CHAPTER 8

CLIMATE CHANGE AND GROUNDWATER

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8.0 Introduction

Global climate change threats the supply and management of water resources. The Intergovernmental Panel on Climate Change (IPCC) suggested an increase in the global mean surface temperature by 0.6 ± 0.2°C since 1861, and predicts an increase of 2 to 4°C over the next 100 years. Global sea levels have risen between 10 and 25 cm since late 19th century. Elevation in temperature also affects the hydrologic cycle directly by increasing evaporation of surface water and vegetation transpiration. Consequently, these changes influence amount, timing and intensity of precipitation, which indirectly impact the flux and storage of water in surface and subsurface reservoirs (i.e., lakes, soil moisture, and groundwater). The ripple effect of climate change on water resources may lead to several water quantity and quality problems such as seawater intrusion, water quality deterioration, potable water shortage, etc.

Global climate change directly influences quantity and quality of surface water resources by potential long term changes in climatic variables in terms of air temperature, precipitation, and evapo-transpiration; whereas, understanding the link between the changes in climate variables and groundwater is more complex and enigmatic. The larger anomaly in rainfall pattern manifests frequent and prolonged periods of shallow or depleted groundwater table that also affects baseflows, and, reduced freshwater availability in coastal areas due to seawater intrusion on account of sea level rise. Thus, groundwater resources are indirectly linked to climate change via interaction with surface water resources and recharge process. Therefore, determination of climate change impact on groundwater resources relies on credible forecasting of changes in major climatic variables as well as accurate estimation of groundwater recharge.

This chapter provides an insight into potential impact of climate change on groundwater resources and importance of addressing this scenario as well as its consequences. This narration will contribute to the sustainable management of groundwater resources in the Indian context and will provide the premise for long-term monitoring of climate changes impact on groundwater resources well into future.

8.1 Impact of Climate Change on Groundwater

Although the effect of climate changes on surface water has obvious recognition due to its visible fluctuation in surface water levels and water quality, the potential impact on groundwater resources is of serious concern because groundwater is widely distributed source of drinking water supply and irrigation. However, effect of climate change on surface water resources bodies have been studied extensively but very little research exists on the potential effects of climate change on groundwater.

It is being recognized that groundwater is not a separate entity from the surface above or from the regional hydrological cycle and needs to be managed in a wholesome manner along with surface water resources. Thus, to comprehend the likely consequences of climate change on the hydrological cycle and groundwater resource, it is essential to gain an understanding of the influence of changes in climatic variables on the surface runoff and groundwater.

Changes in precipitation and evapo-transpiration plays significant role on groundwater recharge directly and on groundwater withdrawals or discharge indirectly. Groundwater systems in semiarid and arid regions are critically effected, because even minor variability in precipitation can lead to extreme changes in recharge (Green, Bates, Charles, & Fleming, 2007; Woldeamlak, Batelaan, & De Smedt, 2007). According to recent studies, the spatial variability in projected precipitation is highly effected by global warming and is predicted to boost positive and negative changes in regional precipitation, as well as changes in seasonal patterns (Cook, Smerdon, Seager, & Coats, 2014; IPCC, 2007). Little agreement has been noticed between the magnitude and direction of predicted evapo-transpiration patterns (Barnett et al., 2008). However, increased air temperatures may boost evapo-transpiration, which may result in a reduced runoff and soil water content in certain regions (Chiew & McMahon, 2002). Evapo-transpiration has less effect on groundwater recharge and base flow in temperate and humid regions due to seasonal timing of recharge events (Hunt, Walker, Selbig, Westenbroek, & Regan, 2013). The excess precipitation period is associated with increased recharge and reduced water demand such as for irrigated agriculture, due to lower temperature, solar radiation and higher humidity in these periods (Rosenberg et al., 1999). On the contrary, an increased spatial extent and temporal duration of extreme drought under future climate scenarios are predicted(Bates, Kundzewicz, & Wu, 2008; IPCC, 2007).

The heightened variability in climatic variables such as precipitation, temperature, and evapo-transpiration that is predicted under different climate change scenarios will have variable effects not only on different aquifers but also on different locations within an aquifer due to variations in spatial parameters such as hydraulic properties and distance from the recharge areas.

Chen, Grasby, and Osadetz (2002) Observed that water table responds with respect to precipitation variability in a mid-continent carbonate-rock aquifer differently in individual wells because of the spatial variation in permeability of overlying sediments and recharge characteristics; i.e. groundwater levels at some locations of the aquifer responded to high-frequency precipitation events while certain other areas did not exhibit much change in water levels. . It could be due to the interconnection of highly permeable channels or preferential-flow paths from land surface to the water table (Chen et al., 2002), or differences in thickness of the unsaturated zone.

In mountainous regions, spatial variation in groundwater dynamics may significantly affect stream flow responses to warming (Tague & Grant, 2009). While determining impact of climate change in mountainous regions, groundwater dynamics like subsurface drainages are as important as topographic differences in snow regimes (Tague, Grant, Farrell, Choate, & Jefferson, 2008). Singleton and Moran (2010) have noted that recharge mechanism, storage capacity and residence time of high elevation aquifers are understudied and not understood well. The recharge process in mountain aquifers are complex due to lack of knowledge in changes in the timing of snow packs melting in terms of direction and magnitude which makes it difficult to predict response of mountain aquifers to climate change. A negative feedback between early timing of snowmelt and evapo-transpiration exist in snowmelt dominated watersheds. In this case, snowmelt increases soil water content in the season where evapo-transpiration will be lower which accelerates infiltration and recharge. While, when potential evapo-transpiration is greater and shift in snowmelt timing may reduce soil water content which causes reduction in evapo-transpiration and has an unidentified effect on net infiltration and recharge. The aggregate impacts of these are unresolved challenges which concerns subsurface hydrologic responses to climate-change effects on surface-water hydrology. Therefore, there is a need to understand and evaluate climate change impact on aquifer systems. As part of the hydrologic cycle, it can be anticipated that any changes in climate will affect groundwater systems by altering recharge (which encompasses changes in precipitation and evapo-transpiration), potentially by changes in nature of the interactions between the groundwater and surface water systems, and changes in demands related to irrigation. The following section describes the effect of climate change on soil moisture, groundwater resources and coastal aquifers.

8.1.1 Soil Moisture

The amount of soil water content is a critical parameter for agricultural management. It has profound influence on the rate of change of actual evaporation, groundwater recharge, and generation of runoff. Global climate models have been applied to simulate soil moisture contents on a very coarse spatial resolution and the results from these models indicate possible direction of changes.

At a regional level, the impact of global climate change on soil moisture depends on the degree of climate change as well as the soil characteristics. The soil water-holding capacity will affect possible changes in soil moisture deficits. As the soil water holding capacity lowers, the sensitivity to climate change will be more. Climate change may also affect soil characteristics through changes in water logging or cracking which alters the storage properties of soil. In cold climate regions, infiltration and water holding capacity of soils also depends on frequency and intensity of freezing. Further, changes in temperature, precipitation and evaporation results in corresponding changes in organic matter content which leads to enhanced losses of green house gases in mineral and organic soils. The emission of green house gases will also affect other soil functions like poorer soil structure, stability, topsoil, water holding capacity, nutrient availability and erosion. The emission of green house gas is also accelerated by the increase in temperature. However, these effects could be counteracted by enhanced nutrient release resulting in increased plant productivity vis-a-vis litter inputs. Increased precipitation enhances peat formation and methane release and vice versa(Defra, 2005).Intensified droughts will leads to shrinking of clay in soils and deformation in building foundations and higher soil temperature may also exacerbate chemical attack to engineered structures with clay caps (e.g., in contaminated landfills), with possibility of increased leachate generation and enhanced landfill gas emissions (Chander, 2012).

The impact of pesticide toxicity due to changing climate variables could vary depending upon the interactions between pesticides and the environment, incidence of pests and diseases under a changing climate. Changes in the amount and intensity of rainfall can increase the risk of pesticides; e.g. drier climate increases pesticide persistence, intense rainfall enhances bypass flow and downward movements. High temperature could counteract leaching process by causing rapid degradation. High intensity precipitation can enhance atmospheric nitrogen deposition on soils which leads to soil disturbances. Flooding and subsidence causes changes in hydromorphology and ecosystem status (wetland and waterlogged habitats) and also enhances soil erosion, leading to the pollution of surface waters.

Trends in soil temperature are important but rarely reported indicators of climate change. There is a close correlation between air and soil temperature. The temperature regime of the soil is governed by gains and losses of radiation at the surface, the process of evaporation, heat conduction through the soil profile and convective transfer via the movement of gas and water. The extent of effect will be varied according to multiple factors and its association between soil and atmospheric temperature. Qian, Gregorich, Gameda, Hopkins, and Wang (2011)conducted a study associated with variation of soil temperature associated with climate change in Canada. It has been found that air temperature and snow cover depth played an important role in controlling the soil temperature variation. Soil temperature along with soil moisture is a prime mover in most soil processes. Warmer soil temperature will accelerate soil processes, rapid decomposition of organic matter, increased microbiological activity, quicker nutrients release, increase nitrification rate and generally accentuate chemical weathering of minerals.

8.1.2 Groundwater Recharge and Resources

Although groundwater is a major source of water across the globe, specifically for water supply in rural areas in arid and semi-arid regions, however there has been paucity on research about the potential effect of climate on groundwater. Aquifers are reliable source of water which can store water for decades to millennia. However, the sustainability of groundwater systems requires that groundwater withdrawals should match groundwater replenishment.

Understanding aquifer replenishment through rainfall and interaction with surface water bodies is essential to quantify the impact of climate change on groundwater resources. Recharge is the fraction of total precipitation which eventually in filtrates the ground surface and percolates to the water table. Infiltrated water may enter the aquifer rapidly, through macro pores and cracks, or move slowly by infiltration process through the soil pores. Variation in effective rainfall will alter recharge and the change in the duration of the recharge period too. Groundwater recharge may likely increase in mid latitudes for projected scenarios of increased winter rainfall. However, higher evaporation indicates persistence of soil deficiency of water for an extended period that may begin earlier, thus offsetting the increased total effective rain in the region.

Recharge mechanism in aquifers varies with difference in properties / factors associated with them. Aquifers may be confined or unconfined in nature. An unconfined aquifer is replenished via rain or surface water infiltration and the recharge rate varies according to permeability of surface geological material. A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, recharged by rain or surface water infiltrating the permeable rock at some considerable distance away from the confined aquifer. Groundwater in these confined aquifers can sometimes be thousands of years old.

Various studies have attempted to estimate recharge rate by application of C-14 isotopes and modeling. These techniques are applicable for aquifers which are recharged from a short distance over a short duration. Whereas deep-seated aquifers having recharge zone located at larger distances with recharge occurring after decades or centuries pose a challenge in terms of resolving the climate change impact. While attempting modeling of groundwater recharge, the properties of recharge medium are less known due to heterogeneity. Crosbie et al. (2012) Investigated the impact of climate change on groundwater recharge in Australia. As per the study, groundwater recharge and changes in precipitation are extensively interconnected.

According to Hiscock et al. (2011), the projections for potential recharge derived from ensemble of four GCMs for Europe exhibit strong latitudinal dependence on the climate change. According to the hydrological models with uncertainty in GCM projection of precipitation, a substantial reduction in groundwater recharge in southern Europe (Spain and Northern Italy) and an increase in the same in northern Europe is projected (Denmark, southern England, Northern France). This study also implies that projected changes in groundwater recharge for a chalked aquifer for 2080s is between -26 % and +31% (Jackson, Meister, & Prudhomme, 2011). The recharge projections for southern British Columbia for the year 2080s ranged from -10 % to +23 % compared to past recharge records. The extreme propagation of uncertainty arises from selection of GCMs, downscaling, and hydrologic model showed 53, 44 and 24% of historical recharge records for three Australian sites, respectively. It is observed that simulation results are more deviated due to uncertainty from downscaling rather than selection of different emission scenarios. Simulated climate conditions often predict extremes (such as multi-year droughts) that are outside of the historical baseline climatology (Holman et al. 2009).

8.1.3 Coastal Aquifers

Encroachment of seawater in coastal aquifers, due to landward hydraulic gradient of water table is known as saltwater intrusion. The phenomenon fundamentally occurs because of over extraction of aquifer and land use changes(Singh, 2014; Werner et al., 2013) and threatens urban coastal communities worldwide besides deteriorating productive and consumptive value of costal land.(Bobba, 2002). Climate change further exacerbates saltwater intrusion due to sea-level rise combined with global warming, which would increase demand for freshwater, and with reduced precipitation, ultimately diminish surface water availability for aquifer recharge (IPCC, 2014).

Shallow coastal aquifers are more vulnerable to saline water intrusion and groundwater in low-lying islands is very sensitive to climate change. Decrease in rainfall along with sea level rise amplifies the diminution of the available freshwater volume as well as shrinkage of freshwater lens in the island.

The response to sea level rise varies for confined and unconfined aquifers. Drivers of saltwater intrusion generally exhibit similar trends in governing physical, geological and chemical processes of interaction. The rate and magnitude of these interactions are highly context-specific, assuring the necessity of local investigation for development of adaptation strategies and management. It is needed to research the variation in groundwater recharge and sea level rise to assess the climate change impact on fresh groundwater resources in coastal groundwater systems.

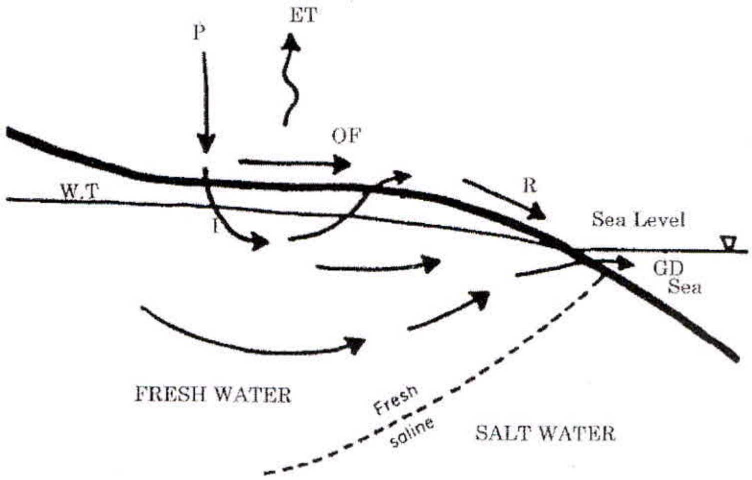

***Figure 8.1**: Schematic illustration of water balance in a coastal groundwater system. (Source: Bobba, 2002).*

8.2 Climate Change Scenario for Groundwater in India

Climate change impact on the groundwater resource is anticipated to be quite severe. About 85% of rural area is depending on groundwater as a major source of drinking water supply. India has a potential of 447 BCM/year of replenishable groundwater (CGWB, 2017). Unfortunately, water table in different regions of India has receded in recent years due to immense withdrawal of subsurface water which has raised serious questions about sustainability of groundwater. The over extracted regions include north western parts of Punjab, Delhi, Haryana and Uttar Pradesh. In western parts of the country, Rajasthan is under groundwater stress due to arid climate and lower groundwater recharge rate. In Peninsular India, groundwater availability is less on account of poor aquifer characteristics.

Another concern associated with groundwater decline is increase in emission of CO_2 due to increased energy requirement for pumping. One of the studies implies that estimated annual carbon dioxide emission has been increased by over 1% for groundwater level decline by 1m in Indian context. A much rational study reveals that according to the area of irrigation, decline in groundwater level for each metre will cause increase in CO_2 release by 4.8%. (Mall, Gupta, Singh, Singh, & Rathore, 2006).

Climate change is expected to affect groundwater due to changes in temperature, precipitation and evapo-transpiration. It is quite clear that different aquifer systems are affected by hydrological processes to varying extent; e.g. Coastal and Island aquifers are impacted by sea level rise and resulting seawater encroachment, where as in land alluvial aquifers are impacted by varying frequency and severity of floods. It has been observed that thickness of fresh water lens was estimated to shrink from 25m to 10m and from 36 m to 28 m for two small flat coral islands for a sea level rise of 0.1 m only (Mall et al., 2006). This observation points towards the importance of aquifer geometry and the impact of climate change.

Agricultural demand, specifically for irrigation, is considered very susceptible to climate change. The necessity and timing of irrigation is controlled by changes in climate at field level. It implies increased water demand due to increased dryness which may get repressed as the soil moisture content increases at critical seasons of a year. As per the national estimates of irrigation requirement, demand would increase by 2025 and globally, it would increase by 3.5-5 % by 2025 and 6-8 % by 2075 without considering climate change scenario. India's agricultural sector meets 52% of its irrigation requirement through groundwater. Therefore, decline in groundwater levels and increased irrigation demand due to climate change need to be addressed urgently in the present scenario as well for meeting crop production requirements for future.

The strong relation between soil moisture and air temperature plays significant role in climate change and frequency of climate anomalies. It is expected that the increase in air temperature in the future would continue. High moisture content in warm air regulates the energy balancing mechanism in environment. The elevated moisture content in the atmosphere may result in climate extremes in the form of intense precipitation, snowfall and increased frequency of floods / droughts. Consequently, soil moisture content, groundwater recharge and frequency of flood / drought events are directly linked to climate change. Several studies have been conducted to study these aspects and it is have found that rise in temperature and decrease in rainfall will lead to soil moisture deficit, further reduction in recharge, and ultimately lead to recession in groundwater levels. However, the hydrological impacts of possible climate change for Indian region(s) / basin(s) have not been studied extensively.

It has been estimated that climate change will increase the demand of power generation capacity approximately by 1.5%. The increased energy consumption in a number of fields is predicted which includes need for cooling space for building, irrigation needs and groundwater pumping.

Various studies have shown that groundwater recharge and discharge conditions are function of precipitation climatic variables, landscape characteristics and human impacts. Therefore, projecting the recharge and discharge patterns are of great significance for future climate scenarios and address issues pertaining to integrated water resource development and management in the years to come.

Literature implies that most of the research studies have investigated the impact of climate change on water resources by coupling climate change scenario with hydrological models. Response of aquifers towards climate change has been researched by associating models of atmospheric processes with unsaturated soil and groundwater models. In these studies, the groundwater model is calibrated to different stresses of climate change and associated groundwater condition. Few of the recent studies on impact of climate change on groundwater resources in India are discussed below.

Ghosh Bobba (2002) analyzed the effects of human activities and sea-level changes on the spatial and temporal behavior of the coupled mechanism of salt-water and freshwater flow through the Godavari Delta of India. The density driven salt-water intrusion process was simulated with the use of a SUTRA (Saturated-Unsaturated TRAnsport) model. Physical parameters, initial heads, and boundary conditions of the delta were defined on the basis of available field data, and an areal, steady-state groundwater model was constructed to calibrate the observed head values corresponding to the initial development phase of the aquifer. Initial and boundary conditions determined from the areal calibration were used to evaluate steady-state, hydraulic heads. Consequently, the initial position of the hydraulic head distribution was calibrated under steady-state conditions. The changes of initial hydraulic distribution, under discharge and recharge conditions, were calculated, and the present-day position of the interface was predicted. The present-day distribution of hydraulic head was estimated via a 20-year simulation. The results indicate that a considerable advance in seawater intrusion can be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channelled from the reservoir for irrigation, industrial and domestic purposes.

Mall et al. (2006) studied sustainable development of surface water and groundwater resources by taking into account climate change and future research needs in India. It was observed that Indian sub-continent is extremely perceptive to climate changes. It is projected that most irrigated areas in India would require more water around 2025 and global net irrigation requirements would increase relative to the situation without climate change by 3.5–5% by 2025, and 6–8% by 2075. In India, roughly 52% of irrigation consumption across the country is extracted from groundwater; therefore, it can be an alarming situation with decline in groundwater and increase in irrigation requirements due to climate change. This point towards need of a crucial research work on following objectives:

- Study phenomenon associated with climate variability and extreme events, its impact on water resources and subsurface water potential.
- Understand the variation of rainfall trend and its impact on run-off and aquifer recharge.
- Investigate the sea level rise due to deglaciation and enhanced rainfall.
- Sea-water intrusions into coastal aquifers.

- Estimating the extent of vulnerability of water resources to climate change; identify the key risks related to climate change on water resources and prioritize the adaptation measures.

According to the National Environmental Policy, it is pointed out that India's precipitation patterns, ecosystems, agricultural efficiency and natural resources are highly impacted by anthropogenically induced climate change. A comprehensive planning and suitable adaptation measures only can prevent the catastrophe of human induced climate change.

Shah (2009) reviewed the mitigation approaches and adaptation measures with regard to climate change and groundwater in India. From earlier times, India has been using surface storage and natural flow to irrigate the crops. However, there has been a sharp descent in the natural irrigation and a huge rise in irrigation through groundwater development by means of large number of small, private tube wells, in the past 40 years. Due to this reason, groundwater has witnessed significant decline in many areas of the country. Climate change may act as a amplifier for this phenomenon. It will multiply the threat to groundwater resource and also increase groundwater's utility for drought-regulated agriculture. Pumping of groundwater with electricity and fuel accounts for around 16–25 million metric tons of carbon emissions which is roughly 4 to 6% of national carbon emission. With a perspective of climate change, western and peninsular India are predicament regions with respect to groundwater. The western and peninsular regions of India, in particular, need to address climate change mitigation and adaptation strategies. In order to accomplish mitigation and adaptation, the country should concentrate on the aspect of subsurface storage (managed) rather than surface storage of water as the prominent water strategy with proactive management of supply-side and demand-side management, and should wisely learn from the experience of other countries (such as Australia, United States) which have good experience in management of aquifer recharge.

Singh(2012) studied the significance of climate change on dynamic groundwater in a drought-prone area viz., Sonar basin in the Bundelkhand region of Madhya Pradesh. The study addresses the generation of future rainfall and temperature, recharge estimation and groundwater simulation for proper management and augmentation of groundwater in the basin for future scenarios. Future rainfall was generated based on the SRES GCM projections for the South-Asia region for baseline, A1FI and B1 scenarios for the time-slice 2004-2039. The site-specific soil, vegetation and climate database needed for the VHELP model were generated and site-specific groundwater recharge was estimated at twelve locations in the basin. The groundwater simulation was done by the water balance method by dividing the whole basin into twelve zones. Finally, the quantification of the impact of climate change on the groundwater recharge and levels for the time-slice 2004-2039 was done. Historical rainfall and temperature show declining and increasing trend, respectively (1972-2003), as a result, future rainfall has a declining trend for the baseline, A1FI and B1 scenarios. As compared to the baseline scenario, the following changes have been obtained for the time-slice 2004-2039:

- change in temperature under A1FI and B1 scenarios is +1.27 and +1.22 °C, respectively.
- change in rainfall under A1FI and B1 scenarios is +3.0 and +4.4%, respectively.
- change in GW recharge under A1FI and B1 scenarios is +2.1 to +3.8% and +1.8 to +6.1%, respectively.
- change in GW levels under A1FI and B1 scenarios is +8.0 and +14%, respectively.

The additional quantity of water required to recharge groundwater in order to attain the sustainable groundwater levels is estimated to be 4.3%. This is approximately 0.6% of the average annual precipitation in the area. The research may also serve as a decision support tool for exploring different scenarios of groundwater levels under varying recharge conditions and then assess the quantity of water required for artificial groundwater recharge to maintain the sustainability of groundwater. However, vast scope exists for refinement in the study with regards to various data and uncertainty associated with climate change.

Panda and Jena (2016) examined variation in groundwater recharge due to changes in climate and consequent adaptation strategies. The study region pertains to Eastern part of India, having a sub-tropical humid climate and sandy loam soil. Rainfall in the area is found to have wide temporal and spatial variation. Groundwater is being overexploited in this region due to deficit of surface water for meeting the irrigation and domestic demands. Excess groundwater withdrawal is leading to continuous depletion of groundwater levels in the region. Urgent actions are therefore needed to reverse the depleting groundwater levels. It may be via artificial recharge and will be significant under the climate change scenarios.

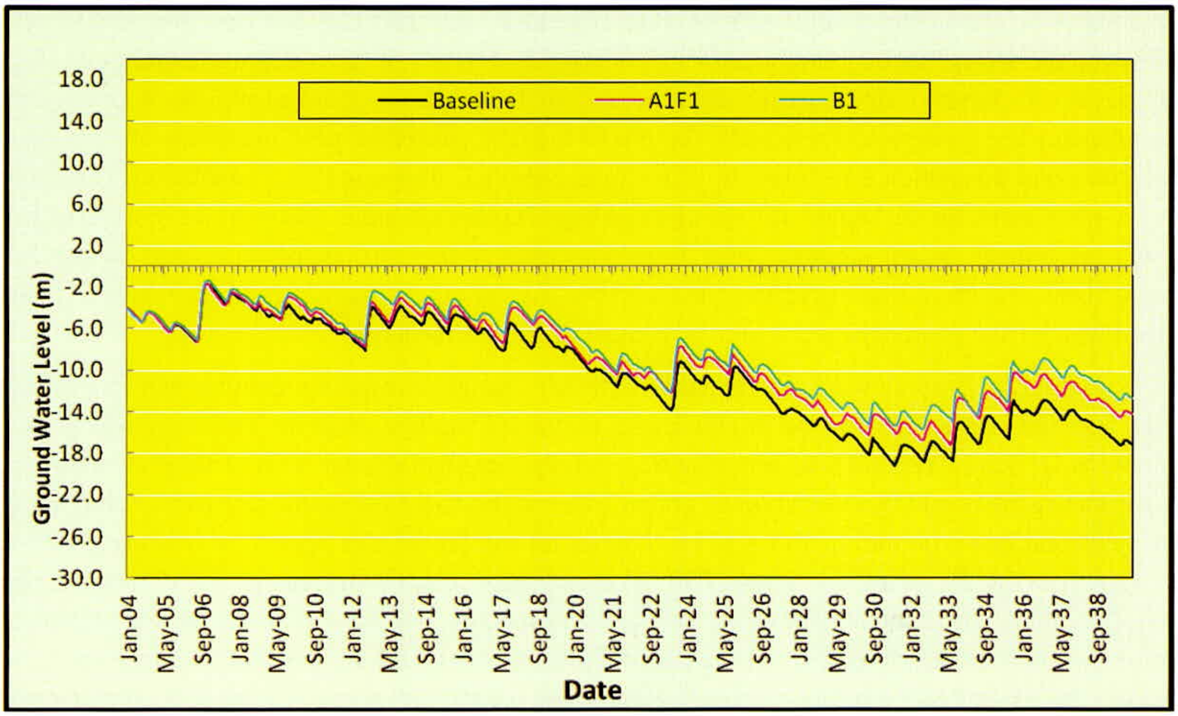

Figure 8.2: *Groundwater Level Variation in Response to Future Rainfall in Zone-1(Source: Singh, 2012)*

Groundwater recharge was modeled using HELP3 software (a quasi-two-dimensional, deterministic, water-routing model) along with global climate models (GCMs) and three global warming scenarios. Changes in groundwater recharge rates were examined for a 2030 climate with a variety of soil and vegetation covers. Sensitivity analysis was done to evaluate the relationship between changing mean annual recharge and mean annual rainfall for various combinations of soil and vegetation. The relationship was found to be statistically significant ($p<0.05$) with a coefficient of determination as 0.81. Vegetation dynamics and water-use affected by the increase in potential evapo-transpiration for large climate variability scenario led to a significant decrease in recharge from 49-658 mm to 18-179 mm respectively. It was suggested that under the climate variability and land use/land cover change scenarios, appropriate conjunctive use, irrigation scheduling and enhanced recharge practices affecting the groundwater recharge need to be properly understood for sustainability of groundwater resource.

Asoka et al. (2017) used satellite data and local well measurements to characterize the regional patterns of change in groundwater storage and the relative contribution of groundwater pumping and monsoon rainfall in such changes. It was found that groundwater storage has declined in northern India at the rate of 2 cm per year and increased by 1 to 2 cm per year in southern India between 2002 and 2013. It was reported that variability in groundwater storage in north-central and southern India is due to rainfall and recharge variability. On the other hand, variability in groundwater storage in north-western India is mainly due to variability in pumping for irrigated agriculture due to changes in monsoon rainfall. It was suggested that climate-induced pumping is affected by variability in rainfall which is also coupled to warming patterns in the temperatures of sea surface over the Indian Ocean.

Bhanja et al. (2017) studied the measurement of groundwater levels in 3907 wells spread in 22 major river basins of India. It was aimed to assess the spatiotemporal variability of groundwater storage (GWS) anomalies. A dense monitoring network of 3907 observation wells was used to study the dependency of groundwater storage variability on both extent and spacing, the two components of the scale triplet. The results indicate that the mean GWS anomaly sampled at a 0.25-degree grid scale closes to unweighted average over all wells. The absolute error corresponding to each basin grows with increasing scale, i.e., from 0.25 degree to 1 degree. GWS anomalies (relative to the long-term mean) present strong seasonality, with annual maxima observed during the monsoon season and minima during pre-monsoon season. It implies that the spatial variability of GWS anomaly varies with climatic conditions. The study affirms that groundwater storage in most regions varies in strong synchronization due to the impact of monsoons. In India, the spatial variability in groundwater is more strongly affected by climate (such as annual rainfall) in comparison to other factors, such as natural groundwater discharge, etc.

Fishman (2018) concluded that an increase in intra-seasonal rainfall variability (independently of the effect of rising temperatures) will lead to a significant reduction in rice production in India by the year 2050. However, these projections do not take into account the adaptation possibility which includes the expansion of irrigation. Historical data on irrigation, rice yields, and rainfall indicate that irrigated locations experience much lower damages from increasing variability in rainfall. If physical water availability is also accounted, then sustainable use of irrigation water can mitigate less than a tenth of the climate change impact under current irrigation practices. Also, if India continues to deplete its groundwater, then the impacts of increased variability are likely to increase by half.

8.3 Concluding Remarks

- It is necessary to investigate the relationship between climate change and the loss of fresh groundwater resource in different regions. The impact of future climate change may be felt more severely in India because our economy is largely dependent upon agriculture. We are already under water stress condition due to the rise in population and the corresponding increase in demands for energy, fresh water, and food. Though there are uncertainties about the exact magnitude of climate change and its probable impacts, suitable measures need to be taken to prevent or minimize the causes of climate change and mitigate its adverse impacts.

- Problems in groundwater management in India have potentially huge implications due to global warming. The most optimistic assumption suggests that an average drop in groundwater level by one metre would increase India's total carbon emissions by over 1%, because the time of withdrawal of the same amount of water will increase fuel consumption (Mall et al., 2006).
- The studies addressing the impact of climate change on groundwater resources are still in infancy. More field data are required to be generated for getting reliable outcomes. It may help in proper validation of the simulation for the current scenarios. But it is certain that climate change is going to affect the future recharge rates and hence quantum of available groundwater resources. But the climate change impact may not necessarily be negative, as observed by a few investigations. However, quantifying the impact of climate change is difficult and also subject to uncertainties in future climate predictions. There have been mixed and conflicting results based upon general circulation models (GCMs) which raise doubts about their reliability in predicting the future hydrologic conditions. But the global warming threat is real and impacts of climate change phenomena may be many and disturbing.
- Comprehensive water management strategies should be adopted to integrate groundwater and surface water which will considerably reduce the human vulnerability to extremes changes in climate, and also facilitate water and food security.
- Though climate change has been declared unequivocal, the research studies to assess the impacts of climate change on groundwater resources are meager. Reason for this shortfall is that long historical data are required to analyze the characteristics of climate change which may not always be available. Even if the required data are available, there may be uncertainty in model parameters, and driving force of the hydrological cycle. Due to various limitations inherent in the models and unpredictability of various processes driving the hydrological cycle, predicting the long-term effect of a dynamic system is very difficult. Based on available data, the physically-based model of a groundwater system with possible climate change scenarios is essential in order to prevent the deterioration of regional water-resource issues in the future. In spite of the uncertainties in climate change, response strategies derived from the model simulation studies may be quite useful in water resource management.
- There is a need to intensify efforts for monitoring of groundwater abstractions and research on modeling techniques, aquifer characteristics, and recharge rates. It can provide a sound basis for assessing the impacts of climate change and sea-level rise on recharge and groundwater resources.
- From a climate change point of view, India's groundwater hotspots are western and peninsular India. These are critical for climate change mitigation as well as adaptation. To achieve both, India needs to make a transition from surface storage to 'managed aquifer storage' as the center pin of its water strategy with proactive demand- and supply-side management components (Shah, 2009).
- The Indo-Gangetic aquifer system has been getting heavy recharge from the Himalayan snow-melt. As snow-melt-based run-off increases during the coming decades, their contribution to potential recharge may increase; however, a great deal of this may end up as 'rejected recharge' and enhance river flows and intensify the flood proneness of eastern India and

Bangladesh. As the snow-melt-based run-off begins declining, one should expect a decline in run-off as well as groundwater recharge in this vast basin (Shah, 2009).

- In order to assess the probable impacts of future climate changes and socio-economic conditions on groundwater recharge, hydrogeologists must work in coordination with socio-economists, agriculturalists, and soil scientists etc.

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