Uncertainties and Challenges in Distribution of Groundwater Recharge in Climate Change Scenario

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Abstract:

Groundwater use is of fundamental importance to meet the rapid expanding urban, industrial, and agricultural water requirements throughout the world and also in India. To quantify the distribution of groundwater recharge is a prerequisite for efficient and sustainable groundwater resource management in the arid and semi arid regions. Groundwater recharge in these regions shows variability, as per the assessment carried out by using various methods such as Soil Water Balance (SWB) analysis, Integrated Landscape Hydrology Model (ILHM), Water Table Fluctuations (WTF), Isotopic Tracers methods - Chloride Mass Balance, Carbon-14, etc, WetSpass model, SWAT-MODFLOW model, Empirical method, Numerical Modelling, etc. The interaction of soil, climate, slope, geology, geomorphology, land use land cover, rainfall, drainage pattern and other methods used for recharge determines the recharge process. The study reveals that the reasons causing this variability are ranging from uncertainties in recharge influencing factors to change in climatic conditions. The study also shows that the uncertainties in distribution of groundwater recharge occur differently in different regions, due to the impact of various factors such as change in climatic conditions, land use, soil types, etc. In conclusion, it can be stated that realistic estimation of recharge depends mainly on identifying prominent features influencing recharge for a certain region and probable flow mechanism for targeted aquifer, multiple dependent models / approaches may be applied for estimation of recharge and output may be compared to actual field conditions.

Keywords: groundwater, recharge, uncertainties, challenges

Introduction

Understanding the spatial and temporal distribution of groundwater recharge is a pre-requisite for efficient and effective groundwater management and modelling. In a country like India, it is essential that a careful water balance study is carried out. The scarcity of water and the competition for freshwater demand for domestic, industrial and agricultural uses is increasing. The spatio-temporal attributes of groundwater use data are ideally suited for analysis. It is very common that the period of lowest natural groundwater supplies coincides with largest demand and vice versa. Sometimes region deficient in surface water supplies may be underlain by excessive groundwater reserves. Therefore the need for reliable estimate of groundwater recharge is well recognised. A better understanding of the methods, their applicability and limitations is an important pre-requisite to choose the appropriate techniques for groundwater recharge estimation. Even though the number of studies were conducted, determination or estimation of groundwater recharge still remains fraught with uncertainty.

This paper aims to focus on concepts of groundwater recharge, uncertainties and challenges, which occurs in the study of distribution of recharge, in different regions in accordance with the influence of various prominent factors. Efforts have also been made to adopt the appropriate method for selected region of study suiting the various controlling factors and climate change scenario.

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International Conference on Climate Change - 2017 (ICCC 2017)
Groundwater Recharge

Types of Recharge

Recharge is defined as the downward flow of the water reaching the water table forming an addition to the groundwater reservoir (Jacobes J. de Vries & Simmers, 2002). Lerner (1990).

Direct Recharge: In this type water is added to the groundwater reservoir in excess of soil moisture deficit and evapotranspiration by direct vertical percolation through the vadose zone.

Indirect Recharge: Water from the surface courses like rivers and canals percolate to the groundwater.

Localised Recharge: It is an intermediate form of groundwater recharge resulting from surface of near surface concentration of water.

Recharge Mechanisms

Groundwater recharge involves movement of moisture through the unsaturated zone. There are two major mechanisms, which control such moisture movement viz. Interstitial (Matrix) flow and Macropore recharge. In interstitial flow mechanism recharge, water is stacked as layers one above the other. Any fresh layer of water is added on the surface pushes an equal amount of water beneath so that the moisture of the last layer is added to the groundwater. During this movement the younger water never overtakes the older water.

Macropore recharge occurs through preferred pathways in the soil matrix like cracks, fractures, solution holes, animal burrows, root tubes, etc. Jacobes J. de Vries & Simmers (2002) suggested an additional term ‘preferential flow’ to describe flow caused by unstable wetting fronts and differential soil physical characteristics within the soil.

However, not all this water essentially reaches the water table. It might be hampered by low conductivity horizons and disappear as interflow to nearby local depressions, where it runs off or evaporates instead of joining the regional groundwater system. In shallow aquifers a rise in the water table by recharge could initiate a local groundwater system with associated local seepage discharge within the considered area. A similar problem in areas with a high water table is associated with a time scale: water may initially join the groundwater reservoir but might subsequently be extracted by evapotranspiration.

The term potential recharge as introduced by Rushton (1988) includes the excesses of precipitation over evapotranspiration, which subsequently disappear through a local discharge system or by evapotranspiration from the saturated zone. However, this could become ‘permanent’ recharge by lowering the water table after extraction. Moreover, lowering of a shallow water table can induce additional recharge by reducing evapotranspiration.

These conceptual problems do occur, normally, in areas with deep water tables, far below the root zone. Under such conditions, virtually all water that passes the root zone is assumed to have escaped evapotranspiration and could recharge the groundwater reservoir.

Various techniques are available for estimation of groundwater recharge (Simmers, 1988; Scanlon, 2002). The recharge estimation methods have been divided into three broad categories (Table 1).

- Methods based on physical parameters
- Chemical and Isotopic methods
- Numerical modelling and Empirical methods
Methods used in previous studies

Various methods such as Soil Water Balance (SWB) analysis, Integrated Landscape Hydrology Model (ILHM), Water Table Fluctuations (WTF), Isotope Tracers methods - Chloride Mass Balance, Carbon-14, WetSpass model, SWAT-MODFLOW model, Empirical method, Numerical Modelling, etc., of groundwater recharge shows the variability in the climate change scenario.

The present research work summarises o the existing studies and their respective significance in various field conditions as well as climate change scenario. These studies are categorised into three broad types:

(a) Based on methods with physical parameters

WetSpass Model

In this WetSpass (Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State) model, the methodology used delivers spatially distributed recharge as a function of vegetation, soil type, slope, groundwater depth, precipitation regime, and other climatic variables. Adnan M. Aish (2010), developed a WetSpass model for estimating spatially distributed, long-term average recharge for the Gaza Strip, for partly semi-arid and partly desert climate, with mostly coastal aquifers. Mustafa Al Kuisi (2013) carried out study for GIS based spatial groundwater recharge estimation in the Jafr basin, Jordan. These investigations have demonstrated that the estimation of groundwater recharge using WetSpass is in good agreement with those obtained by other studies. O. Batelaan (2007) made an attempt to develop spatially distributed water balance model to simulate long-term average recharge depending on land cover, soil texture, topography and hydrometeorological parameters. Parameter estimation for the model is performed on the basis of literature values of water balance fluxes from mainly Belgium and the Netherlands. Moreover, it was concluded that the shallow groundwater levels in valleys cause negative recharge conditions as a result of evapotranspiration by abundant phreatophytic vegetation. GIS analysis showed how recharge strongly varies for different combinations of land cover and soil texture classes. Z. Zomlot et. al. (2015) assessed controlling factors causing spatial distribution of groundwater recharge and base flow in Flanders, Belgium, using spatially distributed water balance model WetSpass.

Soil Water Balance Analysis

Alan Mair (2013) carried out a study to estimate groundwater recharge on the island of Jeju, Korea, for baseline, drought, and climate-land use change scenarios, in which soil water balance analysis was conducted. The Soil Water Balance (SWB) computer code was used to compute groundwater recharge and other water balance components at a daily time step using a 100 m grid cell size for an 18-year baseline scenario.

Gravity Recovery and Climate Experiment (GRACE)

Alexander Y. Sun. (2013) conducted a study aimed for predicting groundwater level changes using GRACE data with an aim to investigate the feasibility of downscaling Gravity Recovery and Climate Experiment (GRACE) satellite data for predicting groundwater level changes and, thus, enhancing current capability for sustainable water resources management. The statistical downscaling method adopted in this study was Artificial Neural Network (ANN).

Integrated Landscape Hydrology Model (ILHM)

David W. Hyndman (2007) prepared a ILH Model which accounts for the processes and mass balance in a most rigorous manner than semi-distributed codes, which tend to lump or oversimplify important watershed processes and use parameters that cannot be independently measured.
Hydrologic model

Mikko I. Jyrkama (2007) conducted a study to characterize both the temporal and spatial effect of climate change on groundwater recharge. In this study, 40 years of actual weather data, and future changes in the hydrologic cycle of the Grand River watershed were used. The impact of climate change is modelled by perturbing the model input parameters using predicted changes in the regions climate.

RIB model

X. Sun (2013) conducted a study for groundwater recharge estimation in arid and semi-arid areas by developing a rainfall infiltration breakthrough (RIB) model, by establishing a relationship between rainfall events and groundwater level fluctuations (WLF) on a monthly basis.

Aquifer systems

Thomas Meixner (2016) carried out a study for analysing the implications of projected climate change for groundwater recharge in the western United States, in which an analysis is presented by synthesizing existing studies and applying current knowledge of recharge processes. In this study, available climate-change projections were analysed to determine likely changes in temperature and precipitation in the sub-regions containing eight representative aquifers. A confidence level (high, medium or low) was assigned to predicted recharge changes. This structured approach provides a template for how large scale regional assessments of the response of groundwater recharge to climate change might be useful for other regions.

SWAT model

Anna Malago et al. (2016) carried out a case study of the Island of Crete (Greece) for regional scale hydrologic modeling of a karst-dominant geomorphology for quantification of a spatially and temporally explicit hydrologic water balance of karst-dominated geomorphology in order to assess the sustainability of the actual water use, using SWAT model and a karst-flow model (KSWAT model).

WTF, DHB & HB method

T. Ahmadi et al. (2013) conducted a study for estimation of groundwater recharge using various methods in Neishaboor Plain, Iran, using three methods, based on the water balance principle (rainfall-groundwater level relationship), including Water Table Fluctuation (WTF), Distributed Hydrological Budget (DHB) and Hydrological Budget (HB).

GIS-based NDVI model

Vijai Singhal and Rohit Goyal (2012) carried out a study for understanding effect of rainfall and vegetation density on groundwater recharge using a methodology based on spatial distribution of parameters such as Normalised Difference Vegetation index (NDVI) for part of Pali district in Rajasthan, India. New methodology, for different cause, has been developed and demonstrated for understanding affect of rainfall and vegetation density on recharge.

(b) Based on chemical and isotopic methods

Tracers Isotope / Carbon-14 and Chlorine Mass Balance composite method

Glenn A. Harrington et al. (2002) conducted a study, aimed to estimate the average recharge rate over the interval between where the groundwater sample first entered the saturated zone and above. Two environmental tracer methods were applied in this study to the Ti-Tree basin in central Australia to focus on the importance of
recharge from flood outs of ephemeral rivers in this arid environment. The results of the two tracer approaches indicate that recharge rates around one of the rivers and an extensive flood plain were generally higher than rates of diffuse recharge that occurred in areas of lower topographic relief. Richard Taylor et. al. (1996) conducted a study for supporting for soil moisture balance approach using stable isotope tracers and flow modelling i.e. it includes three different methods.

Chlorine Mass Balance method

Jozsef Szilagyi et. al. (2011) carried out a study for mapping mean annual groundwater recharge in the Nebraska Sand Hills, USA. Monthly precipitation (P) values came from the PRISM and monthly evapotranspiration (ET) values were derived from linear transformations of the MODIS daytime land-surface temperature values into pixel ET rates with the help of ancillary atmospheric data (air temperature, humidity, and global radiation). The uncertainty level of the resulting recharge-rate estimates can be easily defined from known or estimated levels of inaccuracy in the P and ET variables. Tianming Huang and Zhonghe Pang (2010) conducted a study for estimating groundwater recharge following land-use change using chlorine mass balance of soil profiles in Loess Plateau of China. A model was prepared in this study for the use of chloride to evaluate reduced groundwater recharge following a land-use change. F. Manna et. al. (2016) conducted a study for groundwater assessment in an upland sandstone aquifer of southern California using Chlorine Mass Balance (CMB) method. Felix Oteng Mensah et. al. (2014) conducted a study for evaluation of groundwater recharge estimates in a basin in tropical environment by using natural tracers. The current study evaluates the performance of the CMB methodology in a typical tropical climatic environment where the availability of groundwater resources is critical to socioeconomic conditions of populations and the survival of ecosystems that depend on such groundwater resources for sustenance. Jacob Nyende et. al. (2013) conducted a study in investigating surface water and groundwater in fractured aquifer under influence of climate variability using application of isotopes and recharge analysis in Kyoga basin in Uganda. In this study the impact of climate variability on water resources (surface and ground) was conducted to assess the effect of meteorological forcing on isotopic and recharge characteristics of the granitic and fractured aquifer, using environmental isotopes and also using EARTH model in determining the groundwater levels response to rainfall of the fractured aquifer.

Radiation-based method

Mohammad Valipour (2015) conducted a study aimed to compare radiation-based methods to determine the best method under different weather conditions. The potential evapotranspiration was estimated using 22 radiation-based methods and compared with the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith method.

(c) Based on numerical modelling and empirical methods

GROWA model

H. Bogena et. al. (2005) conducted a study for finding out uncertainties in the simulation of groundwater recharge at different scales using GROWA model, which consists of several modules for determining the long-term annual averages of water-balance components, viz. Actual evapotranspiration, total discharge, direct runoff and groundwater recharge.

Frequency Domain Analysis

Joaquin Jimenez-Martinez et. al. (2013) conducted a study for temporal and spatial scaling of hydraulic response to recharge in fractured aquifers, using frequency domain analysis. In order to reduce potential sources of non-linearity coming from unsaturated zone processes, the recharge at the bottom of the soil layer was used as input for the frequency domain analysis. Transfer functions are calculated in a range of temporal scales from 1 day
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upto a few years, for a fractured crystalline-rock aquifer located in Ploemeur (France), using recharge and groundwater fluctuations as input and output respectively.

Numerical Modelling method

(i) Precipitation model

Sarit Kumar Das and Rajib Maity (2014) carried out a study for finding potential of probabilistic hydrometeorological approach for precipitation-based soil moisture estimation. The time series of in situ soil moisture and meteorological variables at a monthly scale from different monitoring stations across India are utilised.

(ii) Leaf Area Index

P. Ala-aho et.al. (2015) conducted a study for estimation of temporal and spatial variations in groundwater recharge in unconfined sand aquifers using Scots pine inventories. The modelling approach uses data-based estimates for the most important parameters controlling the total amount (canopy cover) and timing (thickness of the unsaturated zone) of groundwater recharge. Scots pine canopy was parameterised to Leaf Area Index (LAI) using forestry inventory data. Uncertainty in the parameters controlling sediment hydraulic properties and evapotranspiration (ET) was carried over from the Monte Carlo runs to the final recharge estimates.

MODFLOW model

Nam Won Kin et. al. (2008) carried a study for development and application of the integrated SWAT-MODFLOW model, with main factors are the land use, surface runoff and other factors. SWAT is a basin scale, continuous time model that operates on a daily time step and designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. MODFLOW is used in layered aquifer systems with the use of modular three-dimensional block-centered finite difference code. The main program of the SWAT-MODFLOW model is simply a modified version of the main program of SWAT. H. Hashemi et. al. (2014) conducted a study with an extended modelling approach to assess climate change impacts on groundwater recharge and adaptation in arid areas. Rainfall-runoff modelling used to simulate runoff from a basin for given meteorological data. Future runoff was simulated using a conceptual box model (Qbox) utilizing the three future climate scenarios for the future periods. A GW flow and recharge model was used to simulate GW flow and estimate aquifer hydraulic parameters by MODFLOW.

WAVES model with improvements

Russell S. Crosbie et. al. (2013) conducted a study for finding out the potential climate change effects on groundwater recharge in the High Plains Aquifer, USA, using WAVES numerical model with improvements. WAVES require three main data sets: climate, soils, and vegetation. The upper boundary condition is forced with climate data and the lower boundary condition is free drainage, consistent with previous studies of the impacts of climate change on recharge.

Empirical Formulae

Oluseyi O. Adeleke et.al. (2015) conducted a study for estimation of groundwater recharges in Nigeria using empirical formulae. In this study comparative analysis of three empirical formulae to estimate recharge, which is a prerequisite for groundwater resource management was carried out.
Results from previous studies

(a) Based on methods with physical parameters

WetSpass Model

Results of the WetSpass model developed by Adnan M. Aish (2010) show that the estimated distributed recharge can be used in regional steady-state groundwater models and decrease the uncertainty in simulations. Results from the study of Mustafa Al Kuisi (2013), using WetSpass model, shows that there is a good agreement in the simulated recharge. The water balance model of O Batelaan (2007) coupled to a regional groundwater model is applied and successfully tested on the 17 catchments. Study showed that the resulting recharge has a spatial complex pattern, depending to a large extend on the soil texture and land cover. Z. Zomlot (2015) found that the annual recharge shows a large spatial variation and negative recharge occurred in zones with shallow groundwater. Negative recharge occurs, in case the total evapotranspiration is higher than the infiltration. Soil properties appear to have a major contribution in spatial variation of recharge.

Soil Water Balance Analysis

Alan Mair (2013)’s model was capable to estimate recharge in a temperature-humid area of diverse land use, high rainfall temporal and spatial variability, high topographic relief and generally high infiltration capacity. The model produces reliable estimates of spatially-varying recharge in temperature-humid climates.

GRACE Model

It was observed in the study, conducted by Alexander Y. Sun. (2013) that, downscaling of GRACE data to multiple wells at the sub-grid scale is feasible. Practical application of model for local water resources is limited. Approach developed can be applied to force multiple ANNs developed for a network of wells, the outputs of which can be combined via spatial interpolation techniques.

ILHM

ILH Model accounts for the processes and mass balance in a most rigorous manner than semi-distributed codes, which tend to lump or oversimplify important watershed processes and use parameters that cannot be independently measured.

Hydrologic model

The results of the study indicate that the overall rate of groundwater recharge is predicted to increase as a result of climate change. It is also observed that the higher intensity and frequency of precipitation could also contribute significantly to surface runoff, while global warming may result in increased evapotranspiration rates.

RIB model

The Pearson correlation coefficients indicate that the results of the rib model are more significantly correlated to observed values than those of the CRD method. The Spearman correlation coefficients between rainfall and observed WLF together with recharge estimates obtained from other methods in these areas demonstrate that the recharge estimates on a monthly basis are more realistic than those on a daily basis.

Aquifer systems

In the most of the systems studied, vadose zone storage and the dynamic interaction of surface water flows with groundwater recharge was not included. Recharge to the Death Valley regional flow system occurs almost
entirely from infiltration of precipitation and runoff in mountain systems and is low, reflecting the area’s extreme aridity. Recharge to the Central Valley is dominated by irrigation recharge, with mountain system recharge (MSR) and diffuse recharge playing subsidiary roles. Diffuse recharge is the primary recharge mechanism for the Columbia Plateau aquifer system, with irrigation providing the balance of the recharge. Recharge to the Williston Basin consists almost entirely of diffuse recharge, with a small amount of focused recharge through streambeds.

SWAT model

Results demonstrated that the karst-flow model correctly simulated the discharge of springs increasing the SWAT model performance. However, the karst-flow model markedly overestimated the discharge for five springs, may be due to the quality of the observed data.

WTF, DHB & HB method

Hydrological Budget (HB) was used to calculate groundwater recharge, which shows 61% of the total groundwater recharge including net groundwater inflow, infiltration and irrigation return flow. The difference between groundwater recharge rate estimated through Distributed Hydrological Budget (DHB) and Water Table Fluctuation (WTF) is less than 20%.

GIS-based NDVI model

With the increase in value of NDVI from 0.13 to about 0.18, the value of groundwater recharge increases, as water is retained at the surface due to increase in vegetation density and thus has stronger chance of infiltrating into the ground. However, when value of NDVI is beyond 0.18, groundwater recharge starts decreasing with increase in NDVI value.

(b) Based on chemical and isotopic methods

Tracers Isotope / Carbon-14 and Chlorine Mass Balance composite method

Glenn A. Harrington et. al. (2002) recorded the results that the mean carbon-14-derived recharge rate for the entire Ti-Tree basin is 3.5 mm/year. However, the median carbon-14-derived rate is only -0.9 mm/year, which is close to the mean rate determined from chloride mass balance (0.8 mm/year). Recharge rates are generally higher for boreholes located around the Allungra Creek floodplain and the northern section of the Woodforde River, compared with other parts of the basin. This is consistent with enhanced recharge in these areas after infrequent storm events. Richard Taylor et. al. (1996) noted in soil moisture balance technique that despite the slight rise in the annual rainfall observed between the periods, the increase in recharge results primarily from changes in land use, which have reduced evapotranspiration. Results simulation of groundwater flow model show that the water table in the regolith can be adequately represented when recharge is applied at a rate of 200 mm per year. Stable isotope measurements of Entebbe precipitation, supported in part by the limited data set generated in the study area, reveal that heavy monsoonal rainfall in the Victoria Nile basin not only is more depleted in heavy isotopes than lighter rains in a manner commonly known as the ‘amount effect’ but also displays an isotopic composition which, falling parallel to the global meteoric waterline, is unaffected by evaporation.

Chlorine Mass Balance method

Jozsef Szilagyi et. al. (2011) found that the mean annual recharge rate estimates based on this method were consistent with independent estimates based on base flow/stream flow, groundwater modelling and chloride mass balance given their uncertainty ranges. The semi-arid climate of a large portion of Nebraska Sand Hills
region necessarily increases the error range for water balance recharge estimation. Tianming Huang and Zhonghe Pang (2010) found the results that the regional afforestation and other land-use conversions have resulted in deep soil desiccation and have caused an upper boundary to form with low matrix potential, thus preventing the soil moisture from actually recharging the aquifer. F. Manna et al. (2016) observed that the annual total volume of runoff discharged at the outfalls varies. The aerial distribution of chloride demonstrates the absence of a visible trend, with a uniform distribution of values across the site and observation wells shows no evident trend, indicating no source of chloride other than atmospheric. Felix Oteng Mensah et al. (2014) noted the results that the observed pattern is consistent with conditions of lower relative humidity than 100% and high ambient temperatures as is common in the study area. The ratio of the rarer isotope to the more abundant isotope provides an indication of the relative enrichment of the two isotopes in the medium or the original source of recharge. Jacob Nyende et al. (2013) found the result showing that oxygen-18 and deuterium compositions mostly plot below the Local Meteoric Water Line (LMWL) indicating that the surface water and groundwater in the aquifer was exposed to evaporation before or in the recharging process and groundwater levels response to rainfall events by the EARTH method is the quantitative estimation of groundwater recharge for Pallisa District watershed.

Radiation-based method

The results indicate that each method estimates the potential evapotranspiration under specific weather conditions. The results show that the Stephens method estimates the potential evapotranspiration better than other methods for provinces of Iran.

(c) Based on numerical modelling and empirical methods

GROWA model

H. Bogena et al. (2005) found the results of the groundwater recharge calculation for the macro scale study area and the corresponding uncertainties as a result of the uncertainties of all data sets used. In the consolidated rock region, the low hydraulic conductivity of the solid rocks leads to groundwater recharge rates that are often less than 100 mm/a. Only the karstified carbonate rocks show significantly higher hydraulic conductivities and the groundwater recharge rate increases to more than 300 mm/a. In the unconsolidated rock region, groundwater recharge levels between 200 and 300 mm/a are most common. This distinct dichotomy in the distribution of groundwater recharge rates is also apparent for the corresponding uncertainties.

Frequency Domain Analysis

The computed transfer functions are plotted for the wells located around the pumping site, showing the general pattern, i.e. a flat section at low frequency, a decreasing section at intermediate frequency, and finally, different behaviours at high frequency are observed in all cases, which confirm that the fractured aquifer acts as a low-pass filter. No remarkable changes are detected for the characteristic response time, or in the asymptotic behaviour at low frequency.

Numerical Modelling method

(i) Precipitation model

Precipitation-based probabilistic estimation of soil moisture using the proposed hydrometeorological approach is tested with in situ observed soil moisture data and with soil moisture data of the Climate Change Initiative project. The results are found to be promising and able to provide the information on uncertainty associated with the estimation. Result also shows that the parameter of the developed model is linked to the predominant soil textural class.
(ii) Leaf Area Index

The WTF method agreed well with the simulated values, with overlapping estimates between the methods for all but two recharge events. Also the median value of simulations was close to the WTF method, with some bias to higher estimates from the simulations. Both annual recharge and infiltration displayed an increasing trend.

MODFLOW model

Nam Won Kin et al. (2008) observed that the results, which were compared and simulated hydrograph by SWAT was compared with that by SWAT-MODFLOW, shows that the SAWT was notable to correctly reproduce the stream flow dynamics in low flow, even after a comprehensive calibration. The differences in the low flows were due to insufficient baseflow resulting from the limitation of the groundwater module in SWAT. H. Hashemi et al. (2014) found the results that, in arid regions, the change in precipitation, surface runoff, and GW recharge are expected to be the most substantial consequence of climate change. In the future scenarios, there will be no significant change for all climate variables during the spring and summer season relative to the historical climate. During the cold and wet seasons, both temperature and potential evaporation is slightly increased in all projected scenarios. In general, the average reduction in precipitation in the near and far future is about 2 and less than 1 % respectively.

WAVES model with improvements

The trend show expected relationships between recharge and rainfall (positive correlation), soil texture (higher rates under coarser-textured soils), and vegetation (lower recharge rates under perennial vegetation). The historical climate baseline raster produces spatial trends that are consistent with previously published recharge estimates for the High Plains.

Empirical Formulae

The result revealed that the three empirical formulae gave comparable results. Low rainfall causes low groundwater recharge infiltrating into the aquifer, this is due to increase in temperature and evapotranspiration and vice versa. Low recharge causes high runoff over the surface. It is evident that the recharge in no-stationary and likewise, the annual rainfall, but are stationary after the second differencing, hence there exists a long relationship between the climate parameters.

Discussion for previous studies

(a) Based on methods with physical parameters

The WetSpass model was used in various regions such as Gaza strip, which is a characteristically semi-arid and desert climate, in Jafr basin, which is arid desert and in Belgium and the Netherlands, where area is dominated by agriculture, forests, built up areas and meadows. GIS-based WetSpass methodology is a tool which can simulate the spatial distribution of long-term average groundwater recharge.

Soil Water Balance Analysis

The Soil water balance model does not include a mechanism to account for additional sources of groundwater recharge, such as fog drip, irrigation, and artificial recharge, and may also overestimate evapotranspiration losses. As such this study represents a conservative estimate of total recharge.
GRACE Model

Results indicate that GRACE data play a modest but significant role in the performance of Artificial Neutral Network ensembles, especially when the cyclic pattern of groundwater hydrograph is disrupted by extreme climate events.

ILHM

ILHM is well suited for forecasting purposes because it allows forcing data and component process models to be interchangeable.

Hydrologic model

Groundwater recharge is influenced not only by hydrologic processes, but also by the physical characteristics of the land surface and soil surface. 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. Studies concerned with climate change should therefore also consider the spatial change in groundwater recharge rates.

RIB model

The RIB model is capable of recharge estimation, if specific yield is known and certain assumptions are met. RIB model can be used only under certain conditions in shallow unconfined aquifers with relatively low transmissivity.

Aquifer systems

Together these results show that the wet areas will get wetter and the dry areas will get drier. Recharge is a threshold process, as dry places get drier, recharge will decrease more sharply than precipitation declines. The results of available studies indicate that this overdraft will become more severe as recharge declines and pressure to increase groundwater pumping grows. In contrast, there is a potential for increased recharge across the northern set of aquifers, though confidence in the expected changes is low.

SWAT model

SWAT model has allowed the estimation of the water balance of Crete resulting in significantly different estimates. In the wettest year the main component of hydrological process was the deep aquifer recharge, while in the driest year the evapotranspiration had the main role. As a consequence, during the wet conditions there was high infiltration, but also the surface runoff was larger than that during driest and normal hydrological condition.

WTF, DHB & HB method

Hydrologic Budget (HB) is a lumped method and wouldn’t report any further information about distribution of groundwater recharge rate in region. Groundwater recharge resulting from both rainfall deep percolation and irrigation return flow for each sub-zone can be estimated using DHB method. WTF method gives distinct results for contribution of rainfall and irrigation return flow towards groundwater recharge. There is a good agreement between groundwater recharge estimated using the DHB and WTF model. The difference between these results and those of the HB method arises from (1) considering net groundwater inflow as an average groundwater recharge in this method and (2) assuming constant groundwater level to calculate groundwater flow from one cell to adjacent cell during a month time period which is not well matched with aquifer condition in reality.
GIS-based NDVI model

It can be seen that overall there is a linear trend between groundwater recharge and rainfall. The value of groundwater recharge depends strongly upon the density of vegetation before the monsoon. Increase or decrease in groundwater recharge would be due to the reason that vegetation density increased to such a level that the interception and absorption of water out weights the factors responsible for further increase in recharge.

(b) Based on chemical and isotopic methods

Tracers Isotope / Carbon-14 and Chlorine Mass Balance composite method

Glenn A. Harrington et. al. (2002) discussed that the stable isotopic compositions and, to a lesser degree, the raw chloride concentrations of soil and groundwater samples provide compelling evidence that the groundwater in the Ti-Tree Basin is recharged only after the most intense rainfall events of at least 150 to 200 mm/month. Carbon-14 data was combined with physical parameters including sample depth, aquifer depth, and distance from the groundwater flow divide to obtain estimates of the average recharge rate between where a groundwater sample first entered the saturated zone and the borehole. This approach, however, is limited by both the ability to construct accurate groundwater flow lines and having a sample (bore) density that reflects the scale of the different recharge areas. Richard Taylor et. al. (1996) shown that owing to the conservative behaviour of stable isotopes in low-temperature groundwater systems, groundwater will retain the isotopic signature of recharging precipitation provided that (1) the isotopic content of the incident rainfall is not affected by soil zone processes immediately before infiltration, and (2) the source of recharge is restricted to the direct infiltration of rainfall.

Chlorine Mass Balance method

Jozsef Szilagyi et. al. (2011) discussed that the associated error bounds in the recharge estimates may be significant in arid and semi-arid regions where a large portion of the precipitation was evaporated/ transpired. Such uncertainty was considered acceptable for many problems in view of the current state of uncertainty associated with other recharge estimation techniques. Tianming Huang and Zhonghe Pang (2010) in their study shows that the decrease in groundwater recharge when the vegetation is converted to a type with higher water demands. In the study by F. Manna et. al. (2016) the main uncertainty in the application of the method is related to the assumption that atmospheric chloride must be the only source of chloride in the sub-surface system. Uncertainties can be derived by the slope effect, i.e. the mixing of water due to up-slope recharge. This process is believed to minimally affect the results of the analysis because of the topographic and hydrogeological characteristics of the study area. Felix Oteng Mensah et. al. (2014) mentioned that the ratio of the rarer isotope to the more abundant isotope provides an indication of the relative enrichment of the two isotopes in the medium or the original source of recharge. The sources and origin of groundwater recharge in the Voltaian was assessed using stable isotope data of precipitation, groundwater, and surface water from parts of Voltaian. Jacob Nyende et. al. (2013) mentioned that the clustering of groundwater samples observed suggests that both evaporation and isotopic exchange with the aquifer minerals may be occurring into the system. The effect of evaporation is greatest for light precipitation.

Radiation-based method

Evapotranspiration has a significant role in irrigation scheduling and water resources management. The highest precision of evapotranspiration could be obtained using lysimeter or imaging techniques, but their costs are too high. The radiation-based method is one of the most widely used methods to estimate potential evapotranspiration. Finally, a list of the best performances of each method is presented to use in other region studies according to mean, maximum, and minimum temperature, relative humidity, solar radiation, elevation, sunshine, and wind speed. The precision of estimation by radiation-based methods was very sensitive to
variations of the parameters used in each method. Thus, the coefficients of the radiation-based methods need to be adjusted based on weather conditions of each province.

(c) Based on numerical modelling and empirical methods

GROWA model

Most parts of the consolidated rock region show uncertainties well below 20%, except for the karstified carbonate rocks with significantly higher values (more than 30%). The unconsolidated rock region, on the other hand, shows uncertainties between 15 and 40%. In order to facilitate an analysis of the differently scaled data ensembles on the calculated groundwater recharge, averaged values of the uncertainties in percent of the mean groundwater recharge are calculated. The differences between the scales cannot be generalised since the identified uncertainties are determined by the individual characteristics of the catchment area and the available database.

Frequency Domain Analysis

The estimation of recharge at the bottom of the soil horizon is uncertain. The observed non-classical log-log slopes for some observation wells are not influenced by uncertainties in the computation of input recharge, and thus correspond to an intrinsic property of the aquifer.

Numerical Modelling method

(i) Precipitation model

Soil moisture has a significant impact on the temperature-evaporation-precipitation feedback loop and plays a significant role in numerical weather prediction using climate variables at a regional scale. It also controls the terrestrial water balance through partitioning precipitation among infiltration, runoff, and evapotranspiration. The capillary action that determines the evaporative demand and withdrawal of the water through plant roots is driven by soil moisture content.

(ii) Leaf Area Index

The method used here to estimate LAI from forestry inventories introduces a new approach for incorporating large spatial coverage of detailed conifer canopy data into groundwater recharge estimations.

MODFLOW model

SWAT is not able to represent the spatial distribution of the groundwater table because the model is an HRU-based quasi-distributed model rather than a grid-based fully distributed model. Since SWAT-MODFLOW uses MODFLOW as the groundwater model, it is capable of calculating the spatially distributed groundwater table and also capable of simulating the spatio-temporal variation of groundwater recharge rates. H. Hashemi et. al. (2014) observed that the results of projected climate variables (precipitation, temperature, and evapotranspiration) show no significant increase or decrease in rainfall quantity relative to the historical climate but a slight increase in surface runoff.

WAVES model with improvements

The trend for future recharge projections differs from the trend of the future rainfall projections. There is a general trend across all three sites for the slope of the mean annual rainfall versus mean annual recharge to decrease with increasing recharge. Model results show a trend with projected increases in recharge for the low
global warming scenario and then a reduction in recharge with further increases in global warming that is not related to changes in rainfall.

Empirical Formulae

There is no significance at any level among the other parameters with regression analysis, which was conducted to evaluate the effect of climate parameters on estimated recharge. All parameters showed minimal relationships to estimated recharge, except precipitation, which showed a dominant role of rainfall percolation of water into the ground in the study area.

Summary and Conclusions for previous studies

(a) Based on methods with physical parameters

WetSpass Model

Adnan M. Aish (2010) concluded that the comparison of results of WetSpass model and previous studies shows good agreement and indicates the validity of the simulated recharge, changes in land use impact the recharge and the presented recharge map can serve not only as a basis for future land use conditions, but also as a basis for comparisons with past land use conditions, and the model is especially suitable for studying effects of land-use changes on the water regime in a basin. Mustafa Al Kuisi (2013) concluded that the aquifers receive recharge from the western highlands by direct and indirect infiltration of rainfall. This model is specially suited for studying long-term effects of land use changes on the water regime in a watershed. Z. Zomlot (2015) concluded that the groundwater is strongly influenced by soil texture and land use; the spatial correlation, however, is relatively low

Soil Water Balance Analysis

Soil water balance Model can produce reliable estimates of spatially-varying recharge in temperature-humid climates.

GRACE Model

GRACE satellite data only takes ∆TWS but not changes of individual hydrologic components such as surface water, soil moisture and groundwater.

ILHM

ILHM is well-suited for forecasting purposes because it allows forcing data and component process models to be interchangeable; thus a model developed and calibrated with current data can be rapidly converted to a forecast simulation by adding the appropriate component process code.

Hydrologic model

Groundwater resources are related to climate change indirectly through the process of recharge, and directly through the interaction with surface water bodies such as rivers and lakes. The process of groundwater recharge is not only influenced by the spatial and temporal variability in the major climate variables, but also dependent on the spatial distribution of land-surface properties and the depth and hydraulic properties of the underlying soils.
RIB model

The sensitivity analysis showed that the recharge rate by the RIB model is specifically sensitive to the parameter of specific yield; therefore the accurate representative specific yield of the aquifer needs to be selected with caution. The RIB model is a simple and efficient method to estimate groundwater recharge and fill water level data gaps in shallow unconfined aquifers where groundwater levels respond distinctly to rainfall.

Aquifer systems

Anticipated changes in recharge mechanisms display definite regional patterns in magnitude and confidence. MSR is expected to decrease with high certainty in the southern and western portions of the region and with lower certainty in the northern and eastern portions. Patterns of expected recharge change (in total recharge and recharge mechanism) inherit all of the uncertainties of the underlying GCMs and downscaled average climatologies. Uncertainties regarding the impacts of future climate change on MSR, focused recharge, and irrigation recharge present the greatest opportunities for improvement through process level studies.

SWAT model

The seasonal variation of volume of springs suggests that these valuable sources should be conserved and preserved in particular from April to September when available volumes are the lowest and agriculture and tourism demand increases. The analysis of the water balance also showed that water resources are not homogeneously distributed in Crete and change significantly in different hydrological conditions.

WTF, DHB & HB method

In the HB method specific yield is the only estimated parameter. Although it plays a critical role in the water budget, this parameter has a limited domain of variation. Accuracy and reliability of groundwater recharge estimated with these methods depends on those of the input datasets and their assumptions. The DHB and WTF models provided spatial and temporal distribution of natural groundwater recharge. The WTF model clearly exhibited groundwater recharge components.

GIS-based NDVI model

This delivers a new methodology for understanding affect of rainfall and vegetation density on groundwater recharge based on spatial distribution of these parameters in a given geographical area. The study establishes a very strong polynomial correlation of second degree between groundwater recharge and NDVI indicating increase in recharge with increase in NDVI values upto a certain level.

(b) Based on chemical and isotopic methods

Tracers Carbon-14 and Chlorine Mass Balance composite method

Glenn A. Harrington et. al. (2002) concluded that the application of the carbon-14 and chloride approaches to the arid Ti-Tree Basin in central Australia has revealed the magnitude and spatial extent of recharge from ephemeral rivers. The equations used to estimate recharge rates from carbon-14 data and the length scale over which they apply also rely on knowledge of the aquifer characteristics (e.g. porosity) and geometry. Richard Taylor et. al. (1996) concluded that the combined techniques reveal that recharge is restricted to the heavier rainstorms of the monsoons. The magnitude of the recharge estimate demonstrates a stronger dependence on the number of heavy rain events than on the total volume of rainfall.
Chlorine Mass Balance method

Jozsef Szilagyi et al. (2011) concluded that the application of a water balance recharge estimation technique based on MODIS and ancillary climate data demonstrates that the mean annual recharge rate based on this method are consistent with independent estimates based on baseflow, groundwater modelling and chloride mass balance given their uncertainty ranges. The MODIS-based method may be applicable for estimating spatially distributed mean annual recharge rates in sandy areas of the world, where basic climate data (precipitation, air temperature and humidity, global radiation or sunshine duration) are available. Tianming Huang and Zhonghe Pang (2010) concluded that reduced groundwater recharge caused by land-use change can be estimated by comparing the chloride concentration in the soil water from the base of the root zone to the base of the chloride concentrated zone, for pre-converted and converted land uses, based on the chloride mass balance and using the unconverted land use as the background for comparison. Regional afforestation and other land-use conversions to vegetation with higher water demand may have caused soil-water depletion and solute concentration, and are, therefore, not favourable to groundwater recharge and ecosystem restoration. F. Manna et al (2016) concluded that the application of this approach was exceptionally well-suited for this study area because of the extraordinarily large number of groundwater samples collected from a dense network of monitoring wells collected over three decades combined with a robust surface water drainage monitoring program. The analysis of tritium concentration in the groundwater indicates that recharge occurred at the shallowest monitoring wells assuming a plug downward flow rate of 0.2 m per year. It is also found that infiltration water slowly moves the aqueous phase of the contaminant mass stored in the unsaturated zone toward the water table important for remediation plans. Felix Oteng Mensah et al. (2014) concluded that the CMB approach performs well in a tropical setting in providing fairly accurate estimates of groundwater recharge for groundwater resources evaluation. Jacob Nyende et al. (2013) concluded that replenishment of groundwater in the study area is entirely through precipitation, shallow underground waters have undergone evaporation and the evaporation line above the GMWL. Also the EARTH model analysis indicates that groundwater fluctuations are affected by the natural climate variations and anthropogenic influences.

Radiation-based method

The precision of estimation by radiation-based methods is very sensitive to variations of the parameters used in each method. Thus, the coefficients of the radiation-based methods need to be adjusted based on weather conditions of each province. Only if the radiation-based methods are used for suitable and specific weather conditions, the highest precision of recharge estimation is obtained.

(c) Based on numerical modelling and empirical methods

GROWA model

The Gaussian error propagation method is a usefully technique for analysing the influence of input data on the simulated groundwater recharge. The present uncertainty analysis showed that the BFI and precipitation uncertainties had the greatest impact on the total groundwater recharge error. This result is achieved by using a specific model and is therefore not simply transferable to other hydrological models. Furthermore, it has to be noted that this analysis has the character of a worst case study, since the climate parameter used in this study shows a significant correlation.

Frequency Domain Analysis

The contribution of different hydrogeological structures to the hydraulic response to recharge is indicated by the dependency of the transfer function amplitude on frequency. The variability of transmissivity and storage coefficient tends to decrease with scale, and the average estimates converge toward the highest values at large scale. The small-scale variability of diffusivities, which implies the existence of a range of characteristic
temporal scales associated with different pathways, is suggested to be at the origin of the unconventional temporal scaling of the hydraulic response to recharge at high frequency.

Numerical Modelling method

(i) Precipitation model

The strength of association is higher between soil moisture and precipitation compared to that between soil moisture and temperature. The model parameter is higher for those locations having higher clay content, whereas the parameter is lower for those locations having a coarse texture. This suggests that the signature of soil texture is manifested in the model parameter as reflected in soil moisture simulation curves obtained using the study approach. The result indicates the importance of soil texture information and the spatial transferability of the proposed Hydrometeorological approach.

(ii) Leaf Area Index

A physically based approach to simulate groundwater recharge for sandy unconfined aquifers in cold climates was developed. The method accounts for the influence of vegetation, unsaturated zone thickness, presence of lakes, and uncertainty in simulation parameters in the recharge estimate. It is capable of producing spatially and temporally distributed groundwater recharge values with uncertainty margins, which are generally lacking in recharge estimates, despite understanding of uncertainty related to recharge estimates being potentially crucial for groundwater resource management. However, the parameter uncertainty defined for the study area was of minor significance compared with inter-anual variations in the recharge rates introduced by climate variations.

MODFLOW model

The application demonstrates that an integrated SWAT-MODFLOW is capable of simulating the spatio-temporal distribution of groundwater recharge rates, aquifer evapotranspiration and groundwater levels and that it enables the interaction between the saturated aquifer and channel reaches, which plays an important role in the generation of groundwater discharge in the basin, especially during the low flow period. The comprehensive results demonstrate that the model is able to represent the integrated watershed modelling results that contain surface hydrologic components such as distributed recharge rates, groundwater levels and discharge, with or without well pumping. H. Hashemi et al. (2014) concluded, it appears that the GW abstraction has the most substantial effect on GWL drawdown that needs to be taken into account in the water resources management plan. The methods used in this study are suitable for assessing the climate change impacts on GW for local-scale aquifer systems. GWL projection by MODFLOW, particularly in a sophisticated aquifer system, shows the great potential of recharge modelling to address the sustainable GW management through adaptation scenarios.

WAVES model with improvements

Russell S. Crosbie (2013) concluded that vegetation is not necessarily a strong determinant of the sensitivity of recharge to climate change as sensitivity differs based on the amount of historical baseline recharge and not necessarily vegetation type. Sensitivity of recharge to changes in rainfall is least for high baseline recharge and greatest for low baseline recharge. Sensitivity is greater than one, meaning that there is amplification with greater changes in recharge than changes in rainfall.

Empirical Formulae

The study shows that there is variability in climate parameters. The study also shows that the climate has a significant effect on groundwater resources, which is revealed from the rainfall variable; however, evapotranspiration and solar radiation have a relationship with each other.
Discussions

The study reveals that the reasons causing the variability in groundwater recharge are ranging from uncertainties in recharge influencing factors to change in climatic conditions. The study also shows that the uncertainties in distribution of groundwater recharge occur differently in different regions, due to the impact of various factors such as change in climatic conditions, change in land use, soil types, etc.

Broadly, according to the present study the uncertainties and challenges could be shortly enumerated, as per grouping of their types, as below:

Based on methods with physical parameters

Using the distributed recharge from WetSpass in a steady-state groundwater model will improve the prediction of the simulated groundwater level and recharge and this will lead to a stable solution for the groundwater level and recharge areas. Sometimes, for simplicity an assumption needed to be considered such as changes in tree and plant phenology (i.e. lower or higher leaf or plant area index) under drought or climate change conditions translate into minimal changes in interception storage capacities. Since outputs from the model are grid maps and not the tabular values, it would be helpful to combine two or more grid maps. WetSpass is especially suited for studying long-term effects of land use changes on the water regime in a watershed. In the case of GRACE satellite, it only tracks changes in terrestrial water storage but not changes of individual hydrologic components e.g. surface water, soil moisture, and groundwater and hence practical application of GRACE data for local water resources management, especially nowcasting and forecasting is limited. Combination of process-based APLIS modelling and GIS data analysis, makes us able to provide spatio-temporal information of groundwater recharge and sub-surface flow dynamics also during varying hydroclimatic conditions for karst aquifers. Forecasting those changes at regional scales requires new modelling tools, such as ILHM, which take advantage of increases in computational power and the latest GIS and remote sensing datasets. Together, the two datasets i.e. the soil moisture data and water table data, allow for a holistic assessment of the groundwater recharge process from the ground surface through the unsaturated zone down to the water table. Quantifying the impact of climate change on groundwater resources requires a physically based approach, such as hydrologic model, for estimating groundwater recharge that includes all of the important processes in the hydrologic cycle, such as infiltration, surface runoff, evapotranspiration, and snowmelt. Analysis of aquifer systems in a region can be done by splitting the aquifers sub-region wise and model-based study of projected climate-change effects on recharge can be done. RIB model is suitable for shallow unconfined aquifer systems, under certain conditions such as sufficient data about long time series of groundwater level and rainfall available in similar regions.

Based on chemical and isotopic methods

Groundwater recharge is possibly the most important, but generally the most difficult, component of a water resource evaluation. Determining recharge rates in arid regions, where net water fluxes are extremely low, is particularly difficult because many of the techniques used to estimate recharge in wetter environments (e.g. water balance, applied tracers) can yield large uncertainties when applied to arid regions. Therefore, to determine recharge rates in arid and semi-arid regions, tracer approach proves to be extremely valuable. MODIS-based method, with ancillary data, may be applicable for estimating spatially distributed mean annual recharge rates in sandy areas of the world where basic climate data from the year 2000 and on are available. The uncertainty level of the resulting recharge-rate estimates can be easily defined from known or estimated levels of inaccuracy in the precipitation and evapotranspiration variables. Radiation method is best suited method to estimate potential evapotranspiration. Natural tracer method, which is based on baseflow recession, is applicable mostly in the large basins. EARTH model helps to determine the groundwater levels response to rainfall of the fractured aquifer.
Based on numerical modelling and empirical methods

The precipitation uncertainties have the greatest impact on the total groundwater recharge error and GROWA model, in which the Gaussian error propagation method is used, is best suited for analysing the influence of input data on the simulated groundwater recharge. For quantification of the recharge in fractured aquifers, frequency domain approach proved to be useful, considering its ability to handle the multi-scale heterogeneity and the range of temporal scales involved. SWAT-MODFLOW is a combination of two numerical models, which is capable of simulating a spatio-temporal distribution of groundwater recharge rates, aquifer evapotranspiration and groundwater levels and it enables an interaction between the saturated aquifer and channel reaches. MODFLOW method is suitable for assessing the climate change impacts on groundwater for local-scale aquifer systems. Computational methods to estimate groundwater recharge vary from simple water balance models, where water stores and fluxes are represented conceptually and related with adjustable parameters, to physically based models using Richards’ equation to solve water fluxes through an unsaturated zone. A physically based method, such as LAI method, is useful for estimation of recharge for sandy unconfined aquifers. WAVES model uses three datasets i.e. climate, soils and vegetation and is applicable where sensitivity analysis is of importance.

Conclusions

In conclusion, it should be noted that realistic estimation of recharge depends mainly on identifying prominent features influencing recharge for a certain region and probable flow mechanism for targeted aquifer. Multiple dependent models / approaches needs to be applied and output could be compared with actual field conditions. The interaction of soil, with climate in the region, slope in the terrain, geology, geomorphology of the area, land use land cover, rainfall, drainage pattern and various other methods used for recharge determines the recharge quantity. The carbon-14 and chloride approaches have advantages over “conventional” numerical modelling approaches, because the degree of spatial parameterization required for the latter can generally not be matched by available data or understanding. Combination of three methods viz. Water table fluctuation (WTF), distributed hydrological budget (DHB) and hydrological budget (HB) proved to be a good example to know how to overcome the gaps in datasets and also the processing the datasets due to their limitations or gaps therein. Thus such combination of methods proved to be more reliable for estimation of groundwater recharge and also the impacts of the climate change on recharge. When these methods are coupled with remote sensing and GIS method, these combined methods are very useful and suitable as these are easy to use, cost effective, simple, requiring a few non-deterministic data such as groundwater level measurements, rainfall, aquifer properties, and groundwater extraction datasets.

It is also seen that whenever two or more methods or models are combined for bringing down the gaps in either datasets or the processing the datasets, helps to understand the uncertainties and encompass the maximum possible process components under one roof so as to take the challenge in estimating groundwater recharge rate under climate change scenario. Due to such combination of different methods or models relationship between different available hydrogeological and climate components can be assessed with great accuracy and can obtain better understanding of effects of climate change on groundwater recharge and also behaviour of groundwater recharge.

Combination of process-based modelling and GIS analysis allows circumventing the problem of data scarcity that most distributed models face and also can assess the impact of hydroclimatic extremes on groundwater recharge.
Table 1 Groundwater Recharge Estimation methods

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Acknowledgements

We hereby acknowledge the encouragement and support extended by the Head, Research Center and Faculty members at Dr. D. Y. Patil Institute of Engineering and Technology, Pimpri, Pune, India.

References


