



## **Modeling the Impacts of Climate Change on Groundwater Resources: A Review**

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### **Authors' contributions**

*This work was carried out in collaboration among all authors. All authors designed the study, wrote the protocol, and the first draft of the manuscript. Author SRA managed the analyses of the study. All authors managed the literature searches. All authors read and approved the final manuscript.*

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### **ABSTRACT**

Global atmospheric general circulation models (GCMs) were developed to simulate the current climate and are used to predict climate change. Several Global Climate Models (GCM's) are available for understanding and projecting climate change. GCM requires to be downscale on a basin-scale and combined with applicable hydrological models considering all components of the hydrologic process. The performance of such coupling models, such as groundwater recharge quantification, should help to make correct adaptation strategies. Climate change has the ability to affect both the quality and quantity of available groundwater, mainly through impact on recharge, evapotranspiration, pump-age and abstraction. As a consequence, groundwater is a significant contributor to the streamflow in areas with fairly shallow water resources, knowing how climate change could impact groundwater supplies is crucial for long-term water resource management. The effect of climate change on groundwater systems is very difficult to predict. Part of the uncertainty of climate predictions is embedded of possibilities. Better insights, a more profound knowledge of mechanisms and modeling skills are required to determine this critical resource's potential in the face of predicted climate change.

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## 1. INTRODUCTION

Climate change poses uncertainties about water availability and management [1,2,3,4]. The Intergovernmental Panel on Climate Change (IPCC) reports that the global mean surface temperature has increased from 1861 by  $0.6^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$ , and expects a 2 to  $4^{\circ}\text{C}$  increase in the next 100 years [5]. Increases in temperature often influence the hydrological process by actively raising the evaporation of available surface water and the transpiration of plants. Such adjustments will also affect the amount of precipitation, timing and strength and indirectly affect the distribution and conservation of water in surface and groundwater reservoirs. (i.e. lakes, soil moisture and groundwater). Additionally, other related impacts can exist, such as intrusion of seawater, loss of water quality, shortage of potable water, etc. [6].

Increased amount of precipitation in brief, intense periods may result in poor absorption resulting in low supply of soil moisture. In comparison, water storage schemes in the region such as amount of lakes, boreholes etc. will also change the availability of water. Global warming would also affect water availability by increases in evaporation and depletion of ground water. Finally, global warming can lead to saline intrusion by sea level rise.

Agricultural demand particularly for irrigation water which is a considerable portion of the country's total water demand is considered more vulnerable to climate change. A shift in environment at the field level can alter irrigation needs and timing. Increased dryness may contribute to increased demand but if soil moisture content decreases at crucial periods of the year, demand may be decreased. Most irrigated areas in India are projected to need more water about 2025, and global net irrigation needs are projected to rise by 3.5–5% by 2025 and 6–8% by 2075 compared to the situation without climate change [7]. In India, groundwater absorbs about 52% of irrigation consumption throughout the country; thus, it can be a troubling circumstance with decreasing groundwater and rising irrigation needs due to climate change.

Warm air becomes more moisturizing and increases surface moisture evaporation. With more moisture in the environment, occurrences

of rainfall and snowfall appear to be more extreme, hence growing flood risk. However, if the soil has little to no moisture to evaporate, the solar radiation event may raise the temperature, which can lead to prolonged and more extreme droughts. Therefore climate change may impact soil moisture, groundwater recharge and flood frequency or drought events and eventually groundwater level in different areas. It is projected in a number of studies that increasing temperature and declining rainfall that reduce net recharge and influence groundwater rates.

Specific hydrological models were used to study the effect of climate change on the groundwater and surface resources. Groundwater recharge is not only determined by hydrological processes but also by the physical characteristics of the soil and surface structure. One of the earliest study was conducted in the Coastal Plain of Western Australia, used a one dimensional unsaturated zone model (based on Richard's equation) was used to examine the effect of changing rainfall on recharge. The simulations showed that recharge could be modified by a much larger proportion than rainfall, but that this depends significantly on the vegetation cover [8]. Further, an annual recharge time-series was created, using a soil moisture balance model for the island of Samsøe (Denmark) from 1865 to 1983 and it was concluded that recharge varied with climate, and that climate change scenarios potentially could lead to reduced recharge in a region of north-west Europe stretching from the south-west of France to southern Sweden [9]. Gureghian with team used a quasi-linear method of Richards' equation to analyze the effect of climate change on groundwater recharge levels at the Yucca Mountain. For the next ten thousand years they used two separate climate change models for temperature and precipitation, relying on suggestions by a group of experts. The research findings show minor variations in the average motion of the wetting front between the two climate models [10]. Loaiciga researched a karst aquifer in south-central Texas and found climate change's effects not just on streaming regeneration but also on pumping levels. The effect of climate change on the streamed recharge was calculated using runoff scaling factors dependent on the ratio of forecasted historical and potential streamflows from related general and regional climate models. The report found that the surge in groundwater usage

coupled with forecasted population increases would present a greater danger to the aquifer than climate change [11].

The key purpose to study the relationships between the aquifers and the environment is to establish how climate variability and climate change affect groundwater resources. It is expected that changes in temperature and precipitation will alter groundwater recharge to aquifers, causing shifts in water table levels in unconfined aquifers as a first response to climate trends [12,13]. Although the most notable impacts could be changes in surface water levels in lakes [14], the greatest concern of water managers and government officials is the potential decrease of groundwater supplies for municipal and agricultural uses. These changes may decrease quantity, and perhaps, quality of water, which would also have detrimental environmental effects on fisheries and other wildlife by changing baseflow dynamics in streams [15,16]. Aquifer recharge and groundwater levels interact, and depend on climate and groundwater use; each aquifer has different properties and requires detailed characterization and eventually quantification (e.g, numerical modeling) of these processes and linking the recharge model to climate model predictions [17]. In practice, any aquifer that has an existing and verified conceptual model, together with a calibrated numerical model, can be assessed for climate change impacts through scenario simulations. The accuracy of predictions depends largely of scale of project and availability of hydrogeologic and climatic datasets.

Groundwater modeling has been a significant technique in support of the groundwater management planning and decision-making processes. Groundwater models offer a theoretical context for understanding the dynamics and controls of groundwater systems and the processes that affect their output, especially those that are triggered by human interference in those systems. Models are progressively an important part of research on water resources assessment, conservation and restoration, and offer important and cost-effective input for the preparation and evaluation of new groundwater strategies, legislation and development designs. There are many different ground-water modeling codes available, each with their own capabilities, operational characteristics and limitations.

In addition to discrete perturbations, however, the results inferred from general circulation models (GCMs) have also been used to predict the effects of climate change on regional hydrology. Hydrologic models enable researchers to speculate on the long-term consequences of changes in hydrologic and climate behavior on the level of water fluctuation. The following report gives an overview on the current knowledge and use of groundwater models and addresses the problems associated with these methods. The topic reflects on the modeling approaches currently accessible and discusses in this sense the requisite potential research fields. The climate change occurs due to interaction of atmosphere with the underlying surface–ocean, land and ice on the earth surface, and is assessed from the observed data and projected with the help of climate models. Climate parameters (precipitation and temperature) changes affect the demand for water as well as supply and have been the focus of several studies over the past decade. Thus, the whole has been briefed under the following headings.

2. Climate change models
3. Groundwater simulation models
4. Climate change impacts studies on groundwater resources

## 2. CLIMATE CHANGE MODELS

Climate models are the main tool used to establish future climate change projections. Changing climate poses an unprecedented hydrological challenge. The quantitative analysis of information about the occurrence, distribution and circulation of earth's waters under climate projections becomes increasingly complicated owing to unpredictable consequences related to anthropogenic emissions. According to the sixth IPCC Technical Paper of IPCC on Climate Change and Water [18], changes in the large-scale hydrological cycle have been related to an increase in the observed temperature over several decades.

The IPCC has developed a number of socio-economic scenarios that describe future Green House Gases and sulphur emissions. These projections of future emissions are called IPCC SRES Scenarios (Special Report on Emissions Scenarios) and are based on a number of assumptions in driving forces [19]. The SRES team identified four narrative storylines that depict various social, technical, demographic, economic, and environmental developments

labeled as A1, B1, A2 and B2; Scenarios A2 and B2 project CO<sub>2</sub> concentrations of about 850 ppm and 600 ppm respectively. A number of general circulation models (GCMs) were built on the basis of these scenarios.

## 2.1 General Climate Models

GCM is a three dimensional model of the general circulation of the atmosphere and ocean including representations of the land surface and snow and ice, derived from fundamental physical laws (such as Newton's laws of motion). Sometimes an (A) (O) or (C) is added to the acronym to signify, respectively, that the model is strictly atmospheric, ocean, or a coupled ocean-atmosphere model [20].

GCM were used predict climate change and its effect on rice-wheat crop production for the years 2020, 2050 and 2080. However, GCMs efficiency is typically low at grid cell size, whereas climate change impacts are mostly of concern at grid scale or subgrid scale, such as a hydrological catchment, a region, or a farm [21].

## 2.2 Statistical Downscaling Models

The effects of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda was investigated. Investigation involved analysis of historical data, which indeed shows evidence of climate change based on the temperature and discharge patterns found. The statistical downscaling model (SDSM) was used for the climate change analysis to downscale potential climate change projections, which were derived from the UK climate model HadCM3. The downscaled climate was used as input to the hydrological model of WetSpa, a physically distributed rainfall-runoff model used to simulate the resulting changes in hydrology. In the wet seasons (March-May; October-December), downscaled climate shows a rise in precipitation increasing from 30% in the 2020s to over 100% in the 2080s. The corresponding temperature increase was from 1 to 4°C. These changes were shown to give rise to intensification of the hydrological cycle. The mean annual daily base flow for the current period of 157 mm/year (69% of discharge), was expected to increase by 20-80% between the 2020s and 2080s. The corresponding increase in recharge was from 20 to 100% from the current 245 mm/year [22].

Statistical downscaling models (SDSM) was developed and applied for temperature and

precipitation in South Wollo Zone, Ethiopia, to calculate the changes in historic, current and the future climate changes. Projected changes in precipitation and temperature were analyzed using outputs from GCMs and daily station data (1980-2012) which were collected from 6 observed meteorological stations (predictand) using SDSM version 4.2.9. A historical modification procedure was used to downscale large scale outputs from GCM models to station climate data. The results revealed that both temperatures showed an increasing trend; the increase in mean maximum temperature and mean minimum temperature change were 6.17 and 5.65°C respectively by 2080s from the base period 1980-2012. While, a decreased in percentage change of about 14.2 to 43.3% from the mean annual precipitation was recorded by the year 2080s [23].

Goly and team analyzed and compared various statistical downscaling models (SDSM) utilizing multiple linear regression (MLR), positive coefficient regression (PCR), step regression (SR), and supporting vector machine (SVM) techniques to predict monthly rainfall volumes in Florida state. In downscaling models, mean sea level pressure, air temperature, geopotential height, relative humidity, U wind, and V wind were used as the explaining variables/predictors. Data for these variables were obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset and the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model, version 3 (CGCM3) GCM simulations [24].

The climate change impact prediction in upper Mahaweli basin, Sri Lanka was described in a study conducted by Herath and team. Statistical downscaling model (SDSM) was used in a study to forecast future study area rainfall trends. Observed point rainfall data from 10 study area gauge stations and Hadley Center Coupled Model, Version-3 (HadCM3) Global Climate Model (GCM) data were used for model calibration and validation processes. Precision of the input data was checked before model calibration. A2 (high emission scenario) & B2 (low emission scenario) identified by the Intergovernmental Panel on Climate Change (IPCC) has predicted regular rainfall from 1961 to 2099. Under A2 scenario the total annual rainfall, maximum annual rainfall and annual averaged daily rainfall show an increasing trends and

under B2 scenario all the above mentioned parameters show decreasing trends [25].

Sigdel *et al.* (2016) applied the statistical downscaling model (SDSM) in the three climatic regions of Nepal to minimize precipitation. The study involved the calibration of the SDSM model using large-scale atmospheric variables comprising reanalysis data from the National Centers for Environmental Prediction (NCEP), model validation, and the outputs of downscaled A2 and B2 scenarios of the HadCM3 model for the future. During the validation period the average R2 value was 0.84, suggesting SDSM's strong applicability for simulating precipitation. In both scenarios A2 and B2, the change in the mean annual precipitation in the three climatic regions will present a tendency of precipitation surplus as compared to the mean values of the base period during the forecast period 2010-2099. On the average for all three climatic regions of Nepal, the annual mean precipitation would increase by about 13.75% under scenario A2 and increase near about 11.68% under scenario B2 in the 2050s [26].

In another SDSM was used in downscaling weather files like maximum temperature ( $T_{max}$ ), minimum temperature ( $T_{min}$ ) and precipitation. The study included the calibration of the SDSM model by using observed daily climate data ( $T_{max}$ ,  $T_{min}$  and precipitation) of thirty one years and large scale atmospheric variables encompassing National Centers for Environmental Prediction (NCEP) reanalysis data, the validation of the model, and the outputs of downscaled scenario A2 of the Global Climate Model (GCM) data of Hadley Centre Coupled Model, Version 3 (HadCM3) model for the future. Daily Climate ( $T_{max}$ ,  $T_{min}$  and precipitation) scenarios were generated from 1961 to 2099 under SRES A2 defined by Intergovernmental Panel on Climate Change (IPCC). The results showed that temperature and precipitation would increase by 0.29°C, 255.38 mm (30.97%) in MC (Mid-century) (2030-2059); and 0.67°C and 233.28 mm (28.29%) during EC (End-century) (2070-2099), respectively [27].

### 3. GROUNDWATER SIMULATION MODELS

Onta and Das coupled a three-dimensional groundwater flow model with a one-dimensional consolidation model to simulate piezometric levels and land subsidence in a complex multi-aquifer system of the lower Central Plain of Thailand. The model was developed using

MODFLOW with input past data of 1955 to 1990. The responses of the aquifer system to different pumping schemes were then predicted for the period 1991-2010 by developing pumping schemes based on past experience for probable future scenarios. The model results indicated that the present rate of groundwater withdrawal must be controlled to prevent continual decline of ground water levels. The study helped the government agency concerned develop and implement updated groundwater management policies, land subsidence control strategies and action programs in Bangkok Metropolitan Area [28].

Three dimensional groundwater modeling experiments was performed to simulate the groundwater flow in the Glacial Lake Agassiz Peatlands of northern Minnesota, USA. The steady-state MODFLOW model encompassing an area of 10,160 km<sup>2</sup> of the study area was constructed for groundwater simulation. Numerical solutions indicated that the Itasca Moraine, located to the south of the peatlands, acted as a recharge area for regional groundwater flow. Groundwater flow within the peatlands consisted of local flow systems with streamlines less than 10 km long and the groundwater from distant recharge areas did not play a prominent role in the hydrology of these peatlands [29].

Osman and Bruen studied stream seepage, partially penetrating an unconfined aquifer for the case where the water table falls below stream bed level. They considered the effect on seepage flow of suction in the unsaturated part of the aquifer below a disconnected stream and allowed for the variation of seepage with water table fluctuations. The technique was incorporated into the MODFLOW and was tested by comparing its predictions with those of a widely-used variably saturated model, SWMS 2D (model for simulating water flow and solute transport in two-dimensional variably saturated media). Comparisons were made for both seepage flow and local mounding of the water table. It was concluded that the suggested technique compares very well with the results of SWMS 2D [30].

Senthilkumar and Elango used three-dimensional mathematical model to simulate regional groundwater flow in the lower Palar River basin, in southern India. The study area was characterised by heavy abstraction of groundwater for agricultural, industrial and

drinking water supplies. Apart from a number of wells distributed over the area, there were three major pumping stations on the riverbed. The model simulates groundwater flow with 70 rods, 40 columns, and two layers over an area of approximately 392 km<sup>2</sup>. For the period 1991-2001 the model simulated a transient-state condition. Based on the modeling results, the aquifer system was shown to be stable at the current pumping rate, except for a few locations along the coast where the groundwater head drops from 0.4 to 1.81 m below sea level during the dry seasons. In addition, in the eastern part of the area, the groundwater head declined by 0.9 to 2.4 m below sea level when the aquifer system was subjected to an additional groundwater withdrawal of 2 million gallons per day (MGD) at a major pumping station [31].

To investigate the various hydrogeological conditions and to simulate the behavior of the flow system under different stresses in the unconfined aquifer of Bou-Areg three-dimensional finite-difference groundwater flow model was used. The modeling package MODFLOW, employed in the Groundwater Modeling System (GMS), was applied for this purpose. Both steady-state and transient simulations were done for the two layers using observed groundwater levels for 1990-2006. The simulation results show that the hydraulic head fluctuations depend on the seasonal variation in the recharge from natural precipitation and irrigation infiltration. In addition, the model can simulate the positive hydraulic head fluctuations in the Bou-Areg aquifer, with different hydrogeological device responses [32].

Elango and Sivakumar carried out a study in the coastal aquifer located south of the city of Chennai, India. The aquifers in this area were under stress due to pumping of groundwater to meet the ever increasing water needs of the city. The study was conducted with the aim of developing a numerical model for this area to understand system behavior with changes in hydrological stresses. The finite difference computer code MODFLOW (Modular 3D finite difference flow) with Groundwater Modeling System (GMS) as pre-processor and post-processor was used to simulate the groundwater flow in this study [33].

Ahmad and Umar carried out the groundwater flow modeling in Yamuna-Krishni interfluvium to simulate the behavior of the flow system and evaluate the water balance. Using various

boundary packages available in Visual MODFLOW, Pro 4.1, the horizontal flows, inlet losses from unlined canals, recharge from rainfall and irrigation return flows were applied. Using the river boundary package the river-aquifer interaction was simulated. Specific zones were applied with hydraulic conductivity values ranging from 9.8 to 26.6 m / day. Pumping rates of 500, 1000, 1500, 2000 and 2500 m<sup>3</sup>/day were applied to appropriate areas of the model to simulate areas of stress. The zone budget showed a water balance deficit for the period June 2006 to June 2007. The total recharge to the study area was 160.21 mcm. The groundwater draft through pumping was of the order of 233.56 mcm, thus leaving a deficit balance of -73.35 mcm. The model's sensitivity to input parameters was tested by varying the interest parameters over a series of values. These analyses have shown that the model is most responsive to parameters of hydraulic conductivity and recharge. Simulation of the model for different scenarios indicated that in order to mitigate the water table decline, artificial recharge of groundwater and conjunctive use of surface water and groundwater is required [34].

The mathematical groundwater model was developed for the northern part of Mendha sub-basin in the semi-arid northeastern Rajasthan using conceptual groundwater modeling approach. Groundwater Modeling Software (GMS) which supports the MODFLOW-2000 code was used for this function. For the purpose of modeling the Source/ Sink Coverage, Recharge Coverage, Extraction Coverage, Return Flow Coverage and Soil Coverage were considered. Considering the current levels of groundwater drafting and regeneration, the model was planned to produce groundwater scenario over 15 year duration from 2006 to 2020. The water budget predictions showed a reduction in groundwater storage system from 349.50 to 222.90 mcm, while groundwater abstraction showed an increase from 258.69 to 358.74 mcm per annum. The predicted water table contour maps for the years 2007, 2015 and 2020 were also generated [35].

Gaur along with team developed a groundwater assessment methodology through combined use of MODFLOW numerical model and GIS spatial modeling and applied it to sub-basin of Banganga River, Rajasthan, India. The thematic maps of the basin such as geology, geomorphology, soil, drainage, slope and land use/land cover were overlapped with the

groundwater flow vector map developed from the numerical model to identify potential groundwater zones. Different scenarios were conceptualized by varying the discharge of the well and proposing the location of new water harvesting structures, which revealed that increasing the discharge of the wells in the potential zones put less stress on the aquifer. The locations of rainwater harvesting structures were suggested to reduce the overall decline of groundwater in the area [36].

Siarkos and Latinopoulos carried out the study to assess the possible impacts of potential point sources of pollution on the groundwater quality and to delineate the wellhead zones in the watershed of N. Moudania. Numerical modeling process that consists of the simulation of groundwater flow in the aquifer of N. Moudania by applying the three-dimensional finite difference model MODFLOW and the delineation of protection zones for domestic water supply wells by applying MODPATH Post-processing Particle Tracking Package. A steady state model has been developed in respect of the flow model. Hydraulic conductivity distribution estimation was optimized using a trial-and-error technique. Finally, suggestions were given for the control and management of the identified potential point sources of pollution, especially if they were located within the protection zones of the examined water-supply wells [37].

MODFLOW with SWAP package was applied to simulate a regional groundwater flow problem in Hetao irrigation district, upper Yellow River basin of North China. The MODFLOW-2000 model was used to simulate three dimensional groundwater flows, interacting with the SWAP package through an exchange of net recharge flux and average water table depth in each SWAP zone. They developed a SWAP package for the MODFLOW-2000 model to simulate the vadose zone flow processes, and estimated groundwater recharge and evapotranspiration for groundwater modeling in relation to shallow water problems. The MODFLOW-2000 was coupled with SWAP package and then tested using a 2-D saturated-unsaturated water table recharge experiment and a regional groundwater flow simulation in arid irrigation district of North China [38].

Groundwater flow modeling was attempted in Yamuna Interfluvial Region to simulate the behavior of flow system and evaluate zone budget. Visual MODFLOW, pro 4.1 was used in this study to simulate groundwater flow. The

model simulates groundwater flow with a uniform grid size of 1000 m by 1000 m over an area of around 1345 km<sup>2</sup> and contains three layers, 58 rows and 37 columns. The seepage losses from unlined canals, horizontal flows, rainfall recharge and irrigation return flows were applied using various boundary packages available in Visual MODFLOW, pro 4.1. Using the river boundary package the river-aquifer interaction was simulated. Simulated pumping rates of 500 m<sup>3</sup>/day, 1000 m<sup>3</sup>/day and 1500 m<sup>3</sup>/day were used in the pumping well package. The zone budget for the steady state of the study area showed that the total annual direct recharge is 416.10 mcm and that the total annual groundwater draft is 416.63 mcm through pumping. Two scenarios were considered for predicting response of the aquifer system under various conditions [39].

In another study groundwater modeling technique and application of MODFLOW, a modular three-dimensional ground water flow model was used and it was concluded that groundwater models provide a scientific and predictive tool for determining appropriate solutions to water allocation, surface water-ground water interaction, landscape management or impact of new development scenarios. However, if the modeling studies are not well designed from the outset or the model doesn't adequately represent the natural system being modeled, Modeling effort may be largely wasted, or decisions may be based on flawed model outcomes, with adverse long-term consequences [40].

The study was carried out for Sirhind Canal Tract of Punjab to understand the spatial and temporal pattern of groundwater. Groundwater model was simulated using PMWIN. Recharge was measured for irrigation and runoff according to GEC (1997) methods. Analysis of the sensitivity showed that the model was more sensitive to specific yield than to hydraulic conductivity values. The simulated model can be used effectively to manage the water resources in a sustainable manner [41].

Bouaamlat along with members developed a groundwater model to assess the impact of climatic variations and development in Tafilalet oasis system (TOS) in the lower Ziz and Rheris valleys of arid southeastern Morocco. By implementing a spatial database within a GIS and using the Arc Hydro Groundwater tool with code MODFLOW-2000, numerical simulations

were carried out. The results of steady-state and transient simulations in the period 1960-2011 showed that the water table is in at equilibrium between recharge, which is mainly by surface-water infiltration and discharge by evapotranspiration. Hydraulic heads became more sensitive to annual variations after the commissioning of the Hassan Addakhil dam in 1971, than to seasonal variations. Heads were also influenced by recurrent droughts and the highest water-level changes were recorded in irrigated areas. The model provides a way to manage groundwater resources within the TOS. It can be used as a method for projecting the effect of different development strategies on groundwater safety against overexploitation and water quality deterioration [42].

The groundwater conditions were investigated and reported a comprehensive review on application of GIS (Geographic Information System) followed by coupling with MODFLOW package for ground water management and development. Two major areas were discussed stating GIS applications in ground water hydrology. (i) GIS based subsurface flow and pollution modeling (ii) Selection of artificial recharge sites. Although the use of these techniques has increased rapidly in groundwater studies since the last decade the success rate is very limited. Based on this review, it was concluded that GIS and MODFLOW integration has great potential for future revolutionizing the monitoring and management of vital groundwater resources [43].

To know the behavior of groundwater in Kashmir Himalayas researchers used ArcGIS 10.2 for delineation of subcatchment and then various physiographic maps were prepared using LISS III image of the Kashmir Valley. The delineated map was input to the GMS (MODFLOW) 10.2 for digitizing the area. The various global, optional packages and layer property of the study area were collected as raw data from different Government organizations and some of the packages were computed. Three different simulations were carried out after giving all the inputs as global and optional packages to GMS for different time slices. The groundwater behaviour for different time slices was analyzed and flow budget was computed on the basis of precipitation conditions. As a consequence of increased precipitation, average annual groundwater recharge from all sources and sinks would increase by 7712.45 m<sup>3</sup>/year in Mid-Century (MC) (2030-2059) and 373847.6 m<sup>3</sup>/year in End-Century (EC) (2070-2099) and the

average groundwater levels would rise by 0.9 mbgl (metres below ground level) in MC and 1 mbgl (metres below ground level) in EC, compared to baseline time period (1985-2015) [44].

#### 4. CLIMATE CHANGE IMPACT STUDIES ON GROUNDWATER RESOURCES

Wilkinson and Cooper investigated the effects of climate change on aquifer storage and groundwater flow to rivers using an idealized representation of the aquifer/river system. The generalized aquifer/river model can incorporate spatial variability in aquifer transmissivity and was applied with parameters characteristic of Chalk and Triassic sandstone aquifers in the United Kingdom, and was also applicable to other aquifers elsewhere. The model was run using historical time series of recharge, estimated from observed rainfall and potential evaporation data, and with climate inputs perturbed according to a number of climate change scenarios. Simulations of baseflow suggested large proportional reductions at lower flows from Chalk under higher evaporation change scenarios. Simulated baseflow from the slower responding Triassic sandstone aquifer showed more uniform and less severe reductions. The change in hydrological regime was less extreme for the low evaporation change scenario, but remained significant for the Chalk aquifer [45].

The effect of climate change on the water yield and groundwater recharge was studied in the Ogallala aquifer in the central United States. Three specific GCMs were used to forecast shifts in the future climate related to anticipated variations in temperature and CO<sub>2</sub> concentrations. The analysis showed that recharge was lowered in all scenarios, depending on the simulation conditions, ranging up to 77% [46].

The potential effects of climate change on intrusion of seawater in coastal aquifers by using two coastal aquifers one in Egypt and the other in India, was investigated. This study evaluated the impact of likely climate change on intrusion of sea water. The sea water levels would rise under climate change circumstances for many reasons, including variations in atmospheric pressures, expansion of warmer oceans and oceans, and loss of ice sheets and glaciers. The rise in sea water levels would impose additional saline water heads at the sea side and therefore more sea

water intrusion is anticipated. Three realistic scenarios mimicking climate change were considered. The Nile Delta aquifer was found to be more prone to climate change and sea level rise in these conditions. A 50 cm rise in the Mediterranean Sea level will result in a further 9.0 km intrusion into the Nile Delta aquifer. In the Bay of Bengal the same increase in water level will induce an extra 0.4 km intrusion. Additional pumping would cause serious environmental effects in the case of the Nile Delta aquifer [47].

The study was carried out in a semi distributed rainfall runoff model to model the river Kennet, UK in which the outputs from three GCMs developed by the Headley Centre in 1996 were used. They concluded that under all scenarios, a groundwater recharge and storage would be reduced due to a shortening of the recharge season and a reduction in total annual runoff [48].

The karst aquifer in south-central Texas was studied and considered the impact of climate change not only on streambed recharge, but also on pumping rates (i.e. groundwater use). The effect of climate change on the streambed recharge was calculated using runoff scaling factors dependent on the ratio of historical and future stream flows expected from linked general and regional climate models. The report suggested that the surge in groundwater usage coupled with forecasted population increases would present a greater threat to the aquifer than climate change [49].

The possible changes in groundwater level due to climate change in Pennsylvania, US, by undertaking a statistical analysis of the historic relationship between groundwater levels and precipitation was studied by Neff and team. The process involved grouping the borehole groundwater level records by "precipitation-based regions" and normalising the hydrograph data to account for differences in geology. The groundwater levels were then averaged within each of the five precipitation-based regions. To predict future groundwater levels, this statistical model relating contemporary groundwater levels and rainfall was applied to the climate change scenarios from two GCMs [50].

Kirshen in 2002 used the groundwater model MODFLOW to study the impact of global warming on a highly permeable aquifer in the northeastern United States. A different model based on precipitation and potential

evapotranspiration was used to predict the groundwater recharge. Depending on the climate scenario used, both simulated and GCM-predicted shifts to the input parameters were used, resulting in higher, slightly different, and substantially lower recharge rates and groundwater elevations [51].

In Lansing, Michigan, Croley and Luukkonen studied the effect of climate change on groundwater levels. The groundwater recharge values were based on an empirical stream flow model which was optimized using the two GCM results. The research findings showed that the simulated level of steady state groundwater was typically projected to rise or decline due to climate change, depending on the GCM used [52].

Eckhardt and Ulbrich investigated the impact of climate change on groundwater recharge and stream flow in a small catchment in Germany. The input parameters were modified based on simulations from five separate GCMs in their hydrologic model. The study findings suggested that, owing to rising temperatures, more precipitation would occur as rain in winter, resulting in higher recharge and stream flow in January and February. The increased recharge from the snowmelt disappeared in March, while recharge and stream flow were potentially reduced in the summer months [53].

The Grand Forks aquifer, located in south-central British Columbia, Canada was used as a case study area for modeling the sensitivity of an aquifer to changes in recharge and river stage consistent with projected climate-change scenarios for the region. Evidence indicated that variations in recharge to the aquifer under the various climate-change projections, modeled under steady-state conditions, had a far smaller effect on the groundwater environment than changes in river-stage level of the Kettle and Granby rivers that pass through the region. All simulations showed relatively small changes in the overall configuration of the water table and general direction of groundwater flow. High-recharge and low-recharge models culminated in a rise of roughly +0.05 m and a reduction of -0.025 m in water level elevations around the aquifer, respectively. Simulated changes in river-stage elevation to represent higher than normal flow rates (by 20 and 50%) resulted in average increases in water-stage elevations of 2.72 and 3.45 m, respectively. Simulated changes in river-stage elevation, representing lower than base

flow rates (by 20 and 50%), culminated in average adjustments in water-stage elevations of -0.48 and -2.10 m. Average river-stage elevation (between current base flow and peak-flow stages) was consistent with actual recorded water table elevations in the valley [54].

An integrated hydrological model (MOHISE) was used to examine the effect of climate change on the hydrological process in typical water basins in Belgium. This model considers most hydrological processes in a physically consistent manner, particularly groundwater flows that are modeled using a spatially distributed approach to finite-elements. Considering IPCC climate change scenarios, the combined strategy was used to determine the effect of climate change on the water cycle in Belgium's Geer basin. The groundwater model was described in detail and results were discussed in terms of climate change impact on the evolution of groundwater levels and groundwater reserves. From the modeling application on the Geer basin, it appeared that, on a pluri-annual basis, most tested scenarios predicted a decrease in groundwater levels and reserves in relation to variations in climatic conditions. However, for this aquifer, the tested scenarios showed no enhancement of the seasonal changes in groundwater levels [55].

Holman in 2006 described an integrated approach to assess the regional impacts of climate and socio-economic change on groundwater recharge from East Anglia, UK. Several factors have an impact on future groundwater depletion including changing precipitation and temperature conditions, coastal floods, urbanization, woodland development, and cropping and rotation changes. In view of the findings, significant causes of ambiguity and limitations in the calculation of recharge were addressed. The ambiguity of, and significance of, socio-economic situations was illustrated of discussing the implications of unforeseen future changes. There have been changes in soil properties across a number of time scales, such that future soils may not have the same infiltration properties as recent soils. It defined the possible consequences of assuming unchanging soil properties [4].

The impacts of climate change on fresh groundwater resources were examined specifically for salinity intrusion in water resources stressed coastal aquifers. Their study used the climate model of the Hadley Centre,

HadCM3 for years 2000-2099 for high and low emission scenarios (SRES A2 and B2). The annual fresh groundwater resource losses in both scenarios suggested an increasing long-term trend in all stressed areas, except in the northern Africa / Sahara zone. They also found that individual precipitation and temperature did not demonstrate good correlations with a loss of fresh groundwater. They also addressed the impacts of fresh groundwater resource depletion on socio-economic trends, predominantly population development and fresh groundwater resources per capita [56].

Scibek and Allen in 2006 developed a methodology for linking climate models and groundwater models to investigate future impacts of climate change on groundwater resources. The technique was evaluated using an unconfined aquifer, found near Grand Forks in south central British Columbia, Canada. Scenarios for climate change from model runs in the Canadian Global Coupled Model 1 (CGCM1) were downscaled to local conditions using the Statistical Downscaling Model (SDSM). A three-dimensional transient groundwater flow model, applied in MODFLOW, was then used to simulate four climate scenarios in 1-year test runs (current in 1961-1999, 2010-2039, 2040-2069, and 2070-2099) and to compare groundwater to present levels. The effect of spatial distribution of recharge on groundwater levels, compared to that of a single uniform recharge zone, is much larger than that of temporal variation in recharge, compared to a mean annual recharge representation. From the downscaled CGCM1 model, the projected future climate for the Grand Forks region would result in further recharge to the unconfined aquifer from spring to summer season. However, because of dominant river-aquifer interactions and river water recharge, the overall impact of the recharge on the water balance is minimal [57].

The impact of land-use changes was studied in the near future, from 2000 until 2020, on the groundwater quantity and the general hydrologic balance of a sub-catchment of the Kleine Nete, Belgium. This study involved coupling a land-use change model with a water balance model and a groundwater model. The future land-use was modeled with the CLUE-S model. Four scenarios (A1, A2, B1 and B2) based on the Special Report on Emission Scenarios (SRES) were used for the land-use modeling. Water balance components, groundwater level and baseflow were simulated using the WetSpa model in conjunction with a

MODFLOW groundwater model. Results showed that the average recharge slowly decreased for all scenarios. The predicted reduction in recharge resulted in a small decrease of the average groundwater level, ranging from 2.5 cm for scenario A1 to 0.9 cm for scenario B2, and a reduction of the total baseflow with maximum 2.3% and minimum 0.7% respectively for scenario A1 and B2 [58].

Jyrkama and Sykes in 2007 presented a physically based methodology that can be used to characterize both the temporal and spatial effect of climate change on groundwater recharge. The analysis was based on the hydrologic model HELP3 and was used with high spatial and temporal resolution to predict future groundwater recharge on a regional scale. The framework was used in their study to simulate past circumstances, with 40 years of historical weather records, and future changes to the Grand River watershed hydrological process. The impact of climate change was modeled by perturbing the model input parameters using predicted changes in the regions climate. The results of the study indicated that the overall rate of groundwater recharge is predicted to increase as a result of climate change [59].

The effects of climate change on the groundwater systems in the Grote-Nete catchment, Belgium, covering an area of 525 km<sup>2</sup>, was modeled using wet (greenhouse), cold or NATCC (North Atlantic Thermohaline Circulation Change) and dry climate scenarios. Wet scenarios were adopted with low, central and high estimates of temperature changes. Using the WetSpass model, seasonal and annual water balance elements including groundwater recharge were simulated, while mean annual groundwater elevations and discharge were computed using a steady-state groundwater model MODFLOW. WetSpass results for the wet scenarios showed that wet winters and drier summers were expected relative to the present situation. MODFLOW results for wet high scenario indicated a rise in groundwater levels by as much as 79 cm, which may impact meadow distribution and species richness. Evidence reported similarly to the present for cold scenarios represented drier winters and wetter summers. The dry scenarios predicted dry conditions for the whole year. Over the summer there was no recharge, which was due mostly to high forest evapotranspiration rates and low precipitation. On the eastern part of the Campine

Plateau average annual groundwater levels drop by 0.5 m, with a peak of 3.1 m. It might bring aquatic ecosystems, shrubs and crop production in danger [60].

Toews and Allen in 2009 developed a regional-scale numerical groundwater model for the Oliver region of the south Okanagan, British Columbia, Canada, to simulate the impacts of future predicted climate change on groundwater. The study predicted an increased contribution of recharge to the annual water budget in future time scales (the 2050s and 2080s), calculated at 1.2% (2050s) and 1.4% (2080s) of the overall annual budget compared to the current circumstances [61].

Allen examined historical groundwater levels for selected observation wells in the south coastal region of British Columbia, Canada, to gain a better understanding of historical trends. Negative trends in groundwater level influenced most records over a common period (1976-1999) and tended to be linked to longer-term negative regional trends in precipitation, while variable trends were evident in the shorter periods used for this analysis. Water chemistry data from selected monitoring wells on one island were analyzed to investigate possible effects of varying recharge on groundwater quality. Future climate projections from a global climate model (CGCM1) were used as input to a recharge model to study the sensitivity of recharge to precipitation and temperature changes predicted for the area. A stochastic daily weather series was driven the recharge model, calibrated to historical climate data. Daily weather series reflect a historical climate, including two future time periods (2020s) and (2050s). Simulated recharge increased progressively in the future using this particular global climate model; however, precipitation projections for this region of British Columbia were highly uncertain. Both positive and negative shifts in annual precipitation were predicted using a range of global climate models [62].

Surjeet Singh and C P Kumar in 2011 carried out research work on Impact of Climate Change on Dynamic Groundwater System in a Drought Prone Area. The work dealt with the databases and their study, generating future rainfall and temperature, estimating recharge and simulating groundwater for better control and increase of groundwater in the basin. All the thematic maps were produced in ILWIS3.2, and data required were collected. Future rainfall was generated for

baseline, A1F1 and B1 scenarios for the 2004-2039 time-slice based on the SRES GCM projections for South Asia region. The site-specific soil, vegetation and climate database required for the Visual HELP model was developed, and site-specific groundwater recharge at twelve basin locations was calculated. The groundwater simulation was achieved by dividing the whole basin into twelve areas, utilizing the water balance method. Finally, the quantification of climate change effects on groundwater recharge and time-slice rates for the duration 2004-2039 has been completed [63].

The collaborative study on Impact of climate change on groundwater resources in Kolondieba catchment area, Sudanese climate zone in Mali was conducted in which high demand for evaporation and short recharge period led to fluctuations in groundwater levels. Steady state groundwater flow modeling with the aid of MODFLOW found that groundwater flows through the river network while the transient flow model showed a decline in water level over time, with an average drop in groundwater varying from 2 to 15 cm each year in the 1940-2008 regions. The results indicated that the model can be used to predict the groundwater level using downscaling values of the Climate Global Model data [64].

In another study Kumar assessed the effect of climate change on groundwater resources, latest scientific studies and methods for evaluating the effect of climate change on groundwater resources in India in the form of soil moisture, groundwater recharge and coastal aquifers. A short analysis has been provided of the work studies carried out in the last years. Estimation of groundwater recharge was performed utilizing WHI UnSat Suite and WetSpss. Weather station climate data was evaluated; GCM models and future predicted climate change datasets were established with variables in temperature, precipitation and solar radiation [65].

One of the groundwater studies in High Plains of US in which 16 global climate models (GCMs) and three global warming scenarios were used to analyze changes in groundwater recharge rates for a 2050 climate relative to a 1990 climate. Groundwater recharge was modeled using the WAVES model Soil Vegetation Atmosphere Transfer for a range of soil and vegetation forms covering the High Plains. The median forecast under a climate of 2050 showed a rise of +8% in the Northern High Plains, a marginal decrease of

-3% in the Central High Plains, and a larger decrease in the Southern High Plains (-10%), amplifying the current spatial trend in recharge from north to south. Predicted recharge variations between dry and rainy future climate scenarios saw both an increase and decrease in recharge levels, with the size of this variation exceeding 50% of actual recharge. On a relative scale, recharge sensitivity to rainfall changes showed that regions with high current recharge rates were less sensitive to rainfall changes, and vice versa [66].

## 5. CONCLUSION

In summary, climate change is likely to have an impact on future recharge rates and thus on the groundwater resources underlying them. As some of the studies showed, the effect may not always be a deleterious one. However, quantifying the effect is complicated, and is susceptible to the uncertainty inherent in future predictions of climate. Mixed and conflicting results have been obtained by simulations based on general circulation models (GCMs), raising questions about their reliability in predicting future hydrological conditions. Groundwater recharge is not only determined by hydrological processes but also by the physical characteristics of the soil and surface structure. Many climate change studies have focused on modeling the temporal changes in the hydrologic processes and ignored the spatial variability of physical properties across the study area. While it is essential to know the average difference in the level of recharge and groundwater over time, such changes will not occur equally over a regional catchment or river basin. Long-term water resource planning requires both spatial and temporal groundwater recharge information in order to properly manage not only water use and exploitation but also allocation and development of land use. Studies concerned with climate change should, therefore also consider the spatial variation in groundwater recharge rates.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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