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A Review of Case Studies on Climate Change Impact on Hydrologic Cycle: An Indian Perspective

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ABSTRACT

In recent times, several studies focused on the global warming that may affect the hydrological cycle due to intensification of temporal and spatial variations in precipitation. Such climatic change is likely to impact significantly upon freshwater resources availability. In India, demand for water has already increased manifold over the years due to urbanization, agriculture expansion, increasing population, rapid industrialization and economic development. Numerous scientific studies also report increases in the intensity, duration, and spatial extents of floods, higher atmospheric temperatures, warmer sea, changes in precipitation patterns, and changing groundwater levels. This work briefly discusses about the present scenario regarding impact of climate change on water resources in India. Due to the insufficient resolution of climate models and their generally crude representation of sub-grid scale and convective processes, little confidence can be placed in any definite predictions of such effects, although a tendency for more heavy rainfall events seems likely, and a modest increase in frequency in floods. Thus to analyses this effect, this work considers real problems about the changing flood characteristics pattern in two river regions, and the effect of spatial and temporal pattern in rainfall. In addition to these, the work also examines the trend of groundwater level fluctuations in few blocks of Ganga–Yamuna and Sutlej-Yamuna Link interfluves region. As a whole, it examines the potential for sustainable development of surface water and groundwater resources within the constraints imposed by climate change.

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I. INTRODUCTION

Climate change is a statistical description of weather conditions and their variations over a long period of time. Changing climate is not a new phenomenon, but a natural process of earth's evolution. When looked at a broader spatial scale, i.e. at a macro-scale, the global climate has varied substantially through the earth's history. This can be witnessed from prehistoric temperature records reconstructed from the chronologies of tree-rings, lake sediments, ice-cores etc. (Hodder et al., 2007; St. George et al., 2009, Sauchyn et al., 2015). Nevertheless, the historically recorded temperature indicates that the earth's temperature has increased by approximately 0.74 ˚C (ranging between 0.56 ˚C and 0.92 ˚C) over the past century (1906–2005). The impacts increased temperature on the earth's environment and the fresh water resources is summarized by the Intergovernmental Panel on Climate Change (e.g. IPCC, 1998; 2001; 2007).

The movement of water among various spheres of the globe, i.e. atmosphere, lithosphere, hydrosphere, and biosphere is collectively called the hydrological cycle. Precipitable water in the atmosphere reaches atmosphere in the forms of rainfall, snowfall, sleet etc. and it either becomes an instant runoff over the surface or infiltrates into the soil to be stored as soil moisture or percolates deeper to be stored as groundwater. The water stored as soil moisture is taken up by the plants/trees and is transpired back into the atmosphere during the process of photosynthesis. Surface and subsurface (shallow or deeper groundwater) runoff joins the surface water bodies including rivers, lakes, reservoirs, or oceans. Water enters back into the atmosphere through evaporation from the surfaces of these water bodies. The intrinsic interactions between surface and groundwater systems, through recharge and discharge, is a vital part of the hydrological cycle. However, they are often considered as separate entities in water balance models, because of the increase in computational efforts required to replicate and solve the complex interactions between the systems (Alley, 2001). For example, distribution of water resources or flood management in a watershed is based on the streamflow variability to greater extent and to very little extent on the groundwater variability (IPCC, 2007). Contrarily, the management of groundwater resources cannot be undertaken without the knowledge of the magnitude and seasonality of recharge (Loáiciga, 2003).

The movement of water between the spheres of the globe is primarily driven by the solar energy. An increase in net solar radiation in the earth's atmosphere increases the temperature which in turn speeds up the processes of hydrological cycle, that are dependent on the changes in temperature, including evaporation, condensation, precipitation etc. Nevertheless, an increase in net solar radiation in the earth's atmosphere does not always increase the precipitation in all geographic regions, because the interactions between the changes in hydrological cycle and the weather patterns (global or local) are complex in nature. This article reviews the existing literature, case studies in specific, on the impacts of climate change on surface and groundwater resources Indian subcontinent. In addition, the potential for sustainable development of water resources and the future research needs in the aspect are examined in this article.

II. GREENHOUSE EFFECT ON HYDROLOGICAL CYCLE

A part of the shortwave radiation reflected back into the atmosphere by the earth surface is absorbed by several greenhouse gases including water vapour, carbon dioxide, ozone, etc. This is a natural phenomenon, also known as the greenhouse effect, which traps heat in the atmosphere increasing the temperature near the earth's surface. Increased concentrations of such gases in the atmosphere gradually increases the average temperature of the lower atmosphere (troposphere). Increased temperature near the earth's surface increases the rate of evaporation and the surface moisture content is altered rapidly. This process increases the moisture content within the atmosphere, which might lead to intense precipitation events (rainfall or snowfall) increasing the potential for disastrous floods, e.g. flash floods, urban floods etc. A schematic representation of these processes is shown in Figure 1. Therefore, a warmer climate has a potential to alter the hydrological processes and accelerate the hydrological cycle, which might lead to frequent occurrences of flood or drought events.

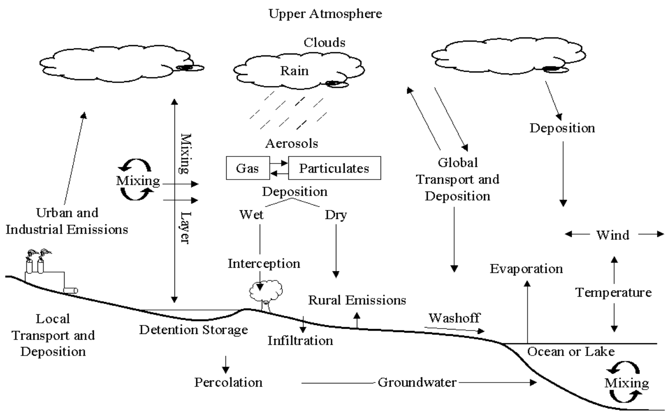

Figure 1 : The warming effect and their effect of greenhouse gases on the hydrologic cycle in microscopic scale, and phenomenon associated on a region.

The natural processes of geomorphologic changes and/or man-made or natural changes in land-use/land-cover has a potential to alter the natural hydrological cycle. Such processes include (i) aeolian or water erosion of soil (Nearing et al., 2001; 2005), (ii) deterioration in soil properties (O'Neal et al., 2005), (iii) loss of natural vegetation or conversion of forest to a cultivable land (Goss, 2005). Several researchers across the globe have studied or assessed the impacts of climate change on regional hydrology, i.e. water availability, characteristics of floods and droughts, eta. (e.g. Mirza et al., 2003; Szwed et al., 2010; Perazzoli et al., 2013).

In summary, the projected changes in future climate, i.e. a warming climate, impacts the spatial and temporal distribution of precipitation events, glaciers, sea level etc. Melting glaciers along with the intensified precipitation events, if any, leads to an increase in the runoff yield and has a potential to adversely affect the water balance across India. In addition, changing climate has a potential to impact the groundwater resources, because of the projected changes in precipitation magnitude and intensity, rate of infiltration and evapotranspiration. This work focuses on reviewing the impacts of climate change on two vital components of the hydrological cycle, i.e. surface runoff and ground water storage. For example, how an increase in precipitation intensity may lead to altering the surface runoff, recharge and ground water storage. Changes in flood frequency and fluctuations in groundwater table in response to a likely heavy rainfall event may roughly be projected using a calibrated hydrological model. However, the confidence or accuracy of such projections is debatable because of the insufficient resolution and crude representation of the regional hydroclimatic processes in the climate model.

Table 1: The details of selected tropical cyclonic systems in the study area

#	*Period*	*Year*	*Max. Intensity*	*Coast of Landfall*
1	22-28 October	1996	3.5	Dissipated
2	23-27 October	1997	3.5	Bangladesh
3	17-20 May	1998	3.5	Bangladesh
4	7-8 May	1996	2	Bangladesh
5	27-29 October	1996	2	West Bengal

III. MODELLING OF RAINFALL INTENSITIES ASSOCIATED WITH GLOBAL WARMING

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time, and the classical period is 30 years, as defined by the World Meteorological Organization (WMO). A simple way of differentiating is that climate is what we expect e.g. cold winters and weather is what we get e.g. a blizzard or high intensity rainfall called cloud bursting during a non-monsoon period having an intense rainfall for a small period that goes above the recorded design criteria or standard code. The spatial distribution of normal annual rainfall in India, averaged over the last 30 years is illustrated in Figure 2. To illustrate making the inferences from the possible future changes in the frequency of tropical higher rainfall, a diagnostic computation of the yearly genesis parameter (YGP; Gray, 1975) for two prominent tributaries of river Ganges, India is discussed below.

Five samples (Tables I and II) of tropical disturbances (cyclonic systems) formed over the Indian Sea between 1995 and 2005 (11 years) have been analysed. These are focused majorly along the coastal belt of India and some in Gangetic plains that can be seen from the scale positions of the rain gauge stations. This discussion has been taken here so as to relate this rainfall intensity both temporally and spatial scales with the corresponding trend changing with surrounding temperature or in proximity as universal global warming. The cyclonic data was obtained from Annual Reports of the Regional Specialized Meteorological Centre (RSMC) at India Meteorological Department (IMD), New Delhi. The cyclonic data includes the period of its occurrence, year, intensity and the coast of landfall, Table I. The classification of cyclonic system based on its characteristics is listed in Table II, these values are estimated from post-analysis of all available observations. The intensity of cyclone and the location (latitude and longitude coordinates) of its landfall are available at 6-h intervals (1990-1994) and at 3-h interval (since 1995). Several low-pressures systems form over Indian Sea and only a few are transformed into cyclonic storms. The potential of such systems to intensify into a cyclonic storm can be identified using a genesis potential parameter (GPP), which is based on the thermodynamic and dynamic variables, at the early stages of their development. The GPP is a useful parameter for predicting the intensity of any tropical disturbance over the Indian Sea. The low-pressure systems or cyclonic storms can be categorized in to non-developing and developing systems, knowing the wind speed and the peak intensity, estimated from GPP.

Table II: The details of selected tropical cyclonic systems in the study area

Classification of cyclonic system	***T. No.***	***Wind Speed (knots)***	***Wind Criteria (knots)***
Deep Depression (DD)	2.0	30	28-33
Cyclonic Storm (CS)	3.0	45	34-47
Severe Cyclonic Storm (SCS)	3.5	55	48-63
Very Severe Cyclonic Storm (VSCS)	4.5	77	64-119
Super Cyclonic Storm (SUCS)	8.0	170	C120

The cyclone of October 1999, formed over the Bay of Bengal and hit the coast of Odisha is called a super cyclone and is the most intense tropical cycles occurred over the past 100 years, the average GPP of this cyclone was 14.4. A similar cyclonic storm with an average GPP of 11.9 occurred the same year in June. Coupled with the above discussed results, if the observed trends in climate and a few other predictions are assembled, the results somewhat agree with the report by Hingane et al. (1985), i.e. changes in precipitation patters and an increase in temperature. Table III lists a few studies that evaluate or analyse the trends and/or changes in precipitation and temperature over the past century. Table IV lists out a few projections of temperature and precipitation, across India for the next century, with the changing concentrations of greenhouse gases in the atmosphere (Bhaskaran et al.,1995).

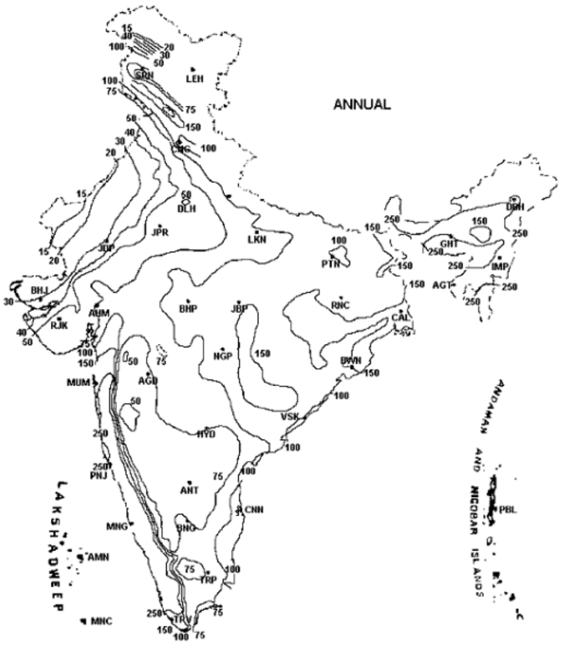

Figure 2: The details of selected tropical cyclonic systems in the study area.

Figure 3 depicts the anomalies of summer monsoon rainfall (1871 – 2004) along with a 10-year moving average and Figure 4 shows the annual variability of mean monthly rainfall observed near Lucknow city. The seasonal variability in rainfall across central and eastern Gangetic plains can be understood by comparing the seasonal mean rainfall observed at Bhopal (representative of Central Gangetic Plains) and Lucknow (representative of eastern Gangetic Plains) meteorological stations, Table V. Bhopal receives higher magnitude annual mean rainfall compared to that observed near Lucknow City.

Some elevated places in the Himalayan North regions receive sustained winter snowfall, that strongly influence the country's climate by preventing cold Central Asian winds from blowing in, keeping the bulk of the Indian subcontinent warmer than most locations at similar latitudes. Simultaneously, the deserts in this specific region play a role in attracting moisture-laden southwest summer monsoon winds that, between June and October, provide the majority of India's rainfall. Four major climatic groupings predominate, into which fall seven climatic zones that, as designated by experts, are defined on the basis of such traits as temperature and rainfall. Groupings are assigned codes according to the Köppen climate classification system. In Table II, the rainfall data for selected Indian cities represent the full variety of major Indian climate types.

Table-III: Observed climate change during the 20th century over India

Region	Temperature	Rainfall
All-India	– Increase in 0.4 ˚C/100 yearsin mean annual temperature – Increase in maximum temperature – 0.6 ˚C / 100 years – Minimum temperature trend less – General increase in the diurnal range of temperature	– Westward shift in rainfall activities over the IGPR – Monsoon rainfall is trend less and is mainly random in nature over a long period – Decadal departures in summer monsoon rainfall are found above and below the long time average alternatively for three consecutive decades
Indo-Gangetic Plain Region (IGPR)	– Annual surface air temperature of the IGPR shows rising trend (0.53 ˚C / 100 years during 1875 – 1958) – Decreasing trend (-0.93 ˚C/100 years during 1958 – 1997)	– Summer monsoon rainfall over western IGPR shows increasing trend (170 mm/100 years) from 1900 – Over central IGPR it shows decreasing trend (5 mm/100 years) from 1939 – Over eastern IGPR, it showed a decreasing trend (50 mm/100 years) during 1900 – 1984

Region	Temperature	Rainfall
		abd increasing trend (480 mm/100 years) during 1984 - 1999
Western and eastern Himalayas	No trend in minimum temperature	– Western Himalayas gets more snowfall than eastern Himalayas during winter – More rainfall in the eastern Himalayas than in the western Himalayas during monsoon season.

The increasing temperature and its impact on several components of the hydrological cycle poses a threat to the watershed's hydrology, particularly in the Himalayan region that has undergone substantial changes over the past century. In general, the response of hydrological systems, sedimentation and erosion processes in the hilly regions across India could be significantly altered due to the changing climate. Some aspects of the climatic change and their effect on the surface water resources of India are enumerated in the following section. The YGP is an empirical diagnostic of the frequency of Tropical Cyclones (TC) based on six physical parameters computed from seasonal means of atmospheric and oceanic variables. In this work, YGP is used to the large-scale fields simulated by a General Circulation Models (GCM) which can be used to simulate human-induced climate change. GCM represents the effects of factors like reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. In this discussion, we apply the YGP diagnostic to the results of three climate simulations performed with the atmospheric General Circulation Model for the region of Ganges and the Brahmaputra basin regions. These two basins are fed by both rainfall and glacial-melt, and the total annual streamflow in these two rivers is nearly 40% of the surface runoff yield.

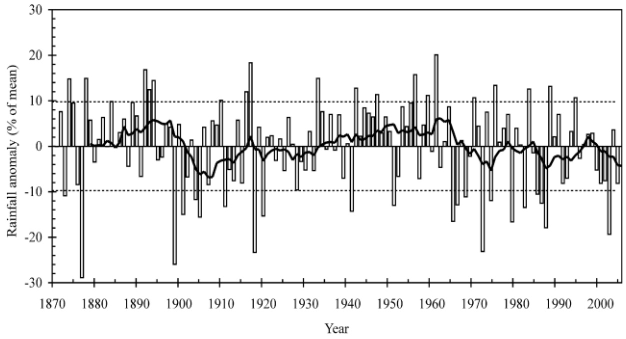

Figure 3: All-India summer monsoon rainfall anomalies (1871-2004). Dark line indicates a 10-year moving average (Mall et al., 2006)

IV. The Climatic Effect on Streamflow Pattern

In India, the rivers are mainly categorized major and intermediate rivers based on their catchment size and their average annual runoff potential (Umapathi and Ramashesha, 2001). The major rivers of India altogether have a catchment area of approximately 252.8 million hectares, whereas that of the intermediate rivers is nearly 24.9 million hectares. While all of the major rivers and majority of the intermediate rivers are perennial in nature, discharge in a few intermediate rivers is seasonal. This variability results from the non-uniform distribution (both temporal and spatial) of rainfall over India (e.g. Gupta, 1995). The major rivers of India, together have a potential for 1869 billion m^3 of average annual flow, Table VI. However, the Indian Rivers do not remain at a high stage throughout the monsoon season. It is the spell of heavy rainfall events alone lasting for a considerable amount of time (i.e. few hours to days) that produce huge flow in these rivers with contributions from surface and subsurface runoff (e.g. Ramakrishna, 1999). Such variability in the river flows has a huge impact on the riverine flood management and also the management of available water during drought periods (e.g. IPCC, 2007).

Table-IV: Projected climate change during the next century over India

Region	Temperature	Rainfall
All-India	Increase in winter temperature by 1 – 4 ˚C with increased CO_2	Rainfall increased by approximately 20%
All-India	Average temperature change is predicted to be in the range of 2.33 – 4.78 ˚C with a doubling in CO_2	Increase in frequency of heavy rainfall events
All-India	– Area averaged annual mean surface temperature rise is [projected to range between 3.5 – 5.5 ˚C vy the end of century – More warming in winter season	– Increase of about 5 – 10% in annual mean rainfall – Decline of 5 – 25% in winter rainfall – Increase in monsoon rainfall by 10 – 15% – Increase in monsoon season rainfall over northwest India by 10% or more by 2050 – Western semi-arid region of India could receive higher than normal rainfall in a warmer atmosphere – Decrease in winter rainfall between 10 – 20% over central India by 2050

V. Climate Change and the Flood Characteristics

Globally, floods are among the top-reported natural disasters, affecting nearly 140 million per year (WDR, 2003; 2004). For example, nearly 70% of Bangladesh in 1998 was inundated, compared to an annual average of 20–25% (Mirza, 2003; Clarke and King, 2004). In addition, the changing climate add another level of complexity in understanding the flood characteristics. There are a number of factors that contribute to flood risks implied by a warmer climate, including: (i) more frequent wet spells in middle/ high latitude winters; (ii) more intense mid-latitude storms; (iii) increased frequency of extreme precipitation events; (iv) increased magnitudes of precipitation events of high intensity; and (v) use changes and surface degradation e.g. deforestation and urbanization. The combination of more intense and frequent storms with land use changes, the increased average temperatures (results in melting of ice), and thermal expansion of oceans as a result of rising sea levels and coastal erosion, and flooding of wetlands and lowlands have a significant impact on the reduced protective capacity from extreme storms and floods, as higher sea levels provide a higher base for storm surges. This will act as a further feedback mechanism, accelerating ongoing climate change.

A large numbers of studies have shown significant trends in several measures of streamflow and a few of these studies demonstrate that these trends are linked with the trends in the primary hydroclimatic variables including temperature and precipitation. In the present study, we focus on how the possible climate change will affect the flooding return period magnitudes in the two major river basins of India. Studying the potential meteorological impacts of climate change involves comparing two future scenarios, one with and the other without climate change. Uncertainties involved in such an assessment include the timing, magnitude and the nature of climate change, and the impacts of flood management on natural resources. In view of the above scenario, an attempt has been made here to give a brief resume of the possible impacts of climate change on India's surface water flows for the considered areas.

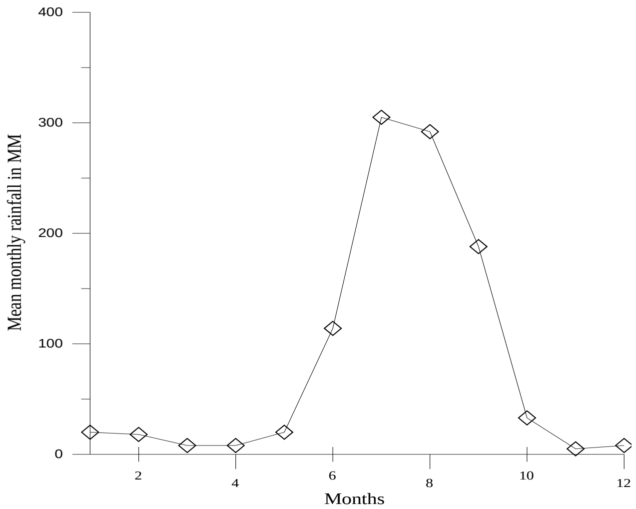

Figure 4: Mean monthly rainfall for Lucknow City

Statistical significance of each statistical test differs. There is evidence of a coherent pattern of change in annual streamflow, with some regions experiencing an increasing trend. Interannual variations in streamflow are also influenced by large-scale climatic patterns or low-frequency atmosphere-ocean oscillations, i.e. teleconnections. This section discusses the flood patterns in several sub-watersheds of Brahmaputra and Upper Ganga River basins (Bhunya et al., 2007; 2008; 2009). The summary statistics of annual peak flow in these watersheds, their catchment area and the length of the main stream are listed in the Table VII. The coefficients of variation (C_v) and skewness (γ) for the annual peak flow data are observed to be varying in the range of 0.23 to 1.9 and -0.48 to 4.4 respectively. The variation of C_v means the dispersion of annual peak flood data in the region, and this can be judged from the deviation of the points from the straight line fit in the τ - C_v diagram. The heterogeneity measure, H_i (Hosking, 1991) is moderately high for Brahmaputra watershed, which means they are not homogeneous, which might be due to the changes in land use patterns or other geomorphological changes. Similarly, the H_i for Upper Ganga watershed is less than 2, which means it is a possibly heterogeneous region, Table VIII. These factors affect the flood estimation with some probability of exceedance. Such criteria area generally used for flood estimations in our major projects. In summary, it was found that the total annual streamflow in these watersheds is increased linearly with the changes in temperature, but the most prominent effect of increase in temperature has been noticed on the glacier melt run-off. Similar assessments of the impacts of climate change were not analysed for the watersheds of central India. Such impact studies are critical for this region, especially for the drier scenarios.

Table-V: Average rainfall in selected Indian cities (mm)

Season	Month	Bhopal	Lucknow
Winter (Jan – Feb)	January	4	20
	February	3	18
Summer (Mar – May)	March	1	8
	April	3	8
	May	11	20
Monsoon (Jun – Sep)	June	136	114
	July	279	**305**
	August	**360**	292
	September	185	188
Post-Monsoon (Oct – Dec)	October	52	33
	November	21	5
	December	7	8
Annual Rainfall (mm)		1,043	1,019

VI. Derivation of Regional Indices using Analysis of Individual Flood Gauges

It is not certain how individual catchment areas will respond to changing evapotranspiration rates and precipitation. It is likely, however, that drier hydrological regimes will be more sensitive to changes in climate. Relatively small changes in temperature and precipitation could cause relatively large changes in run-off. Arid and semi-arid regions will therefore be particularly sensitive to reduced rainfall and to increased evapotranspiration. It is widely accepted that the frequency of heavy precipitation events and severe flood events have increased significantly, in most regions in India (e.g. Mirza, 2003, Mall et al., 2006). However, it is not yet conclusive that these extreme events are the indicators of changing climate. A better understanding of the climate system and its interaction with the region's hydrology is important to conclude that these extreme events are resulting from the changes in the climate. Nevertheless, monitoring and evaluating the extreme events is vital to be able to predict or forecast and cope with them.

The use of empirical flood frequency analysis is widespread throughout hydrological practice. The basic assumption of flood frequency analysis is that annual maximum flood peaks are distributed independently and identically. The implied assumption is that the climate is statistically static at all timescales — the risk of a flood of a given magnitude is taken as being the same from one year to the next, irrespective of the underlying climate mechanisms. However, it is well known that persistent climate modes modulate regional climates on multiple time scales around the globe. The most well-known of such persistent climate modes is perhaps the El Nino/Southern Oscillation (ENSO) operating on an inter-annual time scale. At longer timescales, indices of multi-decadal variability have been derived such as the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) (Mantua et al., 1997).

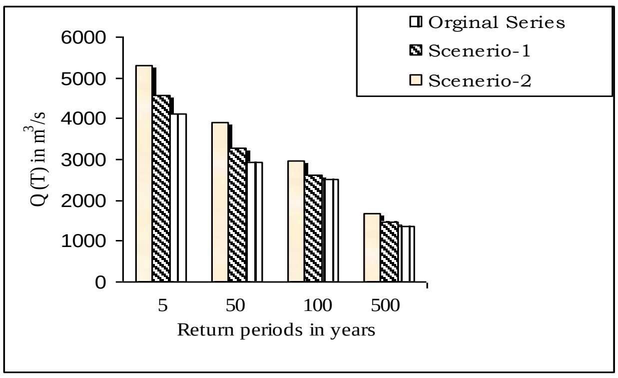

Figure 5: Comparison of 100 year return period floods for the original series, Scenario-1 and Scenario-2 under climate change

The sparse precipitation gauging network in these watersheds makes it impossible to confirm or verify the influence of precipitation on runoff in the rivers, but it is believed to have risen. There is a consensus that the increasing temperature and winter precipitation have an influence on the variability in flood magnitudes in the tributaries of Brahmaputra River in particular, i.e. Dudhnai, Krishnai, and Kulsi. Although it was previously thought that these changes were induced by climate, the timing of the dominant flow event has also changed but was not consistent spatially. Generally, the frequency of occurrence of more intense rainfall events in many parts of Asia has increased, causing severe floods, landslides, and debris and mud flows, while the number of rainy days and total annual amount of precipitation have decreased. The increasing frequency and intensity of floods in many parts of these areas are attributed largely to increasing summer (and/or other dry months) month temperatures in particular. More intense rain and more frequent flash floods during the monsoon would result in a higher proportion of runoff and a reduction in the proportion reaching the groundwater. Changes in snow- and glacial-melt, in addition to the rising Himalayan snowline, will negatively impact the seasonal variability of streamflow leading earlier occurrence of peak flow and water shortage during summer months (Stern, 2007).

Table-VI: Major river basins of India

River	**Origin**	**Catchment Area (km^2)**	**Average Annual Potental (b. cu. m/year)**
Indua	Mansarovar (Tibet)	3,21,289	73.31
Ganga	Gangotri (Uttar Kashi)	8,61,452	525.02

River	Origin	Catchment Area (km^2)	Average Annual Potental (b. cu. m/year)
Brahmaputra	Kailash Ganga (Tibet)	1,94,413	585.60
Barak and Others		41,723	298.02
Sabarmati	Aravali Hills	21,674	3.81
Mahi	Dhar (Madhya Pradesh)	34,842	11.02
Narmada	Amarkantak (MP)	98,796	45.64
Tapi	Betul (MP)	65,145	14.88
Brahmani	Ranchi (Bihar)	93,033	28.48
Mahanadi	Nazri Town (MP)	1,41,589	66.88
Godavari	Nasik (Maharshtra)	3,12,812	110.54
Krishna	Mahabaleshwar	2,58,948	78.12
Pennar	Kolar (Karnataka)	55,213	6.32
Cauvery	Coorg (Karnataka)	81,155	21.36
	TOTAL	**25,28,084**	**1,869.00**

Pandey et al. (2013) evaluated the impacts of climate change on annual peak floods, using the floods of various return periods computed from 98 years of annual maximum flood data using the L-moment approach. Two hypothetical scenarios were also created to study the impacts of climate change and annual floods. The description of these scenarios are listed below:

- **Scenario-1:** The highest 20% values of the annual peak floods have been increased by 20%.
- **Scenario-2:** The highest 20% values of the annual peak flood have been increased by 20% and the lowest 20% values of the annual peak flood have been decreased by 20%.

The flood quantiles for original series, scenario-1 and scenario-2, for several return periods are listed in Table IXA. The deviations in floods for Scenario-1 and Scenario-2 with respect to the original flood series are listed in Table IXB. Figure 5 compares the flood quantiles for the return periods of 5, 50, 100 and 500 years, extracted from the original, and 2 other modified peak flow datasets, i.e. scenarios 1 & 2 described above. Scenarios 1 & 2 are developed from the original peak flow datasets with the presumption of changing climate. In the developed world, the return period of extreme events may still be substantially greater than the recovery period from the disasters which the events cause. For less adaptable societies in the developing world, however, a shorter return period of extreme events may not allow them to fully recover from the effects of one event before the next event strikes.

Table-VII: Statistical summary of annual peak flow and other vital watershed characteristics

Watersheds		Upper Ganga	Brahmaputra
No. of Sub-catchments		16	23
Mean Annual Peak Flood (m^3/sec)	**Mean**	3211	3435
	Max.	12,985	11,689
	Min.	294	149
Catchment Area (km^2)	**Max.**	22,949	14,197
	Min	335	198
Length of Main Stream (km)	**Max.**	293	248
	Min.	21	48

Frequent occurrences of unprecedented extreme events in the recent decades suggest that these events are becoming more common indicating more intense precipitation events in the latter half of the 20th century (IPCC, 2001). The temporal distribution of extreme events plays an important role in determining the peak of the design storm hydrograph.

The critical values of probable maximum precipitation (PMP) and their temporal distribution, vital for the estimation of design flood, are provided by the IMD. For each important storm to be considered in the design flood, WMO recommends the use of spatial and temporal distribution of rainfall (CWC, 1993).

In this review, the sensitivity of the temporal distribution of storm pattern has been conducted by considering two more distribution patterns apart from the storm pattern available for the design storm. In this work, to study the impact of increase in peak of the unit hydrograph on the design flood peak, different unit hydrographs have been applied with the design storm of one bell (considered to be reference design storm). The results (Figure 6) shows the variation of percentage increase in the peak of the unit hydrograph to about 30% increase, and there is an increase of about 25% in the design flood peak.

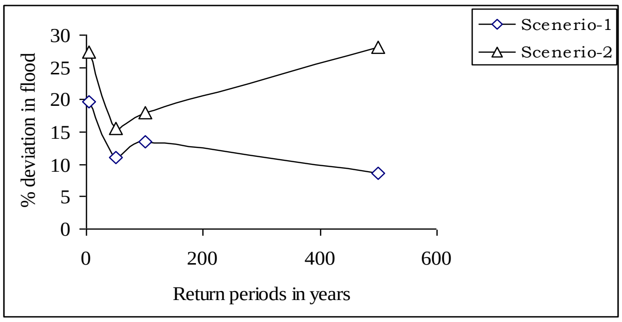

Figure 6: Variation of percentage increase in peak of flood hydrograph with percentage increase in peak of UH

From the analysis that we took only for two selected small catchments i.e. Br-187 (sub zone- 1f) in Ganges plain & Pagaladiya sub-catchment in Brahmaputra basin results roughly the effects of precipitation on runoff. However, the study the effects due to temporal variation in runoff for a PMP are difficult to ascertain, largely because of the deficiencies and sparseness of the precipitation network.

Uncertainties in projected changes in the hydrological system arise from internal variability of the climate system. However, uncertainties arise from the incorporation of climate model results for two reasons: the different spatial scales of global climate models and hydrological models, and biases in the long-term mean precipitation as computed by global climate models for the current climate. A number of methods have been used to address the scale differences, ranging from the simple interpolation of climate model results to dynamic or statistical downscaling methods, but all such methods introduce uncertainties into the projection. Biases in simulated mean precipitation are often addressed by adding modeled anomalies to the observed precipitation in order to obtain the driving dataset for hydrological models. Therefore, changes in inter annual or day-to-day variability of climate parameters are not taken into account in most hydrological impact studies. This leads to an underestimation of future floods, droughts and irrigation water requirements.

Table-VIII: Heterogeneity Measures of data used

Watershed	Heterogeneity Measure (H_i)	
	All Stations	Discordant Station Removed
Upper Ganga (16*)	6.08 [c]	1.92 [b]
Brahmaputra (23*)	3.07 [c]	-

* Denotes the number of sub-catchments that are discordant with the rest

[a] Homogeneous (H_i < 1)

[b] Possibly Heterogeneous (1 < H_i < 2),

[c] Heterogeneous (H_i > 2)

VII. The Climatic Effect on Groundwater Flow Pattern

Quest for the knowledge of the impacts of climate on groundwater system or vice-versa has gained significance in the recent times with the increasing concern of water availability in the times of changing climate. A better understanding of changes in the groundwater levels throughout the historical period is vital to evaluate the response of any groundwater system to a changing climate, which helps in projecting plausible trends in groundwater levels.

The initial step for such studies requires physically-based modelling approach for estimating groundwater recharge, and the associated impact assessment of changing climate on groundwater resources. The method must not only account for temporal variations in the climatic variables and their impact on the hydrologic cycle, but also consider the spatial variation of surface and subsurface properties across the study area. Furthermore, influences due to land use, unsaturated zone thickness and surface water can be derived through time series analysis. Many climate change studies have generally focused on modeling the temporal change in the hydrologic processes and ignored the spatial characteristics due to model limitations. It is therefore necessary to review the earlier works on changing pattern between groundwater systems and climate and outline a simple method to study this impact using a sample data that can characterize the spatial and temporal effect of climate change on groundwater recharge. An example application for the hydro geologic conditions in the hydrologic cycle of the Gangetic watershed has been presented.

Recharge refers to the quantity of water being added into a groundwater system, whereas the discharge refers to the quantity of water withdrawn from or exiting the system. In this paper, the quantity of soil water passing through the unsaturated (vadose) zone and joining the groundwater table (saturated zone) is referred to as recharge. Recharging of confined and/or deeper aquifers is done either laterally or vertically through aquitard leakage from saturated zones. Figure 7 illustrates the main processes for clarification, and it explains the process of infiltration that is the volume rate of water flowing into a unit area of soil surface, whereas percolation is the process by which water migrates down through the soil profile in the unsaturated zone.

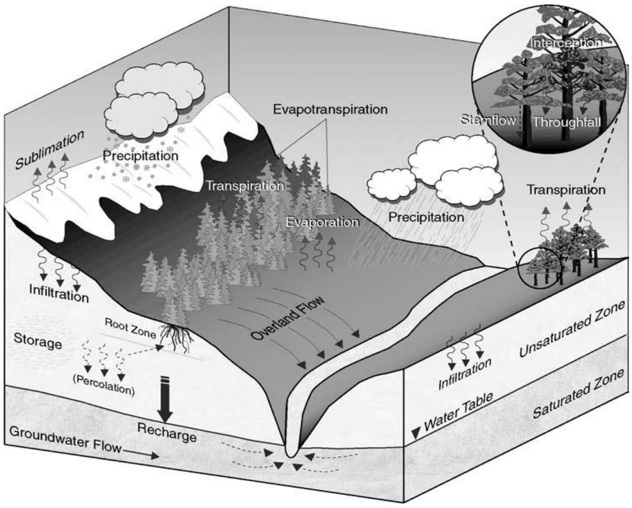

Figure 7: The associated phenomenon related to the effects of warming on groundwater systems as a part of the hydrologic cycle at macroscopic scale.

Precipitation forms the driving force for natural recharge, although other artificial techniques, for example infiltration ponds can be used to recharge the groundwater systems. In general, the natural surface water bodies are the areas of discharge and not recharge. Therefore, seasonal variations in the surface water bodies that are in close proximity with the aquifers, might be resulting from the altering periods of recharge and discharge. Because of the direct interactions between surface water bodies and climate, the changing climate could directly impact the surface water bodies and hence the relative importance of the recharge and discharge. As shown in the hydrologic cycle in Figure 7, precipitation is formed either as rain or snow. If the precipitation is in the form of a rainfall, after reaching the surface, it may either flow overland to reach the nearest surface water body (e.g. stream or ditch) or infiltrate into the soil to percolate deeper and reach the groundwater table (saturated zone). The quantity of rainfall infiltrating into the soil forms the potential groundwater recharge. However, the actual quantity of water reaching the saturated zone (e.g. aquifer) might differ because of the presence of low permeability drift or of the presence of excessive moisture in the unsaturated zone. Therefore, it is vital to differentiate and quantify the actual recharge from the potential recharge. It encompasses complex processes controlling recharge e.g. precipitation, irrigation and soil water movement like the process of infiltration and saturation excess runoff, and bypass recharge to estimate the groundwater recharge.

VIII. Influence of Changing Climate on Groundwater Recharge

It is increasingly recognized that groundwater cannot be considered in isolation from the regional hydrological cycle, but the possible changes in regional climate and/or land-use may influence the regional hydrological cycle and groundwater system in particular. To get a better understanding on the interactions of various climatic and non-climatic factors on groundwater recharge and surface runoff, two examples are quoted.

A study by Yadav and Kumar (2010) evaluates the change in groundwater levels in 5 development blocks of Rewari District, Haryana (India). On an average, the depth of water table in these blocks ranges from 30 m (minimum) to 100 m (maximum). Overexploitation of groundwater in these blocks has led to a declining water table and the shallow tube wells failed to function. In one of the blocks, Khol block, the decline in e water level was so severe that it had to be declared a dark zone. in this block, the water table in 1974 was at 18.02 m, which has gone down to 42.46 m in 2009. The condition in such areas is becoming very serious where there is a dearth of canal water. Although the Khol block is declared a dark zone by the Central Groundwater Board, the farmers continue to extract groundwater, as there is no other alternative for irrigation. The groundwater levels in the other blocks also declined, although the decline is comparatively less, Table X. Yadav and Kumar (2010) concluded that the condition of the groundwater resources in this district is very critical, which was caused by the overexploitation of groundwater below the mean rainfall. A long term Sutlej-Yamuna Link for appropriate distribution of available canal water is running for the past several years and people of this district are hopeful about this canal.

In another study, Umar et al. (2008) evaluated the impacts of groundwater exploitation in Kali-Hindon watershed. This inter-stream region is fertile tract for sugarcane cultivation and extends over an area of 395 km^2. The water table in the nrthern part of the watershed is shallow, whereas it is relatively deeper in the southern part. Irrigation and sugarcane industry are the primary consumers of groundwater in this region and uncontrolled exploitation has adversely impacted the groundwater system. The pre-monsoon and post-monsoon depth of water table ranges from 4.6 to 17.7 m and from 3.5 to 16.5 m respectively. In this region, several blocks were identified as being over-exploited where the groundwater development has reached up to 142.15%. Therefore, it was recommended that the further exploitation of groundwater to be stopped in these blocks. Figure 8 illustrates the changes in groundwater levels, as observed from 2-wells located near Baghra and Shahpur blocks, the two critical blocks of the Kali–Hindon watershed. Umar et al. (2008) concluded that the overexploitation and mismanagement of groundwater resources has created adverse impacts on the groundwater regime in this region. They suggested that the groundwater withdrawal in the southern part of the basin should be restricted, whereas the pumping of groundwater may be allowed in the northern part of the watershed.

The above two examples discuss the status of declining groundwater levels in response to the change in demand pattern. In addition, the changing climate has a substantial influence on several components of the hydrological cycle and therefore it is vital to assess and evaluate the potential impacts of climate change on groundwater systems. The changes in precipitation and evapotranspiration has a direct impact on the groundwater recharge, which further influences the surface-groundwater interactions. In addition, the changes in the groundwater use for irrigation and industrial purposes has an influence on the groundwater systems. Besides the influence of climate, recharge is also dependent on the soil characteristics of the aquifer and the overlying soils. This adds another level of complexity in assessing the potential impacts of climate change on groundwater systems. Despite the wide acceptance on the impacts of climate change on various components of the hydrological cycle, research on its impact on groundwater systems is relatively limited. Unavailability of a long-term historical groundwater levels and poor understanding of the driving forces of the changes in groundwater table are also some of the primary reasons.

Table-IX A: Floods of various return periods for original flood series for Br-187 (subzone-1f) in Ganges plain & Pagaladiya sub-catchment in Brahmaputra basin under Scenario-1 and Scenario-2 under climate change

	Return Period (Years)	Original Series	Scenario 1	Scenario 2
Flood Estimates (m^3/sec) for Br-187 (subzone – 1f) in Ganges basin	5	1,362	1,450	1,663
	50	2,511	2,603	2,958
	100	2,938	3,296	3,910
	500	4,131	4,557	5,319
Flood estimates (m^3/s) for Br-15 sub-catchment in Brahmaputra basin	5	125	178	210
	50	177	209	248
	100	245	288	294
	500	564	343	613

Table- IX B: Percentage deviations in floods of various return periods for Scenario-1 and Scenario-2 under climate change

	Return Period (Years)	Scenario 1	Scenario 2
Br-187 (subzone – 1f) in Ganges basin	5	6.5	22.1
	50	3.7	17.8
	100	12.2	33.1
	500	10.3	28.8
Br-15 sub-catchment in Brahmaputra Basin	5	19.6	27.3
	50	11.0	15.6
	100	13.5	18.0
	500	8.6	28.1

The economy of India is largely dependent on agriculture and so the changing climate is expected to have a negative impact on its economy, because agriculture industry is already under stress due to over exploitation of the available water resources. The abnormality in climate lasting for a period of time, defines a new normal. However, prediction such a new normal or it effect on a dynamic system such as groundwater system is a challenge, because of the inherent sources of uncertainty in the models. Despite the availability of required calibration datasets, parameterization of a few complicated hydrological processes, model structuring and other model parameters infuse uncertainty in the model predictions. To prevent or overcome the deteriorating regional water availability or other water-related concerns in the future, it is required to develop a physically based hydrological model of a groundwater system to project the impacts of climate change on groundwater resources. Uncertainties in such predictions or projections are inevitable, but they help in developing new response strategies and in efficient management and distribution of water resources. Despite the uncertainties associated with the projected climate and its impacts on water resources, water managers and engineers are expected to take appropriate measures to prevent or minimize the adverse impacts of climate change. Overall, it is required to assess and quantify the changes in groundwater recharge in terms of changing climate and socio-economic changes.

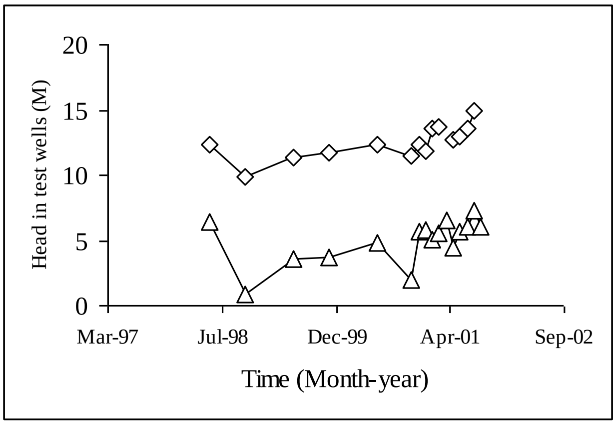

Figure 8: The hydrographs of two permanent gauging stations, Shahpur and Baghra (Umar et l., 2008)

IX. SUMMARY AND CONCLUSION

Spatial resolution is one of the major shortcomings of the climate models and will remain so with the currently available computer resources. This also limits the ensemble size that can be achieved. Nevertheless, assessing the impacts of changing climate on changing flow patterns is vital because this has implications on the effective management of available water and disastrous floods. The changes in major climatic variables including temperature, precipitation and evapotranspiration have a direct impact on the surface water resources, whereas the impact of changing climate on groundwater resources is primarily dependent on the surface (e.g. lakes and rivers) and subsurface (e.g. aquifer) water interactions or indirectly on the process of groundwater recharge. Although, the negative impacts on water resources from the changing climate are generally projected in several impact assessment studies, it is also possible that it could have positive impacts on regions hydrology, for example increased water availability. Therefore, the choice of temporal and spatial resolution becomes vital in the impact assessment studies, because studying the changes in flow patterns at a seasonal (low temporal resolution) timescale might offset the positive impacts such as increased water availability, which can be seen only at a finer resolution. However, the temporal and spatial scales are usually compromised because of the uncertainties in the projections.

Table- X: Block-wise water level fluctuation in district Rewari during 1974-2009 (Yadav and Kumar 2010)

Block	Depth of water table below ground level		Fluctuation during (1974 – 2009)
	1974	2009	
Bawal	10.85	23.15	-12.3
Jatusana	11.19	12.52	-1.33
Khol	18.02	42.46	-24.44
Nahar	10.81	14.38	-3.57
Rewari	7.87	14.88	-7.01

To address these uncertainties and analyse the risks of climate change, it is required to explore the use of probabilistic approaches. Therefore, efforts to construct appropriate probability distributions are being taken up with the objective of getting specified outcomes. At the same time, to allow the water managers to assess the impacts of climate change at a small-catchment-scale and to assess the performance and resilience of the measures taken, it is important to develop/create a climate-linked watershed-scale hydrological model. Additionally, understanding the interactions between surface and sub-surface water is crucial to quantify the impacts of changing climate on sub-surface flow and groundwater resources.

Reliable forecasting or projection of changes in major climatic variables and accurate estimates of groundwater recharge are vital in such impact assessment studies. This article briefly discusses the changes in the temperature and precipitation patterns in India. This review article also discusses the deviations of flood quantiles of a selected return periods using the original annual flood series and two additional scenarios, which are created by altering the original dataset. The first scenario is created by increasing the recorded peak flood by 20% and the second scenario by reducing 20% of the annual peak flows beyond 80th percentile and below 20th percentile of the annual peak flows. Finally, an attempt was made to review the impact of climate change on the trends in the fluctuating groundwater levels and attempted to relate these results with the region's water demand, and trends in regional temperature and precipitation.

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