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Climate Change and its Impact on Irrigation Water Requirements on Temporal Scale

Mohan S* and Ramsundram N*

Professor, Environmental and Water Resources Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India

Abstract

The natural processes and man-made disturbances in the watershed have influenced the micro climate and in turn affect the hydrology of the watershed along the time scale. The increase in emission of greenhouse gases into the atmosphere might induce variation in climatic pattern in the future. In hydrological models, the climatic parameters remain to be deterministic variables in simulating the surface water or groundwater components. In the recent past, climatological cycle and its variability have been incorporated into water resources systems modeling by many researchers. In this study, an attempt has been made to study the influence of climatic variability on irrigation water requirements in an arid region on a temporal scale, which will help in the water resource planning and management of an irrigation system. A climate crop water requirement (CCWR) integrated framework has been developed to estimate the irrigation requirement in Manimuthar river basin, Tamilnadu, India, incorporating variation in climatic parameters over temporal scale. Based on the existing land use pattern and economic development prevailing in the study area, the most likely climatic scenario has been identified as A1B. From the results, it is inferred that the irrigation water requirement is likely to increase by 5% from 2010 to 2020.

Keywords: Climate change; Crop water requirement; Arid region; Scenario analysis; Manimuthar basin

Introduction

The natural processes in any watershed can be influenced by changes in climatic variables and have long term impact on economic and ecological processes [1]. In general, climate change is defined as "the difference between long-term mean values of a climate parameter or statistic, where the mean is taken over a specified interval of time, usually a number of decades" [2]. The hydrologic cycle is a part of the climate system; the interactions between the components in the system give rise to the system complexity and this system complexity has been modeled as a) empirical model, b) water balance model, c) conceptual lumped parameter model and d) process based distributed parameter models [3].The models are then developed to replicate the hydrological cycle, the climate influence by considering the variability in the climate parameters. Intergovernmental Panel on Climate Change (IPCC) developed a global climate model (GCM) which forecast the future climate parameters. Incorporating the parameter values from GCM into hydrological cycle models will have the ability to visualize the impact of climate change on the system. The IPCC has stated that the average global surface temperature has increased by 0.45°C to 0.6°C and the average sea level has increased by 15 to 20 cm during last century [4].The IPCC has created climate scenarios such as (A1, A2, B1, B2 and their combinations) based on economic and environmental development conditions. The potential impacts of climate change for countries with temperate climate like India are; a) current water security problems are likely to increase by 2050, b) substantial impacts on agriculture and forestry are very likely by 2050, c) the current trends of glacial melts suggest that the snow fed rivers could likely become seasonal rivers in the near future and could likely affect the economics in the region [5]. As Southern and Eastern Asia is concerned, climate change increases runoff, but this may not be very beneficial in practice because the increase tend to come during the wet season and extra water may not be available during dry season [6].

Climate parameters (precipitation, temperature and carbon dioxide levels) changes can affect the demand for water as well as supply. Increased water use efficiency attributable to higher carbon dioxide levels, this may tend to increase frequency of water application as temperature rises [7]. Changes in water demand, irrigation practice will enhance the groundwater exploitation; this claim that climate change is likely to have dramatic impact on groundwater resources. From the analysis of rainfall data for 131 year period, it is observed that no clear role of global warming in the variability of monsoon rainfall over India [8]. Even though the above finding states that 'no impact of considering climate parameter for India', but it is worthwhile to consider the climate parameters to quantify the potential adverse impacts on water resources that may occur in future time periods. In India, precipitation has always been extremely variable, with the number of annual rainy days varying from 12 to 100 and there are rain events that have poured about 60% of the total annual precipitation within few hours. It is projected that due to climate change, the inter-annual variability of the monsoon is expected to increase. Also, the rainy days will be less with concentrated rain within a few hours and increase in dry spells [9]. The above said likely impact may create excessive runoff within a short period, thereby reducing the groundwater recharge potentials [8].This excessive runoff in addition may influence the flooding frequency in the watershed, and also increase in dry spells may increase the frequency of drought in the watershed [7]. As the climate parameter (temperature) increases, the atmosphere air gets warmer thus the warm air accelerates the evaporation from soil moisture [8,10]. Irrigation practice or schedule depends on the frequency and quantity of irrigation water required based on the type of crop and rainfall precipitated over the time period. Evapotranspiration governs the crop

***Corresponding author:** Mohan S, Professor, Environmental and Water Resources Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai-600036, India, Tel: 91-9444837600; E-mail: smohan@iitm.ac.in

Ramsundram N, Research Scholar, Environmental and Water Resources Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai-600036, India, E-mail: nramsundram21@gmail.com

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water requirement estimation; Hargreaves et al. [11] recommended a procedure for estimating crop water requirements that only require the measurement of maximum and minimum temperatures. The most popular evapotranspiration estimation procedure is through Penman-Monteith equation, [12] evaluated the Penman-Monteith equation to develop general relationships for estimating daily average values of canopy and aerodynamic resistance parameters. Committee on irrigation water requirements of the Irrigation and Drainage Division of the American Society of Civil Engineers Jensen et al. [13] prepared a manual summarizing all available procedures for estimating irrigation water requirements. Allen et al. [14] Developed an irrigation water requirement estimation a stepwise procedure incorporating improved or modified Penman-Monteith equation considering aerodynamics and stomata opening into evapotranspiration modeling (FAO paper 56).FAO paper 56 formed the basis for estimating the crop water requirement; the Penman-Monteith equation requires information climatic parameters such as air temperature, wind speed, and humidity. The Penman-Monteith equation also requires information on meteorological parameter rainfall that precipitated during time't'. The climatic parameters are subjected to variability based on the atmospheric concentration (composition of greenhouse gases). These lead researchers to study the influence of climatic variability in crop water requirement estimation. In the recent past few research works [15-18] integrated the future climatic variations forecasted by Global Circulation Models (GCMs) within there modeling framework to study the climate change influence on crop water requirements. The developed integrated models, differs in the type of downscaling technique utilized for projecting regional climatic conditions simulated by GCMs to local scale, and also differs in the model used for estimating the crop water requirement.

One of the major findings of Mall et al. [8] is that, the influences of climate parameters in arid and semiarid climatic region are not very significant. This finding or statement might be valid at regional level (India) but may not true at local or micro scale. In this paper an attempt has been made to study the variability in climatic parameters on crop water requirement estimation in an arid region. An integrated framework has been developed and applied to case study Manimuthar basin located Tamilnadu, India.

This paper has been organized in a stepwise procedure starting with the basics of reason behind climatic change, what scenarios are, and what basis emission scenarios are developed. After the introduction of climatic scenarios, what global circulation model (GCM) has been chosen for this study and underlying reason behind the choice of GCM. To achieve the desired objective of the study an integrated climate crop water requirement (CCWR) framework has been developed and the same has been described in detail. With the description of the developed CCWR framework the same has been applied to the case study Manimuthar basin, Tamilnadu, India. The session on case study has been written to summarize the details about the study area. The developed CCWR framework has been allowed to analyze the study area database and interpretation of the outcomes have been discussed in the session on results and discussion. The final research findings and remarks are emphasized as conclusions of this study.

Climatic Scenarios

Global warming is caused primarily due to increase in carbon dioxide emission into the atmosphere from fossil fuel burning and deforestation activity. The increase or decrease in carbon dioxide concentration in the atmosphere might influence the global and local climatic conditions. Future GHG emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socioeconomic development, and technological change [19]. Their future evolution is highly uncertain. Scenarios are alternative images of how the future might unfold and area an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess associated uncertainties [19].The intergovernmental panel on climate change (IPCC) has developed a set of future greenhouse gas (GHG) emission scenarios known collectively as SRES (special report on emission scenarios).The IPCC has grouped future emission scenarios as four major classes or groups, namely; a) A1, b) A2, c) B1, and d) B2 based on level on economic development and environmental concern. Table 1 summaries the aspects considered in developing the future GHG emission scenarios in IPCC-TGCIA [20]. From Table 1, it can be observed that scenario group or classes A1 and A2 are concerned more about activities which will improve the economic development of the world, B1 and B2 are concerned more about environmental sustainability of the world.

An Overview on Climate Models (GCMs)

General Circulation Models (GCMs) predicts the future 100 years climatic parameters using the equation of motion. The predictions of climatic variables in GCMs are classified as eight climatic scenarios [21] based on carbon dioxide (CO_2) emission level ranging from very low to high. Very low CO_2 emission indicates that the scenario has more consideration of environment conservation and low economic development, whereas high CO_2 emission indicates maximum economic development (industrialization, urban growth) and minimum concern to environmental concern. Table 2 summarizes some of the popular GCMs developed by various research laboratories across the world. Every GCM (Table 2) has its unique grid resolution

Scenario Classes	Concerns	Remarks
A1	• Rapid economic growth • Low population growth • Rapid new technology • Concern to wealth rather than environment	• Homogenous world on economic development • Cultural convergence • No difference in per captia income
A2	• High population growth • Strengthen regional cultural identities • Less concern for economic development compared to A1	• Differential world on economic development
B1	• Dematerialization of economy • Introduction to clean technologies • Efforts for rapid technology development	• Convergent world • Global solutions for environmental and social sustainability • Improving equity
B2	• Diverse technological change • Emphasis on community initiative • Concern on environment rather than economic development	• Heterogeneous world • Local solutions for environmental and social sustainability

Table 1: Climatic Scenario Classes.

Model	Resolution(lat/lon)	Description of model
CGCM1	Atmospheric component: ~3.7° x 3.7° Ocean component: ~1.8° x 1.8°	Flato et al., 2000
HadCM2	2.5° x 3.75°	Johns et al., 1997
HadCM3	2.5° x 3.75°	Gordon et al., 2000 Pope et al., 2000
RegCM2	~50 km	Giorgi et al., 1993a, b
ECHAM4	~2.8° x 2.8°	Roeckner et al., 1996

Table 2: GCM models used for water resource problems.

and global area coverage. Among the eight reported scenarios, many of the researches prefer to observe the impact of climate change for A2 and B1 scenarios [21,22]. The selection of these two scenarios is due to 'A2' represented strong economic values and 'B1' represents strong environmental value.

The selection of a particular GCM model is based on the grid resolution that is required for modeling and the purpose for which the researcher is modeling the climatic scenario. For example, if the purpose is to estimate the irrigation requirement in the watershed over the time period, then the GCM has to be selected based on which GCM is considering the vegetation characteristics in is climatic variable prediction. The best suited GCM model for water resource will be HADCM and CSIRO which considers the vegetation characteristics. For this study climatic parameters are taken from HADCM3 model, which has a spatial resolution of 2.5×3.75 (latitude by longitude) and grid resolution of 250 km×320 km.

Climate Crop Water Requirement (CCWR) Integrated Framework

To the study the influence of variation in climatic parameters (Temperature, Wind direction, and humidity) on the irrigation water requirement on temporal scale, climate crop water requirement (CCWR) integrated framework has been developed (Figure 1). The CCWR framework integrates the crop water requirement model (CROPWAT) and spatial climate variable downscaling technique developed by Maurer et al. [23].

Climatic variable downscaling technique

Global climate model output, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset [24], were obtained from www.engr.scu.edu/~emaurer/global_data/. These data were downscaled as described by Maurer et al. [23] using the bias-correction/spatial downscaling method [25] to a 0.5 degree grid, based on the 1950-1999 gridded observations of Adam and Lettenmaier [26].

Irrigation demand estimation module

The irrigation requirement for various crops in the command area has been estimated using the irrigation demand estimation module (Figure 2). The data required for irrigation demand estimation module area) the precipitation that has occurred, b) prevailing climate variables (wind speed, relative humidity, maximum and minimum temperature, and sunshine hours), c) cropping pattern (time of sowing, harvest), and d) type of soil (field capacity, moisture content).

From Figure 2, it can be observed that the module begins with an estimation of excess rainfall for the rainfall that has occurred in the command area. The process is followed by estimation of the crop water requirement of the available crop types in the study area. In this research the crop water requirement for the type of crop and cropping pattern has been estimated using CROPWAT package. CROPWAT uses FAO Penman-Monteith model [14] (equation 1) for estimating reference Evapo-transpiration.

FAO Penmann-Monteith Model to estimate reference evapo-transpiration (ET_o),

$$ET_o = \frac{\left(0.408\Delta(R_n - G)\right) + (\gamma \frac{900}{T+273} u_2(e_s - e_a))}{\Delta + (\gamma(1 + 0.34u_2))} \quad (1)$$

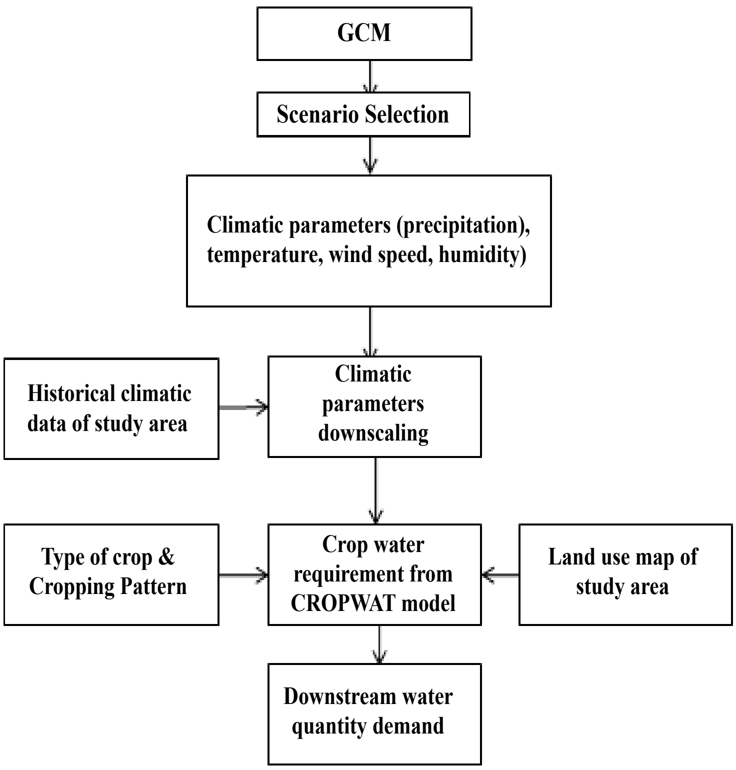

Figure 1: Climate crop water requirement (CCWR) Framework.

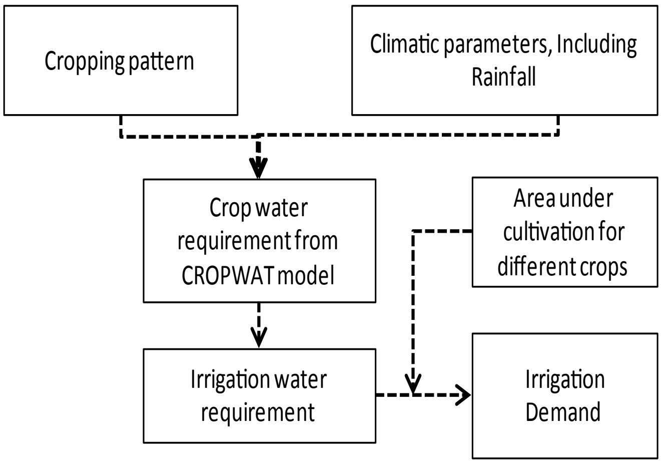

Figure 2: Irrigation Demand Estimation Module.

where,

ET_o = reference evapo-transpiration (mm / day)

R_n =net radiation at the crop surface (MJ/ sq.m /day)

G = soil heat flux density (MJ/ sq.m/ day)

T = air temperature at 2 m height (°C)

u_2 = wind speed at 2 m height (m/s)

e_s = saturation vapor pressure (KPa)

e_a = actual vapor pressure (KPa)

e_s-e_a = vapor pressure deficit (KPa)

Δ = Slope vapor pressure curve (KPa/ °C)

γ = psychometric constant (KPa/ °C)

The crop water requirement for every crop in the command area has been based on the crop coefficient (K_c) and estimated T_o as equation (2).

$$CWR_i = (kc_i ETo_i) \quad (2)$$

Net irrigation water requirements (NIR) for a given year are thus the sum of individual crop water requirements (CWR_i) calculated for each crop 'i'.

$$NIR = \sum_{i=1}^{n} (CWR_i - P.eff) \quad (3)$$

where, 'P.eff' is the effective precipitation after satisfying the infiltration capacity.

Gross irrigation water requirements (GIR) give the overall water requirement for the crop to grow from the time of sowing to the date of harvest.

$$GIR = \frac{1}{E} NIR \quad (4)$$

Where, E is the efficiency of the irrigation system practiced in the command area. In the above irrigation water requirement module, among the variables temperature and precipitation are identified as the important climatic variables. The variability in temperature might affect the atmospheric gradient there by influencing the rate of evapo-transpiration. Variation in temperature is proportional to the precipitation variation in a spacial and temporal scale. From common belief, solar radiation plays a major role in influencing the global surface temperature. But, U.S. climate research program, 2001 has found that, solar radiation received by earth does not influence the global surface temperature. So, in this study net solar radiation has not been considered as a influencing variable in modeling crop water requirement.

To incorporate the temporal variation in the identified climatic parameters, the output of GCM is downscaled to the field grid level. The GCM model simulates the climatic parameters for various climatic scenarios. As described in 'Overview of GCM', the HADCM3 GCM model outputs for scenario A2 (Continuously increasing population, regionally oriented economic development), B1 (Rapid economic growth as in A1, Reductions in material intensity and the introduction of clean and resource efficient technologies) and A1B (balanced emphasis on all energy sources.) Are utilized for this study to predict the future crop water requirements.

Case Study

Tambraparani River Basin lies between geographic co-ordinates latitude 8°26'45" to 9°12'00" N and longitude77°09'00" to 78°08'30" E. The entire basin covers an area of about 5665 sq. km and lies in the revenue districts of Tirunelveli and Tuticorin in southern Tamil Nadu. Figure 3 presents the Tambraparani river basin with multiple sub basins. For this study, Manimuthar one of the sub basin in Tambraprani river basin has been chosen. The Manimuthar originates (numeric 2 highlights Manimuthar basin in Figure 3) from the Mukkuttukal and confluence with Tambaraparani at its 36th km. The major reservoir constructed in the basin across Manimuthar is the Manimuthar reservoir. The irrigation farm fields are located at the downstream of Manimuthar reservoir. The Manimuthar reservoir has an irrigation command area of 161.61 sq.km.

Results and Discussions

From Figure 1, it can be observed that the climatic scenario selection is the first and foremost process in any climate impact analysis. In developing countries, the most commonly used climatic scenarios are; a) Scenario A2, and b) Scenario B1 representing the economic development and environmental concern / protection respectively. Modeling for these two scenarios crudely might miss lead to over or under prediction of actual. To overcome the crude way of selecting scenarios, in this study an exercise has been incorporated for understanding the change in land use pattern in the study area over a period of 30 years. From the analysis, it was observed that Manimuthar basin has a vegetative land cover and very minimum urban and industrial development. It can be observed from the geographic location that catchment of Manimuthar reservoir is majorly covered by hilly terrain. From this, it can be inferred that, there is no much change in land use pattern, so it is most suitable to choose climatic scenarios which are developed based on less CO_2 emission and more dependability on environment conservation [27,28]. The more suited scenario for this basin will be B1, in next 20 years if there is adverse economic development then it is reasonable to model for A1B scenario. To compare with the extreme condition, A2 scenario also has been chosen for modeling.

The climatic parameters of the respective scenarios are downscaled to field grid scale and coupled with crop water requirement estimation model (CROPWAT). Figure 4 shows the temperature prevailing at Manimuthar basin for various scenarios. Table 2 shows relative

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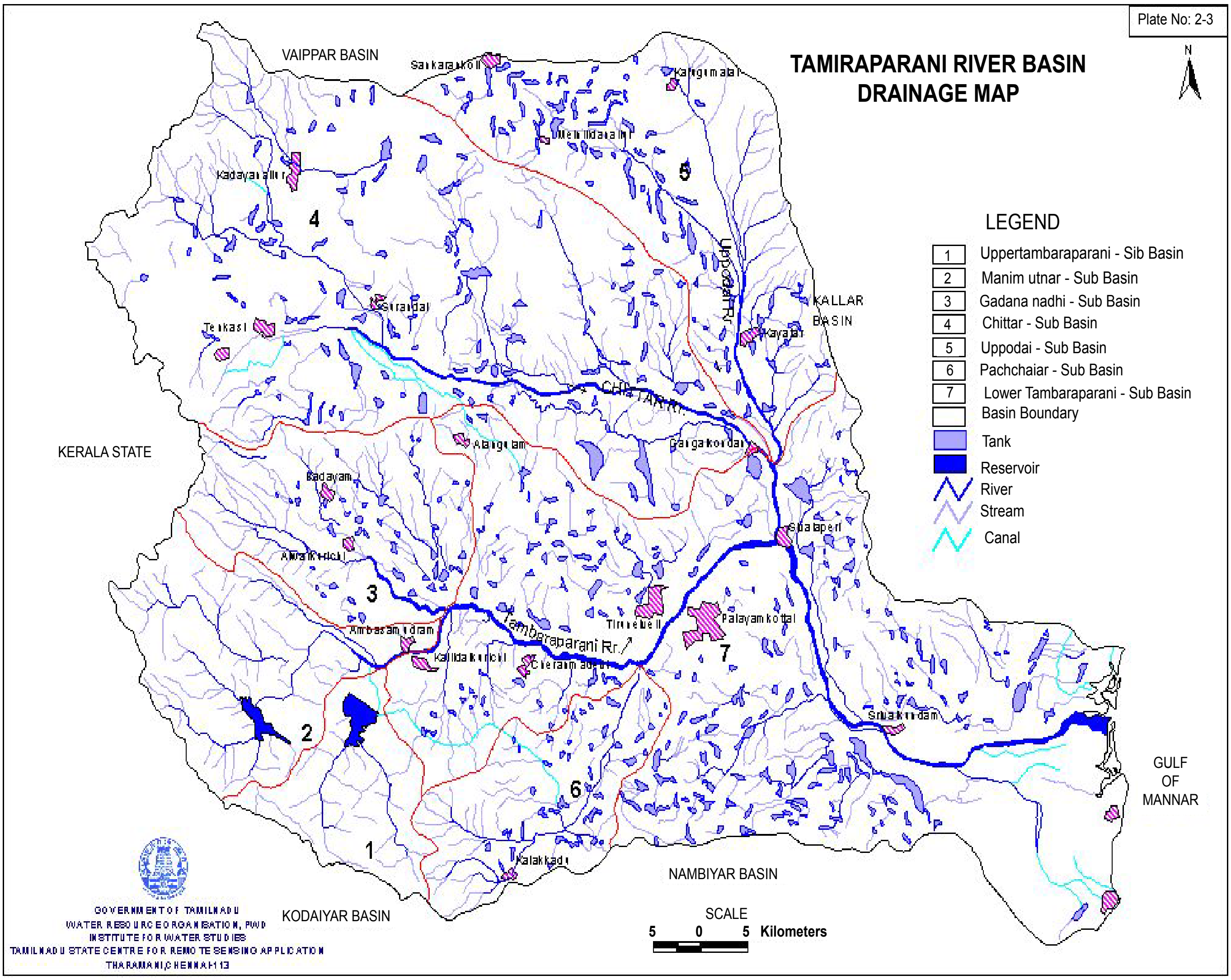

Figure 3: Tamiraparani River basin (numeric 2 in map represents Manimuthar basin)(source: IWS Report).

temperatures for year 2020 and 2050 with reference to the year 2010. From Table 2 an interesting phenomenon of scenarios behavior can be observed, i.e., scenario B1 is more about integrated world, once the population reaches 9 billion, the population will start reducing, and also B1 introduces clean and energy efficient technologies this phenomenon can be observed from the annual average temperature rises by 0.86°C relatively in year 2020 and then the temperature reduces to 0.66°C relatively in 2050 as emission reduces (scenario assumption). Similarly, assumptions of scenario's A2 and A1B are resembled in Table 3.

When we look at the precipitation corresponding to temperature variations for various scenarios, Table 3 might mislead the interpretation at annual scale. In Table 3, the comparative analysis of temperature and corresponding precipitation of scenario B1 and A1B mislead to conclude that as the temperature decreases the precipitation increases. Thus the inferred concept is not logical, as the atmospheric gradient increases as temperature increases and condensation occurs at a faster rate thereby resulting in an increase in precipitation quantity. To have insight into the above concept, the seasonal variations for various scenarios are summarized in Table 4. In Table 4, during summer season of Scenario A2, as temperature increases precipitation also increases. But, in southwest monsoon season, the inverse phenomenon can be seen, i.e., as temperature decreases, precipitation increases. Similar kind of mechanism can be seen in the other two scenarios too [29]. From basic hydrological concepts and atmospheric science, it is understood that wind direction is also a major component in creating atmospheric gradient (Table 4).

The climatic and meteorological parameters are used in irrigation requirement estimation module to predict the future crop water requirements. Figure 5 shows the irrigation water requirement for the Manimuthar command area for various climatic scenarios. From Figure 5a, it can be observed the variation in irrigation water requirement for A2 (extreme economic development) scenario for different months in a year. Similarly, Figure 5b and 5c show the irrigation water requirement for various months in a year for scenario B1 and A1B respectively. From the comparative analysis of water requirements of A2 and B1 (extreme scenarios), it can be inferred that during the year 2050 i.e., when industrial development is assumed to be attained its saturation that is maximum CO_2 emission the irrigation water requirement increases

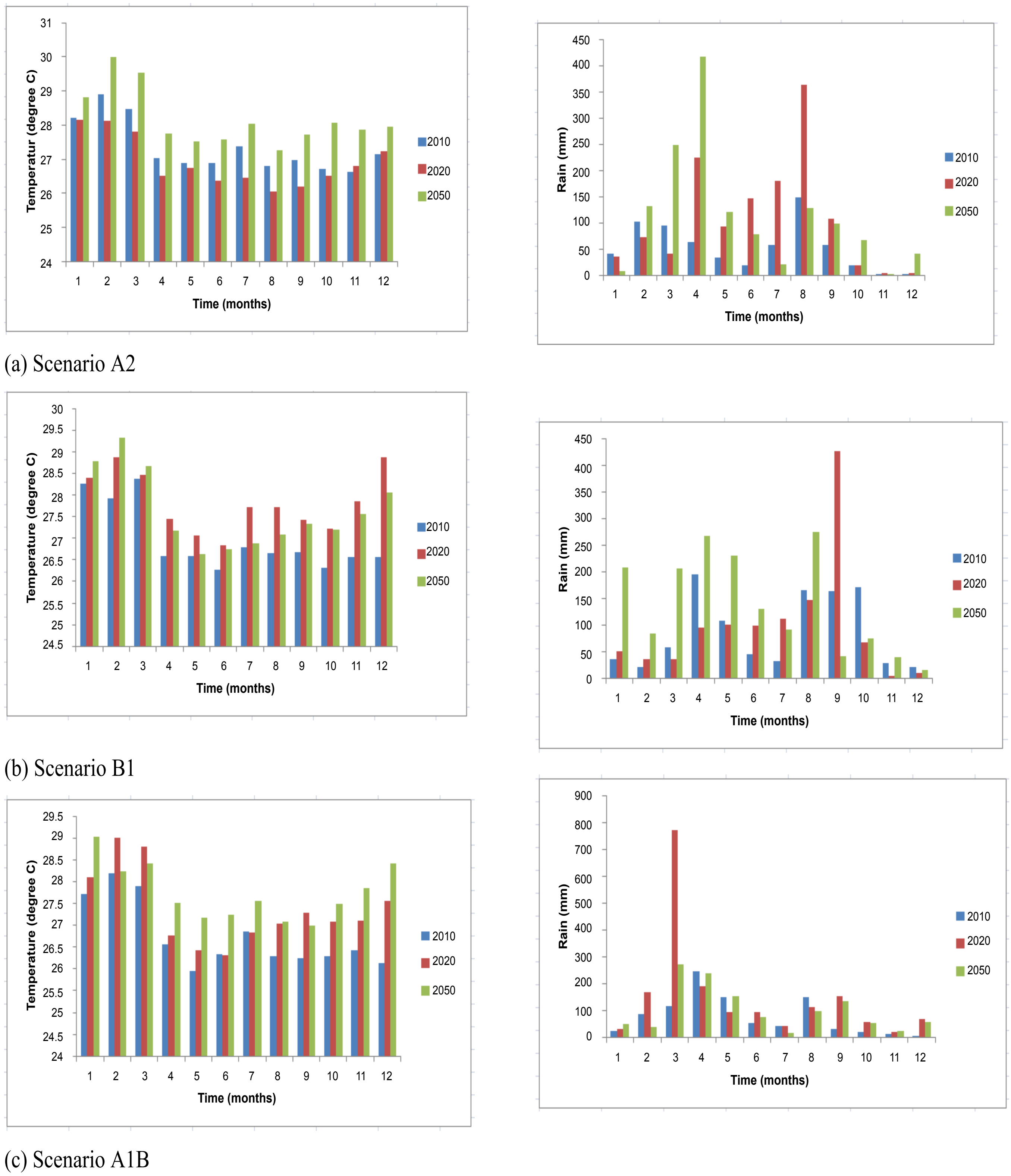

Figure 4: Temperature and corresponding precipitation at Manimuthar sub-basin for various climate scenarios.

adversely compared to irrigation water requirement of scenario B2. With the increase in irrigation water requirement during year 2050 of scenario A2 is contributed by a decrease in rainfall during the respective time periods (Figure 4a). The neutral scenario A1B, where there is balance between economic development and environmental concern, except during the summer season in all other months the

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Scenario\ Year	Temperature relative to 2010 °C)		Precipitation Relative to 2010 (%)	
	2020	2050	2020	2050
A2	-0.42	0.84	100.35	110.93
B1	0.86	0.66	13.51	59.94
A1B	0.61	1.00	94.36	30.01

Table 3: Annual relative variation of climatic parameters with reference to year 2010.

Scenario	Monsoon/ Year	Avg. Rel. 2020 temp(°C)	Avg. Rel. 2050 temp(°C)	Cuml. Prcp.2020 (mm)	Cuml.Prcp.2050 (mm)
A2	Winter	-0.42	0.84	107.10	139.43
	Summer	-0.45	0.79	359.76	785.24
	South West	-0.74	0.66	798.02	324.84
	North East	0.02	1.14	27.89	111.56
B1	Winter	0.54	0.97	85.01	292.21
	Summer	0.48	0.32	231.09	704.18
	South West	0.82	0.42	782.48	537.49
	North East	1.50	1.13	81.98	129.53
A1B	Winter	0.59	0.67	198.82	85.96
	Summer	0.52	0.88	1052.15	663.64
	South West	0.43	0.79	403.07	321.45
	North East	0.96	1.64	143.55	131.35

Table 4: Seasonal relative variation climatic parameters with reference to year 2010.

change in irrigation water requirement is almost same during the year 2020 and 2050.

Table 5 summarizes the relative change in irrigation water requirement across temporal scales for various scenarios compared to irrigation water requirement during year 2010. It can be observed from Table 5 that if there is adverse development of industries in the Manimuthar basin (A2 scenario) then that might increase irrigation water demand by 25% during year 2020 and 15 % during year 2050 compared to the present condition (year 2010). If there is Manimuthar basin has not been subjected to any industrial revolution on urban migration, and continues to be a vegetative land use pattern by the year 2050 there might be an increase in irrigation demand by 20 % compared to present irrigation water requirement. This additional water requirement might be due to increase in vegetative growth. During balance or neutral scenario A1B, the irrigation water requirement achieves a saturation demanding an increase of 5% in irrigation water requirement of the year 2010.

In general, it can be inferred that crop water requirement is inversely proportional to the quantum of rainfall precipitated across the basin. From the results, it can be inferred that A2 scenario reflects the extreme or peak water requirements in the Manimuthar basin. As highlighted in the scenario selection, identification of proper scenario with respect to field condition is more essential for increasing the dependability on the predictions. From the geographic location and existing development activities in Manimuthar basin, it can be that certain that probability of extreme industrial development is very less. Similarly, chance of no urbanization or economic development is also very less. It is worthwhile to depend on the predictions made for climatic scenario A1B.

Conclusions

Increasing population and fast economic development increase the emission of CO_2 in the atmosphere, thereby accelerating global warming and its adverse effects on climatic conditions. In the recent past, one of the most research areas of interest among researchers is to study the influence of climate change on natural resources and to develop strategic mitigation measures. As a part of the above research direction, the current study has been conducted to analyze the impact of

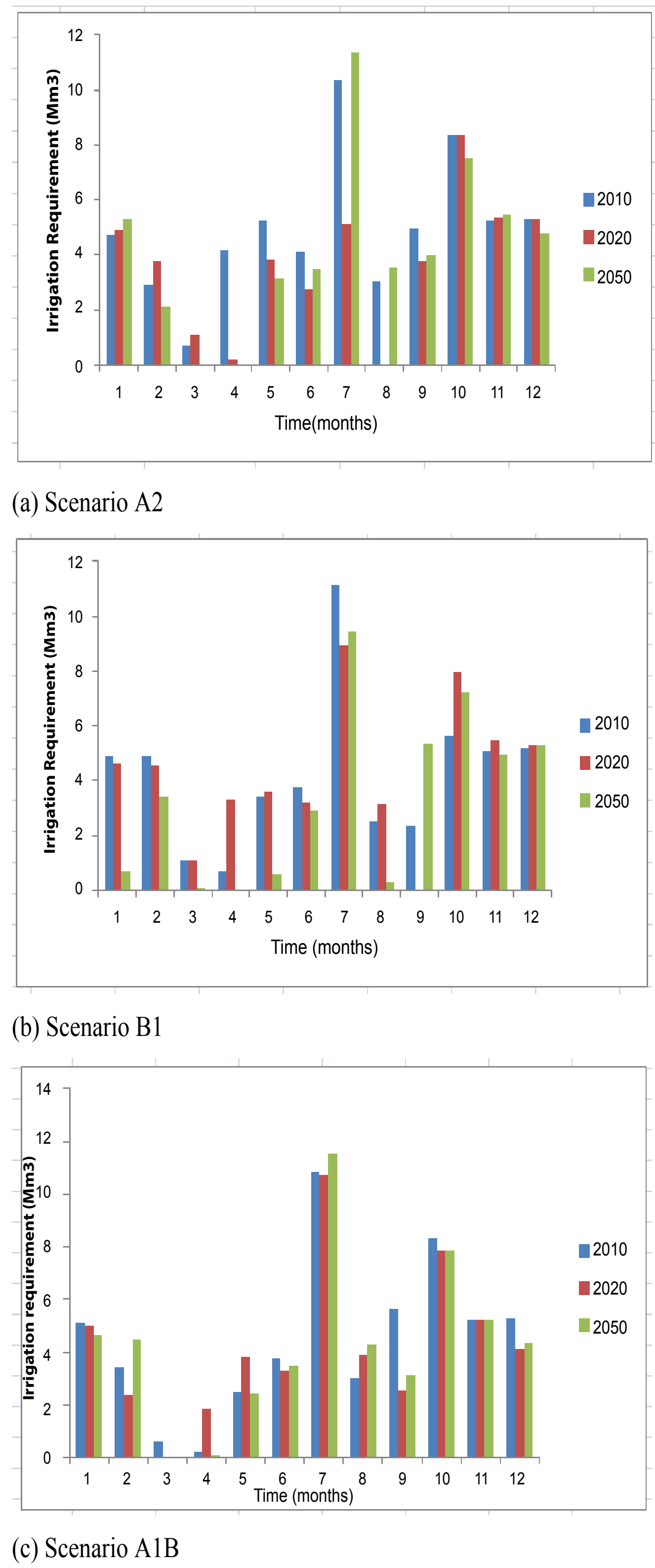

Figure 5: Irrigational requirement for Manimuthar command area.

Scenario/Year	Annual Irr. Req relative to 2010 (%)	
	2020	2050
A2	24.72	14.16
A1B	5.98	4.63
B1	-0.90	20.46

Table 5: Annual relative irrigational requirement with reference to year 2010.

climate change in arid regions on the crop water requirement over time period. In general, it is observed that wind direction also plays a major role as like air temperature on the spatial variability of precipitation across a basin. From case study application, it can be concluded that;

a) Climatic Scenario A1B will be more suitable scenario for Manimuthar basin considering the existing land use and recent development activities that are occurring in the basin.

b) Generalization of results on climate change based on regional modeling may not be suitable for climate modeling. From the results it is inferred that generalization by Mall et al. [8] is not valid for local scale, as the change in climatic variables has contributed to increase in crop water requirement in future years (2020 and 2050).

It is concluded that climate change studies have to be conducted to assess the risk associated with water resources based on future variability in climate and meteorological variables. This assessment has to be done based on proper selection of climatic scenarios based on the land use pattern and most probable economic development that may occur in the study area for which assessment has to be made.

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