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Predicting the impacts of climate change on groundwater recharge in an arid environment using modeling approach

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Abstract

Purpose – Groundwater is an important source of water supply in arid and semi-arid areas. The purpose of this study is to predict the impact of climate change on groundwater recharge in an arid environment in Ilam Province, west of Iran.

Design/methodology/approach – A three-dimensional transient groundwater flow model (modular finite difference groundwater FLOW model: MODFLOW) was used to simulate the impacts of three climate scenarios (i.e. an average of a long-term rainfall, predicted rainfall in 2015-2030 and three years moving average rainfall) on groundwater recharge and groundwater levels. Various climate scenarios in Long Ashton Research Station Weather Generator were applied to predict weather data.

Findings – HadCM3 climatic model and A2 emission scenario were selected as the best methods for weather data generation. Based on the results of these models, annual precipitation will decrease by 3 per cent during 2015-2030. For three emission scenarios, i.e. an average of a long-term rainfall, predicted rainfall in 2015-2030 and three years moving average rainfall, precipitation in 2030 is estimated to be 265, 257 and 247 mm, respectively. For the studied aquifer, predicted recharge will decrease compared to recharge calculated based on the average of long-term rainfall.

Originality/value – The decline of groundwater level in the study area was 11.45 m during the past 24 years or 0.48 m/year. Annual groundwater depletion should increase to 0.75 m in the coming 16 years via climate change. Climate change adaptation policies in the basin should include changing the crop type, as well as water productivity and irrigation efficiency enhancement at the farm and regional scales.

Keywords Climate change, Arid environment, Groundwater recharge, LARS, MODFLOW

Paper type Research paper

1. Introduction

An increase in the average ocean level, air temperatures, general melting of ice, sea level and many other factors leads to climate warming (IPCC, 2007). These predictions indicate that water resources would be affected by climate change (IPCC, 2008), which in turn affect the components of water cycle such as precipitation, evaporation and evapotranspiration and

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thus results in a large-scale alteration in water present in glaciers, rivers, lakes and oceans (Panwar and Chakrapani, 2013). Climate changes influence groundwater resources by modifying recharge rates (Ajami *et al.*, 2012). Water availability and water demand are also modified via climate change (Mayer and Congdon, 2008). The continuous increase in water demand and a decrease in water availability could lead to water storage deficit (Toews and Allen, 2009). Because of increasing water shortage via climate change, groundwater will likely become more important, especially in the arid and semi-arid environments (Mirzavand and Ghazavi, 2015). Although groundwater resources are already limited in the arid and semi-arid areas (Ghazavi *et al.*, 2012), climate change will even increase this pressure (Ranjan *et al.*, 2006). Evaluating the effect of climate change on groundwater resources can lead to sustainable water management strategies (Woldeamlak *et al.*, 2007; Refsgaard *et al.*, 2010). The sustainability of groundwater resources is strongly related to the amount and distribution of runoff and precipitation. Infiltration and percolation from precipitation and seepage from surface water bodies are two major sources of groundwater recharge (Bhattacharya, 2010; Ghazavi *et al.*, 2010).

The relationship between climate change and groundwater resources is poorly understood (Russell *et al.*, 2013; Wyatt *et al.*, 2015).

The water balance model is commonly used to quantify groundwater recharge, but many researchers have also used the empirical rainfall-runoff model to investigate the effects of climatic change on groundwater resources (Yusoff *et al.*, 2002; Brouyère and Carabin, 2004). Simulation of the groundwater system by using climate change-derived inputs is a suitable method to understand the impacts of future predicted climate change on groundwater resources (Hanson, 2012).

A mathematical groundwater model (MODFLOW) is used to predict the current and future condition of the groundwater using climate data derived from a global climate model (Long Ashton Research Station Weather Generator, LARS-WG). Mahat and Anderson (2013) used LARS-WG model to evaluate the impacts of climate and forest changes on stream flow in the upper parts of the Oldman River in southern Alberta. The model projected less than a 10 per cent increase in precipitation in the winter and a similar amount of precipitation decrease in the summer. In India, LARS-WG was used in Bihar to assess the impacts of climate change on the water resources of the region (Reddy *et al.*, 2014). They reported that LARS-WG has a reasonable efficiency to downscale the point rainfall data, and the results obtained are effective in the analysis of the impact of climate change on the hydrology of the basin.

In recent years, because of the extensive drawing of the subsurface water, the water table in many regions of Iran has dropped significantly (Ghazavi *et al.*, 2010). The main aim of this study is to evaluate how climate change should change groundwater recharge in the coming decades. For this propose, the best climate scenarios for an arid area located in Iran was determined. LARS-WG model is used to generate the future daily time series of the precipitation under various emission scenarios. The possible impact of rainfall change on groundwater recharge was also analyzed in the present work.

2. Materials and methods

2.1 Study area

The study area is Mosian plain located within the latitudes 32°22′ and 32° 34′N and longitudes 47° 20’ and 47° 39’E in Ilam Province, west of Iran (Figure 1).

The study area consists of alluvial fans (quaternary sediments) with a bedrock at a varying altitude. The northeast part of the Mosian plain is covered by a layer of

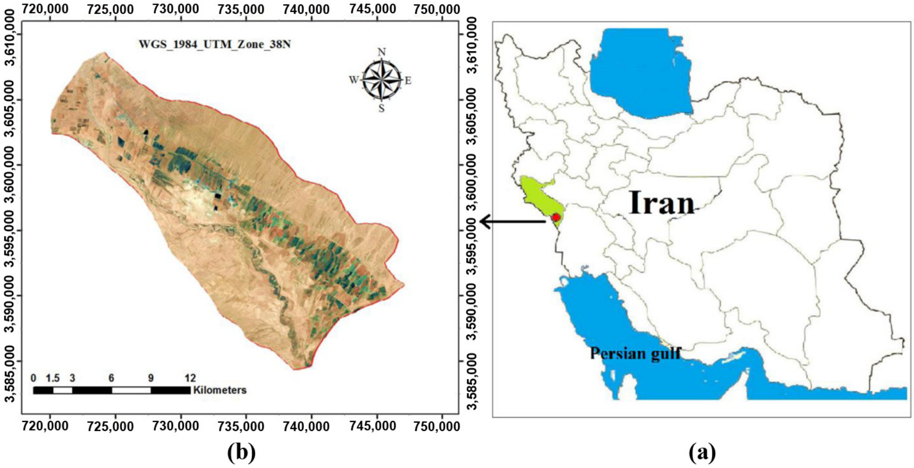


Figure 1.
(a) Location of Ilam Province and study area in Ilam Province and (b) satellite image of the study area (Mosian plain)

conglomerate marl and sandy conglomerate of the Bakhtiari formation, created during the Upper Pliocene period (Figure 2).

Altitude of the study area ranges from 89 to 231 m above the mean sea level. The crop water demand in the study area is 44.97 million cubic meters (MCM), which is supplied from groundwater and surface water resources. Groundwater is the main source of the fresh water in the study area. The Doiraj River that flows through Mosian plain has a total length of 40 km. Doiraj River is the main source of surface water for irrigation and industrial water in Mosian district. The annual discharge via abstraction wells from the unconfined aquifer in the study area is about 17.5 MCM (Ebrahimi *et al.*, 2016).

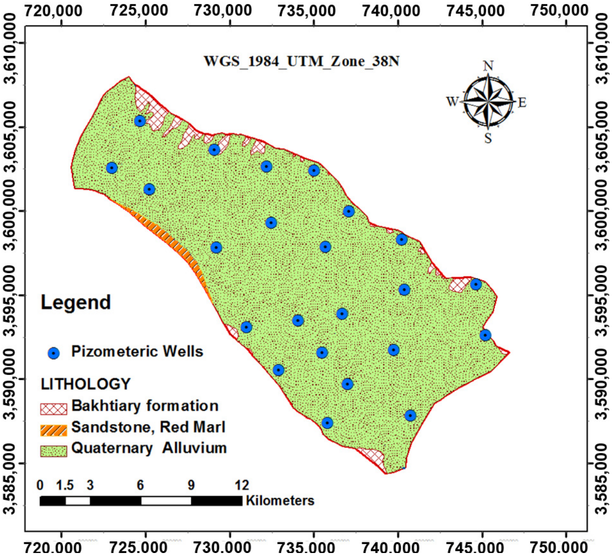


Figure 2.
Lithology of the Mosian plain and location of the piezometer wells

The study area is characterized as an arid region. The average annual rainfall for the base period (1993-2014) was 265 mm, of which 189 mm occurred in the fall-winter period, 73 mm in the spring and only 3 mm in the summer (Figure 3). The mean temperature of the base period was 27°C, ranging from 12.7°C in January to 38°C in July. The average of the minimum and maximum temperatures of the study area is 21°C and 33°C, respectively. A pan evaporation of the study area is about 3,710 mm.

2.2 Methodology

This study was conducted in three main parts:

1. In the first stage, the annual rainfall in the study area (2011-2050) was generated using climatic model, LARS-WG, under different scenarios. The groundwater characteristics of the study area were mapped regionally based on the interpretation of 23 piezometer wells' data by using geology and hydrology information of the study area (Figure 2).
2. In the second stage, groundwater recharge from the rainfall and irrigation in the study area were estimated using inverse modeling approach and remote sensing (RS) (Ebrahimi *et al.*, 2016). For confirmation, the performance of the hydrological model to simulate the aquifer conditions and groundwater recharge (1990-2014) was simulated using MODFLOW.
3. Finally, after model confirmation, the future condition of the aquifer and groundwater recharge from predicted rainfall (2015-2030) was simulated using the calibrated hydrological model and the generated weather data.

2.2.1 Climate scenario formulation. General circulation models (GCMs) are climate models that employ mathematical models of the general circulation of planetary atmosphere or ocean. Currently, they are the most credible tools designed to simulate time series of climate variables (e.g. air temperature, precipitation, wind speed and pressure) on a global scale with respect to increasing greenhouse gas concentration in the atmosphere. Three divergent emissions scenarios (A1B, A2 and B1) have been commonly used in climate change studies that describe different future worlds with respect to demographic developments, socioeconomic development and technical change (IPCC, 2007). The process of converting GCM outputs into local meteorological variables is required for a reliable hydrologic modeling, usually referred as the downscaling technique (Huntingford *et al.*, 2003; Dibike and Coulibaly, 2005). There are two main methods of downscaling the GCM scenarios:

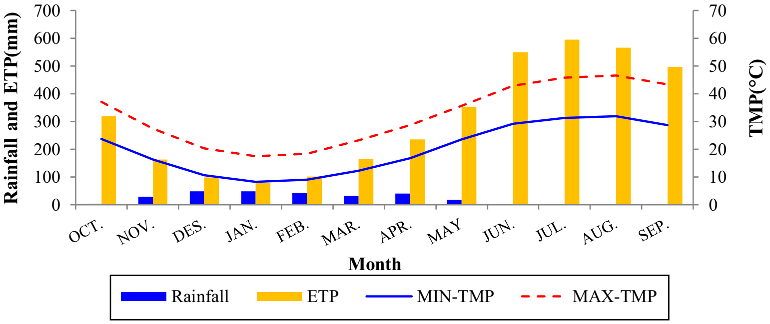


Figure 3. Monthly weather data at Mosian plain (rainfall, evapotranspiration, minimum temperature and maximum temperature)

1. dynamic downscaling techniques, e.g. regional climate models and statistical downscaling techniques (e.g. LARS-WG); and
2. statistical downscaling model.

LARS-WG is a stochastic weather generator, specially designed for climate change impact studies, which is useful to simulate the extreme rainfall events. LARS-WG generates daily weather data series, as well as rainfall, minimum and maximum temperatures and radiation. The applicability of such weather generators has been studied successfully in different climates of the world. The weather generator uses observed daily weather for a given site to determine parameters specifying a probability distribution for weather variables, as well as correlations between the variables. The procedure to produce synthetic weather data is then based on selecting values from proper distributions by using a pseudo-random number generator.

The weather generator distinguishes dry and wet days depending on rainfall values. Rainfall is modeled using semi-empirical probability distributions for each month for the lengths of series of wet and dry days and for rainfall level on a wet day. A semi-empirical distribution $\text{Emp} = \{e0, ei, hi, i = 1,\ldots, 10\}$ is a histogram with ten intervals, $(ei - 1, ei)$, where $ei - 1 < ei$ and hi denote the number of events from the observed data in the ith interval.

Minimum temperature, maximum temperature, and radiation are related to the amount of cloud cover band. LARS-WG uses separate wet and dry day distributions for these variables. LARS-WG produces synthetic data on a daily time step by first determining the rainfall status of the day (Reddy *et al.*, 2014).

Daily measurements of precipitation, temperature and sunny hours are available for Mosian plain and provided by the Meteorological office in Ilam. These climate variables were used to:

- calibrate the stochastic weather generator;
- downscale LARS climate variables; and
- estimate precipitation and temperature of the study area.

In this study, the historical base weather data from 1993 to 2014 were used for LARS-WG model calibration (1993-2009) and validation (2010-2014). The model gives the generated statistical output for the base period of 1993-2014 for evaluation of the model performance.

Long-term (2011-2030) synthetic weather data of rainfall and air temperature were generated using LARS-WG model for the selected area. Data series from 2011 to 2030 were used for hydrological prediction of Mosian aquifer.

The mean and coefficient of variation of data (1991 to 2010) are used to evaluate LARS-WG model. The average of the monthly rainfall data was used to compare observed and generated weather data series. The best GCM was selected using monthly observed and predicted climatic data in the period of 2010-2014.

2.2.2 Groundwater simulation. A three-dimensional groundwater model (MODFLOW) was used to simulate groundwater recharge. Recharge, hydraulic parameters, well initial heads and stream flows are the model inputs. Transient groundwater elevations, surface water flows, elevations and groundwater interactions in modeled streams and river area are model outputs. All necessary input data were generated using historical information of the study area (MahabGhods Consulting Engineers, 1992) and field observations and measurements. All necessary maps were prepared using ArcGIS software.

Groundwater flow in the aquifer system was simulated via MODFLOW by using the finite difference method. In this method, the aquifer is divided into several rectangular blocks by a grid. The grid of blocks is also organized by columns, rows and layers. Each block is commonly called a "cell". For each cell, several inputs, including aquifer properties and well information, rivers and other inflow, and outflow features of the cell are specified. MODFLOW uses the input data to build a set of solutions consisting of the head of every cell in the aquifer system at intervals called "time steps." In addition to water levels, MODFLOW also calculates the water budget for the system (Alexander and Palmer, 2007).

In this research, groundwater condition in October 1991 was selected as the stable initial condition for model calibration (Ebrahimi *et al.*, 2016). For model calibration, hydraulic conductivities (K), recharge and discharge (R) and bedrock elevation were considered. Input parameters were adjusted during model calibration by using a trial-and-error process. The observed and estimated values of water table level were compared for 23 wells. To investigate the effects of climate change on groundwater resources in 2030, the predicted values of annual rainfall by LARS-WG were considered as the initial data in the MODFLOW model.

2.2.3 Groundwater recharge prediction. The inverse modeling approach and RS technology were used to quantify the groundwater recharge via predicted rainfall (Ebrahimi *et al.*, 2016). The regional factor of deep percolation of precipitation was applied to the model for all rainfall layers during a prediction period. According to the results of this study, deep percolation is estimated to be about 10.8 per cent of the annual precipitation (Ebrahimi *et al.*, 2016).

To predict the groundwater recharge via future rainfall, the predicted rainfall (2015-2030) was separated into 32 periods of stress (six-month length). The precipitation layers were prepared using geographic information system (GIS) and forecasted data via LARS model. The quantity of the groundwater recharge was extracted from existing water budget tables.

Because of groundwater decline in the recent years, increasing groundwater exploitation was limited via Iranian Government. So, the authors supposed that groundwater discharge would continue with a rate similar to the latest year. To forecast the impact of the future climate change on groundwater resources in the next 16 years, three scenarios were supposed. For the first scenario, annual rainfall is considered to be equal to the long-term average rainfall (265 mm). Predicted rainfall via LARS-WG model was applied for the second scenario. Given that the HADCM3 is a decade-long scale model, the three-year moving average of predicted rainfall (2015-2030) was used as the annual rainfall in the third scenario.

3. Results and discussion

3.1 Climate series generation

Simulated and observed monthly weather parameters (temperature and precipitation) in the study area (2010-2014) are shown in Figure 4. According to the results, in terms of time of the rainfall events, an acceptable relationship was observed between measured and predicted monthly rainfalls for all models.

According to the results, HADCM3 was selected as the best model for Mosian basin (R^2 = 74 per cent). Results of the HadCM3 model show that the lowest precipitation occurred in May, June, July, August and September. According to HADCM3-SRA2 emission scenario, precipitation will decrease by 3 per cent in 2030. A significant correlation was observed between long-term observed and predicted monthly rainfall; however, the predicted rainfall in September and January was higher and predicted rainfall in February-June was less than long-term measured rainfall (Figure 5a). These results show that future rainfall concentration will change from the late winter and spring to fall.

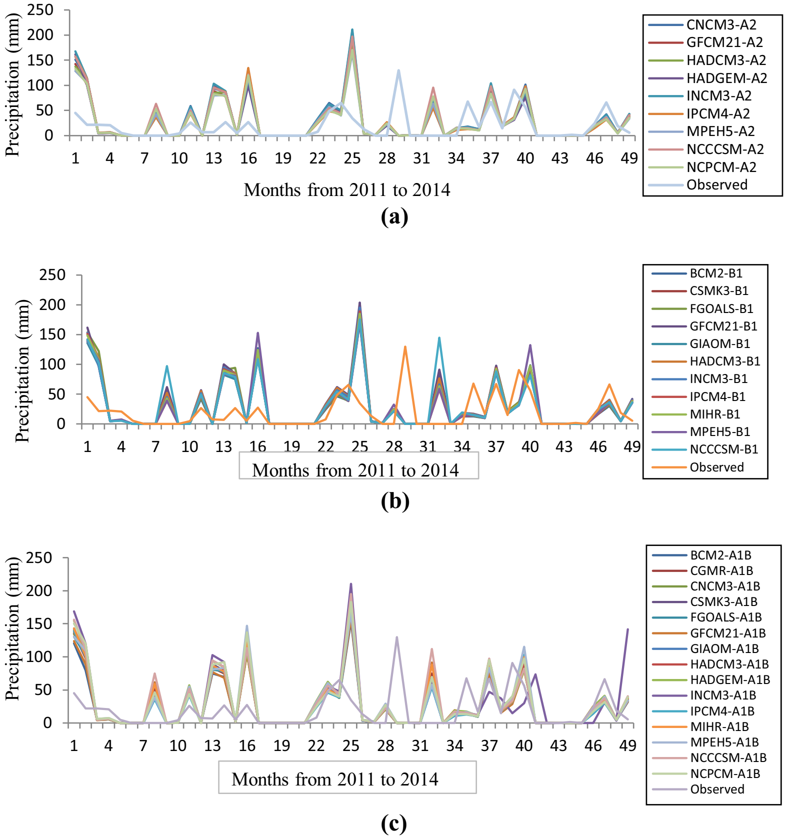


Figure 4.
Monthly precipitation at Mosian during 2011-2014 generated using different climate models under three emission scenarios

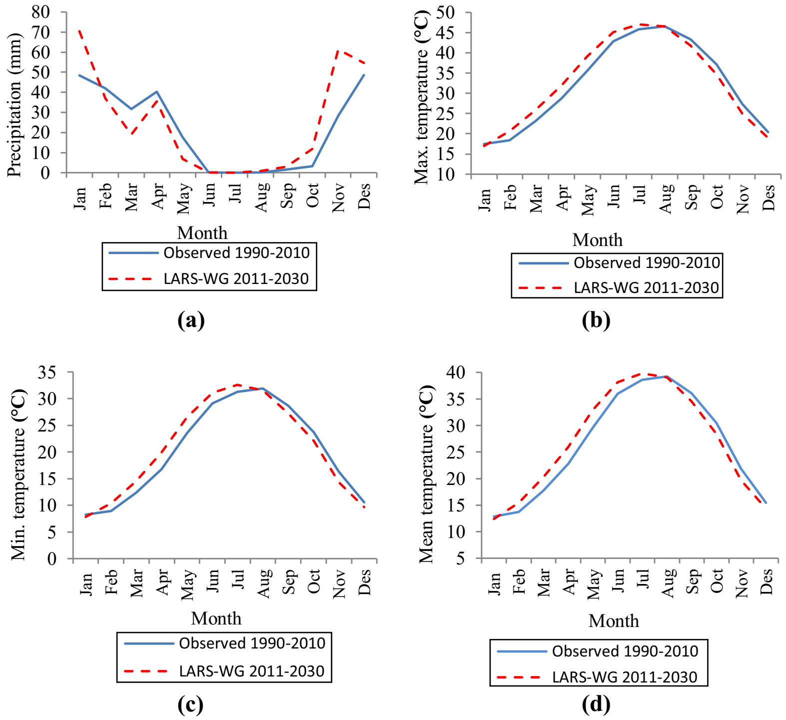
Notes: (a) A2 emissions scenario; (b) B1 emissions scenario; and (c) A1B emissions scenario

Predicted long-term mean monthly temperature (minimum, maximum and mean monthly) from February to July was less than the long-term temperature, whereas predicted temperature from September to January was higher than the long-term temperature. According to these results, the mean winter temperature will decrease, while the mean summer temperature will increase. Consequently, colder winter and warmer summer will occur, but the mean annual temperature will just rise by 0.5°C.

According to the obtained results, the predicted maximum and minimum rainfall for the second scenario (predicted rainfall via LARS-WG) were 305 and 171 mm, respectively. Predicted maximum and minimum rainfall levels for the third scenario (three-year moving average) were 275 and 243 mm, respectively.

3.2 Groundwater flow modeling

Based on the results of groundwater modeling in the unsteady state, the coefficient of determination (R^2) and correlation coefficients (R) were 98 and 99 per cent, respectively (Figure 6).



(a) (b)

(c) (d)

Notes: (a) Precipitation; (b) maximum temperature; (c) minimum temperature; and (d) mean temperature

Figure 5.
Observed and predicted monthly weather parameters at Mosian plain generated using HADCM3 climate model under A2 emission scenario for 2010-2030

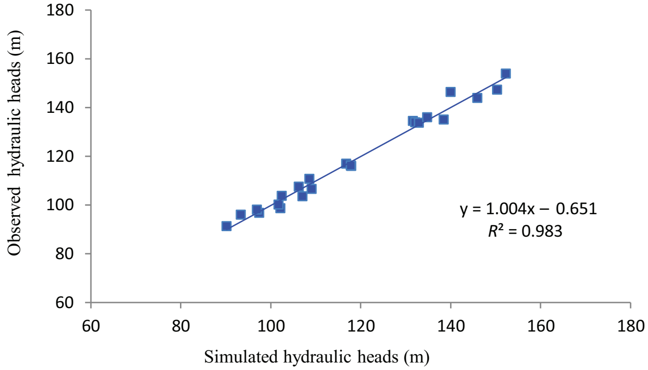


Figure 6.
Observed and simulated hydraulic heads in the steady-state condition (October 1991)

For model calibration and validation in the unsteady state, we considered groundwater level from 1991 to 2014, when the groundwater level decreased sharply (Figure 7). The calibration stage (1991-2006) was divided into 32 tension periods. The model parameters were applied for all periods (except hydraulic conductivity and bedrock elevation that were calibrated in the stable stage). The model was calibrated via a trial-and-error method until an acceptable accuracy was observed between observation and simulation water table level in 23 observation wells. Based on the results, after calibration, the coefficient of determination and correlation coefficient were 0.94 and 0.96, respectively.

For 16 stress periods (2007-2014), data layers were applied for model validation and simulation. For each well, the simulated data were compared with observed data. The R^2 and R for validation period were estimated to be 0.93 and 0.96, respectively. The results of the calibration and validation stages show integrity and efficiency of the model as a management tool to assess various options and scenarios.

3.3 Impact of climate change on groundwater recharge

To investigate the impacts of climate change on groundwater recharge, three management scenarios were formulated (Figure 8):

- *The first scenario*: In this scenario, the long-term precipitation of the study area (265 mm) was considered as the annual precipitation for MODFLOW model. Based on the results of groundwater modeling by using this scenario, the mean of simulated annual natural groundwater recharge by rainfall during 2014-2030 will be equal to 7.457 MCM.
- *The second scenario*: In this management scenario, the predicted annual rainfall by the LARS model was used as the input for the MODFLOW model I the 2014-2030 period. The amount of annual natural groundwater recharge was estimated under this management scenario. The results showed that the annual recharge during the

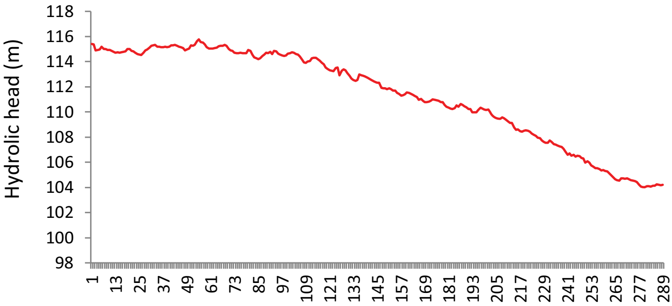


Figure 7.
Monthly average of the hydraulic head of the Mosian plain (1991-2015)

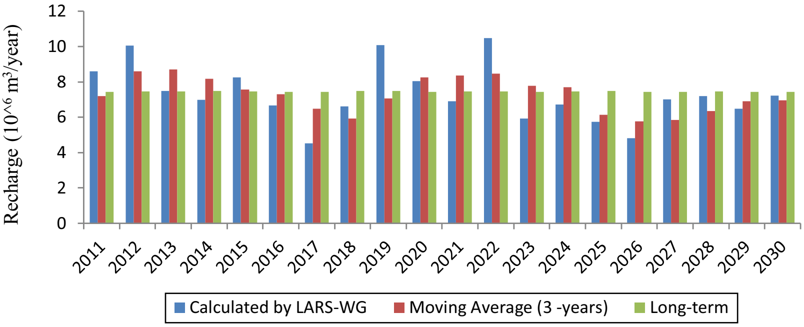


Figure 8.
Predicted groundwater recharge via precipitation in Mosian aquifer during 2011-2030 under three rainfall scenarios

forecast period will vary from 4.511 to 10.467 MCM; so, the average of the annual simulated recharge will be 7.29 MCM.

- *The third scenario*: Using predicted rainfall data by LARS, the three-year moving average of rainfall was calculated as the annual rainfall during the forecast period. According to this scenario, the mean annual natural groundwater recharge will be 7.27 MCM, with a maximum of 8.7 MCM and a minimum of 5.7 MCM. Based on these results, the water table level should decline by about 10 m during this period.

The results of the groundwater modeling show that groundwater recharge via rainfall variability should decrease in the coming 16 years. Simulated groundwater recharge was 7.457 MCM when a long-term average rainfall of the study area was applied. The average of annual groundwater recharge could decrease to 7.29 MCM when using annual rainfall predicted by the LARS model as the input of the MODFLOW. According to the results, the decline in the groundwater level in the study area was 11.45 m during the past 24 years or 0.48 m/year (Figure 7). Annual groundwater depletion should increase to 0.75 m in the coming 16 years via climate change.

4. Conclusion

This study was conducted to assess the impact of climate change on natural recharge in an arid environment. Based on the results, a GCM, HADCM3, was selected as the optimum model to predict the weather parameters in the study area. The results of HADCM3 model show that the mean annual rainfall in the study area will decrease by about 3 per cent, while the mean annual temperature will increase by about 0.5°C. Such a temperature rise was also reported by Goudarzi *et al.* (2015) for the Herat watershed Herat-Azam in Yazd Province in the center of Iran.

Gohari *et al.* (2013) showed that monthly temperature in Zayandeh-Rud River basin, in the center of Iran, will increase by 1.1-1.5°C under climate change condition, while the results of Reddy *et al.* (2014) show an acceptable performance of LARS, an increase in the mean annual rainfall and a decrease in the annual maximum and minimum temperatures in the Yacharam region in India. Comparing these results, the authors conclude that climate change should have different effects on rainfall and temperature depending on geographical condition.

To assess the impact of climate change on natural recharge limits, long-term mean annual rainfall was imported into the model as the annual rainfall during the future period. The aim of this scenario was to predict the aquifer condition considering that the current situation will persist in the studied aquifer. Based on the results, the natural annual groundwater recharge values under second (using predicted rainfall data by LARS) and third (using a three-year moving average of the predicted rainfall) scenarios were estimated to be 0.167 and 0.190 MCM, respectively, less than the long-term amount of groundwater recharge. The authors can conclude that groundwater recharge decreased via climate change.

The results show that the decline of groundwater level in the study area is 11.45 m during the past 24 years or 0.48 m/year. Annual groundwater depletion should increase to 0.75 m in the coming 16 years because of a climate change and over-extraction. Some other studies also showed that natural recharge should decrease as a result of climate change (Woldeamlak *et al.*, 2007; Toews and Allen, 2009; Russell *et al.*, 2013).

Although the studied approach provides some valuable insights into the studied problem, the climate change study should be conducted also using other models and emission scenarios such as the last The International Climate Governance Coalition (ICGC) scenarios (The Representative Concentration Pathways [RCPs]).

As water is the major limitation of the sustainability in the arid and semi-arid regions, climate change adaptation policies in the basin should include changing the crop type and enhancing water productivity and irrigation at the farm and regional scales. In particular, policy-makers should consider minimizing agricultural water demand through changing crop patterns as an effective policy solution for the basin's water problems (Gohari *et al.*, 2013).

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