Hydrological Modeling in a Changing Climate: Issues in Indian Context

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ABSTRACT:
This paper addresses the relevance of the non-stationary assumption in the hydro-meteorological data used for hydrological modeling under varying climate changing conditions. The water resources potential with the drainage area details of the 12 major river basins in India are discussed. The quantification of impact of climate change on the hydrological and water resources of selected river basins in India is presented. The application of Thomas-Fiering model for flow predictions of SRSP reservoir under climate changing conditions has been presented.

1. INTRODUCTION

The climate change will lead to an amplification of the global hydrological cycle and can have major impacts on regional water resources, affecting both ground and surface water supply (Intergovernmental Panel on Climate Change (IPCC), 2007). The extensive anthropogenic changes in earth's climate have been reported to be altering the means and extremes of precipitation, evapo-transpiration, and discharges of rivers. The urbanizations, channel modifications, drainage works, land-cover and land-use practices may lead to changes in the mean and variance of the flood series, flood risk, water supply, and water quality etc. Many hydrological issues such as estimation of future stream flows, predictions in ungauged basins, ground water potential estimations, urban flood modeling, operation of single and multi-purpose multi-reservoirs, environmental planning, etc. have become complex issues under climate and land use change. In this context, the impact assessment of climate change on hydrological and water resources have become a great interest to the hydrological research and water management communities. Over the years, wide verities of hydrological models have been developed to prepare the hydrological estimates under varied regional climate scenarios. These hydrological estimates are very much essential for the design and operation of various hydraulic structures such as dams, weirs, barrages, canals and urban drainage systems etc. Indeed, climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions (IPCC, 2007).Traditionally, the hydrological design practices assume that the hydro-meteorological data such as precipitation, temperatures, wind speeds, and stream flows are stationary (Goel, 2010; Murray and Gunter, 2011).However, there are many physical and varied climate changing factors that may possibly lead to non-stationary in the hydro-meteorological data. In order to get the accurate hydrological design estimates, it is imperative to assume the hydro-meteorological data as a non-stationary component in the hydrological modelling (Goel, 2010). However, the quantification of climate change impact using the non-stationary assumption in the hydrological data is a complex issue. It requires modifications in the conventional hydrological modeling practices. For this purpose, the existing hydrological modeling practices need to be reviewed and necessary modifications have to be incorporated. The present study emphasizes necessity of the non-stationary assumption in the hydrological modeling practices and also presents some of the selected example studies made for the quantification of impact of climate change on water resources of Indian river basins.

2. CLIMATE CHANGE SCENARIO IN INDIA

The UNFCCC (United Nations Framework Convention on Climate Change) defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". Climate change is not only a major global environmental problem, but also an issue of great concern to the Indian country (MWR, 2008). Climate change occurring mainly due to human activities. India being the second largest populated country in the world the climate change is quite frequent due to human activities. Changes in the climate are already causing floods, heat waves, cyclones, rising sea levels, changes in monsoons, decrease in snow cover, adverse affects in forests, unpredictable weather and changes in temperature. Hence, it is imperative for India as a nation to realize the importance of this aspect and make holistic endeavors to work towards resolving these concerns.

2.1 Temperature

The inter-governmental panel on climate change has projected that the global mean surface temperature is predicted to rise by 1.1–6.4°C by 2100 (IPCC, 2007). An analysis of temperature data of all over India shows an increase of 0.42^0 C, 0.92^0 C and 0.09^0 C in annual mean temperature, mean maximum temperature and mean minimum temperature, respectively in last 100 years (MWR, 2008). However, the trends are varying on regional basis. It has been observed that the changes in temperature in India/Indian-subcontinent over last century are broadly consistent with global trend of increase in temperature. The mean temperature in India is projected to increase up to 1.7 º C in kharif (July to October) and up to 3.2 ºC during rabi (November to March) season (Pathak et al., 2012). Table 1 shows the future projection of increase in temperature and changes in precipitation over Indian subcontinent.

Table 1. Climate change projections for the Indian sub-continent

Scenarios		Increase in temperature (°C)	Change in rainfall (%)
2020s	Annual	1.00 – 1.41	2.16 – 5.97
	Winter	1.08 – 1.54	(-)1.95 – 4.36
	Monsoon	0.87 – 1.17	1.81 – 5.10
2050s	Annual	2.23 – 2.27	5.36 – 9.34
	Winter	2.54 – 3.18	(-)9.22 – 3.82
	Monsoon	1.81 – 2.37	7.18 – 10.52
2080s	Annual	3.53 – 5.55	7.48 – 9.90
	Winter	4.14 – 6.31	(-)24.83 – 4.50
	Monsoon	2.91 – 4.62	10.10 – 15.18

Source: (MWR, 2008)

2.2 Annual rainfall

The year-to-year variability in monsoon rainfall (Figure 1) leads to extreme hydrological events (large-scale droughts and floods) resulting in serious reduction in agricultural output and affecting the vast population and national economy. The south-west monsoon is the principal rainy season of India when over 75% of the annual rainfall is received over a major portion of the country.

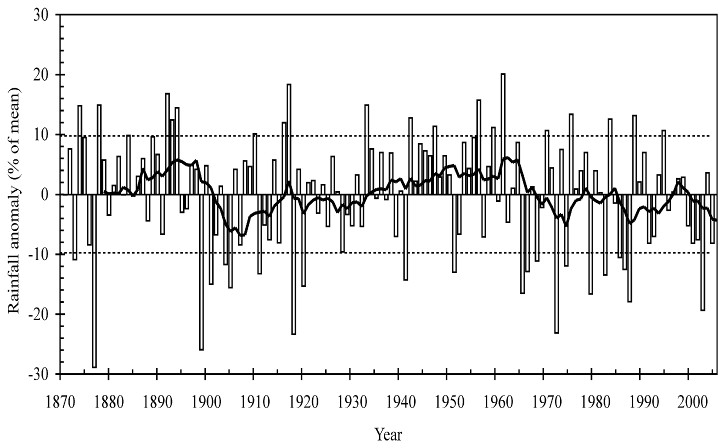

Figure 1. All-India summer monsoon rainfall anomalies (1871-2004) Dark line shows 10-year moving average (Source: Mall et al., 2006)

Considerable areal variation exists for the annual rainfall in India with high rainfall of the magnitude of 200 cm in Assam and North-Eastern parts and the Western Ghats, and scanty rainfall in Eastern Rajasthan and parts of Gujarat, Maharastra and Karnataka. The average annual rainfall for the entire country is estimated as 119 cm. There is a considerable variation of annual rainfall in time at a place. The coefficient of variation of the annual rainfall varies from 15 to 70, from place to place with an average value of about 30 (Subramanya, 2004).

2.3 Indian water resources

Table 2 and 3 shows the water resources potential of major river basins In India. There are 12 major river basins with catchment area of 20000 km^2 and above. The total catchment area of these rivers is 25.3 lakh km^2. The major river basin is the Ganga-Brahamputra-Meghna system, which is the largest with catchment area of about 11.0 lakh km^2 (more than 43% of the catchment area of all the major rivers in the country). The other major river basins with catchment area more than one lakh km^2 are Indus, Mahanadi, Godavari and Krishna. There are 46 medium river basins with catchment area between 2000 and 20000 km^2. The total catchment area of medium river basins is about 2.5 lakh km^2.

Table 2. Water resources of India

Annual precipitation	4000 b.cu.m
Available water resources	1869
Utilizable	1122
Surface water (storage and diversion)	690
Groundwater (replenishable)	432
Present utilization	605
(Surface water 63%, groundwater 37%)	
Irrigation	501
Domestic	30
Industry, energy and other uses	74

Table 3. Major river basins of the country

River	Origin	Catchment area (km^2)	Average annual potential (b. cu. m/yr)
Indus	Mansarovar (Tibet)	321289	73.31
Ganga	Gangotri (Utter Kashi)	861452	525.02
Brahmaputra	Kailash Range (Tibet)	194413	585.60
Barak and other rivers flowing into Meghana like, Gomti,		41723	
Muhari, Fenny, etc.	Aravali Hills (Rajasthan)	21674	3.81
Sabarmati	Dhar, (Madya Pradesh (MP))	34842	11.02
Mahi	Amarkantak, MP	98796	45.64
Narmada	Betul, MP	65145	14.88
Tapi	Ranchi, Bihar	39033	28.48
Brahmini	Nazri Town (MP)	141589	66.88
Mahanadi	Nasik (Maharashtra)	312812	110.54
Godavari	Mahabaleshwar (Maharashtra)	258948	78.12
Krishna	Kolar (Karnataka)	55213	6.32
Pennar	Coorg (Karnataka)	81155	21.36
Cauvery			
	Total	2528084	1570.98
	Other river basins of the country	248505	298.02
	Total	2776589	1869.00

Source: CWC (2002)

The average flow in the river system of the country has been estimated to be 1880 km^3. But over 90% of the runoff in peninsular rivers and over 80% of the annual runoff in Himalayan rivers occur during the four monsoon months of June to September. In addition to 12 major river basins, eight composite river basins combining suitably together all the remaining medium and small river systems have been considered. Thus the entire country has been divided into twenty river basins. The basin map of India (Figure 2) shows all these river basins.

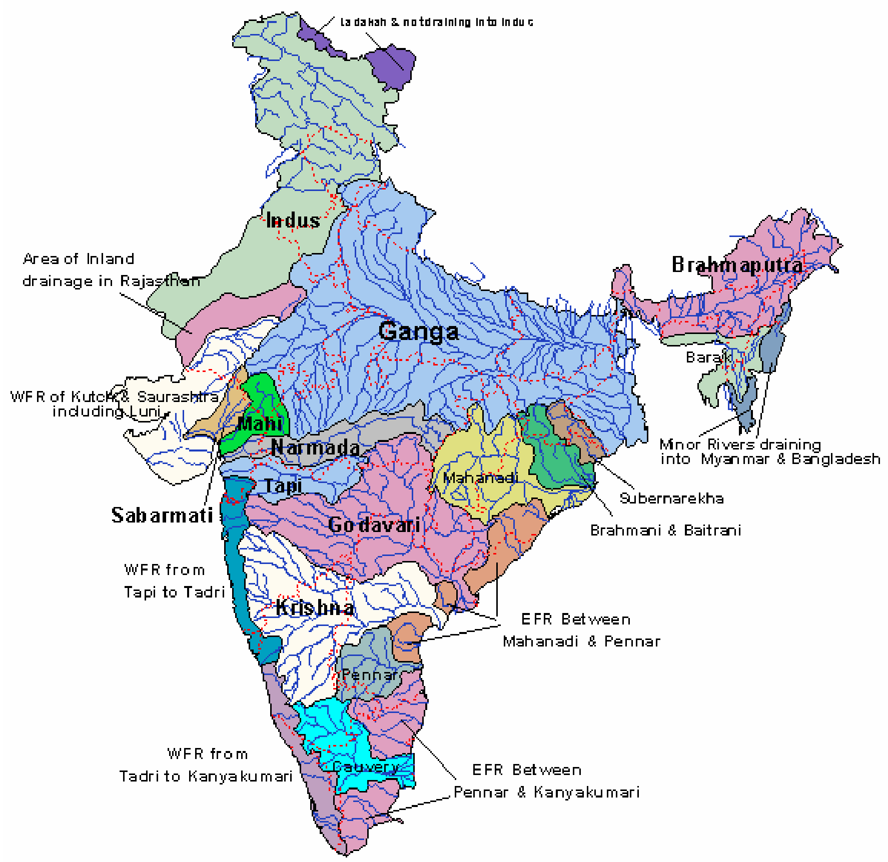

Figure 2. Basin map of India (Source: MWR, 2008)

Gosain and Rao (2003) projected that the quantity of surface run-off due to climate change would vary across the river basins as well as sub-basins in India. However, there is general reduction in the quantity of the available run-off which was shown in Figure 3 (Mall et al., 2006).

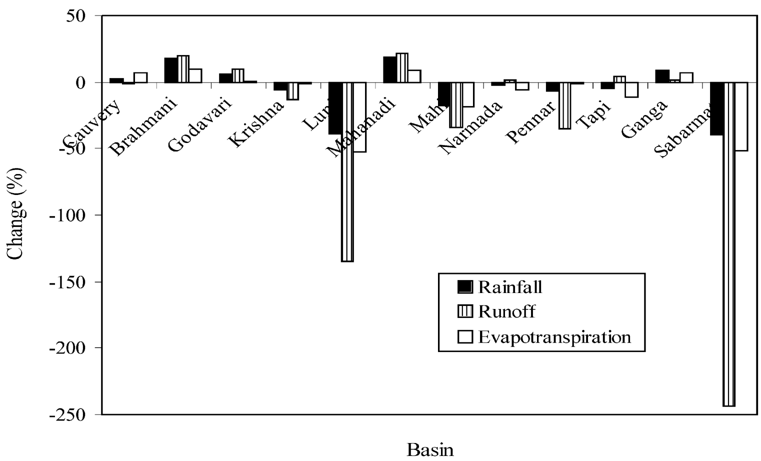

Figure 3. Changes in rainfall, run-off and AET due to projected climate change

An increase in precipitation in the Mahanadi, Brahimani, Ganga, Godavari and Cauvery is projected under climate change scenario. However, the corresponding total run-off for all these basins does not increase. This may be due to increase in evapo-transpiration on account of increased temperature or variation in the distribution of rainfall. In the remaining basins, a decrease in precipitation was noticed. Sabarmati and Luni basins show drastic decrease in precipitation and consequent decrease of total run-off to the tune of two-thirds of the prevailing run-off. This may lead to severe drought conditions in future.

Figure 4 shows (MWR, 2003) the observed and projected decline in per capita average annual freshwater availability and growth of population from 1951 to 2050. This clearly indicates the 'two-sided' effect on water resources-the rise in population will increase the demand for water leading to faster withdrawal of water and this in turn would reduce the recharging time of the water-tables. As a result, availability of water is bound to reach critical levels sooner or later (Mall et al., 2006).

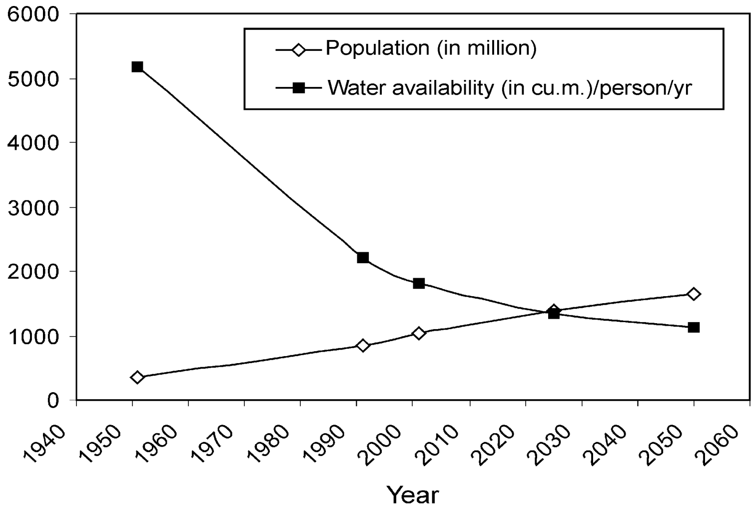

Figure 4. Observed and projected decline in per capita average annual freshwater availability and growth of population from 1951 to 2050

As per the international norms, if per-capita water availability is less than 1700 m^3 per year then the country is categorized as water stressed and if is less than 1000 m^3 per capita per year then the country is classified as water scarce. In India per capita surface water availability in the year 1991 and 2001 were 2309 m^3 and 1902 m^3 and these are projected to reduce to 1401 and 1191 m^3 by the years 2025 and 2050, respectively (MWR,1999).

Further, the Himalayan Rivers are a source of life-giving water for over 350 million people in north-western, northern and eastern India (Arora, 2010). The total surface water run-off of the river systems are given in Table 4 below:

Table 4. Total surface water runoff of the major Himalayan basins

Basin	Runoff (1000 Million m^3)
Indus	209.7
Ganga (at Farakka)	390.0
Brahmaputra (at Bahadurabad, Bangladesh)	606.7

3. REASONS FOR NON-STATIONARITY IN HYDRO-METEOROLOGICAL DATA

Climate change is the major reason for non-stationarity in the hydro-meteorological data. However, there could be other reasons like change in observation practices, change in irrigation practices, land use and land practices, urbanization, deforestation, change of instrument, inadequate length of data and the operation of hydraulic structures are the reasons of non-stationary conditions in the hydro-meteorological data. This view point is also expressed by the IPCC, (2007), stated that the climate change affects the function and operation of existing water infrastructure-including hydropower, structural flood defenses, drainage and irrigation systems as well as water management practices.

4. ASSESSMENT OF NON-STATIONARITY IN HYDRO-METEOROLOGICAL DATA

Hydro-meteorological data networking for most of the river basins in India is still in progress. Some of the river basins are either ungauged or having sparse data information. Assessment of non-stationarity in the hydro-meteorological data is a complex process under varying climatic conditions. The temporal and spatial changes in the hydro-meteorological data have to be considered for performing any statistical test and trend direction studies. Many trend studies are implemented incorrectly because they have ignored the important impact of both spatial and temporal correlation of the hydro-meteorological records.The persistence test of the hydrological data under hydrological climate changing conditions is becoming an unresolved issue. In early 1980's, some trend detection studies were initiated by IITM group. Researchers like, Goel et al., (1998); Burn and Goel, (2001); Singh, et al., (2006); and Goel, (2010) described the importance of the assessment of the non-stationarity under climate changing conditions and prescribed hypothesis tests for stationarity and also prescribed the procedures for the assessment of non-stationarity in the hydro-meteorological data.

5. IMPACT OF CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES: SOME SELECTED ISSUES IN INDIAN CONTEXT

Impact of global climate change on hydrology and water resources needs to be assessed at river basin scales. Many researchers predicted the future scenarios of rainfall and temperature at a basin level using down-scaling of GCM outputs and catchment modelling.The issue of non-stationarity in the hydro-meteorological data, reservoir operation, ground water resource estimation, hydro-power studies, environmental and ecological planning is of prime importance for the climate change modeling. Some of the selected issues in the Indian context are addressed herein.

Mujumdar et al., (2010) carried out the climate change impact assessment and adaptation for Mahanadi river basin in India. A stochastic dynamic programming (SDP) model application has been done. It addresses the uncertainty associated with inflow and is applied to derive optimal monthly operating policy with the objective of maximizing annual power generation. The SDP optimal policy is applied to inflows for current years 1959-2005, years 2045-65 and years 2075-95 for GCM-scenario combination. Performance measures using adaptive SDP policies for years 2045-65 were estimated and shown in Figure 5 below:

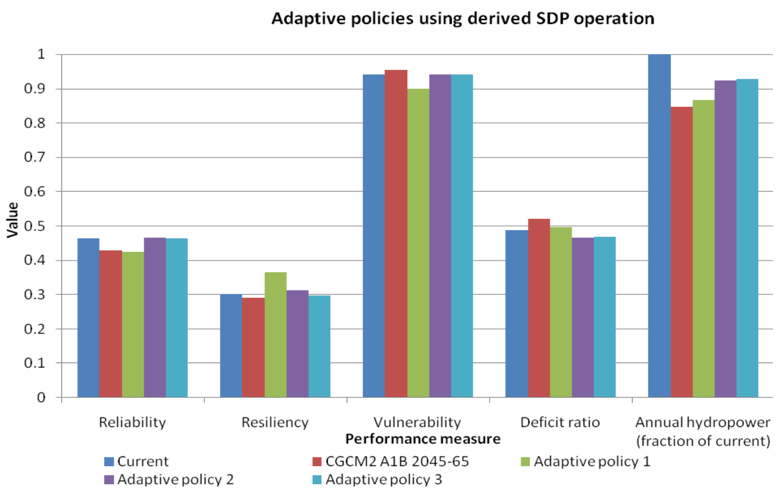

Figure 5. Performance measures using adaptive SDP policies for years 2045-65 (Source: Ghosh et al., 2010)

It is concluded by the Mujumdar et al., (2010) that, the uncertainty modeling of climate change impacts on water availability needs to be utilized in risk assessment and planning of mitigation measures for reservoir systems. They also concluded that the use of downscaling of GCM projections of climate variables is necessary for assessing hydrologic impacts. Inevitably, a large number of uncertainties are introduced in the process. Some sources of the uncertainties are due to the way climate system is modelled by different GCMs, or GCM uncertainties, uncertainties due to how the future socio-economic scenario might really unfold, leading to scenario uncertainties, downscaling methods and identification of climate variables among many other sources. Further, they also concluded that, the weighted projection resulting from the uncertainty models or uncertainty combination can be effectively used for adaptation.

In another similar study Gosain et al., (2006) carried out simulation work on 12 major river basins in India. The SWAT (Soil and Water Assessment Tool) water balance model is one such model and has been used in the study to carry out the hydrologic modeling of the river basins of the country. They concluded that the climate change impact assessment on water resources can be best handled through simulation of the hydrological conditions that shall prevail under the projected weather conditions in an area. Such a treatment is essential because of the fact that the hydrological response is a highly complex process governed by a large number of variables such as terrain, land use, soil characteristics and the state of the moisture in the soil. The last element warrants a continuous time simulation so as to keep track of the changing moisture conditions.

Further, in the present study, an attempt has been made to assess the impact of climate change on the performance of the Sri Ram Sagar Project (SRSP). This Sri Ram Sagar Project built on river Godavari is one of the major peninsular rivers in southern India. This irrigation project is located at Pochampadu village (18 58^o N latitude and 70 20^o E longitudes) in Nizamabad district of Andhra Pradesh (AP) state of Southern India. The varying rainfall and evaporation records available for 44 years (1953-1993) and the varying inflows into the reservoir for the same period were used to assess the performance of the system and these data are shown in Figures 6 and 7, respectively.

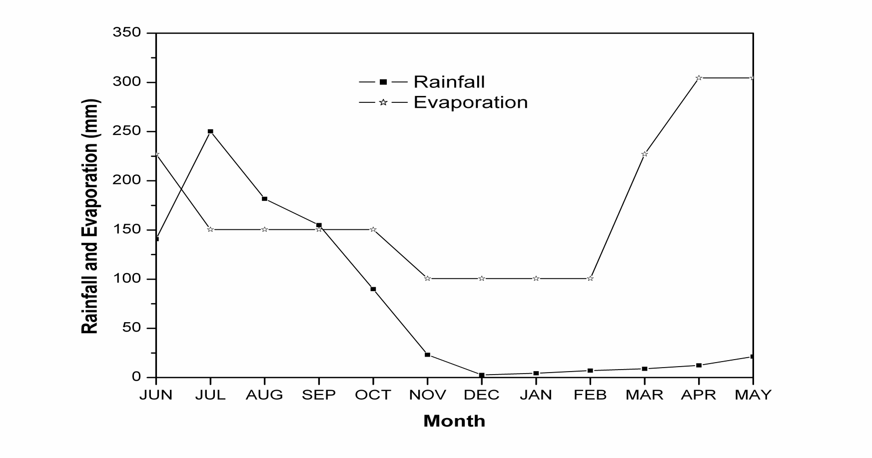

Figure 6. Monthly average rainfall and evaporation variations for 44 years (1950-1993)

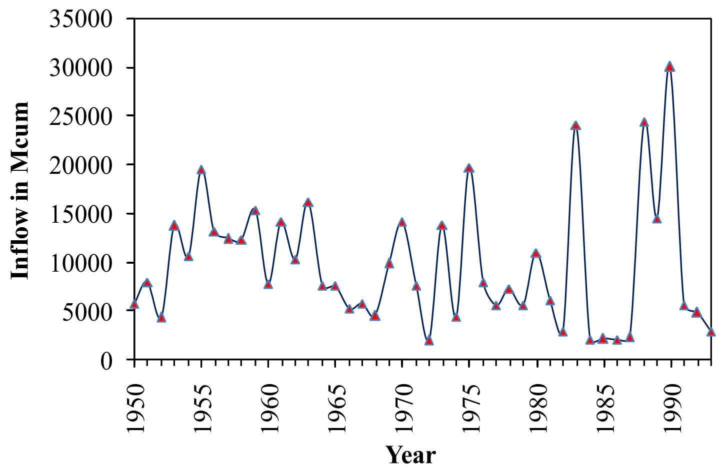

Figure 7. Annual Inflows in to the SRSP reservoir for 44 years (1950-1993)

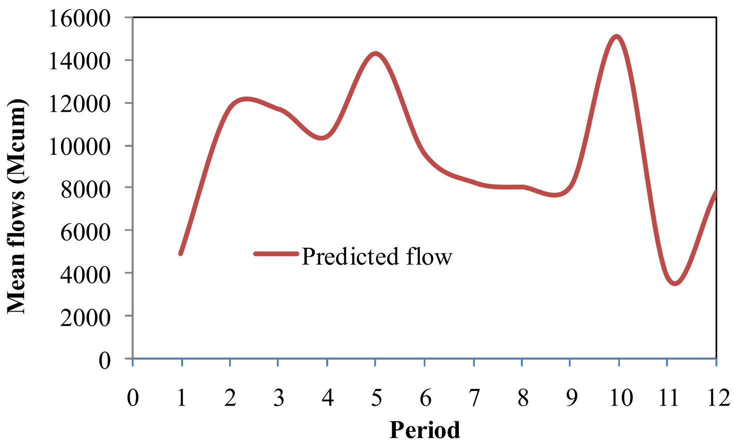

Figure 8. Mean flows into the SRSP reservoir per 100 years projection

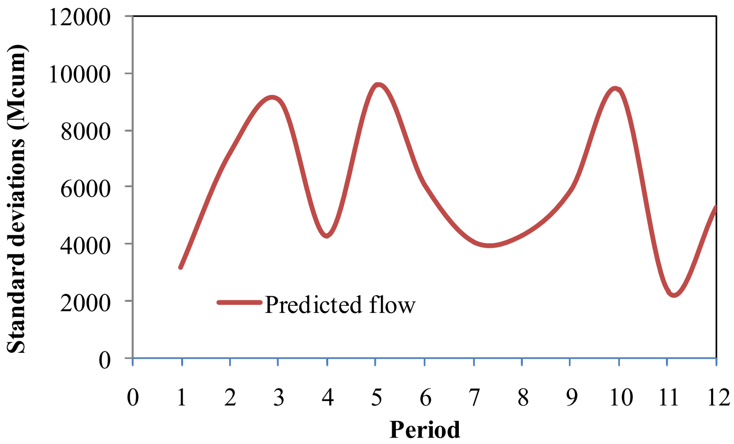

Figure 9. Standard deviations per 100 years projection

Considering the hystoric annual inflows availabe for a period of 44 years (1950-1993) into the SRSP reservoir, the future 100 years inflows were projected using the Thomas-Fiering model. As the monthly flow series are non-stationary, the use of Thomas-Fiering model is appropriate to pridict synthetic monthly flow sequences for the next 100 years under climate changing conditions. Basically, this model is of a Markovian nature with periodic parameters, namely, the monthly means, standard deviations and the lag-zero cross correlations between successive months. In its simplest form the model consists of twelve regression equations, one for each month. The model implicitly allows for the non-stationarity observed in monthly flow data. The application of Thomas-Fiering model for 100 year flow predictions of SRSP reservoir under climate changing conditions has been successful. The standard deviations of the projected 100 years flows into the SRSP were also accurately estimated. Figure 8 and 9 demonstrates the 100 years projected mean inflows into the SRSP reservoir and their standard deviations, respectively. From the pridicted synthetic inflows it is observed that, infuture the SRSP reservoir is at risk of inadequate inflows into the reservoir due to climate changing conditions in the region.The inflows into the reservoir are reduced due to the frequent failures of monsoon in the study area.Though, the kharif season (July-October) gains enough inflows into the reservoir, the rabi season (November-March) is at risk because of the insufficient inflows into the reservoir. Therefore, a suitable optimal operating policy shall be adopted for future releases of water from the SRSP reservoir.

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