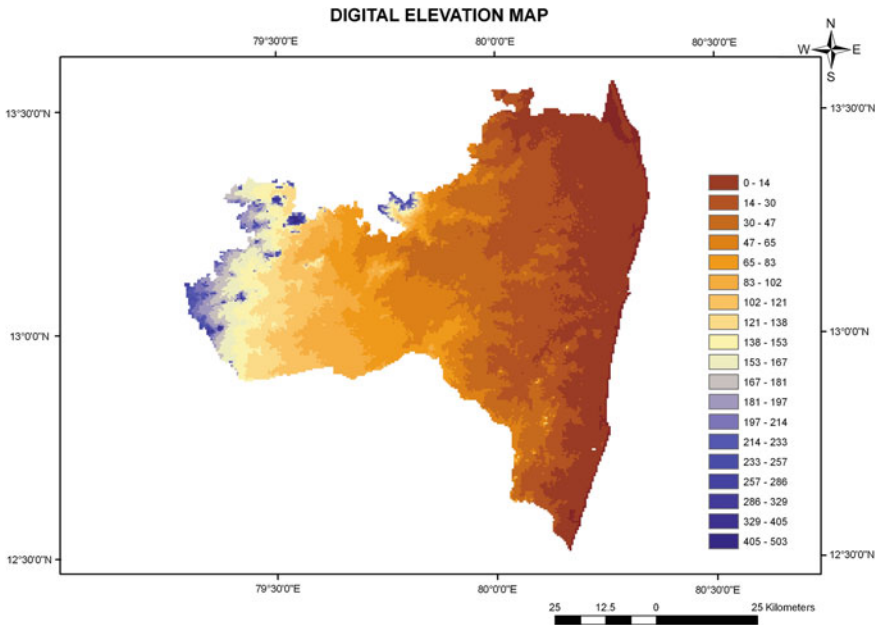


Fig. 4 Digital Elevation Map of Chennai Basin

Table 1 Land use categories of Chennai Basin

Land use	% on Total area	SWAT LU
Agricultural land-close-grown	34.27	AGRC
Agriculture land-generic	21.6	AGRL
Water	12.64	WATR
Pasture	8.89	PAST
Residential	6.81	URBN
Range-grasses	4.12	RNGE
Residential-low density	2.69	URLD
Forest-mixed	2.5	FRST
Forest-deciduous	1.51	FRSD
Agricultural land-row crops	1.26	AGRR
Wetlands-mixed	1.26	WETL
Institutional	0.96	UINS
Commercial	0.57	UCOM
Industrial	0.56	UIDU
Forest-evergreen	0.31	FRSE
Transportation	0.06	UTRN

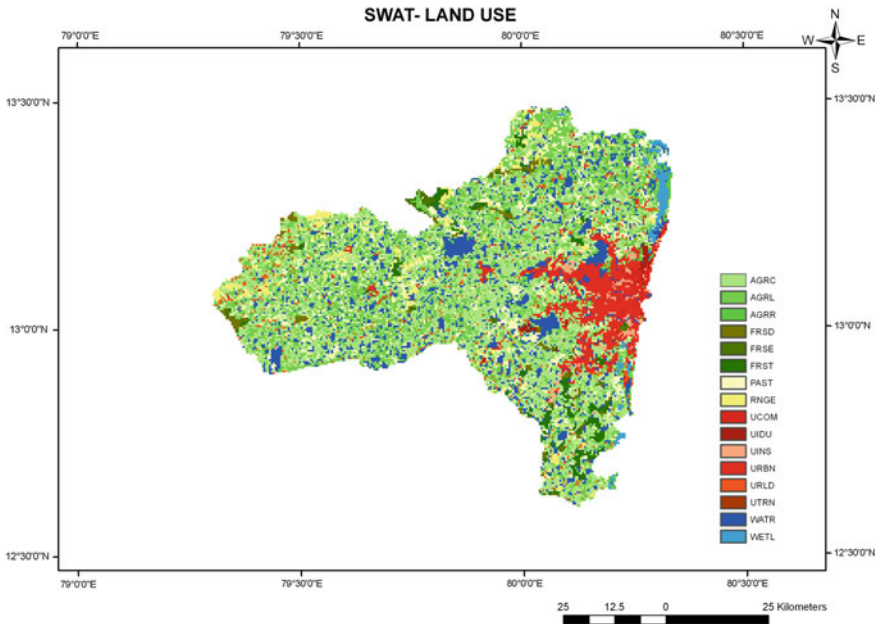


Fig. 5 Land use map of Chennai Basin

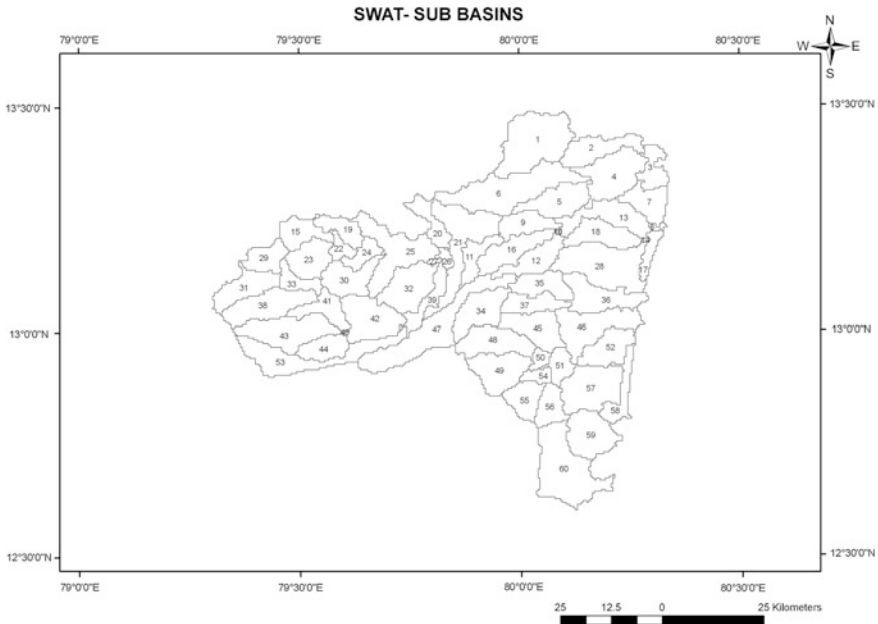


Fig. 6 Sub basin delineation of the Chennai Basin with SWAT using DEM

diversions, etc. The same framework was then used to predict the impact of climate change on the water resources with the assumption that the land use shall not change over time (Gosain and Sandhya 2012). Out of the 88 years of simulation, 30 years belong to IPCC SREA A1B baseline (1961–1990), 30 years belong to IPCC SRES A1B mid-century (2041–2070) and remaining 28 years belong to IPCC SRES A1B end-century (2071–2098) climate scenarios.

The model does not require elaborate calibration. The calibration is not meaningful, if simulated weather data is used for a control period, which is not the historical data corresponding to the recorded observed runoff (Gosain and Sandhya 2012). Hence, this study does not include calibration practice since it uses simulated weather data from PRECIS for the control period. The hydrological model SWAT generated very detailed outputs at daily intervals for each sub basin. Actual evapotranspiration, outflow, soil moisture, surface and subsurface runoff, ground water recharge are some of the main outputs available at daily intervals. These outputs simulated for all the three scenarios have been used for analyzing the possible impact of climate change on water balance components of the Chennai basin.

4 Results and Discussion

The impacts of climate change on the Chennai basin's water availability are calculated as changes from baseline in percentages. Table 2 shows the changes in water balance components from the baseline scenario (BL) to mid-century (MC) and end-century (EC) scenarios. From this table it is perceptible that there is a decrease in rainfall predicted over the basin due to climate change in MC as well as EC periods. In MC, there is about -14.3% decrease of annual precipitation and in EC the decrease of annual precipitation is -9.4% . Though both scenarios show decrease in rainfall, the decrease is less in EC when compared to MC and as a consequence; there is a decrease in the total water yield in MC, and EC scenarios and the ground water flow component in the Chennai Basin.

The annual evapotranspiration shows a slight decrease from BL scenario under increased GHG scenarios. But seasonal analysis shows an increase in rainfall during winter seasons till the end of the century. Post-monsoon season in end century also shows 11.7% increase of rainfall. Though the summer and monsoon seasons show decreasing trends, the decreases are severe in end century.

Figure 7 shows the changes in seasonal water balance components under IPCC SRES BL, MC and EC climate scenarios. In the future scenarios, ET will be increased in winter and post-monsoon season. When compared to the baseline, the ET has an increase of 12.3% in mid-century winter season and 16.7% in end-century winter season. In post-monsoon season it has increased to 9.5% in MC and 39.1% in EC climate scenarios (Table 3). The increase in ET will decrease soil moisture, which leads to severe agricultural drought. More frequent and severe droughts arising from climate change will have serious management implications for water resource users. Agricultural producers and urban areas are particularly vulnerable, as evidenced by recent prolonged droughts in the western and southern United States, which are estimated to have caused over \$6 billion in damages to the agricultural and municipal sectors. If the runoff season occurs primarily, water availability for seasonal crops will decline and water shortages will occur earlier in the growing season, particularly in watersheds that lack large reservoirs (Richard and Dannele 2008). ET will be decreased in summer and monsoon seasons. In MC, it shows a slight decrease to -8.2% in summer season and -5.0% in monsoon season. While in EC climate scenario, the decrease is more. In the summer season, it decreased to as low as -23.8% and in monsoon months to -17.9% .

Mean monthly value of water balance components for all the three climate scenarios are presented in Fig. 8. The ET values are higher during the monsoon months (August, July and September). The month of May shows lower ET. In mid century scenario, increases of $4.9, 7.3, 9.3, 6.5, 2.7, 5.8,$ and 0.9% ET for January, February, March, September, October and November months respectively. While April, May, June, July and August months show decreasing ET. The percentage decrease is $-2.5, -15, -0.2, -7.0,$ and -4 respectively. In the end century ET increase is much in December (Fig. 9). October and November months also show nearly 14% increase from baseline. During the month of August, not much change

Table 2 Chennai Basin's water balance for IPCC SRES A1B baseline, Mid-century, end century scenarios and the changes with respect to baseline scenario

Scenario	Precipitation (mm)	Change in % w. r.t BL	Water yield (mm)	Change in % w. r.t BL	ET (mm)	Change in % w. r.t BL	Shallow GW (mm)	Change in % w. r.t BL
BL	1081.89		561.14		493.05		339.52	
MC	927.48	-14.3	415.81	-25.9	491	-0.5	249.1	-26.7
EC	981.4	-9.4	464.33	-17.3	492.3	-0.2	262.82	-22.6

Negative change indicates decrease from baseline, positive change indicates increase from baseline scenario

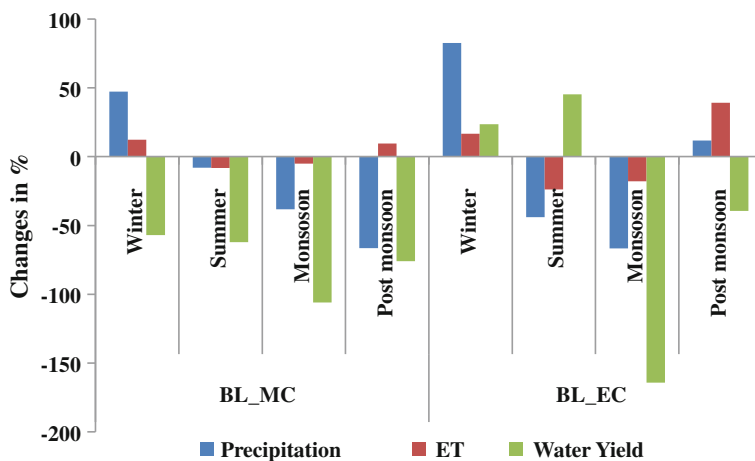


Fig. 7 Seasonal water balance components

Table 3 Season wise changes in water balance components

Changes from baseline	Seasons	Precipitation	ET	Water yield
		Changes in %		
BL_MC	Winter	47.3	12.3	-57.0
	Summer	-8.0	-8.2	-62.1
	Monsoon	-38.3	-5.0	-105.9
	Post monsoon	-66.4	9.5	-76.0
BL_EC	Winter	82.7	16.7	23.6
	Summer	-43.9	-23.8	45.3
	Monsoon	-66.6	-17.9	-164.2
	Post monsoon	11.7	39.1	-39.4

Negative change indicates decrease from baseline, positive change indicates increase from baseline scenario

in both mid and end centuries could be observed while decrease is more in the month of May, viz., -15 % in MC to -35 % in EC scenarios.

Normally, there is a decreasing tendency of water yield in both mid and end centuries. About -25.9 % reductions in MC and -17.3 % reductions in EC period are observed. There is a decrease in water yield in all the seasons of mid century scenario. But in the end century, water yield increases in winter (23.6 %) and summer seasons (45.3 %). This may be due to the increase of rainfall in winter season and decrease of ET in summer season. Water yield is very low in monsoon seasons of both MC and EC scenarios. The reduction of water yield is lowest in end century post monsoon period (Table 3). Although all the three major water

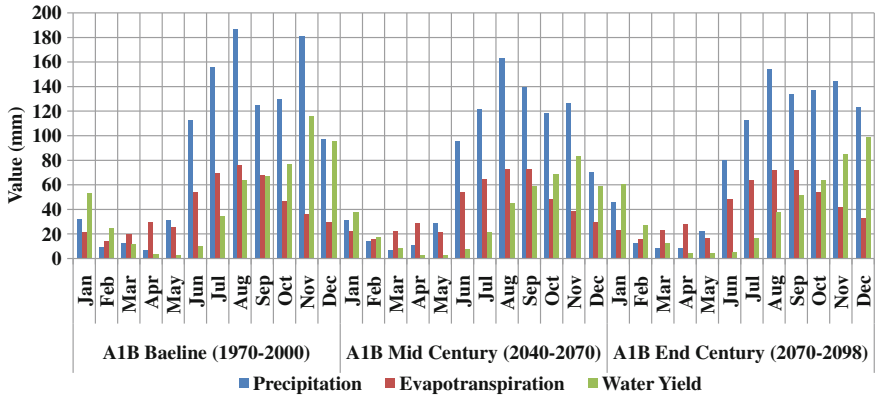


Fig. 8 Monthly water balance components

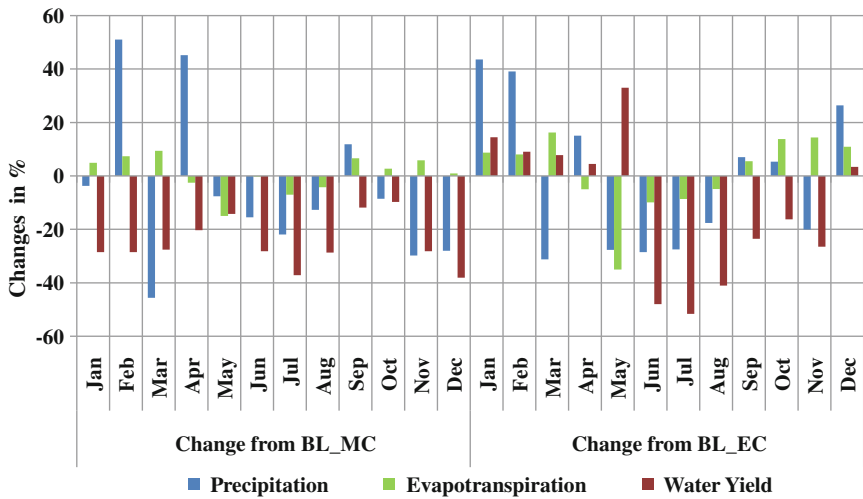


Fig. 9 Percentage change in mean monthly water balance components in MC and EC periods

components show decrease over MC and EC scenarios, the decrease is higher in mid-century when compared to end-century.

Effect of climate change on water balance components has also been analyzed spatially. The spatial distributions of precipitation, water yield, and evapotranspiration along with ground water recharge are analyzed for IPCC SRES A1B BL, MC and EC periods and are shown in the Fig. 10. The spatial variability of the components will help to identify the hot spots and to frame suitable adaptation strategies.

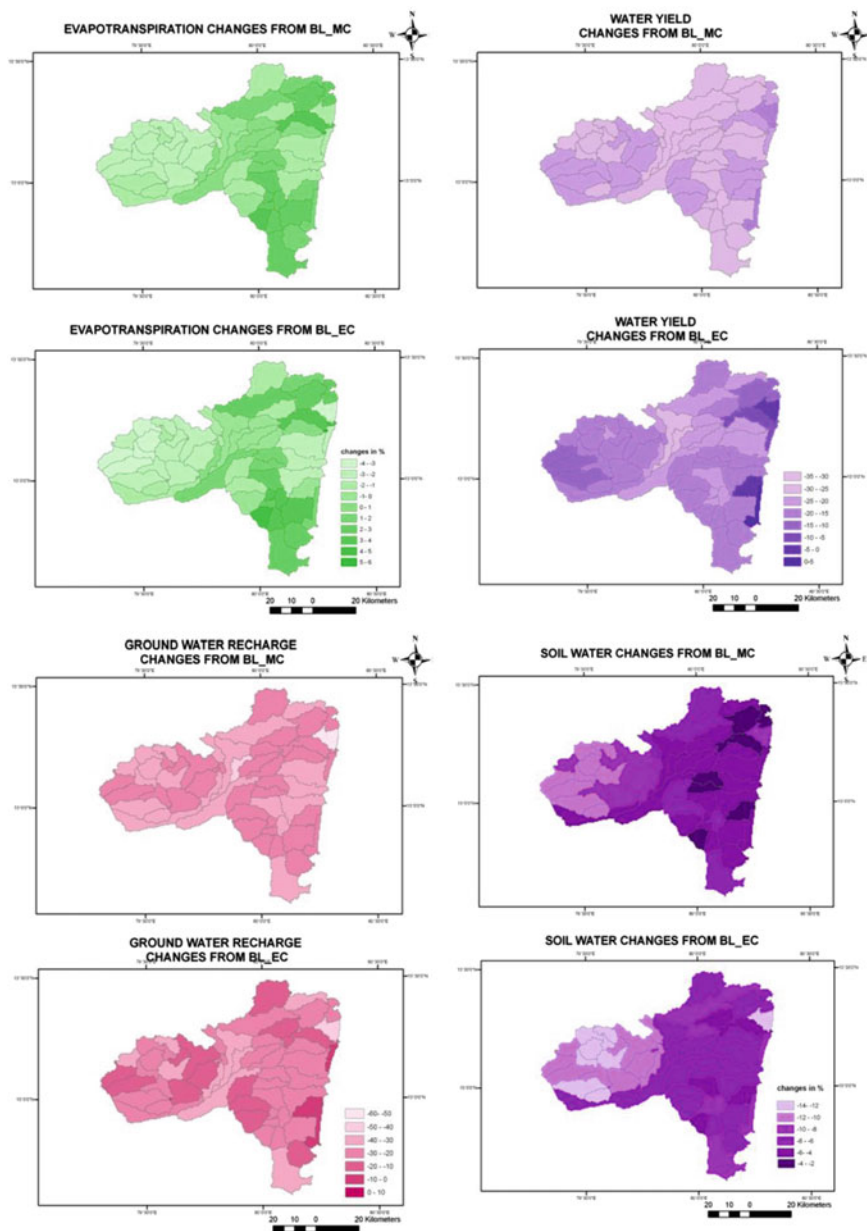


Fig. 10 Chennai basin's changes of water balance components under IPCC SRES AIB scenarios of MC and EC periods

5 Conclusions

- The model used in the present study has generated very detailed outputs at daily intervals and at sub-basin level.
- The results indicate an increase in evaporation rates and reduction of water yield that are expected to reduce water supplies. The greatest deficits are expected to occur in the post-monsoon season, leading to significantly decreased soil moisture levels, and more frequent and severe agricultural drought.
- Climate change is likely to exacerbate the degradation of resources and socio-economic pressures. The decline and degradation of the natural resources, resulted by the unsustainable rates of usage are likely to be aggravated due to climate change in the next 50 years.
- In Tamil Nadu, water supply-demand gap will be 14,100 MCM (504 TMC) (29.7 %) by 2025 (Palanisamy et al. 2011). Based on the model predictions for the Chennai basin, the climate change will increase this supply demand gap. Hence, the development and implementation of climate change adaptation strategies are essential.
- The present study also identifies the hotspots based on the spatial variability of water resource components, wherein site and measure specific water resource management practices have to be implemented.

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