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REVIEWS

Groundwater Resources under a Changing Climate

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Abstract | The effect of changing climate on surface water resources has been studied extensively over the past few decades. However, studies related to the effect on groundwater are relatively few, probably because the effect is neither direct nor simple. This review summarizes the current status, looks at possible mitigation and adaptation strategies, and suggests future direction of research in this area.

1 Introduction

There is an increasing trend in the earth's temperature. Although some scientists ascribe it to natural cycles, there is a general agreement that this global warming is a result of anthropogenic factors, particularly, increase in greenhouse gases (GHGs) caused by fossil fuel burning. Even if the warming is part of a natural cycle, it is escalated by the anthropogenic activities, and it is estimated that this trend will continue for several decades. The change in climate would have, and in fact already has, a significant impact on the water resources, both direct (e.g., a changing precipitation and evaporation pattern) and indirect (e.g., by increase in water demand). While the effect on the surface water resources is more apparent and simpler to evaluate, it is relatively difficult to estimate the possible impacts of climate change on groundwater, due to the significant influence of local geology, land-use, and topography. Groundwater accounts for roughly one third of the global water withdrawals and supplies drinking water for a large portion of the population. Therefore, it is important to study the behavior of the groundwater resources under changing climatic conditions particularly since the subsurface storage is likely to play a major role in the overall management of the water resources. This is due to the fact that the groundwater has a larger reaction time to the climate forcing and significant storage capacity. Most of the world's aquifers are, however, already over-exploited and liable to be subjected to a significant increase in stress due to climate change. Hence, an understanding of the several possible responses of aquifers to changes in temperature, precipitation, evaporation, land-use, etc., is necessary for a sustainable water resources development in the changing climate scenario.

In this review, we first provide a brief description of the climate change and its impact on the hydrologic cycle, with particular reference to the surface water resources. We then look at studies aimed at ascertaining the effect of climate change on the groundwater and, finally, provide a summary of important findings and suggest future research directions.

2 Climate Change

The global climate shows a large spatial and temporal variability due to natural and anthropogenic factors. There is a general consensus among the scientific community that there has been an increase in average air and ocean temperatures, which is likely to continue for several decades irrespective of the mitigating actions. Moreover, several studies have shown that there would be consequent melting of snow and ice, rise in sea levels, changes in precipitation patterns and magnitudes, and increase in frequency of extreme events like floods and droughts. It is estimated[1] that increase in the precipitation amount is very likely at high latitudes, whereas decrease is likely in subtropical regions. Similarly, the globally averaged rise in sea level at the end of the twenty-first century is expected to be between 0.18 to 0.38 m. It should be noted, however, that these estimates are based on the results from several General Circulation Models (GCMs) under different scenarios of future emission of the GHGs. There is, therefore, a large uncertainty associated with the predictions due to the model uncertainties and the scenario uncertainties. Several studies[2] have shown that

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the model uncertainties are much larger than the scenario uncertainties and any conclusion based on the results of a single GCM may not be defensible. The general practice is to run several models and create an ensemble of possible outcomes, from which meaningful statistics pertaining to the relevant variables could be derived. Since our focus in this review is on the impact of the climate change, rather than the change *per se*, we do not go into the details of these aspects.

3 Impact on Surface Water Resources

Two most noticeable direct impacts of a changing climate on the surface water resources are on the precipitation and evaporation. However, there are several factors which may affect the surface water resources indirectly. For example, an increase in the carbon dioxide levels in the atmosphere may lead to a reduction in the stomatal conductance of plants, thereby reducing transpiration. Similarly, the rise in temperature could lead to an altered land use and land cover, which, in turn, would affect the evapotranspiration and precipitation. Although several studies have addressed the issue of the impact of climate change on surface water resources, the results are largely uncertain and often contradictory. For example, most researchers contend that the precipitation over India is expected to show insignificant change as a whole, but may show distinct increasing/decreasing trends when different climatic subdivisions are considered. The nature and magnitude of these trends, however, vary from one study to the other, depending on the model used for the simulations. In addition to the model uncertainty, there are several issues related to the downscaling of the GCM output, which is on a coarse grid, to a finer grid which is more relevant for the hydrological variables. The two methodologies used for downscaling, viz. statistical and dynamic, have their own advantages and disadvantages, and extensive research is continuing to achieve a robust and accurate downscaling model. Dynamic downscaling through a Regional Circulation Model (RCM), using the output provided by the GCM as its boundary conditions, appears to be the preferred option for downscaling. However, the RCMs have their own shortcomings, e.g., their complexity and the presence of several adjustable parameters which may be difficult to calibrate. The statistical downscaling, on the other hand, is much simpler as it is based on the correlation of the relevant variable with some predictors, as observed in the past. A major limitation, however, is the assumption that the past relationships would hold good in the future also, even with a changed climate. Since the thrust of this review is on the impact of climate change on groundwater, we will not discuss the details of downscaling. Major findings of some studies related to the impact of climate change on precipitation and surface water resources may be summarized as below:[3,4]

- Rainfall has increased over large parts of the tropical oceans.
- Annual land precipitation has increased in the middle and high latitudes of the Northern Hemisphere.
- Over the sub-tropics land-surface rainfall has decreased on average, although there is a slight recovery in recent years.
- Changes in annual streamflow often relate well to changes in total precipitation.
- No systematic changes in precipitation have been detected in broad latitudinal averages over the Southern Hemisphere.
- In regions where total precipitation has increased, it is very likely that there have been even more pronounced increases in heavy and extreme precipitation events. However, in some regions, heavy and extreme events have increased even though the total precipitation has decreased or remained constant, possibly due to a decrease in the frequency of precipitation events.
- The patterns in streamflow are generally consistent with those of precipitation: Runoff tends to increase where precipitation has increased and decrease where it has decreased.
- A marked shift in streamflow from spring to winter has been observed at several places, not only due to changes in precipitation but more so due to the rise in temperature, since it implies that the precipitation is in the form of rain, rather than snow, and therefore reaches the rivers more rapidly.
- There is a reducing streamflow trend in Sahel region but weak increasing trend in Western Europe and North America; and increasing relative variability from year to year in several arid and semi-arid regions.
- Land-use and other changes are continuing in many catchments, with effects on streamflows that may outweigh any climatic trends.

4 Impact on Groundwater

We now come to the main aspect of this review. Since the impact of a changing climate on the groundwater is largely area-specific, we describe several studies conducted in different parts of the world. This is followed by an attempt to derive some general conclusions and then suggest some future directions of research. The literature is reviewed in a chronological order and may, at some places, appear to be a little disjointed. However, it does give a sense of how the research in this field has evolved over time.

Probably one of the earliest works related to the impact of climate change on groundwater was in 1992 where analyses of the effect of a changing climate on the estimation of the groundwater recharge in the Columbia Plateau, Washington was carried out.[5] A daily energy-soil-water balance model was used to estimate the recharge under pre-development and current conditions. Synthetic weather was generated on a daily basis with parameters estimated from the historical records. The recharge for pre-development conditions varied considerably for the observed range of climatic conditions but was less sensitive for current conditions because of irrigation. To predict future behavior, two scenarios were considered: an average of three different GCMs with CO_2 doubling, and a most severe case. For the average scenario, recharge increased in the pre-development stage but decreased for current conditions while for the severe scenario, recharge for both pre-development and current conditions decreased. The sensitivity of recharge to the climate variability was also analyzed for both scenarios.

A study in the Mesochora catchment in central Greece[6] considered the effect of climate change on the groundwater-streamflow interaction under two different scenarios of climate change and found a moderate influence on the groundwater-streamflow interaction during the winter months and a very high influence in the spring and summer months. The climate change was simulated through a set of hypothetical and monthly Goddard Institute for Space Studies scenarios of temperature and precipitation. The catchment hydrology was simulated by the US National Weather Service River Forecast System model. The interaction between groundwater and streamflow was expressed by the ratio of the two variables, and the primary reason for the influence of climate change on this ratio was found to be the seasonal shift in the snow accumulation pattern and the runoff reduction and evapotranspiration increase occurring in spring and summer months.

The aquifer freshening time under natural recharge for three coastal aquifers in Greece was studied[7] and it was found that the freshening time for two of the aquifers was of the order of thousands of years but the third aquifer had a significantly smaller freshening time of 15 years. The freshening process showed patterns that had resulted from calcite dissolution and cation exchange. Aquifers with the Quaternary and Neogene formations showed larger freshening time, but the carbonate aquifer had a very small freshening time due to the difference in cation exchange capacities.

Statistical methods based on correlations between groundwater level and rainfall were used to predict the minimum groundwater levels and occurrence of droughts in the UK.[8] A multiple linear regression model was developed and was used with synthetic rainfall data from the climate-change scenarios, to model the future minimum groundwater levels. It was observed that even though an overall increase in rainfall was predicted by some climate change scenarios, changes in the seasonality and frequency of extreme precipitation events may lead to an increase in groundwater droughts in some areas. The Chalk aquifer in southern and eastern England was found to be most susceptible to these effects. The method used in the study made no assumptions regarding recharge processes and was thought to be applicable over a wide range of hydrologic, geological and hydrogeological conditions.

A revised version of the Soil and Water Assessment Tool was used to study the impacts of climate change on groundwater recharge and streamflow over Europe.[9] To improve the reliability of simulations, influence of elevated CO_2 levels on stomatal conductance and leaf area was included. Impacts of two climate change scenarios representing a wide range of scenarios were evaluated. The effects on annual groundwater recharge and streamflow were found to be small. The results show that a smaller proportion of the winter precipitation will fall as snow due to the warming. The spring snowmelt peak is reduced while the winter flood risk increases. Mean monthly groundwater recharge and streamflow in summer were reduced significantly causing problems related to water quality, groundwater withdrawals and hydropower generation.

An integrated hydrological model was used to study the impact of climate change on the hydrological cycle in water basins in Belgium.[10] The model considered most hydrological processes, particularly groundwater flows, in a physically consistent way. Detailed calibration and validation was performed, which enabled quantitative interpretations to be drawn from the groundwater model results. The results were discussed in terms of climate change impact on the evolution of groundwater levels and groundwater reserves. On a pluriannual basis, most scenarios predict a decrease in groundwater levels and reserves. However, the modeled aquifer showed no enhancement of the seasonal changes in groundwater levels.

The Grand Forks aquifer, located in south-central British Columbia, Canada was modeled to study its response to changes in recharge and river stage under projected climate-change scenarios.[11] The variations in recharge were found to have a smaller impact on the groundwater system than changes in river-stage elevation of the rivers flowing through the valley. The overall configuration of the water table and general direction of groundwater flow were not significantly affected. High- and low-recharge simulations showed a change in the water-table elevations of the order of a few centimeters, while changes in river-stage elevation resulted in average changes in the water-table elevation of the order of meters.

The Somme valley in France is not prone to flooding. However, a sudden flood occurred in 2001, which was attributed to the groundwater,[12] probably the first time that such an event resulted from groundwater discharge. It was thought to be due to the changing behavior of groundwater recharge from matrix flow to macropore flow due to accumulated wetness over several years. The return period of such flooding depends on the long-term precipitation fluctuations and similar situation can occur in Belgium and England.

The effects of geology and geomorphology on surface-water-groundwater interactions, evapotranspiration, and recharge under conditions of long-term climatic change were analyzed.[13] Hydrologic data from the glaciated Crow Wing watershed in central Minnesota, USA, was combined with a hydrologic model of transient coupled unsaturated/saturated flow. Historical water-table and lake-level records indicated that larger amplitude and longer period fluctuations occur within the upland portions of watersheds under relatively short-term climatic fluctuations. Under drought conditions, lake and water-table levels fell by as much as 2–4 m in the uplands and by 1 m in the lowlands. The same pattern was also seen on millennial time scales. A sensitivity analysis was carried out to study how aquifer hydraulic conductivity and land-surface topography can influence water-table fluctuations, wetlands formation, and evapotranspiration. The models were run through 10 wet years followed by 20 years of drier and warmer climate. Model results indicated that groundwater-supported evapotranspiration accounted for as much as 12% of evapotranspiration. The aquifers of highest hydraulic conductivity had the least amount of groundwater-supported evapotranspiration owing to a deep water table. Recharge was even more sensitive to aquifer hydraulic conductivity, especially in the lowland regions.

The regional impacts of climate and socio-economic change on groundwater recharge were studied for East Anglia, UK.[14] Many factors affect future groundwater recharge including changed precipitation and temperature regimes, coastal flooding, urbanization, woodland establishment, and changes in cropping and rotations. The study highlighted the importance of socio-economic scenarios, and the inherent uncertainty, in exploring the consequences of future changes. The implications involved in assuming same soil properties in the future were described. It was suggested that one must not neglect the role of policy, societal values and economic processes in assessing the impacts of climate change and the hydrogeologists must collaborate with researchers from other disciplines, such as socio-economists, agricultural modelers and soil scientists.

To estimate the freshwater loss in coastal aquifers due to salinisation, a numerical model based on the sharp interface assumption was used.[15] The model depicted the changes in fresh groundwater loss with respect to climate change, land use pattern and soil condition. An interesting finding was that deforestation resulted in increased groundwater recharge probably because the reduction in evapotranspiration outweighed the increase in runoff. The calculated recharge was used to estimate the freshwater-saltwater interface and percentage of freshwater loss due to salinity intrusion. It was found that in arid areas, the fresh groundwater loss increases as the percentage of forest cover increases.

A study was conducted to evaluate the impacts of climate change on fresh groundwater resources in water resources stressed coastal aquifers.[16] The Hadley Centre climate model, with scenarios A2 and B2, was used for years 2000–2099. In both scenarios, an increasing long-term trend was seen in the annual fresh groundwater resources losses, except in the northern Africa/Sahara region. Precipitation and temperature individually did not show good correlations with fresh groundwater loss. The impact of loss of fresh groundwater resources on socio-economic activities, mainly population growth and per capita fresh groundwater resources was discussed.

Climate models and groundwater models were linked to investigation of future impacts of climate change on groundwater resources.[17] An unconfined aquifer, situated near Grand Forks in south central British Columbia, Canada, was used to test the methodology. Climate change scenarios from a GCM were downscaled to local conditions using statistical downscaling, and the change factors were applied in a stochastic weather generator, and used as input for the recharge model. The recharge model simulated the direct recharge to the aquifer from infiltration and consisted of spatially distributed recharge zones, represented in the Hydrologic Evaluation of Landfill Performance model linked to a geographic information system. A three-dimensional transient groundwater flow model was then used to simulate four climate scenarios in 1-year runs and to compare groundwater levels. The effect of spatial distribution of recharge was found to be much larger than that of temporal variation in recharge. The future climate for the Grand Forks area from the downscaled GCM led to more recharge to the unconfined aquifer from spring to the summer season. However, the overall effect of recharge on the water balance was small because of dominant river-aquifer interactions and river water recharge. In a similar study,[18] one-year long climate scenarios were run, each representing a typical year in the present and future (2020s and 2050s), by perturbing the historical weather according to the downscaled GCM results. A shift in river peak flow to an earlier date in a year was indicated with the shift for the 2040–2069 climate larger than that for 2010–2039, although the overall hydrograph shape remained the same. Away from the river, modeled water level differences were less than 0.5 m, but were found to be greater than 0.5 m near the river. The maximum groundwater levels associated with the peak hydrograph were not changed much because the peak discharge was not predicted to change, only the timing of the peak.

Another study[19] presented a physically based methodology that can be used to characterize both the temporal and spatial effect of climate change on groundwater recharge. The method was based on the hydrologic model HELP3, and could be used to estimate potential groundwater recharge with high spatial and temporal resolution. The impact of climate change on the Grand River watershed was modeled by perturbing the model input parameters using predicted changes in the region's climate. Results indicated that the overall rate of groundwater recharge increases as a result of climate change. The higher intensity and frequency of precipitation will also contribute significantly to surface runoff, while global warming may result in increased evapotranspiration rates. Warmer winter temperatures will reduce the extent of ground frost and shift the spring melt from spring toward winter, allowing more water to infiltrate into the ground. In addition to the temporal changes in groundwater recharge, the results suggested that the impacts can also have high spatial variability.

The effects of climate change on the groundwater systems in the Grote-Nete catchment, Belgium, were modeled using wet, cold and dry climate scenarios.[20] Seasonal and annual water balance components including groundwater recharge were simulated using WetSpass, while mean annual groundwater elevations and discharge were simulated with MODFLOW. WetSpass results for the wet scenarios show that wet winters and drier summers are expected relative to the present situation. MODFLOW results for wet scenario show groundwater levels increase by as much as 79 cm. Results obtained for cold scenarios depict drier winters and wetter summers relative to the present. The dry scenarios predict dry conditions for the whole year. There is no recharge during the summer, which is mainly attributed to low precipitation and high evapotranspiration. Average annual groundwater levels drop by 0.5 m, with maximum of 3.1 m on the eastern part of the Campine Plateau. This could endanger aquatic ecosystem, shrubs, and crop production.

The effect of variability in climate, groundwater withdrawal and land use on dry-weather streamflows in a Korean watershed were investigated using SWAT.[21] A regression equation was derived from 30-year simulation results to predict the total runoff using climate data like precipitation during the dry period, precipitation during the previous wet period, solar radiation, and maximum temperature. It was observed that an increase of 3°C in the daily average maximum temperature, will decrease the total runoff during the dry period by 27.9%. Groundwater withdrawals strongly affect streamflow during the dry period but land use changes do not appear to significantly affect runoff during the dry period. A combined equation was derived to relate the runoff during the dry period to changes of temperature, precipitation, solar radiation, urban area ratio, and groundwater withdrawal quantity.

The effects of climate change on groundwater recharge for three locations in Great Britain were studied[22] using results from a stochastic weather generator, actual evapotranspiration and potential groundwater recharge time-series for the historic baseline 1961–1990 and for future GHG emissions scenario for the 2020s, 2050s and 2080s. Results showed a decrease of 20% in potential groundwater recharge for Coltishall, 40% for Gatwick and 7% for Paisley by the end of this century. The persistence of dry periods was shown to increase during the 2050s and 2080s. It was concluded that future climate may present a decrease in potential groundwater recharge that will increase stress on local and regional groundwater resources that are already under ecosystem and water supply pressures.

In a case study,[23] a hydrological catchment model was applied to the Ucker catchment located in the Northeastern German lowlands for an assessment of the impact of climate change on discharge regime using meteorological time series from 1951–2055. These time series were based on the A1B-Scenario with an increase of 1.4 degrees C in the mean annual temperature. The results predicted an increase in the number of days with low flow conditions in the Ucker river, accompanied by a decrease by 44–94% in ground water recharge, especially at forested areas.

A variably saturated groundwater flow model with integrated overland flow and land-surface model processes was used to examine the water and energy flows in a changing climate for the southern Great Plains, USA.[24] It was indicated that most models aim at studying the response of groundwater to climate change without accounting for energy feedbacks across the complete hydrologic cycle. Similarly, the land-surface models do include an operational groundwater-type component, but do not include physically based lateral surface and subsurface flow, and allow only for vertical transport processes. The proposed model was thought to be a significant improvement and three scenario simulations with modified atmospheric forcing in terms of temperature and precipitation were compared with a simulation of the present-day climate. It was found that groundwater depth resulting from lateral water flow at the surface and subsurface, was an important parameter in determining the susceptibility of regions to changes in temperature and precipitation. This groundwater control was thought to be critical in understanding the processes of recharge and drought in a changing climate.

A mathematical model, "Estimation of Recharge in Over-exploited Aquifers", was used to simulate the monthly water recharge to an aquifer in Spain.[25] Precipitation, temperature, groundwater extraction, stored groundwater surface and storage coefficient were the basic data used in the model. Analysis of natural groundwater recharge for the 100 years of the twentieth century revealed the presence of a logarithmically decreasing trend.

A surface-subsurface flow model was combined with advanced climate change scenarios for the Geer basin, Belgium.[26] Coupled surface-subsurface flow was simulated with the finite element model HydroGeoSphere. The simultaneous solution of surface and subsurface flow equations, and the computation of the actual evapotranspiration as a function of the soil moisture at each node of the evaporative zone, improved the representation of interdependent processes like recharge, which is crucial in the context of climate change. Climate change simulations were obtained from six RCM scenarios which were downscaled using a quantile mapping bias-correction technique. The simulations predicted hotter and drier summer and warmer and wetter winters. It was shown that decreases up to 8 m are expected in the groundwater levels and between 9% and 33% in the surface water flow rates by 2080.

The model WaterGAP was used to study the impact of climate change on groundwater recharge and the number of affected people for four climate scenarios by two climate models.[27] A sensitivity index composed of a water scarcity indicator, an indicator for dependence of water supply on groundwater and the Human Development Index was quantified. Global maps of vulnerability to the impact of decreased groundwater recharge in the 2050s were derived by combining percent groundwater recharge decrease with the sensitivity index. About 16–19% of the global population was likely to be affected by groundwater recharge decreases of at least 10%. The highest vulnerabilities were found at the North African rim of the Mediterranean Sea, in southwestern Africa, in northeastern Brazil and in the central Andes. For most of the areas with high population density and high sensitivity, the groundwater recharge was unlikely to decrease by more than 10% and a fifth to a third of the population could be affected by a groundwater recharge increase of more than 10%, with possible negative impacts in the case of shallow water tables. The spatial distribution of vulnerability showed stronger variation between the two climate models than that between the two emissions scenarios.

A regional-scale groundwater model was developed for the Oliver region of the south Okanagan, British Columbia, Canada, to simulate the impacts of predicted climate change on groundwater.[28] Groundwater systems in arid regions are particularly sensitive to climate change owing to the strong dependence of evapotranspiration on temperature, and shifts in the precipitation regimes. The changes in climate may require increased irrigation, putting stress on existing water supplies. The results showed increased contribution of recharge to the annual water budget relative to the current conditions, estimated at 1.2% in 2050s and 1.4% in 2080s, due to increases in irrigation return flow. Moreover, by the 2080s, increase in groundwater level of up to 0.7 m were estimated.

Since 50% or more of the continent's population relies on groundwater, in a series of papers,[29–32] effect of climate change on groundwater in Africa was studied. It was concluded that the climate change impacts are likely to be significant, though uncertain in direction and magnitude, while the impacts of demographic change on both water resources and water demand are likely to be more certain and much larger. The combined effects of urban population growth, rising food demands and energy costs, and consequent demand for fresh water were likely to overshadow the impacts of climate change on groundwater resources, at least over the first half of the 21st century. Analysis of existing rainfall and recharge studies suggest that climate change is unlikely to lead to widespread catastrophic failure of rural groundwater supplies. Increased demand on dispersed water points were thought to pose a greater risk of individual source failure than regional resource depletion. Predicted increased rainfall intensity may also increase the risk of contamination of very shallow groundwater. The simulations on the upper Ssezibwa catchment, Uganda, were performed using statistical downscaling to downscale future climate change scenarios obtained from the HadCM3 model. The downscaled climate was used with the WetSpa hydrological model to simulate the resulting hydrological changes. An increase in precipitation in the wet seasons ranging from 30% in the 2020s to over 100% in the 2080s was observed and the rise in temperature ranged between 1–4°C. The mean annual daily baseflow of 157 mm/year (69% of discharge), was expected to increase by 20–80% between the 2020s and 2080s and the recharge increased by 20 to 100% from the current 245 mm/year. Similarly, data from a RCM was used with a semi-distributed soil moisture balance model to quantify the impacts of climate change on groundwater recharge and runoff in the humid tropics of southwestern Uganda. The projections showed 14% rise in catchment precipitation, 53% rise in potential evapotranspiration and increases in rainfall intensity.

Effect of changes in land use and climate on shallow groundwater temperatures was studied using an analytic heat transfer relationships for 1-D unsteady effective diffusion of heat through an unsaturated zone into a flowing aquifer a short distance below the ground surface.[33] Both long-term trends and seasonal cycles in surface temperature changes were considered. It was found that a fully urbanized area was likely to have 3°C warmer groundwater than an undeveloped agricultural area at the same geographic location. In the extreme cases of doubling of atmospheric CO_2, groundwater temperatures could rise by up to 4°C. Combination of a land use change and a CO_2 doubling, could lead to rise of groundwater temperatures by about 5°C in the study area.

Future estimates of potential groundwater recharge calculated using a daily soil-water balance model and climate-change weather time series derived using deterministic and stochastic methods were compared for Coltishall, UK.[34] The uncertainty in the results for a given climate-change scenario arising from the choice of downscaling method was greater than the uncertainty due to the emissions scenario within a 30-year time slice. It was recommended that stochastic modelling of potential recharge be used in vulnerable or sensitive groundwater systems, and that multiple recharge time series are sampled according to the relevant time series variables, e.g., for water resource management: recharge drought severity and persistence or, for groundwater flooding: high recharge years.

An estimation of the impact of projected future climate change on evapotranspiration, groundwater recharge, and low-flow conditions in the Ucker catchment in the lowlands of NE Germany was made by applying a hydrological catchment model.[35] Meteorological time series from 1951 to 2055 were generated by the Potsdam Institute of Climate Impact Research based on an increase of 1.4 degrees C in the mean annual temperature and a mean decrease of 8% in annual rates of precipitation. The results indicated that the number of low-flow days will increase and groundwater recharge will decrease by 1%–94%.

Groundwater recharge under irrigated agriculture in response to variations of atmospheric CO_2 concentrations (550 and 970 ppm) and average daily temperature (+1.1 and +6.4°C compared to current conditions) was estimated using HYDRUS 1D for three typical crop sites (alfalfa, almonds and tomatoes) in the San Joaquin watershed in California.[36] A modified version of the Penman-Monteith equation was used to account for the higher atmospheric CO_2 concentration. The results suggest that increasing temperature caused a temporal shift in plant growth patterns and redistributed evapotranspiration and irrigation water use earlier in the growing season resulting in a decrease in groundwater recharge under alfalfa and almonds and an increase under tomatoes. Elevating atmospheric CO_2 concentrations generally decreased groundwater recharge for all crops due to decreased evapotranspiration resulting in decreased irrigation water use. Increasing temperature and atmospheric CO_2 concentration led to a decrease in cumulative groundwater recharge for most scenarios.

The impacts of different climate predictions on diffuse episodic recharge at a low-relief semi-arid rain-fed agricultural area were analyzed for a site in the southern High Plains, United States.[37] A probabilistic approach was used that explicitly accounts for uncertainties in meteorological forcing and in soil and vegetation properties. An ensemble of recharge forecasts was generated from Monte Carlo simulations and soil and vegetation parameter realizations were conditioned on soil moisture and soil water chloride observations. A stochastic weather generator provided realizations of meteorological time series for climate alternatives from different GCMs. Predicted changes in average recharge (−75% to +35%) were larger than those in average precipitation (−25% to +20%), suggesting an amplification of climate change impacts in groundwater systems. Predictions also include varying changes in the frequency and magnitude of recharge events. The temporal distribution of precipitation change explained most of the variability in recharge totals.

A groundwater-surface water-land surface model was used to analyze watershed response and groundwater-land surface feedbacks in the Little Washita River watershed of North America, under observed and perturbed climate conditions.[38] Basin-scale hydrologic sensitivity to temperature and precipitation perturbations was shown to be greatest under energy-limited (direct runoff) conditions compared to moisture-limited (base flow) conditions. Feedbacks between groundwater depth and the land surface water and energy balance were shown to have significant influence on surface fluxes under moisture-limited conditions. Results demonstrated that hydrologic sensitivity to climate change depends on feedbacks between groundwater, overland flow, and the land surface water and energy balance and the magnitude and seasonality of these feedbacks is sensitive to changes in climate.

An optimal-control theory was applied to develop groundwater exploitation strategies that account for potential climate change patterns in Brazil.[39] Some potential water policies based on the modeling results were discussed, with water conservation and water subsidies turning out to be beneficial for current generation and detrimental for future generations.

The low-lying Dutch Delta was studied[40] to assess the impact of climate change and increased anthropogenic activities on coastal groundwater systems. The possible impacts of future sea level rise, land subsidence, changes in recharge, autonomous salinization, and the effects of two mitigation countermeasures were analyzed with a three-dimensional numerical model. The results show that the impact of sea level rise is limited to areas within 10 km of the coastline. More inland, ongoing land subsidence will cause hydraulic heads and groundwater levels to drop, which may result in damage to dikes, infrastructure, and urban areas. The future increase of salt loads will cause salinization of surface waters and shallow groundwater.

A general review[41] of work on global warming and groundwater resources summarized the methods used to analyze the climate change scenarios and the influence of these changes on groundwater resources and discussed the future challenges of adapting to climate change. The adaptation to and mitigation of these effects was also reported, including useful information for water-resources managers and the development of sustainable groundwater irrigation methods. Rescheduling irrigation according to the season, coordinating the groundwater resources and irrigation demand, developing more accurate and complete modeling prediction methods, and managing the irrigation facilities in different ways were suggested as some possible measures.

A study[42] for three points in Australia used a sensitivity analysis of climate variables using a soil-vegetation-atmosphere-transfer model to determine the importance of climate variables in the change in groundwater recharge. Change in recharge was found to be most sensitive to change in rainfall. Increases in temperature and changes in rainfall intensity also led to significant changes in recharge. Although not as significant as other climate variables, changes in solar radiation and carbon dioxide concentration also caused some changes in recharge.

A methodology was presented for assessing the average changes in groundwater recharge under a future climate for the Murray-Darling Basin in Australia.[43] Climate sequences were developed based upon three scenarios from 15 global climate models. The 45 scenarios were grouped into three: a wet future, a median future and a dry future. It was found that for the median future, recharge increases on average by 5% but this is not spatially uniform. In the wet and dry scenarios, the recharge increases by 32% and decreases by 12%, respectively. The differences between the climate sequences generated by the 15 different global climate models made it difficult to project the direction of the change in recharge, let alone the magnitude.

The effects of climate change on Shelter Island, New York (USA) were investigated using a variable-density transient groundwater flow model using two future climate scenarios from the Intergovernmental Panel on Climate Change 2007 report.[44] In the scenario consisting of a 15%

precipitation increase and 0.18 m sea-level rise, there was a 23 m seaward movement of the fresh-water/salt-water interface, a 0.27 m water-table rise, and a 3% increase in the fresh-water volume. In the unfavorable scenario consisting of a 2% precipitation decrease and 0.61 m sea-level rise, the result was a 16 m landward movement of the fresh-water/salt-water interface, a 0.59 m water-table rise, and a 1% increase in lens volume. The unexpected groundwater-volume increase under unfavorable climate change was thought to be due to a clay layer under the island that restricts the maximum depth of the aquifer and allows for an increase in fresh-water lens volume when the water table rises.

A study[45] applied the integrated MIKE SHE model on a small catchment in northern Switzerland using data from eight GCM-RCM combinations corrected by three different statistical downscaling methods, for precipitation and potential evapotranspiration. The RCMs resulted in very different projections of potential evapotranspiration and precipitation. All three downscaling methods reduced the differences between the predictions of the RCMs and all corrected predictions showed no future groundwater stress. The simulations revealed the limitations of the downscaling methods and identified it as an important source of uncertainty in hydrological impact studies. It was recommended that the downscaling methods be tested extensively using verification data before applying them to climate model data.

An overview and synthesis of the key aspects of subsurface hydrology, including water quantity and quality, related to global climate change was provided in a recent study.[46] Available subsurface storage was suggested as a key to meeting the combined demands of agriculture, industry, municipal and domestic water supply, and ecosystems during times of shortage. The future intensity and frequency of dry periods combined with warming trends need to be addressed in the context of groundwater resources, even though projections in space and time are fraught with uncertainty. Research to improve our understanding of the joint behaviors of climate and groundwater is needed, and spin-off benefits on each discipline are likely.

Another review[47] emphasizes that climate changes have the potential to affect both the quality and quantity of available groundwater, primarily through direct impacts on recharge, evapotranspiration and indirect impacts on pumpage and abstraction. Predicting how climate change could impact groundwater systems is difficult primarily due to uncertainties in the predictions of future climate and the complex combinations of processes that affect groundwater recharge, discharge and quality. Improvements in observations, process understanding, and modeling, are needed to assess the impact of projected climate changes.

A substantial improvement upon the state-of-the-art was offered by using a sophisticated transient weather generator in combination with an integrated surface-subsurface hydrological model developed with the finite element model HydroGeoSphere.[48] The weather generator enabled the stochastic generation of large numbers of equiprobable climatic time series, representing transient climate change, and was used to assess impacts in a probabilistic way. 30 equiprobable climate change scenarios from 2010 to 2085 were generated for six different RCMs. Results show that although the 95% confidence intervals calculated around projected groundwater levels remain large, the climate change signal becomes stronger than that of natural climate variability by 2085.

The impact of 28 climate change scenarios on the groundwater system of a lowland catchment in Belgium was studied.[49] Results show a change in annual groundwater recharge between –20% and +7% with an average decreases of 7%. In most scenarios the recharge increases during winter but decreases during summer. The altered recharge patterns cause the groundwater level to decrease significantly from September to January. The groundwater level decreases by about 7 cm on average with a standard deviation of 5 cm between the scenarios.

Coastal aquifers provide a water source for the more than one billion people living in coastal regions. Synthesis studies and detailed simulations have predicted that rising sea levels could negatively impact coastal aquifers through saltwater intrusion and/or inundation of coastal regions. It was shown that coastal aquifers are more vulnerable to groundwater extraction than to predicted sea-level rise under a wide range of hydrogeologic conditions and population densities.[50] Water use is a key driver in the hydrology of coastal aquifers, and concentrating the mitigation efforts to adapt to sea-level rise at the expense of better water management are probably misguided.

A coupled groundwater-surface water model was forced by dynamically downscaled results from a GCM to analyze the effects on water quantity and quality of a relatively large lake used for water supply.[51] The stream inflow to the lake was predicted to decrease during summer, but the storage capacity of the lake was found to provide a sufficient buffer to support sustainable water abstraction in the future. Seawater intrusion into the stream was found to have an adverse impact on the water quality of the lake, thereby limiting its use for water supply. The hydrological impact assessment was based on only one climate change projection, but the range of changes from other climate models indicated that the predicted results were a plausible realization of climate change impacts.

A decline in rainfall since 1975 and increased abstraction has resulted in decline of groundwater levels in south-western Australia. Almost all GCMs project a drier and hotter climate for the region by 2030. To estimate groundwater levels in the region in 2030, five climate scenarios were applied to groundwater models.[52] The climate scenarios were (i) a continuation of the climate of 1975–2007; (ii) a continuation of the climate of 1997–2007; and (iii–v) three climate scenarios from the GCM projected climate under three scenarios of 0.7, 1.0 and 1.3°C temperature rise. A sixth scenario considered increasing abstraction levels to maximum allowed levels under a median future climate (1.0°C warming). Groundwater levels were found to be much less affected than surface water resources by a future drier climate as well as for a continuation of the climate experienced since 1975. For a fixed rainfall, recharge was highest for sandy soils with little or no perennial vegetation and a moderately deep watertable. Groundwater levels were not as affected by a decline in rainfall as reduced groundwater drainage and evapotranspiration losses offset the reduced rainfall amounts. However, once a threshold groundwater level is exceeded, the rainfall fails to refill the available seasonal storage and groundwater levels decline. Projected watertable declined under a drier climate in all areas where perennial vegetation was present and able to intercept recharge or use groundwater directly. In areas under dryland agriculture, projected groundwater levels continue to rise even under a drier future climate. Due to the longer time periods required for the changed recharge and water level conditions in the overlying aquifers to propagate to the confined aquifers, the climate change effects on confined groundwater systems are expected to be modest.

Results from the FP5 PRUDENCE project suggest significant changes in temperature and precipitation over Europe. The Soil and Water Assessment Tool was used to assess the potential impacts of climate change on groundwater recharge in Galicia-Costa, Spain.[53] Climate projections from two GCMs and eight different RCMs were used for the assessment and two climate-change scenarios were evaluated. Calibration and validation of the model were performed using a daily time-step in four representative catchments. The effects on mean annual groundwater recharge were small, partly due to the greater stomatal efficiency of plants in response to increased CO_2. However, climate change strongly influences the temporal variability of recharge. Recharge may concentrate in winter and may significantly decrease in summer and autumn. The length of the dry-season may, therefore, be increased by almost 30%, worsening the problems related to water supply.

5 Summary and Future Direction

There have been several studies in all parts of the world, trying to understand the response of groundwater resources under a changing climate. A perusal of the results show some common effects but there are also variations in the nature and magnitude of the effects. For example, increasing temperatures lead to a decrease in groundwater recharge in most places but show an increase in groundwater recharge in some areas due to additional irrigation return flow. Similarly, deforestation has been shown to increase the groundwater recharge in some studies. One common conclusion of most studies is that any estimation of the effect of climate change is highly uncertain due to the variability in the predictions of different GCMs and different scenarios. Any uncertainty in our understanding of the physical processes affecting groundwater is of secondary importance. In addition to GCM and scenario uncertainty, the process of downscaling the GCM results to the catchment scale is also fraught with its own limitations. To improve upon the reliability of our predictions related to the effect of climate change on groundwater resources, or, for that matter, water resources in general, the future research must focus on developing more robust GCMs and downscaling techniques, so that groundwater response to different scenarios could be readily compared. Any adaptation and mitigation strategy will only then be really useful. However, a few general strategies could be used to shield us from the worst-possible effects of climate change. For example, several studies have pointed out that anthropogenic factors related to water demand are much more responsible for any future shortfall in groundwater availability than the climate change. Therefore, even without the threat of climate change, we must learn to manage our water resources better. And, as suggested in several studies, experts from the fields of policy, social science, and economics, have to be involved in order to achieve a workable and sustainable solution.

Although this review is mainly concerned with groundwater, any related modeling effort depends on a proper modeling of several hydrological processes under a changing climate. Therefore, we describe here some possible research directions and strategies for modeling the effect of climate change on the hydrologic cycle, with emphasis on groundwater-related components.[54] One of the main constraints in modeling the hydrological cycle is the lack of models which are able to integrate the surface water, groundwater and the unsaturated zone. Even when such models are available, they are highly computationally intensive. The other limitation arises due to the lack of relevant data, particularly the actual Evapotranspiration (ET). Although in recent years the availability of the measured ET data has increased significantly due to the global network of flux towers, it has not been widely used for calibration of hydrologic models. It has been shown in several studies that there could be significant errors in the simulated ET values. Since ET, in combination with the precipitation and surface run-off, greatly affects the groundwater recharge, the development of future models should focus on the feedbacks of vegetation on the water balance and the use of measured ET data in calibration for a better accuracy of prediction of different water fluxes. Additionally, application of hydrological models in climate projections may produce erroneous results due to the fact that the empirical ET relationships would not be applicable under changing climate scenario, the plants may adjust their transpiration rate under increased CO_2 levels, and the vegetation may adapt to the climate change by changes in vegetation cover and root depth. Several recent models have the ability to simulate the carbon cycle and vegetation dynamics with the biosphere and atmosphere forming a coupled system in which climate influences the ecosystem, which in turn feeds back to affect the climate. Some models also include land-use change. At present, however, limited studies have considered the vegetation as a dynamic component in the hydrological modeling and there is a huge potential of research in this area. Till then, even though there is a large uncertainty in the hydrological simulations in terms of the effect of vegetation, paired climate simulations, a control and an altered vegetation scenario, should be able to demonstrate, at least qualitatively, the influence of vegetation on the climate and groundwater recharge.

The energy, moisture, and momentum fluxes at the land surface are required as boundary conditions for solving the equations of atmospheric dynamics. The water-balance and energy-balance are linked through the rate of evaporation. There is, therefore, a great need of research for proper understanding of these interactions and their incorporation into the climate-hydrological models.

Another area in which progress needs to be made is the one dealing with extrapolation of conceptual understanding from laboratory or field scale experiments to a considerably larger scale, both spatial and temporal, climate models. Although sophisticated models for the description of heterogeneities are available, lack of field data at various scales hinders our ability to choose between several possible scenarios. Also, the large magnitude of land-use and climatic changes implies that the past trends may not be used for predictions of future behavior. Availability of reliable data at several spatial and temporal scales would lead to an improved understanding of the hydrological processes, their linkage and feedback mechanisms. Some of these linkages, e.g., between sea surface temperature and evaporation, are well known but some other, e.g., between soil, temperature and precipitation, are not known very well. Proper understanding of their physics and the consequent mathematical description of these mechanisms is necessary for any modeling effort aimed at studying the effect of a changing climate on the water resources.

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