ASSESSING THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

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ABSTRACT

Climate change poses uncertainties to the supply and management of water resources. The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature has increased 0.6 ± 0.2 °C since 1861, and predicts an increase of 2 to 4 °C over the next 100 years. Temperature increases also affect the hydrologic cycle by directly increasing evaporation of available surface water and vegetation transpiration. Consequently, these changes can influence precipitation amounts, timings and intensity rates, and indirectly impact the flux and storage of water in surface and subsurface reservoirs (i.e., lakes, soil moisture, groundwater). In addition, there may be other associated impacts, such as sea water intrusion, water quality deterioration, potable water shortage, etc.

While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and poorly understood. The greater variability in rainfall could mean more frequent and prolonged periods of high or low groundwater levels, and saline intrusion in coastal aquifers due to sea level rise and resource reduction. Groundwater resources are related to climate change through the direct interaction with surface water resources, such as lakes and rivers, and indirectly through the recharge process. The direct effect of climate change on groundwater resources depends upon the change in the volume and distribution of groundwater recharge. Therefore, quantifying the impact of climate change on groundwater resources requires not only reliable forecasting of changes in the major climatic variables, but also accurate estimation of groundwater recharge.

A number of Global Climate Models (GCM) are available for understanding climate and projecting climate change. There is a need to downscale GCM on a basin scale and couple them with relevant hydrological models considering all components of the hydrological cycle. Output of these coupled models such as quantification of the groundwater recharge will help in taking appropriate adaptation strategies due to the impact of climate change. This paper presents the likely impact of climate change on groundwater resources, recent research studies, and methodology to assess the impact of climate change on groundwater resources.

Keywords *: Climate change; Hydrological cycle; Groundwater recharge; seawater intrusion; Numerical modeling; MODFLOW; UnSat Suite; WetSpass.*

INTRODUCTION

Water is indispensable for life, but its availability at a sustainable quality and quantity is threatened by many factors, of which climate plays a leading role. The Intergovernmental Panel on Climate Change (IPCC) defines climate as “the average weather in terms of the mean and its variability over a certain time-span and a certain area” and a statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer, is referred to as climate change.

Evidence is mounting that we are in a period of climate change brought about by increasing atmospheric concentrations of greenhouse gases. Atmospheric carbon dioxide levels have continually increased since the 1950s. The continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation. Climate change can have profound effects on the hydrologic cycle through precipitation, evapotranspiration, and soil moisture with increasing temperatures. The hydrologic cycle will be intensified with more evaporation and more precipitation. However, the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation or major alterations in the timing of wet and dry seasons.

Information on the local or regional impacts of climate change on hydrological processes and water resources is becoming more important. The effects of global warming and climatic change require multi-disciplinary research, especially when considering hydrology and global water resources.

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature has increased 0.6 ± 0.2 °C since 1861, and predicts an increase of 2 to 4 °C over the next 100 years. Global sea levels have risen between 10 and 25 cm since the late 19th century. As a direct consequence of warmer temperatures, the hydrologic cycle will undergo significant impact with accompanying changes in the rates of precipitation and evaporation. Predictions include higher incidences of severe weather events, a higher likelihood of flooding, and more droughts. The impact would be particularly severe in the tropical areas, which mainly consist of developing countries, including India.

Coupled atmosphere-ocean global climate models (GCMs) are used to estimate changes in climate. These physically-based numerical models simulate synoptic-scale climate and hydrological processes, and are forced with greenhouse gas and aerosol emission scenarios. A wide diversity of GCMs developed by leading climate centres are available for other researchers to evaluate potential impacts of climate change. To ensure that the predictive elements from a GCM are realistic, a statistical downscaling technique should be employed to bridge the local- and synoptic-scale processes. Statistical downscaling uses a correlation between predictands (site measured variables, such as precipitation) and predictors (region-scale variables, such as GCM variables).

Changes in regional temperature and precipitation have important implications for all aspects of the hydrologic cycle. Variations in these parameters determine the amount of water that reaches the surface, evaporates or transpires back to the atmosphere, becomes stored as snow or ice, infiltrates into the groundwater system, runs off the land, and ultimately becomes base flow to streams and rivers.

Hydrological impact assessments of watersheds (and aquifers) require information on changes in evapotranspiration because it is a key component of the water balance. However, climate-change scenarios tend to be expressed in terms of changes in temperature and precipitation. Consequently, the effects of global warming on potential evaporation (or more inclusively, evapotranspiration) are not simple to estimate. Many global scenarios suggest an increase in potential evaporation, but these factors may be outweighed locally or regionally by other factors reducing evaporation. Various models may be used to calculate potential evaporation using data on net radiation, temperature, humidity, and wind speed, and sometimes plant physiological properties. The estimated effect of a change in climate on potential evaporation depends on the characteristics of the site.

Many rivers and streams that are fed by glacier runoff could be significantly impacted as a result of climate change. As glacier retreat accelerates, increased summer runoff could occur. However, when the glaciers have largely melted, the late summer and fall glacial input into streams and rivers may be lost, resulting in a significant reduction in flow in some cases.

Water resource management plans increasingly need to incorporate the affects of global climate change in order to accurately predict future supplies. Numerous studies have documented the sensitivity of streamflow to climatic changes for watersheds all over the world. Most of these studies involve watershed scale hydrologic models, of which validation remains a fundamental challenge. Moreover, outputs from general circulation models (GCM) can be rather uncertain and downscaling their predictions for local hydrologic use can produce inconsistent results. Therefore, the sensitivity of streamflow to climate changes is perhaps best understood by analyzing the historical records.

Building empirical models to link climate and regional hydrological regimes has a long history. In recent years, many researchers have used empirical rainfall–runoff model to study the impacts of climatic change on hydrology. However, applications of these empirical relationships to climate or basin conditions different from those used in the original development of these functions are questionable.

IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

Although the most noticeable impacts of climate change could be fluctuations in surface water levels and quality, the greatest concern of water managers and government is the potential decrease and quality of groundwater supplies, as it is the main available potable water supply source for human consumption and irrigation of agriculture produce worldwide. Because groundwater aquifers are recharged mainly by precipitation or through interaction with surface water bodies, the direct influence of climate change on precipitation and surface water ultimately affects groundwater systems.

It is increasingly recognized that groundwater cannot be considered in isolation from the landscape above, the society with which it ‘interacts’, or from the regional hydrological cycle, but needs to be managed holistically. In understanding the likely consequences of possible future (climate and non-climate) changes on groundwater systems and the regional hydrological cycle, an important (but not exclusive) component to understand is the influence that these factors exert on recharge and runoff.

It is important to consider the potential impacts of climate change on groundwater systems. As part of the hydrologic cycle, it can be anticipated that groundwater systems will be affected by changes in recharge (which encompasses changes in precipitation and evapotranspiration), potentially by changes in the nature of the interactions between the groundwater and surface water systems, and changes in use related to irrigation.

(a) Soil Moisture

The amount of water stored in the soil is fundamentally important to agriculture and has an influence on the rate of actual evaporation, groundwater recharge, and generation of runoff. Soil moisture contents are directly simulated by global climate models, albeit over a very coarse spatial resolution, and outputs from these models give an indication of possible directions of change.

The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. Climate change also may affect soil characteristics, perhaps through changes in waterlogging or cracking, which in turn may affect soil moisture storage properties. Infiltration capacity and water-holding capacity of many soils are influenced by the frequency and intensity of freezing.

(b) Groundwater Recharge and Resources

Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change.

Aquifers generally are replenished by effective rainfall, rivers, and lakes. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Increased winter rainfall, as projected under most scenarios for mid-latitudes, generally is likely to result in increased groundwater recharge. However, higher evaporation may mean that soil deficits persist for longer and commence earlier, offsetting an increase in total effective rainfall. Various types of aquifer will be recharged differently. The main types are unconfined and confined aquifers. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes, and the rate of recharge will be influenced by the permeability of overlying rocks and soils.

Macro-pore and fissure recharge is most common in porous and aggregated forest soils and less common in poorly structured soils. It also occurs where the underlying geology is highly fractured or is characterized by numerous sinkholes. Such recharge can be very important in some semi-arid areas. In principle, “rapid” recharge can occur whenever it rains, so where recharge is dominated by this process it will be affected more by changes in rainfall amount than by the seasonal cycle of soil moisture variability.

Shallow unconfined aquifers along floodplains, which are most common in semi-arid and arid environments, are recharged by seasonal streamflows and can be depleted directly by evaporation. Changes in recharge therefore will be determined by changes in the duration of flow of these streams, which may locally increase or decrease, and the permeability of the overlying beds, but increased evaporative demands would tend to lead to lower groundwater storage. The thick layer of sands substantially reduces the impact of evaporation.

It will be noted from the foregoing that unconfined aquifers are sensitive to local climate change, abstraction, and seawater intrusion. However, quantification of recharge is complicated by the characteristics of the aquifers themselves as well as overlying rocks and soils. A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometers to thousands of kilometers.

Aside from the influence of climate, recharge to aquifers is very much dependent on the characteristics of the aquifer media and the properties of the overlying soils. Several approaches can be used to estimate recharge based on surface water, unsaturated zone and groundwater data. Among these approaches, numerical modelling is the only tool that can predict recharge. Modelling is also extremely useful for identifying the relative importance of different controls on recharge, provided that the model realistically accounts for all the processes involved. However, the accuracy of recharge estimates depends largely on the availability of high quality hydrogeologic and climatic data. Determining the potential impact of climate change on groundwater resources, in particular, is difficult due to the complexity of the recharge process, and the variation of recharge within and between different climatic zones.

Attempts have been made to calculate the rate of recharge by using carbon-14 isotopes and other modeling techniques. This has been possible for aquifers that are recharged from short distances and after short durations. However, recharge that takes place from long distances and after decades or centuries has been problematic to calculate with accuracy, making estimation of the impacts of climate change difficult. The medium through which recharge takes place often is poorly known and very heterogeneous, again challenging recharge modeling. In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates, and seawater intrusion, as well as monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources.

(c) Coastal Aquifers

When considering water resources in coastal zones, coastal aquifers are important sources of freshwater. However, salinity intrusion can be a major problem in these zones. Salinity intrusion refers to replacement of freshwater in coastal aquifers by saltwater. It leads to a reduction of available fresh groundwater resources. Changes in climatic variables can significantly alter groundwater recharge rates for major aquifer systems and thus affect the availability of fresh groundwater. Salinization of coastal aquifers is a function of the reduction of groundwater recharge and results in a reduction of fresh groundwater resources.

Sea-level rise will cause saline intrusion into coastal aquifers, with the amount of intrusion depending on local groundwater gradients. Shallow coastal aquifers are at greatest risk. Groundwater in low-lying islands therefore is very sensitive to change. A reduction in precipitation coupled with sea-level rise would not only cause a diminution of the harvestable volume of water; it also would reduce the size of the narrow freshwater lense. For many small island states, such as some Caribbean islands, seawater intrusion into freshwater aquifers has been observed as a result of overpumping of aquifers. Any sea-level rise would worsen the situation.

A link between rising sea level and changes in the water balance is suggested by a general description of the hydraulics of groundwater discharge at the coast. Fresh groundwater rides up over denser, salt water in the aquifer on its way to the sea (Figure 1), and groundwater discharge is focused into a narrow zone that overlaps with the intertidal zone. The width of the zone of groundwater discharge measured perpendicular to the coast, is directly proportional to the discharge rate. The shape of the water table and the depth to the freshwater/saline interface are controlled by the difference in density between freshwater and salt water, the rate of freshwater discharge and the hydraulic properties of the aquifer. The elevation of the water table is controlled by mean sea level through hydrostatic equilibrium at the shore.

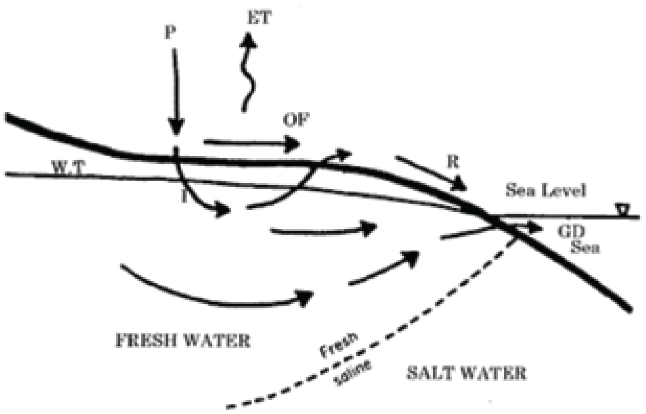

Fig. 1 : Conceptual Model of the Water Balance in a Coastal Watershed

To assess the impacts of potential climate change on fresh groundwater resources, we should focus on changes in groundwater recharge and sea level rise on the loss of fresh groundwater resources in water resources stressed coastal aquifers.

STATUS OF RESEARCH STUDIES

The increase of concentration of carbon dioxide and other greenhouse gases in the atmosphere will certainly affect hydrological regimes. Global warning is thus expected to have major implications on water resources management. The observation of long-term trends in climate for many regions of the world has led to considerable research on the impact of greenhouse gases on climate. To this end, several general circulation models (GCMs) have been used to simulate the type of climate that might exist if global concentrations of carbon dioxide (greenhouse gas) were twice their pre-industrial levels. Recent GCM estimates of the projected rise in long-term global average annual surface temperature are between 1 and 4.5°C under simulated doubled concentrations of CO_2. On the subcontinent scale, there remains considerable uncertainty in the model results and it is not possible to know with confidence the fine details of how the climate will change regionally (Taylor 1997). Consequently, it is customary to use observational data as a baseline and adjust these by the GCM scenarios (Taylor 1997). Because precipitation patterns are significantly influenced by changes in the global-circulation patterns induced by climate change, regional projections for changes in precipitation under doubled CO_2 scenarios remain very uncertain.

There have been many studies relating the effect of climate changes on surface water bodies. However, very little research exists on the potential effects of climate change on groundwater, although groundwater is the major source of drinking water across much of the world and plays a vital role in maintaining the ecological value of an area. Available studies show that groundwater recharge and discharge conditions are reflection of the precipitation regime, climatic variables, landscape characteristics and human impacts such as agricultural drainage and flow regulation. Hence, predicting the behavior of recharge and discharge conditions under future climatic and other changes is of great importance for integrated water management.

Studies which consider the indirect effects derived from climate-change-induced alterations in soil, land cover, salt-water intrusion due to rising sea levels and changes in water demand are less common. These studies represent a move away from impact studies (which may be considered to be vertically integrated, in which climate change acts upon an environmental compartment) towards horizontally integrated studies in which environmental compartments interact with each other. However, they remain an incomplete assessment of the pressures facing groundwater resources associated with the direct and indirect effects of future climate and socio-economic change.

Previous studies have typically coupled climate change scenarios with hydrological models, and have generally investigated the impact of climate change on water resources in different areas. The scientific understanding of an aquifer's response to climate change has been studied in several locations within the past decade. These studies link atmospheric models to unsaturated soil models, which, in some cases, were further linked into a groundwater model. The groundwater models used were calibrated to current groundwater conditions and stressed under different predicted climate change scenarios. Few of the very recent studies on impact of climate change on groundwater resources have been discussed below.

Barthel (2011) presented an integrated approach for assessing the availability of groundwater under conditions of 'global-change'. The approach is embedded in the DANUBIA system developed by the interdisciplinary GLOWA-Danube Project to simulate the interaction of natural and socio-economic processes within the Upper Danube Catchment (UDC, 77,000 km^2 and located in parts of Germany, Austria, Switzerland and Italy). The approach enables the quantitative assessment of groundwater bodies (zones), which are delineated by intersecting surface watersheds, regional aquifers, and geomorphologic regions. The individual hydrogeological and geometrical characteristics of these zones are accounted for by defining characteristic response times and weights to describe the relative significance of changes in variables (recharge, groundwater level, groundwater discharge, river discharge) associated with different states. These changes, in each zone, are converted into indices (GroundwaterQuantityFlags). The motivation and particularities of regional-scale groundwater assessment and the background of GLOWA-Danube are described, along with a description of the developed methodology. The approach was applied to the UDC, where several different climate scenarios (2011–2060) were evaluated. A selection of results is presented to demonstrate the potential of the methodology. The approach was inspired by the European Water Framework Directive, yet it has a stronger focus on the evaluation of global-change impacts.

Yihdego and Webb (2011) carried out modeling of bore hydrographs to determine the impact of climate and land-use change in a temperate subhumid region of southeastern Australia. To determine the relative impact of climate and human intervention on groundwater elevations in western Victoria, southeast Australia, bore hydrograph fluctuations in three aquifers were modelled using a transfer function noise model (PIRFICT) and an auto-regressive model (HARTT), which give generally comparable results. Most of the groundwater-level fluctuations (>90%) are explained by climatic variation, particularly rainfall. The overall non-climate-related trend in groundwater level is downward and small but statistically significant (−0.04 to −0.066 m/yr), and is probably due to the widespread replacement of grazing land by wheat and canola cultivation, as these crops use more water than pasture. A large non-climate-related trend (−0.30 m/yr) for bores in an irrigation area is mainly related to groundwater extraction. The response time of the system is rapid (only 4.85 years on average), much faster than previously estimated. Rates of groundwater flow are much slower; groundwater ages are up to ~35,000 years. Response times effectively represent the time for the system to move to a new state of hydrologic equilibrium; this prediction of the time scale of the impacts of land-use change on groundwater resources will allow the development of better strategies for groundwater management.

Crosbie et al. (2012) investigated episodic recharge with reference to climate change in the Murray-Darling Basin, Australia. In semi-arid areas, episodic recharge can form a significant part of overall recharge, dependant upon infrequent rainfall events. With climate change projections suggesting changes in future rainfall magnitude and intensity, groundwater recharge in semi-arid areas is likely to be affected disproportionately by climate change. This study sought to investigate projected changes in episodic recharge in arid areas of the Murray-Darling Basin, Australia, using three global warming scenarios from 15 different global climate models (GCMs) for a 2030 climate. Two metrics were used to investigate episodic recharge: at the annual scale the coefficient of variation was used, and at the daily scale the proportion of recharge in the highest 1% of daily recharge. The metrics were proportional to each other but were inconclusive as to whether episodic recharge was to increase or decrease in this environment; this is not a surprising result considering the spread in recharge projections from the 45 scenarios. The results showed that the change in the low probability of exceedance rainfall events was a better predictor of the change in total recharge than the change in total rainfall, which has implications for the selection of GCMs used in impact studies and the way GCM results are downscaled.

Neukum and Azzam (2012) investigated the impact of climate change on groundwater recharge in a small catchment in the Black Forest, Germany. Temporal and spatial changes of the hydrological cycle are the consequences of climate variations. In addition to changes in surface runoff with possible floods and droughts, climate variations may affect groundwater through alteration of groundwater recharge with consequences for future water management. This study investigates the impact of climate change, according to the Special Report on Emission Scenarios (SRES) A1B, A2 and B1, on groundwater recharge in the catchment area of a fissured aquifer in the Black Forest, Germany, which has sparse groundwater data. The study uses a water-balance model considering a conceptual approach for groundwater-surface water exchange. River discharge data are used for model calibration and validation. The results show temporal and spatial changes in groundwater recharge. Groundwater recharge is progressively reduced for summer during the twenty-first century. The annual sum of groundwater recharge is affected negatively for scenarios A1B and A2. On average, groundwater recharge during the twenty-first century is reduced mainly for the lower parts of the valley and increased for the upper parts of the valley and the crests. The reduced storage of water as snow during winter due to projected higher air temperatures causes an important relative increase in rainfall and, therefore, higher groundwater recharge and river discharge.

Raposo et al. (2013) assessed the impact of future climate change on groundwater recharge in Galicia-Costa, Spain. Climate change can impact the hydrological processes of a watershed and may result in problems with future water supply for large sections of the population. Results from the FP5 PRUDENCE project suggest significant changes in temperature and precipitation over Europe. In this study, the Soil and Water Assessment Tool (SWAT) model was used to assess the potential impacts of climate change on groundwater recharge in the hydrological district of Galicia-Costa, Spain. Climate projections from two general circulation models and eight different regional climate models 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 in the district. The effects on modeled mean annual groundwater recharge are small, partly due to the greater stomatal efficiency of plants in response to increased CO_2 concentration. However, climate change strongly influences the temporal variability of modeled groundwater recharge. Recharge may concentrate in the winter season and dramatically decrease in the summer–autumn season. As a result, the dry-season duration may be increased on average by almost 30 % for the A2 emission scenario, exacerbating the current problems in water supply.

Lapworth et al. (2013) estimated residence times of shallow groundwater in West Africa. Although shallow groundwater (<50 mbgl) sustains the vast majority of improved drinking-water supplies in rural Africa, there is little information on how resilient this resource may be to future changes in climate. This study presents results of a groundwater survey using stable isotopes, CFCs, SF6, and 3H across different climatic zones (annual rainfall 400–2,000 mm/year) in West Africa. The purpose was to quantify the residence times of shallow groundwaters in sedimentary and basement aquifers, and investigate the relationship between groundwater resources and climate. Stable-isotope results indicate that most shallow groundwaters are recharged rapidly following rainfall, showing little evidence of evaporation prior to recharge. Chloride mass-balance results indicate that within the arid areas (<400 mm annual rainfall) there is recharge of up to 20 mm/year. Age tracers show that most groundwaters have mean residence times (MRTs) of 32–65 years, with comparable MRTs in the different climate zones. Similar MRTs measured in both the sedimentary and basement aquifers suggest similar hydraulic diffusivity and significant groundwater storage within the shallow basement. This suggests there is considerable resilience to short-term inter-annual variation in rainfall and recharge, and rural groundwater resources are likely to sustain diffuse, low volume abstraction.

Mollema and Antonellini (2013) investigated seasonal variation in natural recharge of coastal aquifers. Many coastal zones around the world have irregular precipitation throughout the year. This results in discontinuous natural recharge of coastal aquifers, which affects the size of freshwater lenses present in sandy deposits. Temperature data for the period 1960–1990 from LocClim (local climate estimator) and those obtained from the Intergovernmental Panel on Climate Change (IPCC) SRES A1b scenario for 2070–2100, have been used to calculate the potential evapotranspiration with the Thornthwaite method. Potential recharge (difference between precipitation and potential evapotranspiration) was defined at 12 locations: Ameland (The Netherlands), Auckland and Wellington (New Zealand); Hong Kong (China); Ravenna (Italy), Mekong (Vietnam), Mumbai (India), New Jersey (USA), Nile Delta (Egypt), Kobe and Tokyo (Japan), and Singapore. The influence of variable/discontinuous recharge on the size of freshwater lenses was simulated with the SEAWAT model. The discrepancy between models with continuous and with discontinuous recharge is relatively small in areas where the total annual recharge is low (258–616 mm/year); but in places with Monsoon-dominated climate (e.g. Mumbai, with recharge up to 1,686 mm/year), the difference in freshwater-lens thickness between the discontinuous and the continuous model is larger (up to 5 m) and thus important to consider in numerical models that estimate freshwater availability.

These studies are still at infancy and more data, in terms of field information are to be generated. This will also facilitate appropriate validation of the simulation for the present scenarios. In summary, climate change is likely to have an impact on future recharge rates and hence on the underlying groundwater resources. The impact may not necessarily be a negative one, as evidenced by some of the investigations. Quantifying the impact is difficult, however, and is subject to uncertainties present in the future climate predictions. Simulations based on general circulation models (GCMs) have yielded mixed and conflicting results, raising questions about their reliability in predicting future hydrologic conditions. However, it is clear that the global warming threat is real and the consequences of climate change phenomena are many and alarming.

METHODOLOGY TO ASSESS THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

The potential impacts of climate change on water resources have long been recognized although there has been comparatively little research relating to groundwater. The principle focus of climate change research with regard to groundwater has been on quantifying the likely direct impacts of changing precipitation and temperature patterns. Such studies have used a range of modelling techniques such as soil water balance models, empirical models, conceptual models and more complex distributed models, but all have derived changes in groundwater recharge assuming parameters other than precipitation and temperature remaining constant.

There are two main parameters that could have a significant impact on groundwater levels: recharge and river stage/discharge. To assess the impact on the groundwater system to changes in these two parameters, it is necessary to have a calibrated flow model and to conduct a sensitivity analysis by varying these two parameters and calculating changes to the water balance (e.g., differences in water levels). The research objectives can be:

- To develop a conceptual model of the hydrogeology of the study region;
- To investigate how regional and local weather events affect recharge;
- To determine potential impacts of climate change on recharge for the study area, and to assess the sensitivity of the results to different global climate models;
- To develop and calibrate a regional-scale three-dimensional groundwater flow model of the region and to use that model to assess the impacts of climate change on groundwater resources; and
- To develop and calibrate a local-scale three-dimensional groundwater flow model, and to undertake a well capture zone analysis for the local community water supply wells for the region.

The methodology consists of three main steps. To begin with, climate scenarios can be formulated for the future years such as 2050 and 2100. This is done by assigning percentage or value changes of climatic variables on a seasonal and/or annual basis only for the future years relative to the present year. Secondly, based on these scenarios and present situation, seasonal and annual recharge, evapotranspiration and runoff are simulated with the WHI UnSat Suite (HELP module for recharge) and/or WetSpass model. Finally, the annual recharge outputs from WHI UnSat Suite or WetSpass model are used to simulate groundwater system conditions using steady-state MODFLOW model setups for the present condition and for the future years.

The main tasks that are involved in such a study are:

1. Describe hydrogeology of the study area.
2. Undertake a statistical analysis to separate climate into regional and local events and determine the role of each in contributing to groundwater recharge.
3. Analyze climate data from weather stations and modelled GCM, and build future predicted climate change datasets with temperature, precipitation and solar radiation variables.
4. Define methodology for estimating changes to recharge in the model under both current climate conditions and for the range of climate-change scenarios for the study area.
5. Use of a computer code (such as WHI UnSat Suite or WetSpass) to estimate recharge based on available precipitation and temperature records and anticipated changes to these parameters.

Recharge Estimation by WHI UnSat Suite

UnSat Suite contains the subprogram, Visual HELP, which contains a more user-friendly interface for the program HELP that is approved by the United States Environmental Protection Agency (US EPA) for designing landfills. Visual HELP enables the modeler to generate estimates of recharge using a weather generator and the properties of the aquifer column.

Recharge Estimation by WetSpass

WetSpass is a quasi physically distributed seasonal-water balance model, which takes into account detailed soil, land-use, slope, groundwater depth, and hydro-climatological distributed maps with associated parameter tables for estimating groundwater recharge. The model uses seasonal (summer and winter) geographical information systems (GIS) input grids of the mentioned inputs to estimate annual and seasonal groundwater recharge values.

6. Quantify the spatially distributed recharge rates using the climate data and spatial soil survey data.
7. Development and calibration of a three-dimensional regional-scale groundwater flow model (such as Visual MODFLOW). Since one of the inputs required for WetSpass is the groundwater depth data, which is predicted with the MODFLOW model, an interface may be developed in an ArcView GIS platform to couple the two models, facilitating exchange of data between the two models. The coupled WetSpass-MODFLOW model is run for the present situation and for each of the climate change scenarios on an annual basis.
8. Simulate groundwater flow using each recharge data set and evaluate the changes in groundwater flow and levels through time.
9. Undertake sensitivity analysis of the groundwater flow model.
10. Develop a local scale groundwater model for the specific study area and conduct a well capture zone analysis.

A typical flow chart for various aspects of such a study is shown in Figure 2. The figure shows the connection from the climate analysis, to recharge simulation, and finally to a groundwater model. Recharge is applied to a three-dimensional groundwater flow model, which is calibrated to historical water levels. Transient simulations are undertaken to investigate the temporal response of the aquifer system to historic and future climate periods.

Tasks in the upper part of the chart assemble several climate data sets for current and future predicted conditions, which are used to simulate recharge using HELP module of WHI UnSat Suite. The soil layers are parameterized using a pedotransfer function program, which utilizes detailed soil survey measurements. Mapped monthly recharge from HELP is then used in a three-dimensional MODFLOW model to simulate transient saturated groundwater flow.

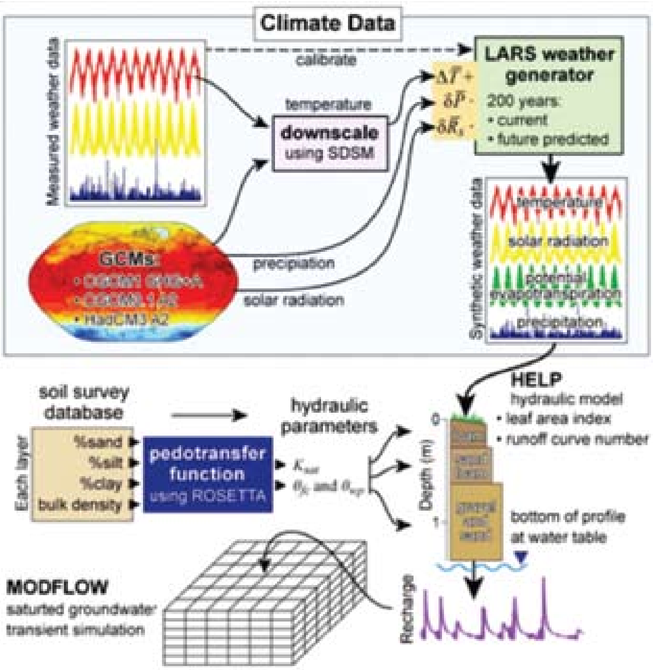

Fig. 2 : Flow Chart of Tasks (Toews, 2007)

CONCLUDING REMARKS

- Precipitation is commonly downscaled in climate change impact studies; however, the reliability of the downscaled result is often poor or unreliable, as there is often little correlation between the predictors and the predictands. A poor correlation is often attributed to mesoscale processes occurring at the site-scale that are not represented in regional models due to their representative spatial and temporal sizes in comparison to larger-scale regional precipitation. Mesoscale precipitation processes generally occur in the summer season in the form of convective clouds, which are a result of local-scale evapotranspiration from elevated temperatures and solar radiation magnitudes. As a result, global-scale models may underestimate the summer precipitation measured at a site.
- Although climate change has been widely recognized, research on the impacts of climate change on the groundwater system is relatively limited. The reasons may be that long historical data are required to analyze the characteristics of climate change. These data are not always available. Also, the driving forces that cause such changes are yet unclear. The climatic abnormality may occur frequently and last for a period of time. Even if the required data exist, uncertainty is embedded in model parameters, structure and driving force of the hydrological cycle. Predicting the long-term effect of a dynamic system is very difficult because of limitations inherent in the models, and the unpredictability of the forces that drive the earth.

A physically based model of a groundwater system under possible climate change based on available data is very important to prevent the deterioration of regional water-resource problems in the future. Although uncertainties are inevitable, new response strategies in water resource management based on the model may be useful.

- The investigation of the relationship between climate change and loss of fresh groundwater resources is important for understanding the characteristics of the different regions. The impact of future climatic change may be felt more severely in developing countries such as India, whose economy is largely dependent on agriculture and is already under stress due to current population increase and associated demands for energy, freshwater and food. In spite of the uncertainties about the precise magnitude of climate change and its possible impacts, particularly on regional scales, measures must be taken to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects.
- Groundwater recharge is influenced not only by hydrologic processes, but also by the physical characteristics of the land surface and soil profile. Many climate change studies have focused on modelling the temporal changes in the hydrologic processes and ignored the spatial variability of physical properties across the study area. While knowing the average change in recharge and groundwater levels over time is important, these changes will not occur equally over a regional catchment or watershed. Long-term water resource planning requires both spatial and temporal information on groundwater recharge in order to properly manage not only water use and exploitation, but also land use allocation and development. Studies concerned with climate change should therefore also consider the spatial change in groundwater recharge rates.
- If the likely consequences of future changes of groundwater recharge, resulting from both climate and socio-economic change, are to be assessed, hydrogeologists must increasingly work with researchers from other disciplines, such as socio-economists, agricultural modelers and soil scientists.

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