CHAPTER 10

IMPACT OF CLIMATE CHANGE ON FLOODS

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10.0 Introduction

India is one of the most flood vulnerable regions in the South Asia. Floods occur often in the region triggered by heavy monsoon precipitation and can cause enormous damages to lives, property, crops and infrastructure. The frequency of extreme floods is on the rise in India. Past extreme floods fall within the range of climate variability but frequency, magnitude and extent of flooding may increase in future due to climate change. From a hydro-meteorological perspective, India is a very important region and encompasses many large river systems: Ganges, Brahmaputra, Indus, Krishna, Godavari, Mahanadi and Narmada. Increases in future flooding can cause extensive damage to rice crops in the monsoon season. This may have implications for food security and hardships especially of poor women and children. Floods can devastate the people living near the flood plains of the rivers causing loss of lives and property. Flooding in coastal cities as witnessed during the Chennai floods of 2015 and Kerala floods of 2018 can be a nightmare for the water managers and district officials. Floods can also impact public health in the flood plains and in the coastal areas.

Floods are likely to be affected by climate change in many ways with changes in temperature, precipitation, river flows and sea levels. These changes would lead to flooding of cities, transport networks, drainage systems, irrigation systems, water supplies as well as public and private installations. The effects of climate change on floods may influence flood risk reduction priorities and may lead to increased flood hazard at many flood prone locations. As per the National Disaster Management Authority, more than 40 million hectares of area in India is prone to floods out of its total area of 329 million hectares. As per the Central Water Commission, about 1,07,487 people died due to heavy rains and floods across India over the last 64 years from 1953 to 2017. Also, there has been damages to crops, houses and public utilities resulting in losses to the exchequer to the extent of about Rs. 365,860 crores. Some of the recent striking examples of extreme floods are the floods faced in Kerala (2018), Chennai (2015), Jammu and Kashmir (2014), Kedarnath (2013), Leh (2010), and Mumbai (2005) are a very few of the regularly increasing flood events in India.

Total economic losses from flood disaster in the southern state of Kerala in 2018 have been tentatively estimated at upwards of Rupees 300 billion and claimed about 483 lives. The predicted rains from August 9 to 15 were 98.5 mm but the state received a rainfall of 352.2 mm. Rainfall of 944 mm occurred in Mumbai on 26th July, 2005, which resulted in the death of more than 500 people. Between 8th November and 4th December in 2015, a series of five extreme precipitation events occurred in Chennai. Heavy rainfall occurred in the Chennai city on 17th November 2015. The recorded rainfall in Chennai was 1,049 mm in November, the highest recorded since November 1918 when 1,088 mm of rainfall was recorded. During 16 to 17 June 2013 the Kedarnath region in Uttarakhand faced a natural disaster along with very heavy rainfall and the resulting flash floods caused the devastating natural disaster. The rainfall of 120 mm within a span of 24 hours caused the flash flood at Kedarnath. The disaster was due to a combined effect of very intense rainfall, outburst of a Chorabari lake and very steep topographic conditions. The Leh region of Ladakh received very heavy rainfall during the midnight of 6th August in the year 2010 and it resulted in very heavy loss to property. The State of Jammu and Kashmir, experienced heavy monsoon rains that began on 2nd September 2014 and led to unprecedented widespread flooding across the state.

The factors which result in floods are rainfall of very high intensity in a very short time period, poor drainage system, unmanaged reservoir regulation and failure of hydraulic structures. This may further result due to several other causes which may include increase in population, rapid urbanization, increasing developmental activities in the flood plains as well as global warming. The general causes of occurrence of floods in our country are: intense precipitation; cyclones; urban flooding; low flow carrying capacity within river banks for containing the high flood flows as well as silting of the river beds; landslides resulting in impediment of flow and meandering of the river water way; drainage congestion; heavy rainfall and flash floods; dam break flood; river bank and river bed erosion; sediment transport by rivers; floods in coastal areas; reduced velocity of flow due to tidal well as backwater effects and glacier lake outburst flood (GLOF) etc.

Climate change will exacerbate flooding problems over India as the temperatures are increasing over South Asia region, and are projected to continue to increase for the next several decades under all plausible climate scenarios, based on the World Bank study, 2018 (https://openknowledge.worldbank.org/handle/10986/28723). These changes in climate would lead to more frequent flooding, increase in demand for water and rise in the medical issues. According to government data that lend perspective to a new World Bank study that says climate change will lower the standards of living of nearly half of India's population by 2050. India has increased frequency of downpours as well as the gaps between rainy days during the monsoon (IndiaSpend, January 2018, http://archive.indiaspend.com/cover-story/indian-summers-could-last-8-months-by-2070-if-global-warming-continues-85534). As India's climate warms, extreme weather, such as intense rain and floods, are predicted to worsen (http://archive.indiaspend.com/cover-story/new-data-predicts-fiercer-floods-in-brahmaputra-indus-65170).

Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD & GR), Government of India has launched National Water Mission (NWM) as part of National Action Plan on Climate Change (NAPCC) with the main objective of "conservation of water, minimizing wastage and ensuring its more equitable distribution both across and within states through integrated water resources development and management".

Climate change may alter the distribution and quality of India's natural resources and adversely affect the livelihood of its people. With an economy closely tied to its natural resource base and climate-sensitive sectors such as agriculture, water and forestry, India may face a major threat because of the projected changes in climate. The global warming may affect the hydrological cycle which could result in further intensification of temporal and spatial variations in precipitation, snow melt and water availability. Some of the impacts of climate change on water resources may be: (i) decrease in the glaciers and the snowfields in the Himalayan region; (ii) increased in droughts due to decrease in the number of rainy days; (iii) increased in floods; (iv) effect on groundwater quality in alluvial aquifers due to increased flood and drought events; (v) effect on groundwater recharge due to variations in rainfall and evapotranspiration; and (vi) rise in saline intrusion of coastal and island aquifers due to rising sea levels etc.

It is evident from above that due to possible impact of climate change on water resources, the most affected areas in India would be (i) drought affected areas, (ii) areas prone to floods, (iii) coastal regions, (iv) areas getting low rainfall, (v) areas with over-exploited, semi-critical, critical conditions of groundwater development, (v) areas having poor water quality and (vi) snow-fed river regions. The impact of climate change of floods and the way forward to develop suitable adaptation strategies are described in the following.

10.1 Literature Review on Floods under Climatic Change

India has experienced several devastating climate extremes during recent decades. About 13.78% of India's geographical area is subjected to flood disasters (Planning Commission 2011), and about 33 million people were affected by flooding from 1953 to 2000 (Kumar et al. 2005). Mumbai, India's financial capital, received a record 944 mm rainfall on July 26, 2005, causing havoc and several casualties (Kumar et al. 2008).

Impact of climate change on floods in India has been reported in many studies. Gosain et al. (2006 and 2011) modelled 12 river basins of India by using the SWAT model for control or present and GHG (greenhouse gases) or future climate scenario of simulated weather data of HadRM2. They reported that Godavari, Brahamani and Mahanadi may not have water shortage but predicted severe flood conditions. A few sub-basins of the Ganga, Brahmaputra, Krishna, Cauvery and Pennar show some decrease in the peak flow magnitudes. World Bank (2008) suggested that the probability of flood frequency and its intensity could increase dramatically in Mahanadi basin. The hydrological model projected daily outflow discharges at a gauge station (located in Naraj northwest of Jagatsinghpur and Pun) and results showed that under different scenarios, the probability of flooding will increase substantially. An increase of stream flow during 1956–2007 in the number of particular flood occurrences in Bahadurabad in the Brahmaputra River has been recorded (Climate Change Cell 2009). Dadhwal et al. (2010) reported an increase by 4.53% in the annual stream flow at the Mundali outlet in the Mahanadi basin attributed to a reduction in forest cover by 5.71% for the period 1972–2003.

Mujumdar (2011) presented the flow duration curves projected for the Mahanadi river in East-Central India, using several GCMs. The flow duration curves specify the flow that may be exceeded at a given level of probability, and are used in hydrologic designs of dams, culverts, bridges, and stormwater drainage networks etc. The mid-level flows (flows that are exceeded 40–70 per cent of the time) govern the performance of the system in terms of the water supply for irrigation and hydropower generation and with many projections indicating a likely decrease in the mid-level flows. In peninsular India, Panda et al., 2013 reported that the streamflow at the Tikerpara gauging site of the Mahanadi River basin declined at a rate of 3,388 million cubic meters per decade for the period of 1972–2007. Some of this reduction is attributed to increased upstream usage. For the Ganges-Brahmaputra-Meghna (GBM) basin, the long-term mean runoff is projected to increase by 33.1, 16.2, and 39.7% in the Ganges, Brahmaputra, and Meghna basins, respectively (Masood et al. 2015), by the end of the 21st century.

Mishra and Lilhare (2016) reported that under the RCP 4.5, out of 18 only 4 river basins (Ganges, Brahmaputra, Narmada, and South Coast) are projected to experience significant increase in streamflow during the monsoon season. In the same climate change scenario, Mahi and Tapi basins are projected to experience a decline in streamflow during the monsoon season, however, with a larger intermodel uncertainty. In the near term climate, in 7 basins (Brahmani, Ganges, Godavari, Mahanadi, Narmada, Pennar, and Subarnarekha) streamflow is projected to increase significantly under the RCP 8.5 scenario. Sudheer (2016) reported that the 5% dependable flow for Barmanghat gauging site in Narmada basin may increase during 2071-99 (end century), varies between 404.7 cumecs (MPIESM) to 610.3 cumecs (CNRM). This suggests that during the future time horizons, the extreme events causing floods may increase marginally towards the end-term (2071-99). Das and Umamahesh (2018) found that mean annual monsoon flows for the periods 2041–2070 and 2071–2000 are likely to decrease compared to the base-line period in Wainganga River basin. Towards the end of the 21st century (i.e. 2071–2100), the decrease in the mean annual monsoon flow is more significant.

There are few studies reported on global flood modelling under climate change. Das et al, 2013 found that by end of century, discharges from the Northern Sierra Nevada with 50-year return periods larger floods will increase by 30–90% depending on climate model, compared to historical values. Corresponding flood flows from the Southern Sierra increase by 50–100%. Hirabayashi et al, 2013 presented a global flood risk for the end of this century based on the outputs of 11 climate models integrated with global river routing model with an inundation scheme to compute river discharge and inundation area. An ensemble of projections under a new high-concentration scenario demonstrates a large increase in flood frequency in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes, with small uncertainty in the direction of change.

Asadieh and Krakauer (2017) found that under RCP8.5 scenario, 37% of global land areas experience an increase in magnitude of extremely high streamflow (with an average increase of 24.5%), potentially increasing the chance of flooding in those regions. . On the other hand, 43% of global land areas show a decrease in the magnitude of extremely low streamflow (average decrease of 51.5%), potentially increasing the chance of drought in those regions.

10.2 Non-Stationarity of Hydrological Data

While climate scientists agree that human-caused climate change is influencing weather, they have often been hesitant to draw direct linkages between this phenomenon and specific extreme weather events. Anthropogenic impact on climate change has proven to be more critical than natural causes, human effects in river basins such as land-cover and land-use changes, urbanization, changes in impervious surfaces and drainage network, deforestation and mining also play an important role, which alters the pattern of extreme hydrological events that draw the attention of society and moves policy makers toward better management practices. In terms of magnitude and ubiquity of the hydroclimatic change, it appears that the stationary assumption is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning (Milly et al. 2008). Leading causes of change (*i.e.* nonstationarity) include human intervention (Konrad and Booth, 2002; Schilling and Libra, 2003; Villarini et al., 2009), natural climate variability (Enfield et al., 2001; Jain and Lall, 2000) and climate change driven by increased greenhouse gases (Milly et al., 2008; Hirsch and Ryberg, 2012). Combinations of these will lead to nonstationary flood frequency, a challenge for which the bulk of existing FFA methods is ill-suited (El Adlouni et al., 2007; Gilroy and McCuen, 2012). The poleward projection of the subtropical dry zone may decrease the runoff in some regions (Lu et al. 2007), whereas intensification of the global cycle will become a reason for increasing flood risk (Milly et al. 2002). Hirabayashi et al. (2013) stated through a study using the 11 atmosphere-ocean general circulation models (AOGCMs) that it is necessary to adapt and mitigate strategies for intensified flood and greenhouse emissions, respectively. A similar kind of research carried out by Milly et al. (2002) found an increase in great-flood frequency in 29 major river basins using a single AOGCM and attributed the cause to radiatively induced climate change. Das et al. (2013) also projected streamflow under climate change and observed that climate change may result in the build-up of streamflow in the future.

Therefore, the extreme quantile of the streamflow cannot be considered as a stationary event anymore in the climate change scenario. Because these hydrological extremes are rare in nature and providing implications about them is a tough task (Mondal and Mujumdar 2016), the nonstationary modeling of extreme events currently is compulsory. High return levels generally are considered in the design of hydraulic structures on the basis of historical series, so that high floods in the future should not cause damage downstream or to structural capacity. However, because of induced climate change, the designed return level is not going to be stationary and the structure may fail more frequently than expected in future periods. Therefore, the differences between the observed and the future return levels should be modeled using a nonstationary approach for assessing the correct measure of risk (Mondal and Mujumdar 2016).

Nonstationarity of hydro-climatic data is a rising concern among the hydrologists and climatologists (IPCC2007). The changing global climate alters the hydrological cycle, which in response is causing variability in the frequency of the extreme events, availability of water, irrigation water use, and quality of freshwater resources (Simonovic 2017). While the significance of climate change impacts on some aspects of the hydrological cycle, such as streamflows remains debatable and inconclusive (e.g., Cohn and Lins 2005; Hirsch and Ryberg 2012), some hydrologists believe that "stationarity is dead" (Milly et al. 2008), the geophysical, biological, economical, and other natural processes are nonstationary (Klemeš 1974 & 1989) and recommend that nonstationary probabilistic models need to be identified and possibly used in some practical cases. Moreover, warming associated with climate change may be causing sea-level rising globally and recent projections of sea level include varying degrees of acceleration in the sea-level rise rate (Bindoff, et al. 2007; Rahmstorf 2007; Vermeer and Rahmstorf 2009; Obeysekera, et al. 2012; Sallenger, et al. 2012, IPCC, 2014). Such increases in sea levels are expected to increase flooding due to storm surges in coastal regions and reduce the reliability of flood-protection systems in coastal watersheds (Obeysekera et al. 2011). In addition, climate change research proposes that the intensity and rainfall associated with major tropical storms may also enhance (Kunkel, et al. 2010), potentially leading to increased rainfall-induced flooding in areas exposed to such storms, while the tropical storm frequency globally may reduce in the future (Knutson, et al. 2010).

Various approaches have been suggested in the literature such as frequency analysis methods to undertake nonstationarity of hydrologic extremes, where the parameters (or moments such as the mean and variance) of a given distribution (e.g., the Gumbel) may vary in accordance with time. They include the following: (1) probability distribution models imbedded with trend components (Cooley 2013; Katz 2013), (2) stochastic models considering shifting patterns (Sveinsson, et al. 2005), (3) models considering covariates (Villarini, et al. 2009, 2010), and (4) probability distributions with mixed components (Waylen and Caviedes 1986; Rossi et al. 1984). In the paleo-flood frequency-analysis techniques, multi-century climatic fluctuations have been incorporated including analysis of wet and dry periods (Biondi et al. 2008). Apart from, some preconceive concepts to handle with nonstationarity in flood-frequency analysis have been proposed, such as adapting the nonstationary peak discharges and applying hydrologic models [taking into account the spatially and temporally varying land-use (Moglen 2003); adjusting flood records for the combined effects of urbanization and climatic change (Gilroy and McCuen 2012)]. Similarly, a flood-frequency analysis framework that necessitates a process-based extracted flood frequency and risk estimation considering possible future evolution of climatic states has been proposed (Sivapalan and Samuel 2009).

10.3 Non-Stationarity in Design flood

Flood frequency analysis or risk analysis for flood hazards is an important part of the engineering practice whose aim is to obtain relationships between design variables corresponding to a chosen hydrologic risk. Flood frequency analysis, as traditionally practiced, is based on assumption that annual maximum floods conform to a stationary, independent, identically distributed random process. Furthermore, the assumption that floods are independent and identically distributed in time is at odds with the recognition that climate naturally varies at all scales, and that climate additionally may be responding to human activities, such as changes over the past century in atmospheric composition or in global land use patterns, which have changed the climate forcing and perhaps the hydroclimatic response on regional scales in recent decades. Numerous studies have demonstrated that estimated flood exceedance probability can increase quite rapidly with time even in the presence of rather mild rising trends in the annual maximum flood. Thus, it is important to acknowledge that non-stationarities are likely to be present in the records and to discuss potential sources of such trends or non-stationarities. The much cited commentary by Milly et al. (2008) entitled "Stationarity is Dead: Whither Water Management?" is one example. There is considerable evidence of regime-like or quasi-periodic climate behavior and of systematic trends in key climate variables over the last century and longer (see NRC, 1998a for one overview). The unambiguous attribution of cause for such non-stationarities in a finite record is difficult, given the rather rich, nonlinear dynamics of the climate system. Even with stationary underlying dynamics (i.e., no change in the governing equations or parameters), finite sample statistics of a nonlinear dynamical system can be non-stationary as the system evolves from one regime to another. The nature of the nonlinear oscillations of the system as well as regime probabilities and its mean state may change as the external forcings (e.g., solar radiation or greenhouse gases) are changed.

The stationarity assumption in flood frequency analysis has persisted because of (a) short historical records that limit a formal analysis of non-stationarities, (b) the lack of a formal framework for analyzing non-stationary flood processes and the associated annual risk, and (c) institutional adherence to engineering practice guidelines. As record lengths have increased, trends in floods and other processes have been observed. The ongoing global climate change debate and identification of interannual and decadal ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation), and their teleconnections to continental hydroclimate, have led to increased awareness of this issue. Cyclical or monotonic non-stationarities pose a serious challenge to flood frequency and risk analysis and flood control design and practice. If cyclical or regime-like variations arise due to the natural dynamics of the climate system, a relatively short historical record may not be representative for design period analysis. Further, by the time one recognizes that the project operation period has been different from the period of record used for design, the climate system may be ready to switch regimes again. Thus, it is unclear whether the full record, the first half or the last half of the record, or some other suitably selected portion is most useful for future decisions without a better understanding and prediction of the climate regimes. In addition, if a monotonic trend in floods is indicated in a reasonably long record and the possibility of global climate change effects is considered, projections of future flood potential are still unclear. For one, the effects of global climate changes may be more in the variability of the process than the mean, and may translate into an increased probability of recurrence of certain regimes of climate more than others.

Non-stationarity may be attributed to climate variability or different human influences (e.g. urbanisation, regulation of rivers, construction of dikes, deforestation, etc. Large number of studies have already performed non-stationary flood frequency analyses. However, the way of incorporating changing climate and anthropogenic influences in hydrologic practice has still not been exactly defined and this is clearly an area which should be considered with much more effort in the future. Most of the non-stationary flood frequency analysis methods proposed in the literature involve parameters of a chosen distribution that are dependent on time. The problem with time varying distribution parameters is that it is difficult to justify why they would continue to change in the future exactly in the same way they did in the past. As an alternative, models have therefore been developed that correlate the distribution parameters to hydrological variables such as land use or climatological variables, for example El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and other circulation indices. However, reliable scenarios of such variables for the future are needed. Some authors allowed the distribution parameters to vary both with hydrological variables and with time. The functional forms of frequency distributions have used several different functional forms, such as linear, quadratic and exponential forms in non-stationary flood frequency analysis. Although different levels of nonlinear modeling of nonstationary models have been utilized in the past, selecting the optimal forms of nonlinear functions for use with different time series and determining the method of selecting a nonlinear function for a non-stationary model are still important issues. Attempts have been made by fitting the series with various linear and nonlinear functions, and best functions are selected based on decision criteria viz. mean absolute percent error (MAPE), root mean square error (RMSE), the Akaike information criterion (AIC), and the Bayesian information criterion (BIC) etc.

10.4 Impact on Flood Under Climate Projections

Wang (2016) et al. showed that the number of extreme events exceeding smaller probability will increase for the next 50 years for the Tangnaihai basin in the Yellow River basin in China. The Tangnaihai basin is a large basin with drainage area of 122,000 km^2. According to the analysis of a number of extreme events exceeding given probability, it is found that the extreme events of long duration rainfall exceeding given probabilities (5%, 10%, and 20%) will become more frequent. It is seen that the values of long duration (15 d, 30 d, and 60 d) flood volume extremes of Tangnaihai basin will rise by slightly increasing rate in the next 50 years. On the hypothesis that rainfall of given frequency could result in to flood of the same frequency, SWAT model was used to deduce design flood with the import of design rainfall for the next 50 years, and the long flood volume extremes were achieved. Flood volume extremes in different duration, 15-day design flood volume of given probabilities (1%, 2%, 5%, and 10%) is increasing by 1%–3% based on BCC-CSM-1.1; similarly, 30-day design flood volume is increasing by 1%–3% and 60-day design flood volume is increasing by 3%–6%, respectively. It obvious that the increasing rate of flood volume extremes in given probability is less than 10%, in other words, the flood volume extremes of the Tangnaihai basin would increase with a slight degree. Generally, the long duration hydrologic extremes of the Tangnaihai basin would increase by a slight degree in the next 50 years. The conclusions were addressed on the basis of BCC-CSM-1.1. The authors state that if several more suitable climate change model products were adopted, the conclusions on impact of climate change in study area will be more reliable.

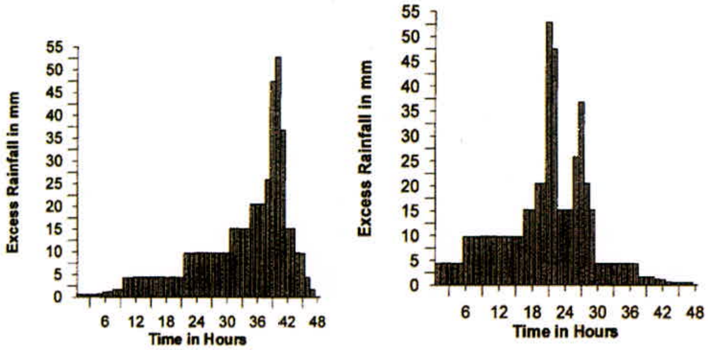
Wobus et al. (2017) state that a growing body of work suggests that the extreme weather events that drive inland flooding are likely to increase in frequency and magnitude in a warming climate, thus potentially increasing flood damages in the future. The authors used hydrologic projections based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) to estimate changes in the frequency of modeled 1% annual exceedance probability (1% Annual Exceedance Probability (AEP), or 100-year) flood events at 57116 stream reaches across the contiguous United States (CONUS). The flood projections were linked to a database of assets within mapped flood hazard zones to model changes in inland flooding damages throughout the CONUS over the remainder of the 21st century. The model generates early 21st century flood damages that reasonably approximate the range of historical observations and trajectories of future damages that vary substantially depending on the greenhouse gas (GHG) emissions pathway. The difference in modeled flood damages between higher and lower emissions pathways approaches USD4 billion per year by 2100 (in undiscounted 2014 dollars), suggesting that aggressive GHG emissions reductions could generate significant monetary benefits over the long term in terms of reduced flood damages. The authors mention that although future work is needed to test the sensitivity of the results to these methodological choices, the results indicate that monetary damages from inland flooding could be significantly reduced through substantial GHG mitigation.

10.5 Impact of Climate Change On Design Flood

Impact of climate change on design flood has been assessed by carrying out a study considering some hypothetical scenarios of climate change i.e. effect of change in rainfall sequencing; effect of rise in the peak of unit hydrograph; effect of change of design rainfall pattern for a snowed as well as rainfed catchment of about 5000 km^2 in area. For this purpose, 1-hour unit hydrograph is derived employing the Clark IUH model. The Clark IUH model parameters viz. $T_c = 9$ and $R = 12$ are estimated. The Clark IUH model is used for estimation of the direct surface runoff (DSRO) hydrograph by converting the excess rainfall hyetograph into DSRO. In this study, the design flood was estimated by convoluting the 2-days design storm value with the unit hydrograph derived using the Clark IUH. The various hypothetical scenarios of possible changes in flood hydrographs due to climate change are described as follows (Pandey et al., 2013).

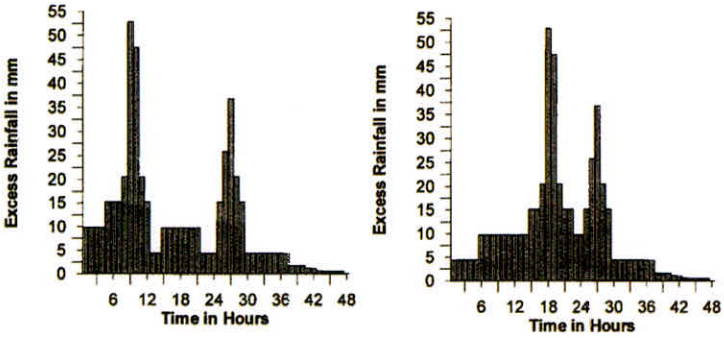
10.5.1 Effect of Change of Sequencing Pattern of Rainfall

The climate change is likely to affect the pattern of rainfall and its intensity, magnitude of rainfall and the number of rain days etc. As a result, the pattern of occurrence of rainfall would also be affected. The design storm has been considered in four cases as shown in Fig. 10.1: (a) design storm as single bell (Case – 1); (b) design storm as two bells (Case – 2); (c) design storm as four bells (Case - 3); (d) design storm as four bells (Case - 4). Design flood hydrographs for various sequence patterns of the hourly rainfall excess are shown in Figure 10.2. The percentage decrease in peak floods for Cases-2, 3 and 4 are observed to be 8.0%, 28.7% and 13.3% with respect to Case-1. Whereas, the percentage decrease in time to for the peak floods for Cases-2, 3 and 4 are observed to be 28.6%, 61.2% and 28.6% with respect to Case-1.



(a) Critically sequenced excess rainfall hyetograph as single bell used for Case-I (reference run)

(b) Design excess rainfall hyetograph considered as 2 bells (Case-II)



(c) Design excess rainfall hyetograph considered as 3 bells (Case-III)

(e) Design excess rainfall hyetograph considered as 4 bells (Case-IV)

Figure 10.1: *Various sequences of hourly rainfall excess patterns*

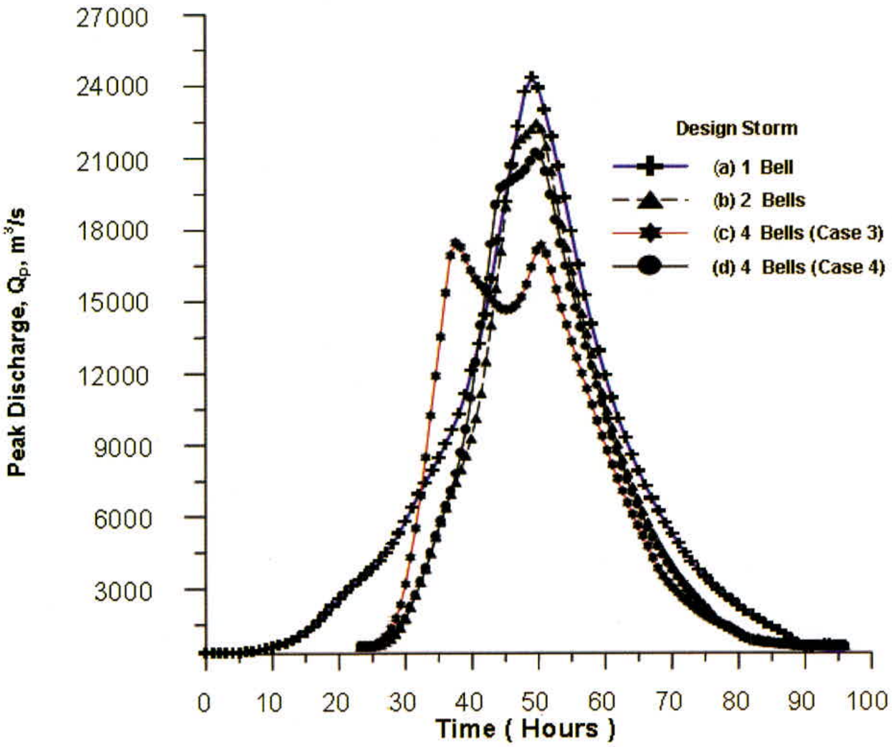


Figure 10.2: *Flood hydrographs for different sequences of hourly rainfall excess*

10.5.2 Estimation of Design Flood for various Percentage Increases in Design Storm Values

The value of design flood (DF) for the study area has been estimated as 6,842 m^3/s. As a result of climate change the hydrological extremes are likely to be effected and the values of rainfall would increase or decrease in different regions; therefore, hypothetical increases are considered in the design storm values for the study area and design flood values have been estimated for such scenarios. When increases of 5%, 10%, 15% and 20% are considered in the value of design flood; it is observed that estimated values of the peak floods are increased by 3%, 8%, 13% and 18% respectively (may vary from case to case) as shown in Figure 10.3.

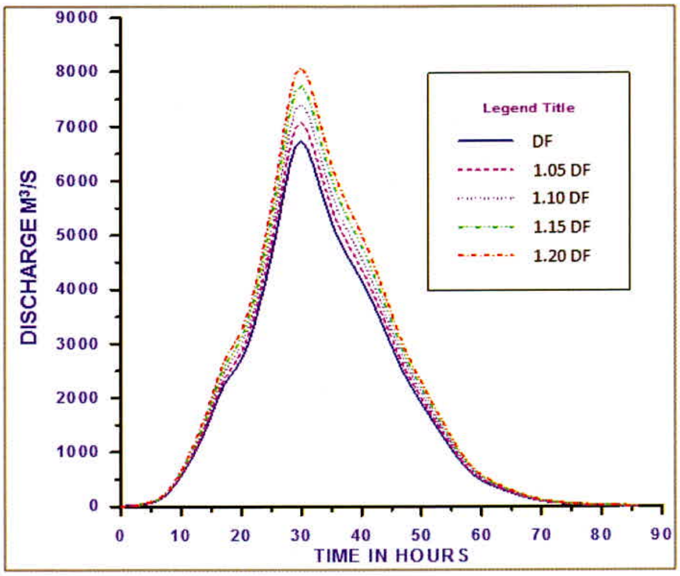


Figure 10.3: *Estimated Values of Peak Floods for the Various Increased Values of Design Strom*

Table 10.1: Estimated Values of Peak Floods and % Deviations in Peaks of Design Floods

Design Flood	1.05*Design Storm	1.10 Design Storm	1.15 Design Storm	1.20 Design Storm
	Peaks of Design Floods (m^3/s)			
6842	7064	7401	7737	8073
	% Deviations in Peaks of Design Floods			
	3	8	13	18

10.5.3 Effect of Increase in Peak of the Unit Hydrograph

For analysing the effect of increase in the peak of unit hydrograph on peak design flood, various increases in the unit hydrograph peaks are considered. The different unit hydrographs are used with the design storm values of one bell (adopted as the reference design storm). Percentage variations in the peak of the unit hydrograph are shown in Figure 10.3. Figure 10.4 shows that design flood peak increases by about 25% for 50% increase of peak of the unit hydrograph.

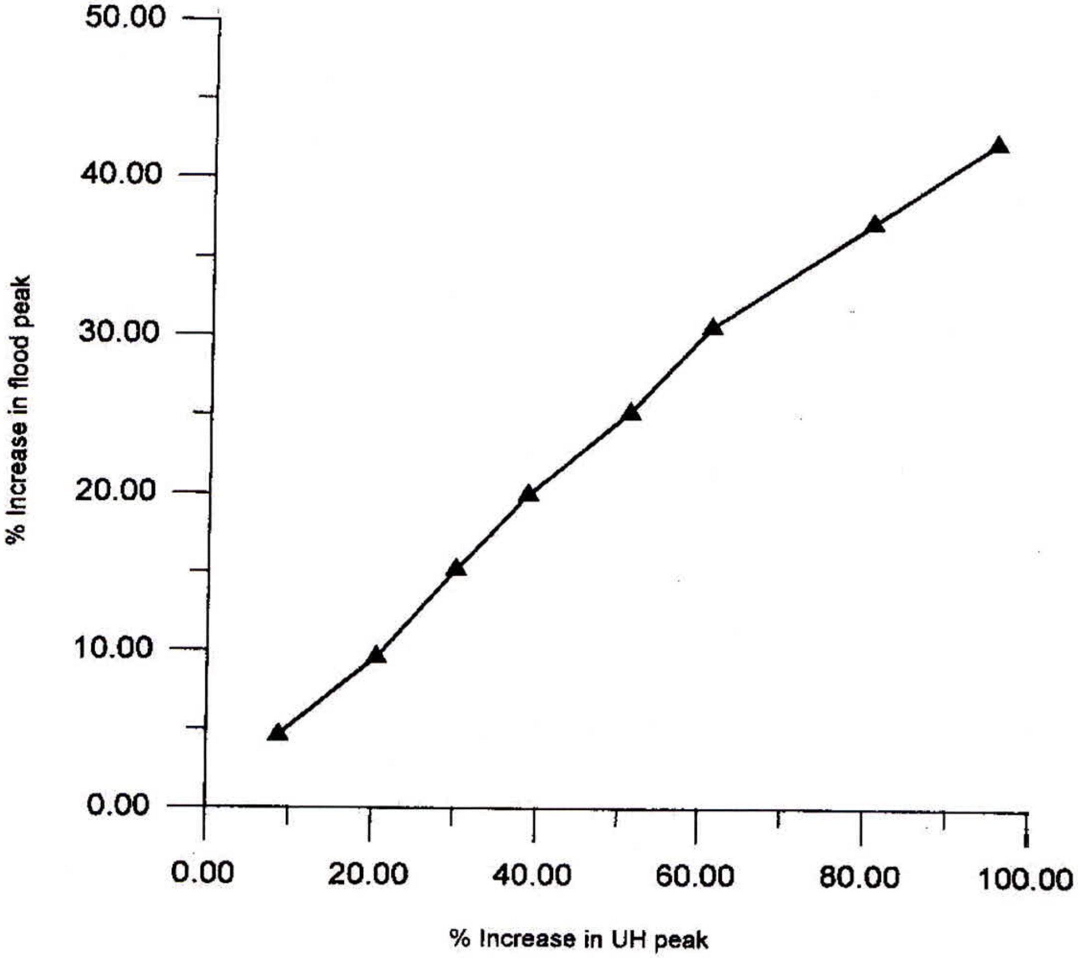


Figure 10.4: *Percentage increase in the peak of flood hydrograph with increase in unit hydrograph peak*

10.5.4 Effect of Change of Temporal Distribution of Design Storm

For studying the sensitivity of rainfall distribution with time two more patterns of time distribution of the rainfall excess values have been considered apart from the distribution pattern obtained from IMD as shown in Figure 10.5. The design flood hydrographs for the three design storm patterns are shown in Figure 10.6. The peak of design flood decreases from 24,359 (reference run/distribution pattern 1) to 20,023 m^3/s that is by 17.8% for the pattern of the design storm. The peak of design flood increases to 27,745 m^3/s that is by 13.9% for the pattern 3 of the design storm. However, it is observed that the time to peak of the design flood is not effected for the design storm patterns considered in the study. It is also observed that the peaks of the design floods are very significantly affected by the pattern of the design flood.

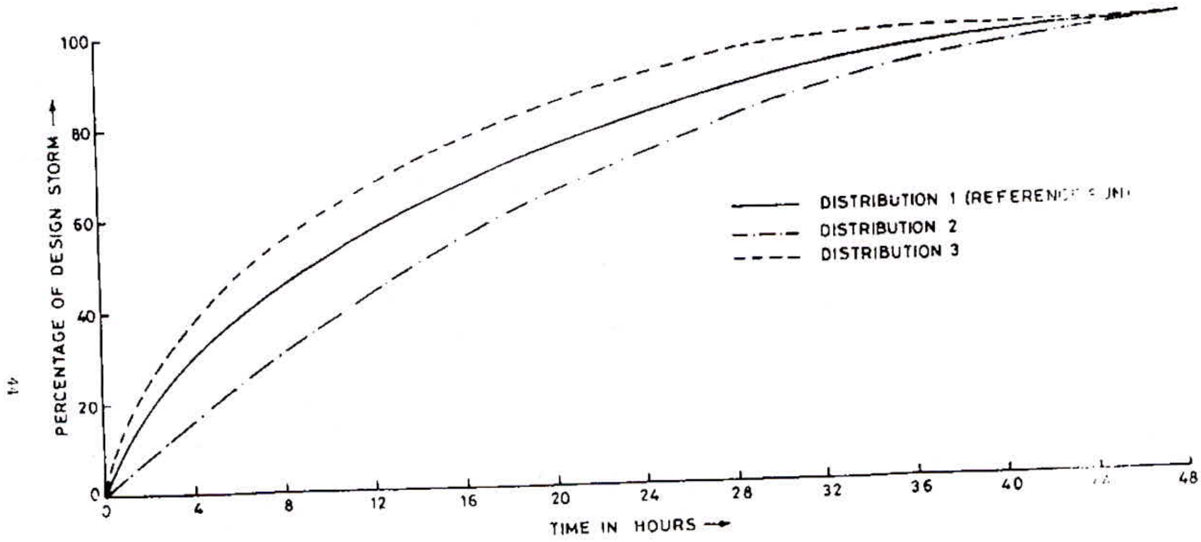


Figure 10.5: Various patterns of the design storm

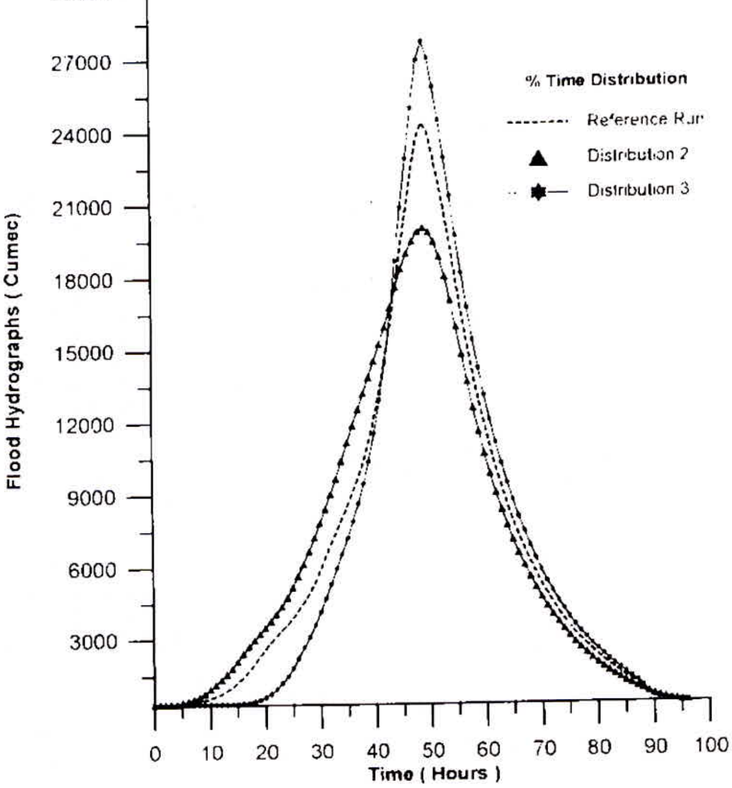


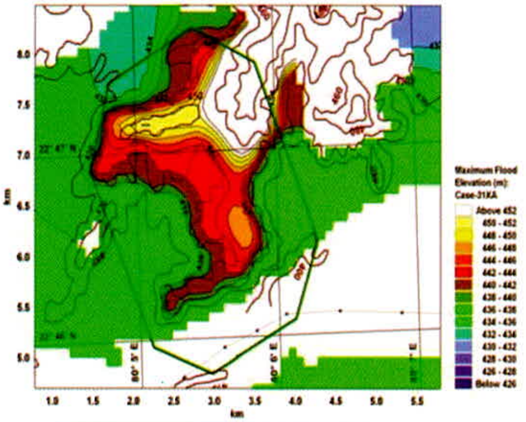
Figure 10.6: Flood hydrographs for different patterns of design storm

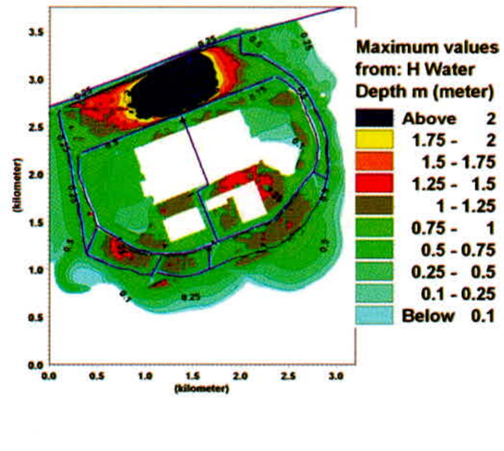
10.6 IMPACT OF CLIMATE CHANGE ON FLOOD INUNDATION

For analysing the impact of climate change on flooding, projections of changes in annual mean temperature as well as rainfall have been studied in New Zealand. For this purpose, six greenhouse gas emission scenarios developed for the IPCC have been used. For estimating the impact of temperature on rainfall, weather models have been adopted to replicate the rain for three historical rainfall events. The rainfall increased by 3, 5 and 33 percent on average for the three events. The Topnet model was used for estimation of flow for the rainfall events. The percentage increases of 4, 10 and 37 in river flow were observed in the study. The flood inundation areas for 50 year return period for a mid-high scenario of the year 2080 has been compared with the present scenario for downtown Westport (Preparing for future flooding: A guide for local government in New Zealand, Ministry for the Environment; 2010).

Flood inundation modelling has been carried out using coupled 1-D & 2-D hydrodynamic model MIKE-FLOOD for estimation of safe grade elevation for nuclear power project at Gorakhpur in Haryana considering safety against design flood of the upstream catchment; at site flooding; dam break flooding of the Bhakra dam; canal breaches and design of external and internal drainage systems for the nuclear power plant site. In this study, it is observed that an increase of 15% in the value of 1000 year return period flood leads to 10 cm increase in the safe-grade level of the important installation at the project site.

Also, flood inundation modelling has been carried out using coupled 1-D & 2-D hydrodynamic model MIKE-FLOOD for estimation of safe grade elevation for nuclear power project for site at Chutka in Madhya Pradesh considering safety against design flood of the upstream catchment; at site flooding; dam break flooding of the Bargi and other dams in the upstream and design of external and internal drainage systems for the nuclear power plant site. In this study also the impact of increase of 15% in the value of design flood has been considered for estimation of the safe-grade level of the important installation at the project site.





10.7 IMPACT OF CLIMATE CHANGE ON HYDRAULIC STRUCTURES

The embankments of a river are designed for 50 year return period flood for a reach of about 12 km. Further, the adequacies of embankment level for design flood with climate change have been evaluated. The daily rainfall values are increased by 15% to study impact of climate change on design floods. With 15% increase in rainfall values, the design rainfall values for 50 year return period is estimated to be 35.7 cm. The comparison of flood peak for 50 year is increased by 13%. The simulated water surface profiles for 50 year return period flood is shown in Figure 10.7.

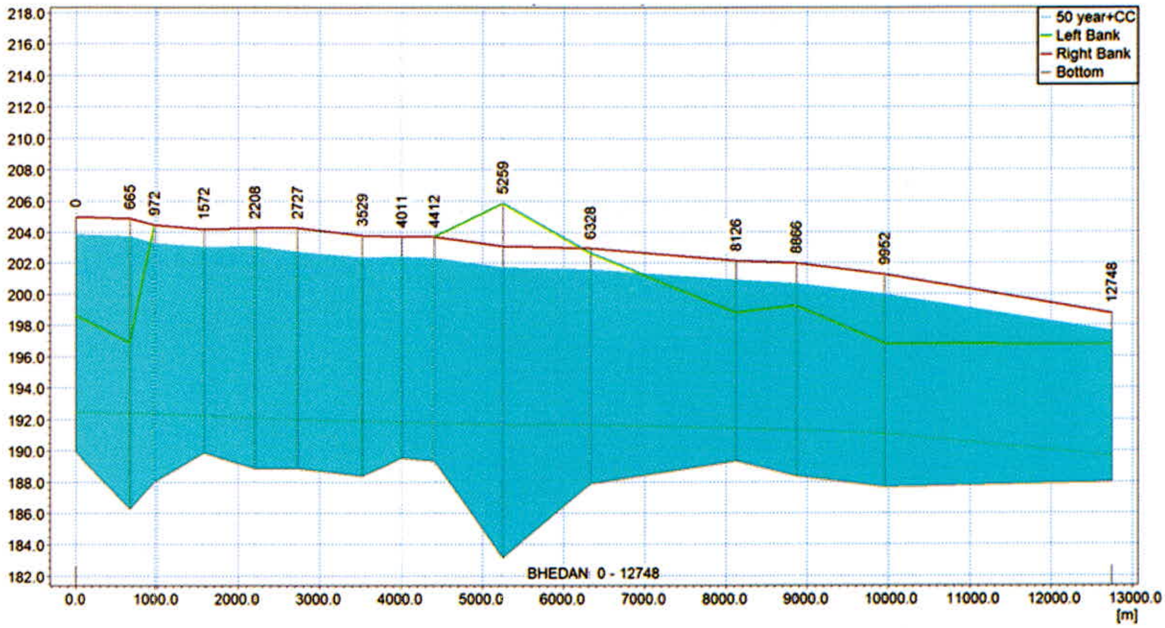


Figure 10.7: Maximum Water surface profile for 50 year+CC return period flood with embankment

The hydrologic and hydraulic analysis for a proposed bridge in lower Himalayas has been carried out for estimation of HFL and flow velocities. The catchment area of the bridge site is 67.06 km^2. The estimated peak floods for 50 and 100 year return periods are 941.62 m^3/s and 1058.75 m^3/s respectively using rainfall data of CWC report (1994). However, the estimated peak floods for 50 and 100 year return periods are 1024.06 m^3/s and 1152.55 m^3/s respectively using rainfall data of CWC report (2015). It is observed that CWC-2015 method provides 8.8 % and 8.9% higher estimates of peak floods for 50 and 100 year return periods as compared to CWC-1994 method. The estimated peak floods for 50 and 100 year return periods are 1157.28 m^3/s, 1386.27 m^3/s respectively using the rainfall data of Narendranagar raingauge station (SUH-LMT).

It is observed that SUH-LMT method provides 22.9 % and 30.9% higher estimates of peak floods for 50 and 100 year return periods as compared to CWC-1994 method. The hydraulic modelling has been carried out using HEC-RAS for various design floods. The bridge geometry is created by adding information of bridge deck, slopping abutments and eleven piers etc. in HEC-RAS. Eleven piers are added based on the centreline of the pier at the upstream and downstream sections. The simulated water level is estimated as 381.66 m, 381.82 m and 382.19 m for discharge of 1157.28 m^3/s (50 year), 1386.27 m^3/s (100 year) and 1982.18 m^3/s respectively (Figure 10.9). The total velocity at upstream and downstream is estimated as 4.02 m/s and 3.96 m/s respectively for the discharge of 1982.18 m^3/s. The increase or decrease in the flood due to climate change may also be considered in the same way for estimating the HFL under the climate change scenarios.

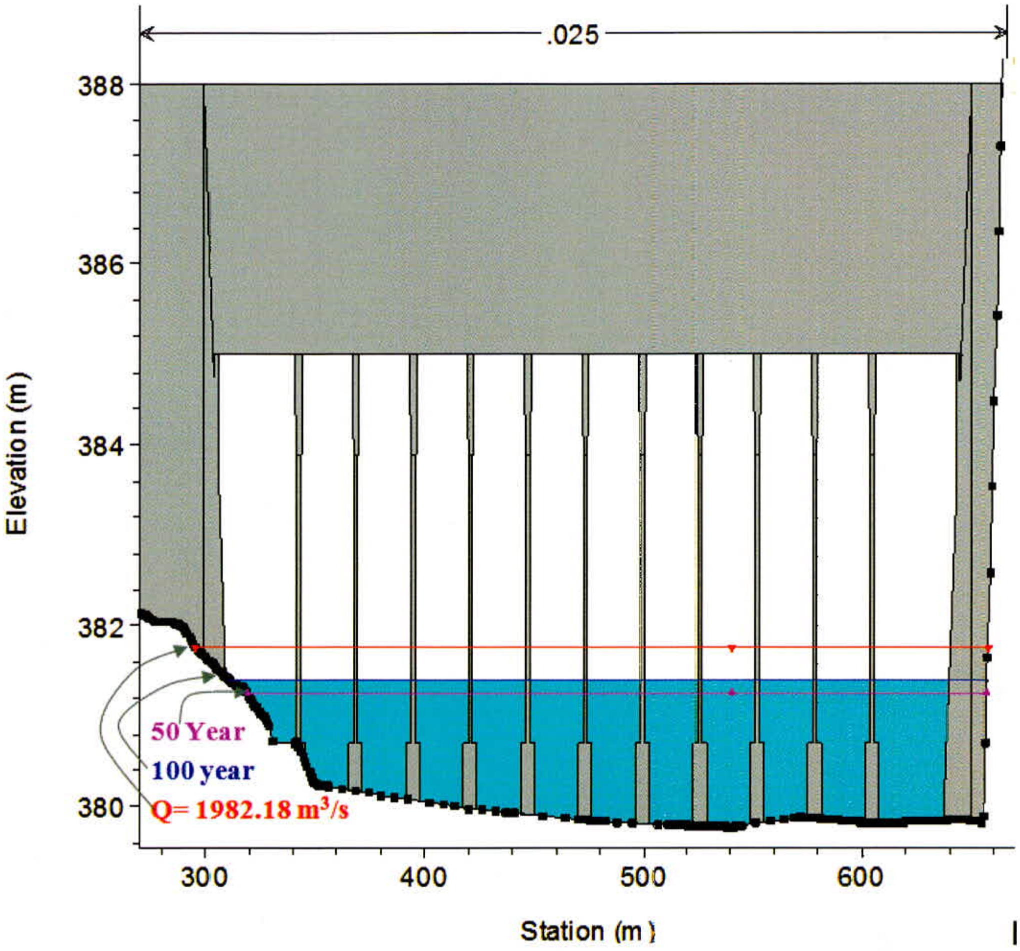


Figure 10.8: Simulated water surface profile for various design floods

10.8 Effect of Increased Return Periods on Flood Frequency Estimates

Now a day, it is generally felt that extreme flood events are likely to be affected due to impact of climate change. In this regard, the large flood events are generally expected to increase because of possibly increase in intensity of severe rainfall and urbanization of the catchments etc. Therefore, the hydrologic design criteria for design of various types of hydraulic structures need to be re-looked. For analyzing this aspect, average values of growth factors of various return periods for the various Subzones may be computed for different increases in the return periods and the resulting percentage increases in the corresponding growth factors with respect to the original growth factors. It is observed that percent deviation in floods of 150 year return period to 100 year return period is minimum 3% for Subzone 3(e) and the maximum 11% for subzone 1(d); whereas the average increase is 7% for 17 Subzones of India (Figure 10.9).

In fact, inclusion of climate change effect in regional flood frequency analysis is a complex procedure and there can be more comprehensive and scientific estimation for this component using procedures based on GCM/ RCM downscaling with various climate change projections employing ensemble modelling approaches by addressing the uncertainty associated with such procedures. The impact of climatic change in regional flood frequency analysis needs to be corroborated by correlation analysis to be carried out in future.

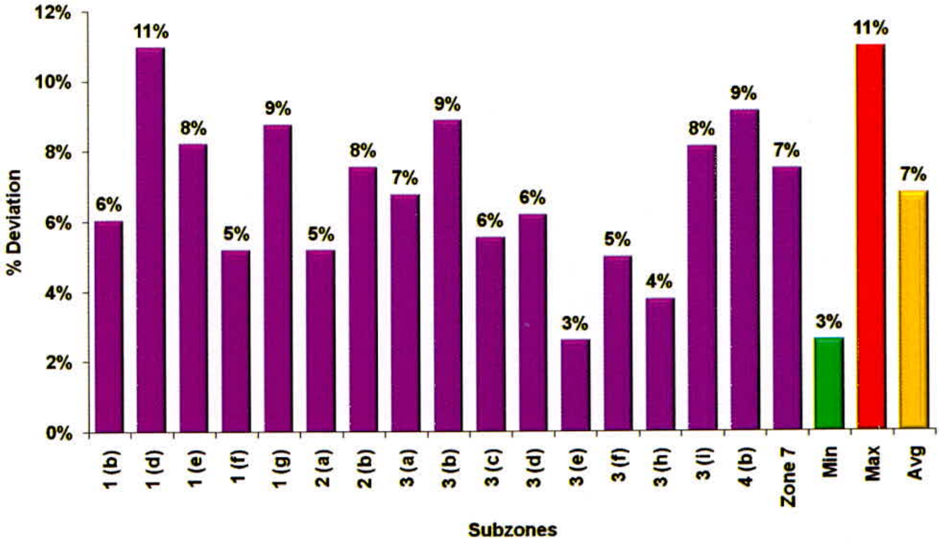


Figure 10.9: Percent deviations in floods of 150 year return period to 100 year return period or 17 sub zones of India

10.9 Adaptation Measures

The major effect of climate change on floods will depend on the magnitude, intensity and distribution of rainfall in time and space. In fact, inclusion of climate change effect on floods is a complex procedure and there should be comprehensive and scientific estimation for this component using procedures based on GCM/ RCM downscaling with various climate change projections employing ensemble modelling approaches by addressing the uncertainty associated with such procedures.

Under design of a hydraulic structure makes it unsafe and susceptible to flood hazard and over design results in its exorbitant cost. For example, it has been observed that for many of the earlier constructed dams in India, design flood estimates are inadequate in the present scenario, mainly because of the new design standards, availability of more data and improvement in the methodologies etc. Under the Dam Rehabilitation and Improvement Project (DRIP), so far review of design flood estimates of about 94 dams have been completed by the project authorities. It has been observed that the revised design flood estimates are higher by 50% for 62% of the dams and about 100% higher for 43% of the dams. These revised design flood estimates necessitate enhancement of spillway capacity to pass design flood and/ or require space in the reservoir for flood cushion. Further, all these aspects require detailed studies in view of considering the impact of climate change on the hydrological extremes. Some of the action points for considering the impact of climate change on floods and their adaptation strategies are mentioned below:

- Setting up of suitable manual and automatic data observation networks for hydro meteorological and related data in the hilly regions for collection of short interval data should be paid attention.
- Data collection, processing, storage, retrieval and dissemination using the state-of-art knowledge in Information Technology sector should be encouraged.

- There should be active collaboration within the institutes and departments engaged in the applications of new methodologies and techniques such as hydrological modelling, soft computing, GIS and remote sensing, down scaling of GCM and RCM data and assessment of impact of climate change etc.
- Estimate design floods for various types of hydraulic structures considering impact of climate change.
    - ✓ Estimate floods of various return periods by using flood frequency analysis for future considering the impact of climate change.
- Estimate flood inundation and flood hazard for the present situation and future considering impact of climate change.
    - ✓ Estimate flood inundation due to floods of various return periods in future considering impact of climate change.
    - ✓ Dam break analysis and generation of flooding scenarios considering failures of single and multiple dams for preparedness, mitigation, response and recovery during emergency to be developed.
    - ✓ Estimate flood hazard and develop flood hazard classification scheme based on extent, depth, elevation and duration of flooding as well as the maximum flow velocity for various return periods using coupled (1-D & 2-D) hydrodynamic flow modelling for the present.
    - ✓ Estimate flood hazard and develop flood hazard classification scheme based on extent, depth, elevation and duration of flooding as well as the maximum flow velocity for various return periods using coupled (1-D & 2-D) hydrodynamic flow modelling for the future considering impact of climate change.
- Early warning and Real-Time Decision Support Systems (RTDSS) for Flood Forecasting
    - ✓ Real time flood forecasting and early warning systems to be developed using the hydrodynamic modelling based on the antecedent rainfall forecasts. Such forecasts may be formulated for 3-day/ 10-day lead time and updated as new QPF data become available;
    - ✓ Real-Time Decision Support Systems (RTDSS) for flood forecasting, flood inundation modelling and early warning to be developed considering the impact of climate change;
    - ✓ Adoption of crowd sourcing and engaging citizen scientists for collection, compilation, processing, analysis and dissemination of data/ information for finding solutions of the flood problems;
- Evaluation of Glacial Lake Outburst Flood (GLOF) hazard
    - ✓ Evaluation of Glacial Lake Outburst Flood (GLOF) hazard and mitigation plans needs to be developed for the potential dangerous glacial lakes;
    - ✓ Develop Mitigation plans for the potential glacial lakes hazards.
- Integrated flood management studies should be carried out for the pilot basins.
- Regulate urban development in flood-prone areas and flood plains
- Preparation of Emergency Evacuation Plans (EAP) for the flood prone areas.

- Design of appropriate drainage systems in urban centres, to quickly drain off the accumulated flood waters in the city.
- Nature-based solutions include widening of natural flood plains, protecting and expanding wetlands, restoring oyster and coral reefs and investing in urban green spaces to reduce flood.
- Checking the insurance policies of infrastructures and buying flood insurances.
- Constructing infrastructures/buildings from flood resilient materials that can withstand direct contact with floodwaters without sustaining significant damages.
- Abandoning affected structures located too close to the shore and relocating houses that are more at risk of flooding to higher ground. Assessment of impact of climate change on floods and revisit of hydrologic design criteria should be taken up. Preparation of standards/ guidelines based on the advanced techniques and tools for integrated flood management should be taken up.
- Appropriate institutional arrangements to achieve these goals would be an effective mechanism to coordinate between different institutions/ departments having expertise in the related interdisciplinary fields.

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