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An extended modeling approach to assess climate change impacts on groundwater recharge and adaptation in arid areas

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Abstract

The impact of future climate scenarios on surface and groundwater resources was simulated using a modeling approach for an artificial recharge area in arid southern Iran. Future climate data for the periods of 2010–2030 and 2030–2050 were acquired from the Canadian Global Coupled Model (CGCM 3.1) for scenarios A1B, A2, and B1. These scenarios were adapted to the studied region using the delta-change method. The modified version of the HBV model (Qbox) was used to simulate runoff in a flash flood prone catchment. The model was calibrated and validated for the period 2002–2011 using daily discharge data. The projected climate variables were used to simulate future runoff. The rainfall–runoff model was then coupled to a calibrated groundwater flow and recharge model (MODFLOW) to simulate future recharge and groundwater hydraulic head. The results of the rainfall–runoff modeling showed that under the B1 scenario the number of floods might increase in the area. This in turn calls for a proper management, as this is the only source of fresh water supply in the studied region. The results of the groundwater recharge modeling showed no significant difference between present and future recharge for all scenarios. Owing to that, four abstraction and recharge scenarios were assumed to simulate the groundwater level and recharged water in the studied aquifer. The results showed that the abstraction scenarios have the most substantial effect on the groundwater level and the continuation of current pumping rate would lead to a groundwater decline by 18 m up to 2050.

1 Introduction

Groundwater (GW) is the major source of fresh water for humans. However, during the last decades, GW decline has been observed both at local and regional scale. GW reserves constitute more than 70 % of water supply in arid environments (Rosegrant and Ringler, 2000; Llamas and Martínez-Santos, 2005; Siebert et al., 2010; Surinaidu et al., 2013) now often being depleted due to over-extraction for irrigated agriculture.

Also, due to climate change, it is anticipated that GW will be increasingly important in arid areas due to extended drought periods (IPCC, 2007). Further, as many GW reservoirs are non-renewable on meaningful time scales for human society (Kløve et al., 2013), climate change adaptation through aquifer management is an urgent need to balance and, especially, rehabilitate already depleted aquifers.

A comprehensive climate change review by Dore (2005) reveals increased variation of precipitation all over the world with elevated precipitation in wet areas and reduced precipitation in dry regions. While there is uncertainty in climate change projections regarding whether there will be increase or decrease in temperature and precipitation in most parts of the world (e.g. McMichael et al., 2004; Bell et al., 2004; Zhang et al., 2006; Priyantha Ranjan et al., 2006; Jyrkama and Sykes, 2007; Beniston et al., 2007; Giorgi and Lionello, 2008; Toews and Allen, 2009; Barthel et al., 2012), almost all climate models predict either no change or noticeable decrease and increase in precipitation and temperature in the arid Middle East, respectively (e.g. Bou-Zeid and El-Fadel, 2002; Felis et al., 2004; Abbaspour et al., 2009; Evans, 2009, 2010).

The climate change impacts are expected to be more extreme in the arid world including the Middle East. Hence, adaptation is needed to cope with changing water resources in view of the economic situation of the region. Furthermore, the impacts for GW resources may be even more severe due to decreased precipitation, increased potential evapotranspiration (ETP), and possibly more intense GW abstraction rates in the future (Brouyère et al., 2004; Surinaidu et al., 2013). Therefore, an adaptive approach that takes into account the past, current, and future conditions of the hydrological cycle is necessary to manage this vital resource in a sustainable way. Moreover, an appropriate technique needs to be applied in order to appropriately predict the future GW availability in particular regions.

Many techniques have been applied for climate change impacts on GW recharge and their influence on reservoirs by scholars around the world. These include direct effects of projected precipitation (e.g. Candela et al., 2009) or runoff (e.g. Eckhardt and Ulbrich, 2003) on recharge and groundwater level (GWL). A common approach for subsurface hydrology prediction is to use the results acquired from General Circulation Models (GCMs). This involves downscaling of the projections from a course-grid scale of a GCM to a finer scale, creating time series of future possible recharge periods, and applying the projected recharge periods as an input to the hydrogeological models (Barron et al., 2010, 2012).

In principal, climate change impacts on GW resources are indirect consequences of changes in precipitation, temperature, ETP, and surface runoff. Hence, hydrological model runs for climate change impact studies should be integrated with simultaneous consideration of the above processes (Kløve et al., 2013).

GW recharge and abstraction are the major constraints for safe GW yield (Döll and Flörke, 2005). In most arid and semiarid environments, direct recharge from rainfall is considered to be less than 1 %. Thus, GW recharge mainly takes place during runoff and infiltration process (Dugan and Peckenpaugh, 1985; Bedinger, 1987; Bouwer, 1989, 2000). Runoff generation highly depends on rainfall quantity and intensity, morphological and geological characteristics, and land surface coverage of a catchment that eventually ends up in terminal salt lakes, swamp or the sea. However, there are techniques that can be employed to artificially recharge the GW by diverting runoff from a river channel to a command area, e.g. spreading basin, infiltration pond, or injection well. Moreover, the lack of perennial rivers and other permanent watercourses in most arid areas means that runoff in the form of flash flood is the main source of surface water (Hashemi et al., 2013). For this, it is important to keep in mind that climate change may influence runoff quantity and temporal variability, which may result in changed GW recharge in the future.

Kløve et al. (2013) noted that for climate change impact studies on GW systems an integrated multidisciplinary monitoring approach is necessary in order to better define the interaction between all hydrology components, land use management, and the GW system. Modeling is needed to link the complex natural processes to GW extraction, land use, and management effects. Though, the acquisition of land use changes, water extraction, and GW data together with groundwater-surface water interaction are fundamental.

2 Review of climate change impacts on groundwater resources

In general, the main aim of studying climate change impacts on GW systems is to predict the, (1) changes in GW recharge rate in different recharge periods (e.g. Eckhardt and Ulbrich, 2003; Scibek and Allen, 2006; Jyrkama and Sykes, 2007; Toews and Allen, 2009; Meddi and Boucefiane, 2013) and to predict the, (2) change in GWLs (e.g. Surinaidu et al., 2013; Goderniaux et al., 2009). It is likely that the signals seen in recharge are also seen in GWLs, but the response would be different as the aquifer size varies (Kløve et al., 2013).

The choice of recharge model is dependent on the system complexity and modeler preferences. For recharge the easiest way may be to use a simple regression model, which is used to predict recharge rate where annual recharge is assumed to vary linearly with annual rainfall (Barron et al., 2010). For this, GCMs simulated precipitation rates are used to predict inflow to a calibrated GW model (Hanson and Dettinger, 2005; Surinaidu et al., 2013). In other words, the predicted recharge is mainly based on direct precipitation, which may not be accurate, particularly, in arid regions where the direct rainfall recharge is expected to be less than 1.0 %. In addition, GW recharge has a random behavior depending on the sporadic, irregular, and complex features of storm rainfall occurrences, land cover and land use variability, soil moisture, and geological composition (Şen, 2008). This leads to nonlinear relationship between precipitation and recharge. Further, Ng et al. (2010) defined that for most climate alternatives, predicted changes in average recharge are larger than the corresponding changes in average precipitation.

Surinaidu et al. (2013) employed a GW modeling approach to estimate the aquifer parameters and GW flow. In their study, the net recharge from all hydrological components and GW discharge in the studied catchment were estimated based on empirical equations derived between rainfall data and GWL. Based on this, the average GW recharge coefficient was estimated to be 11 % of annual rainfall. They also applied linear regression between historical rainfall and river discharge data to estimate the potential surface water available in the future, which then was added to the annual estimated recharge for the future climate scenarios.

Some researchers have used the bucket method (Barron et al., 2010) to predict recharge based on a series of descending storages to estimate the water storage in soil layers. It is assumed that the direct areal recharge to the aquifer occurs from a combination of weather data, stream, soil characteristics, vegetation, and land cover data. Some wide spread models using this method are HELP and SWAT (e.g. Jyrkama and Sykes, 2007; Toews and Allen, 2009; Abbaspour et al., 2009). Eckhardt and Ulbrich (2003) carried out a regional climate change impact study on plant transpiration induced by changes in atmospheric CO_2 concentration and its consequences on GW recharge and stream flow for a central European low mountain range by SWAT model. They concluded that the resulting effects on mean annual GW recharge and stream flow are small due to the balance between the increase in plant interception and ETP due to the temperature rise and the reduction of stomatal conductance resulting in decrease in transpiration.

There are also integrated physically based hydrological models that consider water exchange between surface water, unsaturated, and saturated zones within one model frame, e.g. MIKE-SHE, MOHISE, HydroGeoSphere (e.g. Brouyère et al., 2004; Goderniaux et al., 2011, 2009; Stoll et al., 2011). van Roosmalen et al. (2009) used an integrated process based on a surface–groundwater model in order to study the intricate, nonlinear relationships between the land surface, unsaturated, and saturated zones under changing conditions through the large number of parameters by MIKE-SHE. Their study showed that climate change has the most substantial effect on the hydrology of a large-scale agricultural catchment in Denmark. Yet, it should be mentioned that the model performance highly depends on the quantity of collected data, which may result in less accuracy in data-poor regions.

Kløve et al. (2013) stated that the quantification of climate change impact on GW reservoirs and recharge rates can be explored by GW models with future climate scenarios acquired from GCMs (e.g. Hanson and Dettinger, 2005; Dams et al., 2011; Leterme et al., 2012). In this approach, couple modeling is an appropriate method taking into account the generated runoff produced by climate sequences. This approach can be assumed the most appropriate for predicting recharge in arid areas where surface runoff is the major water supplier. However, the appropriate choice of GW model to adequately estimate the recharge rate is fundamental. Okkonen and Kløve (2011) carried out a sequential simulation of three models to estimate the temporal and spatial variation in surface–groundwater interaction. For this, they used the Watershed Simulation and Forecasting System (WSFS) model to estimate areal precipitation and temperature and to simulate the surface water levels in lakes and rivers in a cold climate watershed in Finland. The output of the WSFS model, precipitation and temperature, were used as input to the CoupModel to simulate aquifer GW recharge rates. The simulated surface water flow and recharge rate were finally imported to MODFLOW to simulate the GW flow, surface–groundwater interaction, and to predict the GWLs change in view of future climate change scenarios. Although, they used CoupModel to estimate recharge rate, the estimated value is based on precipitation and temperature and not surface water availability. Barron et al. (2012) employed extensive couple modeling to project the future GW recharge and GWL at regional scale in Australia. In their study the coupled surface–groundwater model was first calibrated for the period 1975–2007 and the climate sequences were then used as input to the calibrated models for the projection of impacts on runoff and GW balance. They concluded that the methods used are suitable for regional-scale estimates but to assess local impacts on water dependent ecosystems and water yields, finer scale modeling and analysis would be required.

To the authors' knowledge there are very few studies on climate change impacts on GW resources in which the effects of projected rainfall on surface runoff and its consequences on GW recharge are considered, particularly for arid areas and at a local-scale. In view of this, we used an extended couple modeling approach for studying climate change impacts on GW resources and adaptation scenarios in an arid region of Iran. We applied a methodology that is able to estimate GW drawdown, based on already calibrated rainfall–runoff and recharge models. For this, three GCMs scenarios, A1B, A2, and B1, were used as input to a coupled one-way surface–groundwater model for the periods 2010–2030 and 2030–2050. The novelty of this research is to apply several artificial recharge and pumping scenarios employing the calibrated GW model for recharge rate in order to identify the possible GW management alternatives. In the adaptation scenarios through GW modeling, variable pumping for irrigated farmlands and management scenarios through floodwater harvesting systems were undertaken.

3 Description of the study site and observed data

3.1 Study area

The study was carried out in the Gareh–Bygone Plain (GBP), which is located between 53°53′ and 53°57′ longitude and 28°35′ and 28°41′ latitude at an altitude ranging from 1125 to 1185 m above mean sea level, 190 km southeast of Shiraz City, Iran. The landscape is low sloping and the plain is composed of a coarse calcareous alluvial fan with an average thickness of 25 to 30 m on a red-clay bedrock. The plain is mainly covered by sand deposit. This unconsolidated geologic medium has created an unconfined aquifer with an area of 6000 ha constituting part of the 18 000 ha plain.

The longest rainfall record in the area (since 1972) exists at the Baba-Arab hydrometeorological station, 15.7 km southwest of the GBP. The climate of the GBP is extremely dry and hot with a minimum and maximum annual rainfall of 55 and 557 mm, respectively. Mean annual rainfall is 255 mm and the mean annual class-A pan potential evaporation is 2860 mm. Furthermore, temporal and spatial rainfall variation is extreme. The rainfall pattern is mainly influenced by the Mediterranean synoptic system moving from the west to the east of the country. Typically, rain falls after long dry periods as sudden storms and intense showers resulting in flash floods.

There are two ephemeral rivers in the studied area, namely the Bisheh-Zard and Tchah-Qootch Rivers that discharge from two upper intermountain basins (Bisheh-Zard and Tchah-Qootch) with catchment sizes of 192 and 171 km^2, respectively (Fig. 1). These two ephemeral rivers, with recorded discharge on 107 occasions between 1983 and 2012, comprise the main source of incoming surface water onto the GBP. These rivers join in the lower southeastern part of the GBP. Flood duration typically varies between 2 and 40 h. Further, due to the physiographical characteristics of the upper basins a 5 $\mathrm{mm\,h}^{-1}$ intensity rainfall event can generate a significant flash flood. The non-vegetated, steep slope, and the imperviousness of the upper basin surface covered by sandstone, siltstone, and marl are the main factors in determining runoff amount.

Due to the scant water resources in the GBP, an adaptive approach for artificial recharge of GW through floodwater harvesting was proposed in 1983 to improve the livelihood of the inhabitants. The main purpose was to increase GW availability to support irrigated agriculture. Five different but interconnected FWS systems were first established in 1983 with an area of about 1365 ha and extended to twelve FWS systems with the total area of 2033 ha in 1996 (Kowsar, 1991, 2009). The system diverts surface runoff from the ephemeral rivers onto the consecutive recharge basins, which then the floodwater infiltrates down and percolate to GW reservoir. Hashemi et al. (2014) simulated the GW flow and estimated the aquifer GW recharge rate for the GBP by a numerical model. They calculated that the recharge amount in the studied artificial recharge system, known as floodwater spreading system (FWS), varied from a few hundred thousand cubic meters per month during drought periods to about 4.5 million cubic meter per month during rainy periods. The gain through artificial recharge, however, was decreased by too much abstraction by numerous new-drilled pumping wells. Hence, the GW declined over 10 m in spite of the artificial recharge system.

3.2 Climate scenarios

Global climate models also known as general circulation models (GCMs) are used to assess climate, variability, and vulnerability in the future based on historical records. In this study, we used outputs of the Canadian Global Coupled Model (CGCM 3.1) (Flato et al., 2000) version T63, which has a surface grid with a spatial resolution of 2.81° latitude by 2.81° longitude and 31 levels in the vertical (Abbaspour et al., 2009). With this resolution, 36 grid points fell inside the entire Iran territory. Accordingly, three commonly used daily based climate change scenarios, A1B, A2, and B1, were taken into account considering the climate conditions for the near (2010–2030) and far (2030–2050) future. CGCM baseline data between 1961 and 2000 were also used for impact assessments. The baseline data were used to define the changes in climate between the present day and future conditions (IPCC, 2007) through delta-change approach.

Based on the IPCC (2007) report, the A1B scenario depicts a world with a balanced use of fossil and non-fossil fuel as a main energy source. It assumes very rapid economic growth and population reaches 8.7 billion in 2050. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other scenarios. The B1 scenario describes a convergent world with the same global population that peaks in midcentury and declines thereafter (lower than A2), but with rapid changes in economic structures toward a service and information economy. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

3.3 Atmospheric data

In this study, data were collected from the nearest climatic station to the GBP, named Baba-Arab, 15.7 km southwest of the GBP with more than 40 years recorded daily data. Daily rainfall, temperature, and potential evaporation data of Baba-Arab station were used as the historical data for hydrological projections. As the future projection is based upon 20 year time intervals, all climate scenarios were assigned based upon the most recent observed daily time sequences of climate variables from 1 January 1990 through 31 December 2009.

3.4 Hydrological data

Due to missing observed daily potential evaporation for the years between 1990 and 2001, a statistical method was used to project ETP using daily temperature records. For this, the available observed daily ETP as a function of temperature was calculated between 1 October 2002 and 30 September 2011 (Fig. 2). The result shows a strong correlation between ETP and temperature for the studied area ($R^2 = 0.82$). In all future scenarios, the derived regression equation was applied to the projected temperature to achieve anticipated potential evaporation for the same periods.

As mentioned before, there are two ephemeral rivers flowing down from the upper intermountain catchments in the studied area, which are the main source of flash floodwater into the FWS systems. However, there is no reliable observed discharge data for these rivers, and yet the GW recharge model only works with the flood periods and not the magnitude of the floods. Thus, we decided to use the recorded discharge data at the outlet of the contiguous basin, Baba-Arab Basin, with similar characteristics to the studied areas' upper catchments in terms of geology, topography, land use, and climatology (Figs. 1 and 2). Accordingly, the recorded daily data of Baba-Arab discharge station were applied in a rainfall–runoff model to simulate the stream flow from 1 October 2002 through 30 September 2011.

In the studied aquifer, GW hydraulic heads have been recorded on a monthly basis since 1993 by the Fasa District Water Organization. The observed data from six boreholes distributed within the GBP were used in this study to simulate GW flow and estimate aquifer hydraulic parameters between 1993 and 2007. To verify the GW modeling results, the measured hydraulic parameter values derived from two pumping tests (Hashemi, 2009) were also taken into account to compare with the estimated values.

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4 Methods

4.1 Delta-change

Okkonen and Kløve (2011) defined that the delta-change approach (Hay et al., 2000) has the advantage of preserving the observed patterns of temporal and spatial variability from the gridded observations of precipitation and temperature. It is also more relevant to directly compare the observations and future scenarios. Accordingly, the delta-change approach was used to define the differences between the CGCM-simulated current (baseline, 1961–2000) and future scenarios (A1B, A2, and B1 and for periods 2010–2030 and 2030–2050). Then, the derived differences were applied to the historical/observed data to generate future scenarios. It is noted that as all future CGCMs output data were assigned for the two twenty-year periods, 2010–2030 and 2030–2050, the most recent twenty-year historical data between 1990 and 2010 were used to generate climate data for hydrological projections by repeating this twenty-year observed data in each climate scenario.

In the first step, as the local conditions may be varied from what we observe from large scale and in order to regionalize the CGCMs outputs for the entire country, average daily values of the 36 grids covering the whole country were calculated for both baseline and future scenarios to achieve only one value for each single day out of the 36 grids. Then, the differences between the average daily values of the baseline and all future scenarios were derived. In the final step, the derived difference of rainfall and evaporation between the baseline and future scenarios (in percent) was multiplied with the daily values of historical data between 1 January 1990 and 30 December 2009. In the case of temperature data, the observed values (historical data) were scaled by adding the calculated differences between baseline and future scenarios.

4.2 Description of the numerical models

In the IPCC report on climate change and water, Bates et al. (2008) conclude that the climate change affects GW recharge rates and GWLs. However, knowledge of current recharge levels in developing countries is poor; and there have been very few studies on the future impacts of climate variability on GW and surface–groundwater interactions. This issue is even more crucial in the arid world where the agriculture is very much dependent on GW resources.

As the GWL in the arid and semiarid areas is often rather deep and the variation in adjacent surface water level is not affected by GW discharge, there is no need for two-way coupling and, thus, one-way coupling between surface runoff and GW reservoir would suffice (Ataie-Ashtiani et al., 1999). Accordingly, a sequential surface–groundwater modeling was undertaken to simulate the runoff, GWL, and GW recharge for the past, current, and future studied periods. The analysis of climate change impacts on the GW reservoir in the studied region was based upon the projected runoff and GW recharge as the results of rainfall–runoff (Qbox) and GW (MODFLOW) modeling. In the final step, four different adaptation and management scenarios for GW artificial recharge and abstraction rates were applied to the calibrated GW model in order to assess the GW safe yield in the next 40 years (Fig. 3).

4.2.1 Hydrological modeling

Rainfall–runoff modeling can be 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. The model is a modified version of the HBV model (Lindström et al., 1997) in terms of structure, parameterization, and performance. In general, the model includes a soil-water box and a runoff box, which is built on the continuity equation for each box and a number of auxiliary relationships. The model uses daily values of discharge, precipitation, mean temperature, and ETP as inputs to simulate water storage and flow through the soil profile and on the ground surface, respectively.

In this study, the rainfall–runoff model was first calibrated using daily flow data from Baba-Arab discharge station for the historical climate period between 1 October 2002 and 30 September 2008. Then, the model was validated for daily data between 1 October 2008 and 30 September 2011. The calibrated model was then used to simulate runoff in the future utilizing future climate variables projected by the delta-change approach. The future simulated runoff was finally imported to the GW model to simulate the GW flow, estimate the GWL, and the recharged water. It is noted that as the GW recharge package in MODFLOW only works with the flood periods and not the magnitude of the floods. Though, the primary intension was to project the flood periods using the projected climate variables.

4.2.2 Groundwater modeling

A GW flow and recharge model was developed for the GBP using GMS version 9.1 (Owen et al., 1996) to simulate GW flow and estimate aquifer hydraulic parameters by MODFLOW-2000 (Harbaugh et al., 2000). The model was run for both steady-state and unsteady-state conditions and calibrated and verified against observed hydraulic head in the boreholes. In the steady-state modeling, GW flow and boundary conditions were simulated and horizontal hydraulic conductivities were estimated (Hashemi et al., 2012). The outputs of the steady model were thus transferred to the unsteady model to estimate specific yield, recharge rate, and recharged water volume, through both natural river channel and artificial recharge system. The model period spanned between 1993 and 2007. The results showed that the artificial recharge system in a normal year contributes about 80 % in total recharge while the natural river channel recharge contributes about 20 % in the total recharge of GW (see further Hashemi et al., 2013).

For the future recharge projections, the output of the rainfall–runoff model (future projections) was assigned as the input to the GW model. For this, the projected flood events were considered as recharge periods in the GW model. Furthermore, the mean estimated recharge rate acquired from the 14 year calibrated model was assigned as a recharge parameter for all future scenarios. It is noted that not all the surface runoff is diverted to the artificial recharge systems but only when the runoff reaches a certain level. Though, according to the hydraulic structure of the diversion dam and conveyor canal, it was assumed that when the flood peaks over 15 $m^3 s^{-1}$, the flood is diverted to the system and recharge is taken place through both the river channel and the FWS systems. Although the recharge occurs through the river channel in either case (more than 15 $m^3 s^{-1}$ and less than 15 $m^3 s^{-1}$) but as mentioned above, in the case of small flood events the river channel contributes only 20 % or less in total recharge, hence, no recharge was assumed in the GW model in this case.

4.3 Adaptation scenarios through groundwater modeling

Artificial recharge through FWS has been actively promoted in different parts of arid Iran since the 1980s (Ghayoumian et al., 2005). The main objective of the system is GW augmentation and spate irrigation in order to increase agricultural productivity and, in general, enhancing the rural livelihood. Although, the GW artificial recharge has been one of the main interest of the governmental policy throughout the last couple of decades illegal pumping and over-exploitation of aquifers have been the main challenge decreasing this vital resource. As the abstraction rate often exceeds the natural recharge of GW, four different GW recharge and abstraction scenarios were applied to the calibrated GW model taking into account all climate scenarios (A1B, A2, and B1) during the near and far future periods.

In the first scenario, the average abstraction rate between 1993 and 2007 (considering all existing active 80 wells in 2007) was assigned to the model. A maximum recharge contribution through both artificial recharge systems and natural river channel was considered in the model taking into account the output of the rainfall–runoff model. In the second scenario, pumping scenario was assumed the same as scenario one, but the artificial recharge areas was decreased by half in order to consider the efficiency of the system and its influence on the GW reservoir taking into account the size of the system. In the last two scenarios, the abstraction regime was assessed. In these scenarios, two negative abstraction growth rates were modeled based against the control rate, which was used in the first and second scenarios (average rate between 1993 and 2007). Accordingly, in the third scenario, a maximum recharge was assumed including all existing recharge sources but the number of pumping wells was decreased by half (half of pumping wells were randomly turned off). In the fourth scenario, a maximum recharge was assumed considering all recharge areas and future flood periods, with no abstraction by pumping wells (all pumping wells were turned off in the model).

5 Results

In arid regions, the change in precipitation, surface runoff, and GW recharge are expected to be the most substantial consequence of climate change. These factors will most likely affect the region's sustainability in terms of food security, sustainable environmental management, and socio-economic viability for both local and regional scale. In the following sections the hydrological effects and adaptation scenarios of climate change in an arid region are presented. The projections were carried out for both the near and far future. It is noted that daily time steps were used in the climate variable and runoff projections, but a monthly time step was used in the GW recharge projection. This is due to the monthly basis calibrated GW model as a result of available monthly-recorded GWL data. Thus, the monthly average value of projected runoff was assigned as input to the GW model.

5.1 Effect of climate change on climatological regime

Figure 4 presents the projected precipitation, temperature, potential evaporation for all scenarios, and corresponding variables of historical data. As shown, in the future scenarios, there will be no significant change for all climate variables during the spring and summer seasons (from April through October) relative to the historical climate. It can be concluded that based upon CGCMs outputs and the delta-change method, the climate of the studied region would be almost the same as during the last 20 years (1990–2010) for warm and dry seasons. Hashemi et al. (2014) calculated that since the beginning of 1990s the drought period has been the dominant climate condition for the studied area (Fig. 5). This has caused severe GW decline mainly due to the rapid drought as well as over-tapping of GW resulting in less rainfall and high evaporation during the warm season. According to the climate projections, frequent drought periods will continue up to 2050. Consequently, the GW resource will be further stressed in the coming decades.

During the cold and wet seasons (from November through March), both temperature and potential evaporation is slightly increased in all projected scenarios. This increase reaches a maximum of 1.5 °C in January under A1B scenario for the near future. Accordingly, increase in temperature in the cold and wet season causes increase in potential evaporation up to 24 mm for January. The average increases in temperature for the near and far future are 1.0 and 1.6 %, respectively. As a result, the impacts of climate change on temperature and potential evaporation under scenarios A2 and B1 are almost the same for both future periods with minimum difference in comparison with historical records. Under scenario A1B, the most substantial increase in both potential evaporation and temperature can be seen to decrease the water resources.

Figure 4 shows almost no precipitation changes for the warm and dry months between May and November. In these months, the projected precipitation (in all scenarios) simply replicated the historical records. For the wet and cold months (from November through May), a gradual reduction in precipitation for the months between November and February can be seen under the A1B scenario for both future periods. This reduction reaches a maximum in January for the far future. In the near future, under the B1 scenario the largest increase in precipitation for the entire wet and cold months is projected while the precipitation is dominant for the far future under scenario

A2. In general, the average reduction in precipitation in the near and far future are about 2.0 and less than 1 %, respectively.

5.2 Rainfall–runoff modeling and runoff projection

5.2.1 Rainfall–runoff model calibration and validation

The calibration and validation of the rainfall–runoff model were performed using the observed daily discharge data of the Baba Arab discharge station. The parameterization of the model is partially based on the physiographical characteristics of the basin acquired from topographical maps and satellite imageries. Figure 6 shows a comparison of the observed and simulated discharge for the entire model period. The model was first calibrated using observed daily data for the period from 1 October 2002 through 30 September 2008. Then the optimized parameters were transferred to the validation period from 1 October 2008 through 30 September 2011. According to the figure, model performance is quite satisfactory and the result of the validated model confirms the calibration result, however, in both calibration and validation periods the calculated runoff is slightly underestimated. This could be due to the location of rain gauge station within the catchment. Also, recorded data from only one rain gauge station may not represent the whole Baba Arab Basin with 465 km^2 catchment size.

5.2.2 Effect of climate change on runoff

As the Baba Arab (adjacent basin to the studied area) catchment size, 465 km^2, is about the same as the total size of the two upper catchments of the studied area, Bisheh-Zard and Tchah-Qootch Basins with 192 and 171 km^2, respectively, it was assumed that the projected discharge of the Baba Arab Basin, is equivalent to the total discharge of the two upper catchments of the studied region. Table 1 shows the statistics of flood events larger than 15 $\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{d}^{-1}$ for all emission scenarios and future periods. All scenarios in the future periods, indicate an increase in the number of flood events in comparison with the calibration-validation period with recorded 11 flood events for a nine-year period. Under the B1 scenario, more flood events are projected, particularly, in the near future, which is related to the increase in precipitation for the same period. Although scenario A2 indicates more precipitation in the far future but more flood events were projected for scenario B1 with less projected precipitation amount. It can be concluded that based upon scenario B1, more intense rainfall will occur in both future periods resulting in more flood events. This will lead to more surface water available that will require proper water management strategies.

5.3 Effect of climate change on groundwater recharge and adaptation scenarios

Estimates of projected GWL from the calibrated GW model covering the entire studied area were used to determine possible impacts of climate change on GW storage. For this, three emission scenarios and two future periods were taken into account. Table 2 shows the amount of projected recharged water in all future scenarios. According to the table, more water is recharged to the aquifer under scenario B1, particularly, in the near future. Under scenario A1B, less water is recharged relative to other scenarios for both near and far future. Further, the far future average recharge (19.3 Mm^3) is slightly less than for the near future (21 Mm^3). Therefore, the studied area will suffer more regarding GW availability in the years between 2030 and 2050.

As mentioned before, four different adaptation scenarios were undertaken to evaluate the impacts of climate change on GWL. The average GW drawdowns for all emission scenarios are presented in Fig. 7 taking into account the four adaptation scenarios. The figure shows a comparison between the historical GWL (1993–2013) and the average projected GWL under all emission scenarios (A1B, A2, and B1) in the near future. It is noted that since the same rate of GW drawdown was seen in both near and far future. However, only the results of the near future projection are depicted in Fig. 7.

In the first scenario (Fig. 7a), all conditions were assumed according to the last 20 years management of water resources in the studied region. For simulation of future conditions, it was assumed that the GWL in the beginning of the simulation was at

1136 m a.m.s.l. altitude as recorded in 2010. As can be seen, the spatially averaged GWL decreased by about 8 m below the initial GWL in 2010 by 2030. The same decline occurred by 2050. It can be seen that although the recharge takes place through all FWS systems and the river channel, the abstraction has the most substantial effect on GWL. In this case, the GW declines the same rate as during the last 20 years and the general GWL trend strongly reflects the abstraction associated with water resources management in the area.

In the second scenario (Fig. 7b), the artificial recharge area was decreased by half in order to assess the effect of FWS system on GW in terms of system size and capacity. Further, the abstraction rate was assumed the same as during the last 20 years pumping rate in the area. Although, it is expected that the GWL will be further affected as the artificial recharge area was decreased by half. However, as seen from the figure the GWL falls with the same rate as in the first management scenario including the entire artificial recharge area. This is primarily due to the recharge parameters and boundary conditions assigned in the prediction model.

In general, in view of the first and second adaptation scenarios the GWL may fall beyond the aquifer's bedrock (considering the aquifer saturated thickness) and all active wells would dry out permanently by 2020. Furthermore, as the same GW drawdown was assumed for the far future the impact of abstraction is double by the end of 2050.

In the third scenario (Fig. 7c), the artificial recharge areas were kept as in the first scenario, but the abstraction was reduced by half of the recorded rate in 2000s. As can be seen, there is still a decline of GWL up to 5 m that may fall beyond the critical aquifer depth limit in the far future climate scenario.

In the fourth scenario (Fig. 7d), the artificial recharge areas were kept the same as in the first and third scenarios, but the abstraction rate was reduced to zero (no pumping). Under this scenario, the GWL decline can be shown to be reversed with no withdrawal for the studied aquifer. However, the GW increase rate is still less than the declining rate relative to the historical record. Applying this scenario up to 2050 would significantly recover the degraded GBP's aquifer and provide opportunity to manage the GW resources in the far future.

6 Discussion

The climate change methodology utilized in this study can be used to quantify the effects of climate change and management scenarios on GW resource in an arid environment. The developed method is mainly a one-way coupling (e.g. Okkonen and Kløve, 2011) that can be applied to areas where the GW is rather deep and only the surface water recharges into the GW. In this study, the climate variables were first projected for the near and far future using the delta change approach under emission scenarios (A1B, A2, and B1). The outputs of the climate projection were then transferred to a rainfall–runoff model to project the corresponding runoff for both near and far future. It was assumed, as the GW is deep and the climate of the region is extremely dry, no recharge is taking place from the direct rainfall but instead from the following surface runoff. The projected climate variables show, however, no significant increase or decrease, but under B1 and A2 scenarios the rainfall slightly increases in the near and far future, respectively. It should be mentioned that the climate of the studied region during the historical period (1990–2010) has been suffering by drought in which there is already 40 mm decrease of rainfall in comparison with the average recorded rainfall from 1971 through 1990 (Fig. 5). The projections reveal that the climate impacts will continue to be serious up to 2050.

The results of runoff projection showed that the number of flood event increases under the B1 scenario relative to other scenarios in both the near and far future. This would slightly increase the surface water availability that may lead into more infiltration and percolation to the GW table.

Although, the number of flood events and recharged water in the B1 scenario were larger than the other scenarios (Tables 1 and 2), no major differences in GWL was estimated by the GW recharge model between different emission scenarios (A1B, A2, and

B1). This is primarily due to the characteristics of the unconfined aquifer and variable amount of GW inflow from the upper adjacent aquifer and GW outflow to the below adjacent aquifer. Moreover, a similar rate of GW drawdown was predicted by the model for both near and far future.

In general, assuming the same rate of GW inflow and outflow (unconfined aquifer) and not to include any other impacts, i.e. abstraction, on GW reservoir, the mean GWL increases by 2.8, 3.0, and 3.3 m under A1B, A2, and B1 scenarios up to the year 2050, respectively.

The adaptation and management scenarios were undertaken to find the resilience against the GW depletion in the studied aquifer. Assuming the average aquifer saturated thickness is 5 to 10 m, the results revealed that the GWL may fall by approximately 16 m by 2050 applying the same rate of abstraction recorded in the historical period (scenario 1 and 2). As all pumping wells have been deepened to the bedrock, it can be said that the GW is totally depleted by 2030. This will force the farmers who are totally dependent on GW for irrigation to leave their land and migrate to nearby cities and towns to work in the labor market. This will inevitably cause social and political impacts at both local and national levels. The result also revealed that despite of decreasing the rate of abstraction (scenario 3), the GWL still falls by 10 m by 2050. This also leads to the absolute depletion of GW reservoir in the far future.

Under the forth scenario, the simulation reveals that the GW reservoir can be recovered and the GWL decline reversed when the pumping is stopped for the entire aquifer. Although this would have a major impact on the livelihood of the inhabitants but under the other scenarios (first, second, and third scenarios), pumping causes much damage to the aquifer resulting in no available GW for future farming activity. It is apparent that such over-exploitation and degradation may become permanent as the aquifer may lose its capability of storing water.

The result of the second scenario shows that the change in artificial recharge area may not affect the GWL drawdown. This can, in principal, be due to (1) the recharge parameters assigned in the prediction model and (2) the boundary conditions assigned in the calibration periods. As discussed by Hashemi et al. (2013), the river channel exhibits high infiltration rate in the case of, only, major flood event relative to the artificial recharge area. Yet, the average value of the river bed's recharge rate was transferred to the prediction model, therefore, the river channel was assumed the main recharge contributor in all future scenarios. This result in no significant impact on GW recharge/level by decreasing the artificial recharge area. To deal with this, more detailed analysis and data are needed to separate the extreme events from normal events.

It can also be mentioned that the boundary conditions assigned for the model are not perfectly representing the actual inflow to and outflow from the aquifer. Assumptions behind the boundary conditions and their calibrations are explained in research conducted by Hashemi et al. (2012). As discussed in this research, based on the available data and field investigations the major source of inflow water into the aquifer comes through a fault, which conducts water into the aquifer from the upper intermountain basin (Bisheh-Zard Basin). One possible explanation could be over-estimation of GW inflow through the fault that ranks the inflow into higher magnitude of order relative to the predicted recharge from surface water. Hence, the response from different artificial recharge scenarios cannot be reflected in GWL through numerical modeling.

Despite the fact that we believe the GW model is well calibrated based upon available data, we conclude that more detailed field and geophysical investigations are required to better conceptualize the system in terms of inflow to and outflow from the aquifer. With further investigation, we believe that by numerical modeling we would be able to better predict the future role of artificial recharge in climate change adaptation. Thus, leading to sustainable management of GW resources in the arid environments.

In principal, assuming the artificial recharge areas are the main source of GW recharge, extending the FWS systems together by decreasing the abstraction rate seems to be a prominent and affordable solution to reverse the GW decline in the future. This can be accompanied by converting a part of irrigated land into the spate irrigation farming (Ghahari et al., 2014) in order to minimize pumping rate leading to

GW maintenance. In this case, the impact of reduced pumping would be less on the livelihood of the settlers.

7 Summary and conclusions

In the arid southern Iran, the impacts of climate change during the past couple of decades already exhausted the GW resources. Projections of climate variables, surface runoff, and GWL were undertaken in order to assess the impacts of climate change on the reservoir in the GBP in arid southern Iran. For this, a sequential modeling approach including results from a GCM, a hydrological model, and a GW model was employed. The climate variables were projected up to 2050. In the utilized method, the surface runoff was simulated using a calibrated/validated conceptual model. The results of the rainfall–runoff model (flood period) were then imported to the GW recharge model to simulate the GWL response to different adaptation and management scenarios.

Results of projected climate variables (precipitation, temperature, and ETP) show no significant increase or decrease in rainfall quantity relative to the historical climate but a slight increase in surface runoff. However, minor changes in surface water may result in no change in GWL, which is also confirmed by the GW model. Consequently, on average about 40 Mm^3 floodwater recharges the aquifer during the next 40 years, which is insufficient to meet future demands of the rural community that are primarily dependent on irrigated agriculture.

According to the GWL prediction, applying the current management of water resources in the studied area, all pumping wells would dry out by 2020s and this would have severe social and economic impacts on inhabitants. As a result, 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 modeling to address the sustainable GW management through adaptation scenarios.

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Table 1. Summary statistics of projected runoff for the periods 2010–2030 and 2030–2050.

2010–2030	No. of Flood	Min (m^3 s^{-1} d^{-1})	Mean (m^3 s^{-1} d^{-1})	Max (m^3 s^{-1} d^{-1})	SD (m^3 s^{-1} d^{-1})
A1B	24	13	47	201	47
A2	24	13	58	189	54
B1	28	14	63	200	62
2030–2050	No. of Flood	Min (m^3 s^{-1} d^{-1})	Mean (m^3 s^{-1} d^{-1})	Max (m^3 s^{-1} d^{-1})	SD (m^3 s^{-1} d^{-1})
A1B	19	15	65	187	53
A2	25	15	65	193	61
B1	26	14	60	194	57

Table 2. Projected total recharged water (million m^3) under A1b, A2, and B1 scenarios for near and far future.

Scenario	A1b (Mm^3)	A2 (Mm^3)	B1 (Mm^3)	Average (Mm^3)
2010–2030	19.2	19.3	24.4	21.0
2030–2050	18.1	20.6	19.3	19.3
Total	37.3	39.9	43.7	40.3

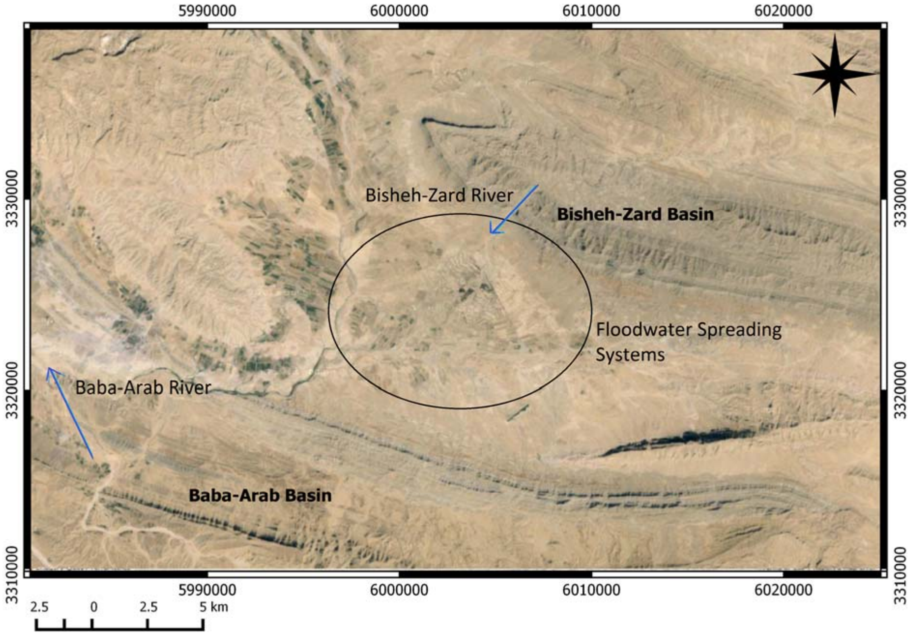

Figure 1. Location of the floodwater spreading systems within the studied area (source: Spot Image through Google Earth).

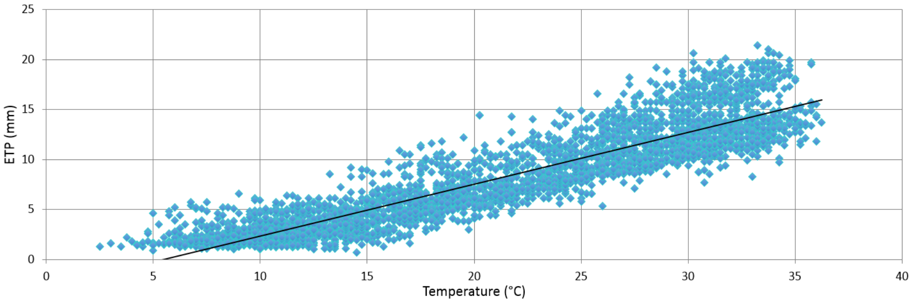

Figure 2. Observed daily mean temperature vs. observed daily potential evapotranspiration (ETP) at the Baba-Arab meteorological station for the period from 1 October 2002 through 30 September 2011.

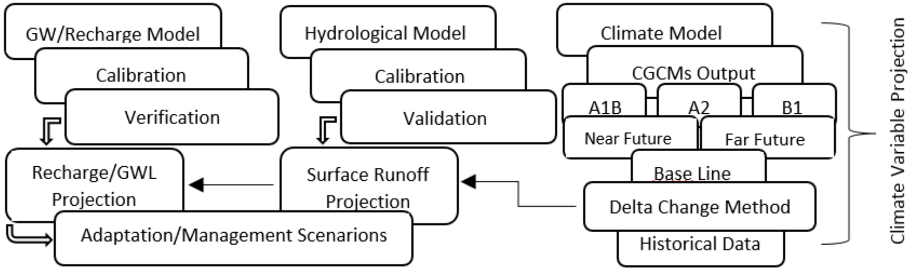

Figure 3. Flow chart showing the methodology used in this study to project climate change impacts on surface water and groundwater recharge/level in an arid region.

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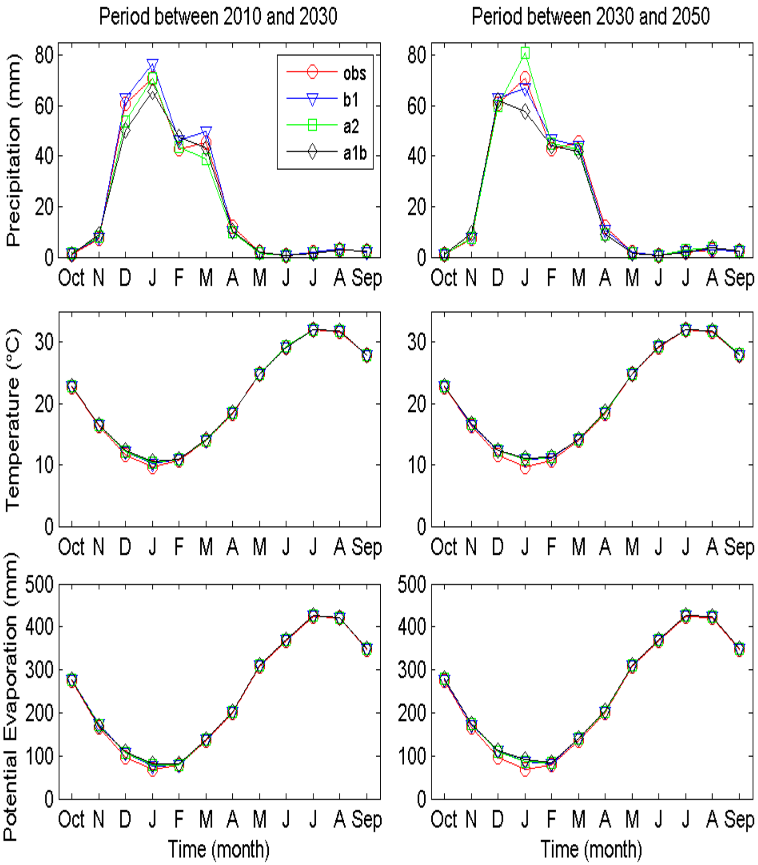

Figure 4. Mean monthly precipitation (mm), temperature (°C), and potential evaporation (mm) for historical climate data (1990–2010) relative to A1b, A2, and B1 scenarios for the periods 2010–2030 and 2030–2050.

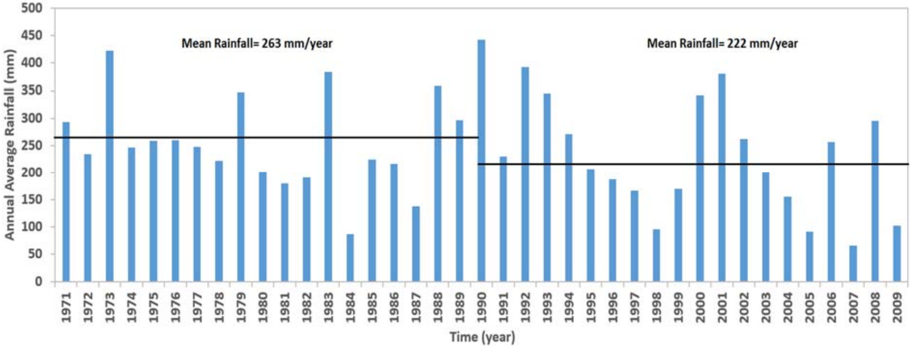

Figure 5. Comparison of mean annual rainfall for the periods 1971–1990 and 1990–2010.

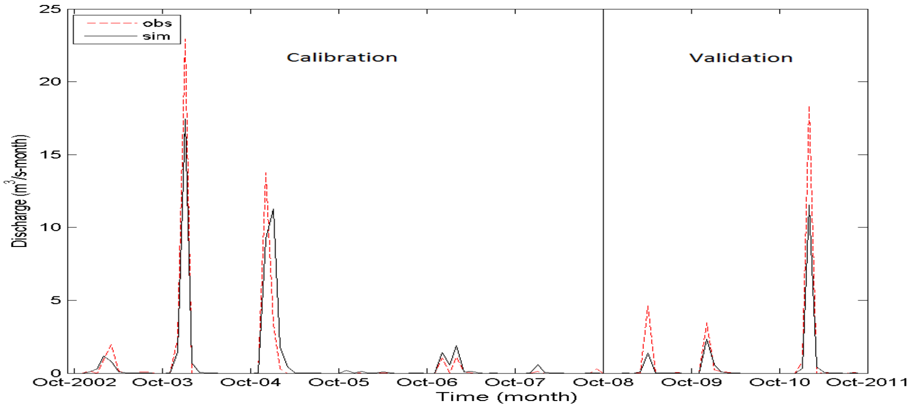

Figure 6. Observed and simulated monthly discharge ($m^3\,s^{-1}\,month^{-1}$) for the Baba Arab discharge station from 1 October 2002 through 30 September 2011.

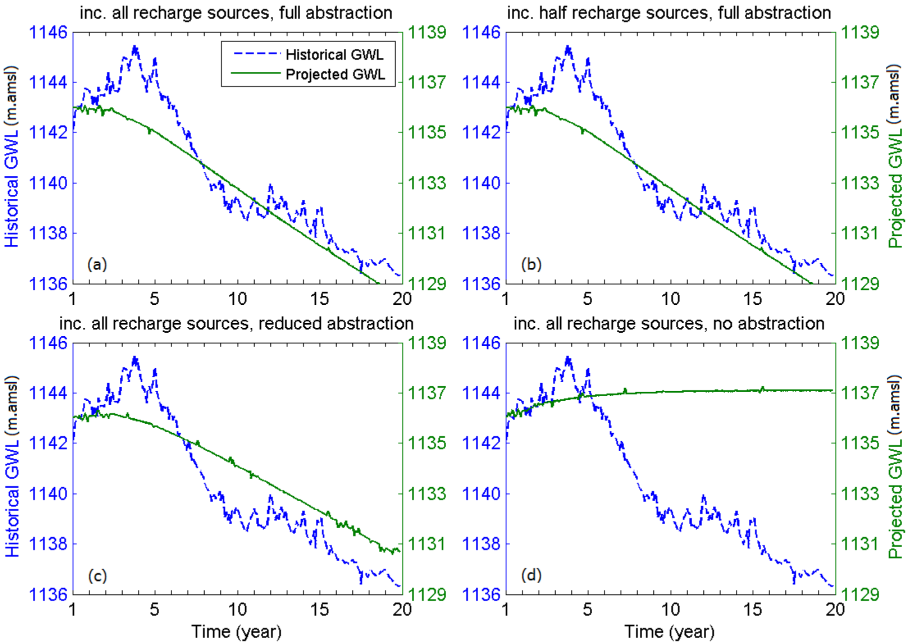

Figure 7. Comparison between historical GWL (1993–2013) and projected GWL (2010–2030) in meter above mean sea level taking into account four adaptation scenarios. The left *y* axis represents the GWL for historical data (dash line) and the right *y* axis represents the projected GWL (bold line). **(a)** shows projected GWL in the case of flood spreading in all FWS systems and full abstraction by pumping wells, **(b)** shows projected GWL in the case of flood spreading in half of FWS systems and full abstraction, **(c)** shows projected GWL in the case of flood spreading in all FWS systems and half abstraction by pumping wells, and **(d)** shows projected GWL in the case of flood spreading in all FWS systems and no abstraction.