Turkish Journal of Water Science & Management
ISSN: 2536 474X / e-ISSN: 2564-7334

Volume: 6 Issue: 1 Year: 2022

Research Article

Predicting Climate-induced Groundwater Depletion: A Case Study in Şuhut Alluvial Aquifer

Yeraltı Suyunun İklime-bağlı Azalışının Tahmini: Şuhut Alüvyon Akiferi Örneği

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Received Date: 06.08.2021, Accepted Date: 29.11.2021
DOI:10.31807/tjwsm.947685

Abstract

In this study, we examined the potential impact of climate change on the depletion of groundwater levels and storage. To achieve so, we simulated the groundwater flow using the HİDROTÜRK hydrogeological model under the climate change projections considering the RCP4.5 and RCP8.5 scenarios. To estimate the model forcing input (recharge and evapotranspiration) for the hydrogeological model, we used precipitation and temperature outputs from two Global Circulation Models, namely HadGEM2-ES and MPI-ESM-MR. To assess the changes in groundwater level and storage, we applied our experimental design in the Şuhut alluvial aquifer in Akarçay Basin (Turkey). The study revealed that there is not necessarily a substantial difference tracked over the estimated groundwater levels between the RCP4.5 and RCP8.5 scenarios until the end of 2050s. Yet, a significant reduction in the hydraulic head (approximately 114 m) and storage change (-17.25 %) – particularly in the western part of the aquifer – is expected in 2100, according to RCP8.5. This study confirmed that the selected climate model not only leads to the different predictions in the groundwater depletion, yet also results in a different degree of confidence in the model simulations.
Keywords: *Akarçay Basin, climate change impact, global circulation models, groundwater depletion, Şuhut alluvial aquifer*

Öz

Bu çalışmada, iklim değişikliğinin yeraltı suyu seviyesi ve depolanması üzerindeki olası etkisi incelenmiştir. Bu kapsamda, RCP4.5 ve RCP8.5 iklim değişikliği projeksiyonları altında, yeraltı suyu akımı HİDROTÜRK hidrojeoloji modeli kullanılarak simüle edilmiştir. Hidrojeoloji modeline iklim girdilerinin (beslenme ve evapotranspirasyon) tahmini için, iki farklı Küresel Dolaşım Modelinin – HadGEM2-ES ve MPI-ESM-MR – iklim çıktıları (yağış ve sıcaklık) kullanılmıştır. Yeraltı suyu seviyesinde ve depolamasında iklime bağlı değişimin iklim senaryoları gözetilerek değerlendirilmesi amacıyla Akarçay Havzası'ndaki (Türkiye) Şuhut alüvyon akiferinde yeraltı suyu akım modeli kurulmuştur. Çalışma sonucunda, RCP4.5 ve RCP8.5 senaryolarının her ikisine göre, öngörülen yeraltı suyu seviyelerindeki düşüşlerin 2050'nin sonuna kadar birbirinden çok farklı olmayacağı

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ortaya konmuştur. Öte yandan, RCP8.5 senaryosuna göre, bu yüzyılın sonuna kadar akiferdeki hidrolik yük kaybının (yaklaşık 114 m) ve depolamadaki azalmanın (%-17.25) – özellikle akiferin Batı kesiminde – önemli ölçüde olabileceği öngörülmüştür. Çalışma ayrıca, iklim modellerinin seçiminin yalnızca farklı model tahminlerine yol açmadığını, aynı zamanda model simülasyonlarının da farklı güvenirlik derecesine yol açtığı sonucunu desteklemiştir.

Anahtar sözcükler: *Akarçay Havzası, iklim değişikliği etkisi, küresel iklim modelleri, yeraltısuyu azalımı, Şuhut alüvyon akiferi*

Introduction

As a critical component of the water cycle, groundwater is the largest freshwater source – except the water stored as ice – (Bovoloet et al., 2009). For this reason, groundwater resources are not only of great importance to humanity but are also essential to nursing ecosystems. However, they are currently under the threat of climate change. The threat is even more severe in the arid and semi-arid regions around the Mediterranean basin in which many aquifers have already been suffered by water scarcity (Döll & Flörke, 2005; Kundzewicz et al., 2007; Kundzewicz & Döll, 2008) due to the increase in water demand for agricultural, industrial, touristic, and domestic uses (Shamsudduha et al., 2011; Taylor et al., 2013; Wada et al., 2013, 2014; Wisser et al., 2008). Therefore, understanding the climate-induced impacts on the groundwater is vitally important to sustain all the benefits from these valuable water resources.

According to the Intergovernmental Panel on Climate Change (IPCC) in 2014 (Stocker, 2014), the changes in precipitation and temperature have a substantial effect on the hydrological cycle all over the world in the 21st century. As one of the highly vulnerable regions, the Mediterranean region (Southern Europe and Non-European Mediterranean countries including Turkey) will be particularly suffered from the multiple stresses due to climate change (IPCC, 2007, 2014; Cramer et al., 2018). The primary influences of climate change in these countries are the reduction in the total amount of precipitation with the alteration of the spatial and temporal pattern of the rainfall, and the increment in the air temperature. For this reason, these two variables are also key climatic drivers for groundwater resources in such that precipitation is the main source of aquifer recharge, while the temperature mainly controls the evapotranspiration process. Thus, it is essential to assess to what extent the aquifer systems will be affected by climate change over the Mediterranean countries.

Despite the fact that groundwater has a rather slower hydrological response to the climate effects than that of surface water (Holman, 2006; Moseki, 2017), revealing the climate-induced impacts on the aquifers is still a challenging task due to the direct and indirect effects of climatic variables, which have not yet fully understood, (Dettinger & Earman, 2007, 2011; Green et al., 2011; Woldeamlak et al., 2007). To a certain extent, while the altered climate drivers directly impact groundwater recharge, increased water demand indirectly puts severe stress on the groundwater storage. For this reason, there is an essential need to quantify the groundwater response considering the depletion of groundwater level and storage over the vulnerable climate regions to better plan and manage the groundwater resources in the immediate future.

In this context, as the mathematical models provide valuable information about hydro(geo)logical behaviours of aquifer systems under the changing climatological and/or hydrological conditions, they play a key role to mimic groundwater flow. Therefore, the models are either used to increase comprehensive understanding of the system's reality or utilized to predict the hydrological response of the system under the different climate projections by delineating the hydrological behaviour of the system of interest.

Regarding the climate projections, the Representative Concentration Pathways (RCPs) are developed to examine potential effects and responses of climate change (Moss et al., 2010; van Vuuren et al., 2011). In line with this, the climatic conditions under the projected time-period(s) are described as climate scenarios based on four different greenhouse gas concentration curves, each of which defines rather different climatic conditions, depending on the volume of greenhouse gases emitted in future years. To illustrate, while RCP2.6 and RCP8.5 represent the climate scenario with the lowest and highest greenhouse gas emissions respectively, the RCP4.5 and RCP6.0 scenarios focus on the intermediate stabilization (Petpongpan et al., 2020; Riahi et al., 2011).

The Global Circulation Models (GCMs) – also known as Global Climate Models – are considered as the most reliable tools to obtain the climate indicators (Dragoni & Sukhija, 2008; Kattenberg, 1996; Parry et al., 2007) while numerically simulating the potential changes in the climate based on the boundary conditions (McGuffie & Henderson-Sellers, 2014). On the ground of this, the selection of a plausible future climate scenario by the GCMs is essential. However, since the different models have their strengths in predicting the system reality to capture the non-identical aspects of the system, the predictions from different climate models principally differ from one another. For instance, some models in GCMs anticipate the drier and warmer climate conditions, whereas the others comparatively provide the wetter and colder (Fajardo et al., 2020), thus resulting in prediction uncertainty in model results (Her et al., 2016; Kaczmarska et al., 2018; Lehner et al., 2019; Pour et al., 2020; Salman et al., 2020; Surfleet et al., 2012). From this point of view, considering the climate predictions from a single climate model is not necessarily the plausible option as it includes a certain degree of uncertainty. Therefore, since the climate projections are predominantly dependent on which GCMs' climate scenarios are considered, it is of great importance to examine the predictions of different climate models for any hydro(geo)logical model experiment to reveal the potential uncertainties sourcing from the GCMs' outputs.

To address the impact of climate change on aquifer systems, this paper examines climate-induced groundwater depletion by predicting the potential decline in groundwater level and storage. To achieve so, we used the climate outputs (precipitation and temperature) of two GCMs considering the RCP4.5 and RCP8.5 climate scenarios to utilize these variables as the hydrogeological model forcing input. As one of the vulnerable groundwater sources to the impacts of climate change due to the decrease in the precipitation amount and increased temperature, the Şuhut groundwater body in Akarçay Basin (Turkey) was selected as a case area. By applying our experimental design into the case area, we aim to *(i)* predict the spatiotemporal variability of the groundwater level over the projected time-period (2021-2100), *(ii)* comparatively evaluate the groundwater depletion considering the two scenarios of two GCMs, and *(iii)* assess the groundwater response to the climate scenarios of each climate models, thereby revealing the model prediction uncertainty.

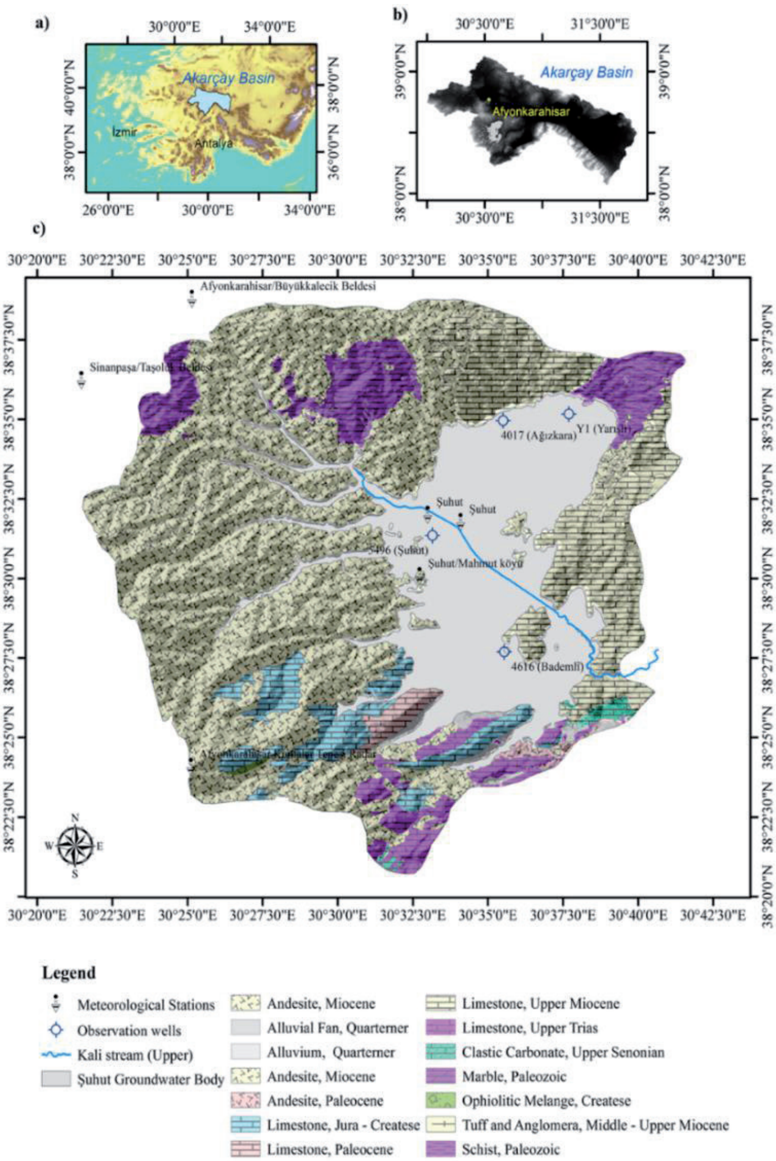
Methodology

Study Area

The Akarçay Basin is located between Central Anatolia, Aegean, and Mediterranean Regions as a closed watershed [Figure 1(a)]. The basin is one of the susceptible watersheds to climate change impact in Turkey (Önder & Önder, 2007) in such that the basin will receive %17-20 less amount of rainfall by 2100 as compared to the reference period for climate projections (1971-2000), while the expected increase in the temperature ranges from 1.5ºC to 4ºC, on average, by the end of the century (General Directorate of Water Management [GDWM], 2015(a), 2015(b), 2016). Furthermore, due to the increased water demand and hydrological drought over the basin, Akarçay Basin could face water scarcity in the immediate future (GDWM, 2016; Kale, 2021).

Figure 1

(a) The Location of the Akarçay Basin (Afyon, Turkey), (b) The Location of the Şuhut Groundwater Body in Akarçay Basin, (c) The Geological Outcrop of the Şuhut Sub-basin Accompanying by Şuhut Groundwater Body



Note. Şuhut Groundwater Body in the Akarçay Basin is indicated by the light-grey colour. The geological map is edited after the Regional Directorate of State Hydraulic Works (hereinafter referred to DSİ (Devlet Su İşleri Genel Müdürlüğü) as Turkish acronym).

The Şuhut sub-basin is one of 8 sub-basins in the Akarçay Basin. The Şuhut basin covers an approximate area of 682 km^2 bordered by the Sandıklı and Kumalar mountains from the west [Figure 1(b)]. The basin is characterized by a flat topography with an elevation ranging from 1120 m to 1150 m, which is also known as the Şuhut Plain. The annual average precipitation over the basin is nearly 487 mm, while the average annual actual evapotranspiration (A_{ET}) accounts for 379.9 mm (DSİ, 2013).

A total number of 14 groundwater bodies covering 3677 km^2 is characterized in the Akarçay Basin by GDWM, 2017. The Şuhut groundwater body (hereinafter referred to as Şuhut alluvial aquifer) is a major domestic and irrigation water supply. which makes it more vulnerable groundwater to the climate change impact in the Akarçay Basin.

The area of the Şuhut alluvial aquifer is approximately 155 km^2 [Figure 1(c)]. The regional groundwater flow direction is towards the southeast of Quaternary aged alluvium in which the system may have a hydraulic connection with the Afyon alluvial aquifer (nearly 750 km^2) according to the previous studies by DSİ (2013), GDWM [2015(b)], [2020(a)] and Sargın (2020).

The geological evolution of the Şuhut sub-basin ranges from the beginning of the Palaeozoic era to the Quaternary period. The western side of the area is mostly covered by the volcanic rocks formed in the Neogene during which the high mountains were mainly shaped under the intensive volcanic activities whereas the northern and eastern parts are characterized by the Pliocene limestone [Figure 1(c)] (Tezcan, 2002; Dişli, 2005). Stratigraphically, the Şuhut Plain is characterized by the four main hydrogeological units including alluvium, tuff, limestone, and volcanic (andesite, basalt, trachyandesite) lava (DSİ, 2013). However, the Şuhut aquifer is formed by the Quaternary alluvium and Plio-Quaternary lacustrine sediments mainly comprising of the sandy-gravelly materials, agglomerate, tuff, and Mesozoic limestone (Kuran, 1958; Gülenbay, 1971; DSİ, 2013). Therefore, the alluvial system may not only feed by the lateral interflow over the fractured volcanic tuffites in the western part of the study area, yet also the fractured/karstified (partially) limestones (includes tuff, siltstone, clay) underlying in the northern and eastern part of the area also contributes to the aquifer recharge (Gülenbay, 1971; Dişli, 2005; DSİ, 2013).

Şuhut Stream – also known as Kali Stream – is the main surface water in the Şuhut Plain [Figure 1(c)]. The stream sources from the Kumalar Mountain in the west and discharges throughout a wide alluvial valley in the plain, thereby reaching the Selevir Dam on the eastern part of the basin. While the Kali stream is fed by the

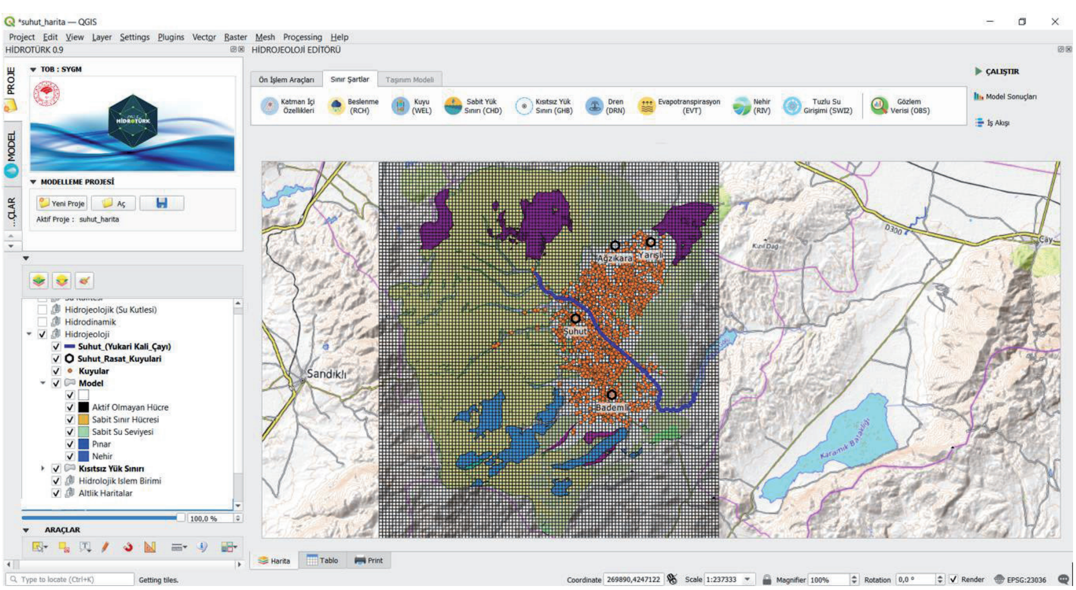
Şuhut alluvial aquifer over the past decades, it currently contributes to the aquifer due to the substantial drawdown in the groundwater level according to the reports by DSİ (2013) and GDWM (2016).

The Model

To simulate the groundwater level, we used the HİDROTÜRK hydrogeological model (Figure 2). HİDROTÜRK model is the first national model platform developed by the Republic of Turkey Ministry of Agriculture and Forestry - General Directorate of Water Management for the sustainable management of the water resources in Turkey [GDWM, 2020(b)]. This platform includes four main model components that each of which simulates the different parts of the hydrological cycle including hydrological, hydrodynamic, and hydrogeological models as well as the water quality and ecological models.

Figure 2

The GUI of the Hydrogeological Model in the HİDROTÜRK Model Platform



The hydrogeological model is one of the MODFLOW-based models that uses a set of Python scripts in the FloPy environment. The MODFLOW-2005 model is served as the core model in the HİDROTÜRK model platform, thereby solving the three-dimensional groundwater flow based on Darcy's Law and the principle of the conversion of mass (Harbaugh & McDonald, 1996, 1988; Harbaugh, 2005).

Since the FloPy Python package is provided by Bakker et al. (2016) without a Graphical User Interface (GUI), the hydrogeological model was constructed in the Geographical Information System (GIS) in the QGIS environment as a plugin to deliver a user-friendly modelling platform (Figure 2). Along with the input-output files to run the core model, the GUI of the model provides 7 main packages including well (WEL), recharge (RCH), evapotranspiration (ETP), river (RIV), constant head boundary (CHD), general head boundary (GHB), and drain (DRN).

Climate Data and Projections

Of all projected climatic scenarios, since RCP4.5 (intermediate level of emission) and RCP8.5 (high level of emission) are two preferred scenarios on a global scale (Riahi et al., 2011; Stocker, 2014), we considered these scenarios for our modelling experiment. To obtain the climate data (precipitation and temperature) we chose the HadGEM2-ES (Hadley Centre Global Environmental Model version 2 Earth System model) developed by the Met Office Hadley Centre (Collins et al., 2011; Jones et al., 2011) and MPI-ESM-MR [Max-Planck-Institute Earth System Model (MPI-ESM) mixed resolution (MR) version] by Giorgetta et al. (2013).

As the HİDROTÜRK hydrogeological model is driven by two hydrometeorological variables (recharge and evapotranspiration), to estimate the input fluxes of the hydrogeological model we used the projected precipitation and temperature data from the HadGEM2-ES and MPI-ESM-MR models considering the RCP4.5 and RCP8.5 scenarios. Both climate variables were processed by 0.1° (10 km x 10 km) resolution using the RegCM4.3.4 regional climate model with the dynamic downscaling method (Turkish State Meteorological Service [MS], 2014; Gürkan et al., 2015; GDWM, 2016; Demircan et al., 2017), and estimated for the 25 watersheds in Turkey over 2015-2100 with a 10-year interval by GDWM (2016).

The Thornthwaite method (Thornthwaite, 1948) was used to obtain the mean total potential evapotranspiration (P_{ET}) values based on the calculated temperatures considering both climate models and projections (Eq. 1).

$$P_{ET} = 16\left(10\frac{T_i}{I}\right)^a \tag{1}$$

where P_{ET} is the annual potential evapotranspiration (mmy^{-1}), T_i is the average annual temperature (^oC). I is the annual heat index, i.e. the sum of monthly indices i ($i = (T/5)^{1.514}$) while a is the heat index calculated by $0.49239 + 1.792e^{-2}I - 7.71e^{-5}I^2 + 6.75e^{-7}I^3$.

The projected changes in the climate variables and calculated forcing inputs for the numerical model are provided in Table 1. During our experiment, the climate inputs for the hydrogeological model are assumed to be uniformly distributed over the model domain due to the gentle topographic slope (about 1% to 4%) of the Şuhut Plain.

Since the hydrological response of the groundwater to climate impact is rather slower than that of surface water, to obtain climate variables from two GCMs for RCP4.5 and RCP8.5 we assigned relatively longer sub-periods for the simulation period (1997-2100) as compared to those estimated by the 10-year intervals by GDWM, 2016. Then, we obtained the mean annual changes in precipitation (ΔP) and temperature (ΔT) from both GCMs considering the mean values of each variable over the 10 years (Table 1).

Along with the RCP4.5 and RCP8.5 scenarios, we run the hydrogeological model by keeping the values of the aquifer recharge (R) and actual evapotranspiration (A_{ET}) constant over the projection period (2021-2100), which is referred as 'Baseline' scenario (see Table 1). Thereafter, we used the Baseline scenario to comparatively examine the groundwater depletion with regard to the climate scenarios.

Model Development

To construct the numerical model, we developed the conceptual model of the Şuhut aquifer, mainly considering the previous hydrological, geological, and hydrogeological studies carried out DSİ. While we used the shapefile of the groundwater body as a hydrogeological model extension area characterized by GDWM (2020(a)), we reconsidered the hydrogeological units to construct the hydrogeological model layers based on the data of 50 boreholes – contain the information of lithology, well depths, borehole geophysics, static and dynamic groundwater levels, yields, and hydraulic conductivity –. We then delineated the hydrogeological characteristics and boundary conditions of the aquifer system based on those borehole data for the numerical model development.

Table 1

The Mean Annual Changes in the Climate Variables and Model Forcing Inputs

		Projected Climate Variables by GCMs				Hydrogeological Model Forcing Inputs			
		HadGEM2-ES		MPI-ESM-MR		HadGEM2-ES		MPI-ESM-MR	
Climate Scenario	Projected period	ΔP (mm)	ΔT (ºC)	ΔP (mm)	ΔT (ºC)	R (mmy^{-1})	A_{ET} (mmy^{-1})	R (mmy^{-1})	A_{ET} (mmy^{-1})
Baseline Scenario	2021-2100					547.5	365.0	547.5	365.0
RCP4.5	2021-2030	30.0	1.8	-50.0	1.0	577.5	423.1	497.5	398.2
	2031-2050	6.0	2.2	-0.5	1.2	553.5	438.0	547.0	404.0
	2051-2100	-20.8	2.9	-25.8	1.7	526.7	460.2	521.7	421.4
RCP8.5	2021-2030	10.0	1.8	-10.0	0.9	557.5	424.7	537.5	394.9
	2031-2050	-2.5	4.8	-11.0	1.4	545	524.3	536.5	411.5
	2051-2100	-50.2	4.5	-77.6	3.2	497.3	514.3	469.9	471.8

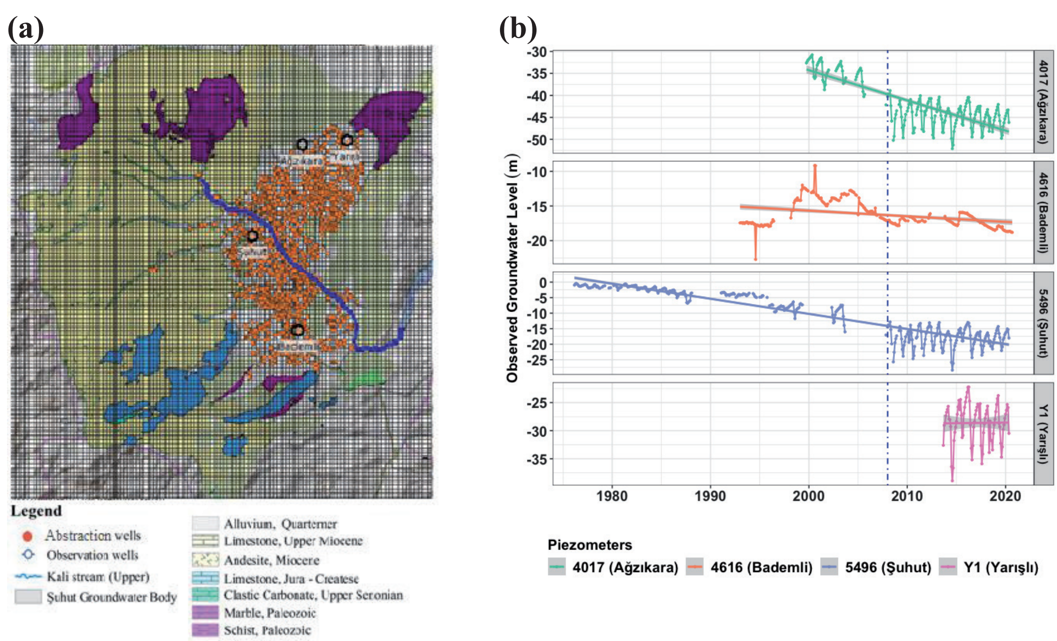
Note. The negative value indicates the decline in each climate variable. The potential aquifer recharge (R) is approximately 548 mmy^{-1}, and average actual evapotranspiration (A_{ET}) accounts for 379.9 mmy^{-1} according to the DSİ, 2013 record

A monitoring network for monthly groundwater level is enabled by 4 piezometers (observation wells) in the Şuhut aquifer by DSİ [Figure 3(a)]. While the Y1 (Yarışlı) and 5496 (Şuhut) piezometers cut the alluvium and limestone units with a depth of 200 m, the 4616 (Bademli) and 4017 (Ağzıkara) piezometers are mainly characterized by the alluvium and volcanic units (DSİ, 2013). In our experimental design, we selected the 4017 (Ağzıkara) well to compare the simulated groundwater levels with the observed values over the reference period (1997-2020). This is mainly because the 4017 (Ağzıkara) well represents one of the vulnerable regions in which the groundwater level experienced a significant drawdown – nearly 35 m over the 20 years (DSİ, 2013) –. Furthermore, the borehole lithology for this well mostly consisted of the alluvial unit.

Figure 3

a) The Spatial Distribution of the 1,281 Abstraction Wells and 4 Piezometers in the Model Area

b) The Monthly Variations of the Observed Groundwater Levels in the Piezometers



Note. The vertical blue dotted line in Figure 3(b) indicates the year-2008 during which the substantial drawdown in the hydraulic heads observed in the observation wells of 4017 (Ağzıkara) and 5496 (Şuhut). The line on each graph indicates the simple linear regression line.

Numerical Model Set-Up

For the numerical model set-up, we defined a one-layer unconfined aquifer system considering the alluvium unit as it mainly characterizes the Şuhut alluvial aquifer. Based on the borehole data, the model layer was delineated by the depth of the hydrogeological unit ranging from 10 m to 300 m (DSİ, 2013). The one-layered model area was discretized into uniform cell dimensions of 50 m x 50 m horizontal resolution considering the hydraulic characteristics of the unconfined layer (hydraulic conductivities and storage characteristics), boundary conditions, and initial hydraulic head. The model top and bottom were defined at 0 m (as topographic surface) and -185 m, respectively. Therefore, the thickness of the aquifer layer was represented by 185 m with -10 m initial head (demonstrates the groundwater level below the topographic surface, referring to the depth of the water table). The initial head for the model layer was defined considering the observed static levels in the abstraction wells [see Figure 3(b)]. As the transmissivity of the aquifer unit varies between 36.3 m^2d^{-1} and 900 m^2d^{-1} (Gülenbay, 1971; Dişli, 2005; DSİ, 2013), the horizontal hydraulic conductivity, K_h was interpolated over the model domain based on the 1,218 wells' data, while we assigned the vertical hydraulic conductivity K_v to ten-times lower than that of K_h values (Domenico & Schwartz, 1998). The specific yield (S_y) of the unconfined aquifer layer was assumed to be uniformly distributed over the model area with an average value of 0.0015 (*dimensionless*) obtained by DSİ (2013).

To assign the stress periods over the model simulation period (1997-2100), we deliberated the main hydro(geo)logical changes in the aquifer system considering the observed water levels in the piezometers [Figure 3(b)]. Therefore, the hydrogeological model was run with a three-year spin-up period (1993-1996) under the steady-state flow condition, thereby reaching a dynamic equilibrium in the modelling system. The historical (1997-2007), reference (2008-2020), and projection periods including the sub-periods of 2021-2030 (near), 2031-2050 (intermediate), and 2051-2100 (future) were set up while considering the substantial depletion in groundwater depth [see Figure 3(b)], thus running under the transient flow conditions.

To simulate the lateral interflow from the Mesozoic limestone underlying down the North and East of the Şuhut Plain, we set this model boundary as GHB. Furthermore, the no-flow condition was considered for the rest of the model domain, mainly assuming the area was mainly covered by a less permeable volcanic unit [see Figure 1(b)]. The WEL was activated by the 997 abstraction wells during the historical period (1997-2007) while a total of 1,281 wells were used during the reference period (2008-2020) and the prediction period (2021-2100).

The model calibration and sensitivity analysis were not performed in our modelling experiment as the hydrogeological model do not include a calibration toolbox. Instead, to increase the model representativeness, we used the piezometers (Figure 3) to comparatively capture the observed hydraulic heads over the reference period (2008-2020) by the simulated ones. Afterward, the post-processing of the model results was visualized using R-Studio (R Core Team, 2021).

To account for the model prediction uncertainty resulting from the selected climate model's outputs, we compared the results of the groundwater level and storage driven by the climate outputs of the two GCMs – HadGEM2-ES and MPI-ESM-MR – over 2021-2100.

Groundwater Depletion

For the sake of revealing the climate-induced changes in the groundwater level and storage, the model simulations were performed under the same boundary conditions throughout 2021-2100, thereby assuming that no further changes will be mentioned in the local water management. Here, our primary aim was to observe the groundwater depletion which only emerges from the climate change impacts. For this reason, we kept the number of groundwater abstraction wells – and the pumping rate in each pumping well – constant.

To quantify the annual groundwater depletion under the climate change projections, we first calculated annual groundwater drawdown (Δh) by

$$\Delta h = h_{sim} - h_i \quad (2)$$

Here, h_{sim} is simulated annual hydraulic head, and h_i is the initial hydraulic head which was defined by -10 m. The annual depletion in water storage (ΔS) is then calculated considering Δh using a similar approach proposed by Healy and Cook (2002) in Eq. 3:

$$\Delta S = S_y \times \Delta h \quad (3)$$

where S_y is the specific yield of the unconfined aquifer (*dimensionless*).
After obtaining the annual changes in water storage under the RCP4.5 and RCP8.5 scenarios, we estimated the relative bias in storage in percent, ΔS (%) by Eq. 3 with

respect to the baseline scenario while assuming that the absence of bias corresponds to the base model (0 %).

$$\Delta S\ (\%) = \frac{\Delta S_{baseline\ scenario} - \Delta S_{climate\ scenario}}{\Delta S_{baseline\ scenario}} \times 100 \quad (4)$$

where $\Delta S_{climate\ scenario}$ is the annual changes in water storage of the corresponding climate scenario.

Results and Discussion

Climate-induced Depletion of Groundwater Levels

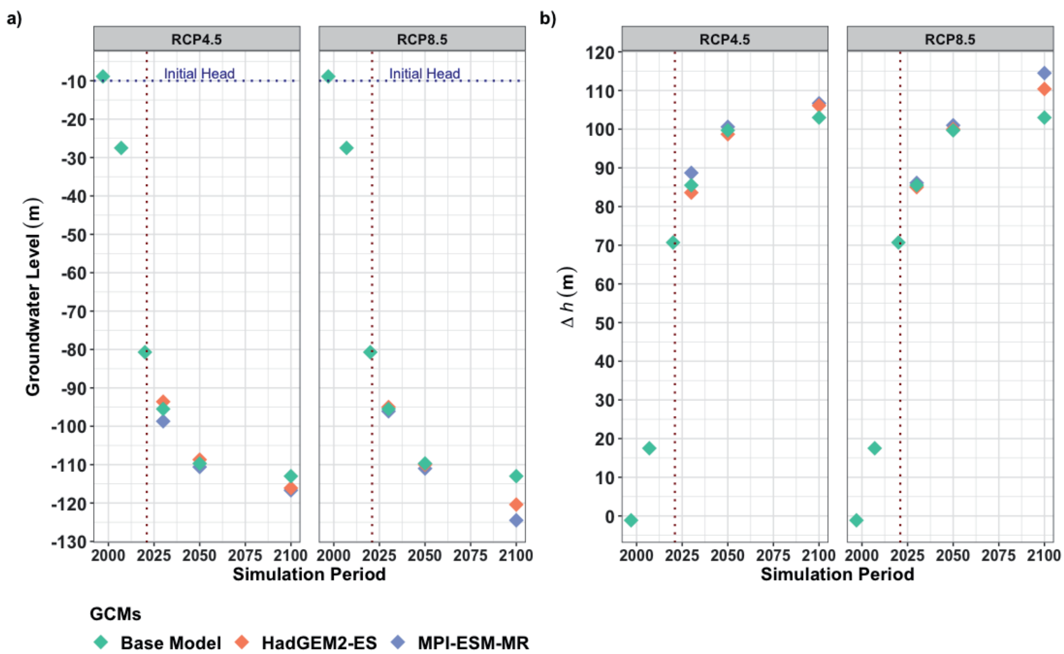
For the comparative evaluation of the climate-induced groundwater depletion over the historical (1997-2020) and projection periods – 2021-2030 (near), 2031-2050 (intermediate), and 2051-2100 (future) –, we obtained the minimum groundwater levels at the last day of each sub-period. Figure 4 demonstrates the simulated groundwater hydraulic heads in the Şuhut alluvial aquifer and the corresponding drawdowns in the groundwater drawdown (Δh) obtained from the HİDROTÜRK hydrogeological model. Overall, the simulation results driven by the climate outputs of the MPI-ESM-MR model provides rather lowered water depths and higher drawdown values than that of the HadGEM2-ES model.

Figure 4(a) confirms that the decline in the groundwater level is inherently dependent upon which climate model's outputs are served as the forcing fluxes during the model conditioning phase. Here, the minimum groundwater level was estimated to -124.5 m with a decrease by more than 10% as compared to the baseline scenario until the end of the century (for RCP8.5 by the MPI-ESM-MR model in 2100), whereas the HadGEM2-ES model led to a less drawdown with an estimated head value of -120.4 m (a -6.55% decrease for the same scenario in 2100). Similarly, the decrease in the groundwater depth is 116.7 m (-2.74%) for the MPI-ESM-MR model under the RCP4.5 scenario, which is a little higher than -116.1 m (-3.26%) by the HadGEM2-ES model. The findings are also supported by the other studies (Döll, 2009; Kurylyk & MacQuarrie, 2013; Pratoomchai et al., 2014), which also state that the model projections vary predominantly depending on the selected GCMs rather than the climate scenarios, only.

Figure 4

(a) The Projected Groundwater Levels Based on the Climate Variables Obtained from the MPI-ESM-MR and HadGEM2-ES Models

(b) The Variations in Groundwater Drawdown (Δh [m]) over the Şuhut Alluvial Aquifer Under the RCP4.5 and RCP8.5 Scenarios



Note. Here, each value indicates the maximum drawdown in the groundwater level estimated by the end of each sub-period over the model simulation. The dashed vertical dark red coloured line separates the historical/references (1997-2020) and projected (2021-2100) periods, thereby indicating past and future hydrogeological flow conditions, respectively.

As for the influences of climate change on the groundwater hydrological response, Figure 4(b) reveals the fact that a remarkable depletion in the groundwater level was already observed during the reference period (2008-2020) in which the additional 284 abstraction wells were drilled in the aquifer system (as it was conditioned in the model area). As a result, the maximum drawdown was represented by an approximate value of 53 m for the baseline climate scenario over the reference period (2008-2020). Even worse, the groundwater levels will be experienced by a dramatic drawdown by reaching the drawdown value of more than 100 m for both scenarios at the end of this century. Thus, the differences in the head losses for both climate models gradually become dramatic – in particular for RCP8.5. Yet, here, the RCP8.5 scenario for the MPI-ESM-MR model still represents the highest value for the estimated drawdown by 114 m.

Spatiotemporal variations of the groundwater level over the end of each sub-period – 2020, 2030, 2050, and 2100 – are indicated in Figure 5. Here, we only provide the numerical results driven by the climate outputs of the MPI-ESM-MR model under the two climate projections since it leads to a relatively sharp decline in the groundwater depth [Figure 4 (a)]. In general, the western part of the Şuhut Alluvial aquifer – in the vicinity of the Şuhut district (see Figure 2) – is the most vulnerable area to climate-induced effects. Over this region, the water depth ranges from -75 m to -85 m for RCP4.5 in 2100 while it varies between -82 m and -88 m for RCP8.5, meaning that the total drawdown is expected to be around 75-88 m at the end of the century. Yet, above all, the depletion in the groundwater level could also become more dramatic over the western boundary of the aquifer in which the considerable decrease in the hydraulic head occurs.

Groundwater Response to Climate Change

The annual variability of the simulated groundwater levels over the simulation period (2008-2100) and the uncertainty bound during the projection time (2021-2100) are provided in Figure 6. Overall, the annual groundwater levels demonstrated a decreasing exponential behaviour for the baseline scenario, thus flattening out between -110 m and -113 m during 2051-2100, whereas the decline in the water level under the climate-change projections slightly deviated from this exponential curve, thus characterized by two inflection points around the years of 2025 and 2050.

In agreement with the decreasing exponential behaviour of the groundwater levels, the water table starts to respond rather slowly to the climate-induced changes in both numerical results in Figure 6 (a). Here, regardless of which climate model's outputs are used as forcing fluxes for the hydrogeological model, the decline in the water level is consistently retarded by the advancing time. More specifically, while the first slowing downward trend of the depth of groundwater levels will be observed between the near (2021-2030) and intermediate (2031-2050) periods, the slowest one is tracked over the future period (2051-2100). From this point of view, this hydrological behaviour in the aquifer system could be marked by the inflection points on the drawdown curves – as indicated by Figure 6 (a) with a dashed dark red line –. This inflection on the drawdown curve could point out at which level groundwater table reaches a threshold value – called here as critical water depth indicated by red dashed line – where the water depletion may not be easily influenced by the dramatic changes over the hydro-climatological conditions. However, it should be noted that this inference is only valid under the assumption that no further changes will be available for the aquifer hydrogeological conditions and/or the local water management.

To get an idea of how sensitive the simulated annual groundwater levels are to the climate scenarios of each GCMs, we used the box-and-whisker plots in Figure 6 (b), thereby evaluating the potential uncertainty sourcing from the selected GCMs. In general, the InterQuartile Range (IQR) of the groundwater variations under the RCP8.5 scenario for both climate models was quite large, indicating that the obtained values were rather sensitive to RCP8.5, thus resulting in greater model prediction uncertainty. Interestingly, the confinement in the predicted values for the RCP4.5 is better than that of RCP8.5 for both models, ensuring a narrower IQR with an average value of -105 m for the HADGEM2-ES model. Therefore, the range of the annual groundwater level reveals that the selection of the climate models - and climate projections - not only leads to the different simulations, but it also defines the level of confidence in the model predictions.

Climate-induced Depletion in Groundwater Storage

The temporal anomalies in the annual water influx are provided in Figure 7. Overall, the annual variations in the input fluxes for both climate models demonstrated a continuous downward trend due to the expectation of the deficit in the precipitation amount in the Şuhut basin (see Table 1). The only exception, here, is the increased influx for the near future (2021-2030) for the RCP4.5 scenario of the MPI-ESM-MR model. This local increment in the influx can be explained by the relative increase in the precipitation amount (+ 30 mm) in comparison to the reference model simulation period (2008-2020).

Figure 5

The Spatiotemporal Distribution of the Depth of Groundwater Levels over the Model Domain

(a) Spatiotemporal Distribution of The Depth of Groundwater Level for the RCP4.5 Scenario

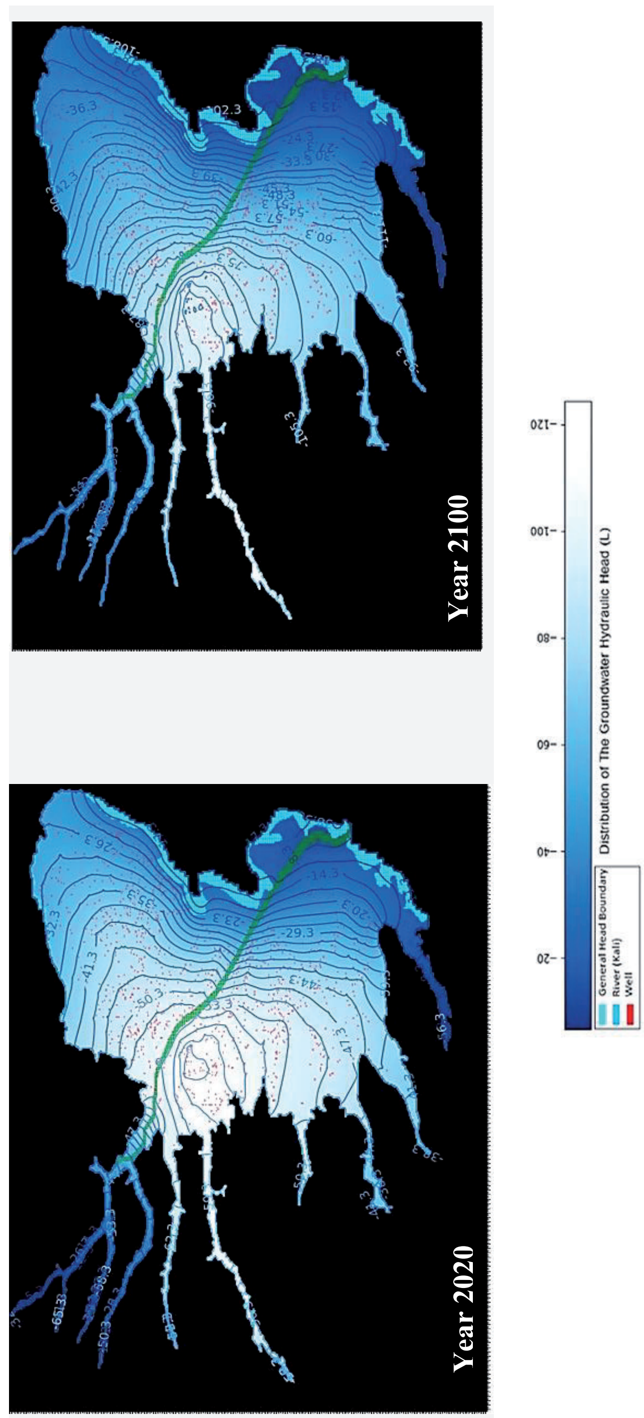
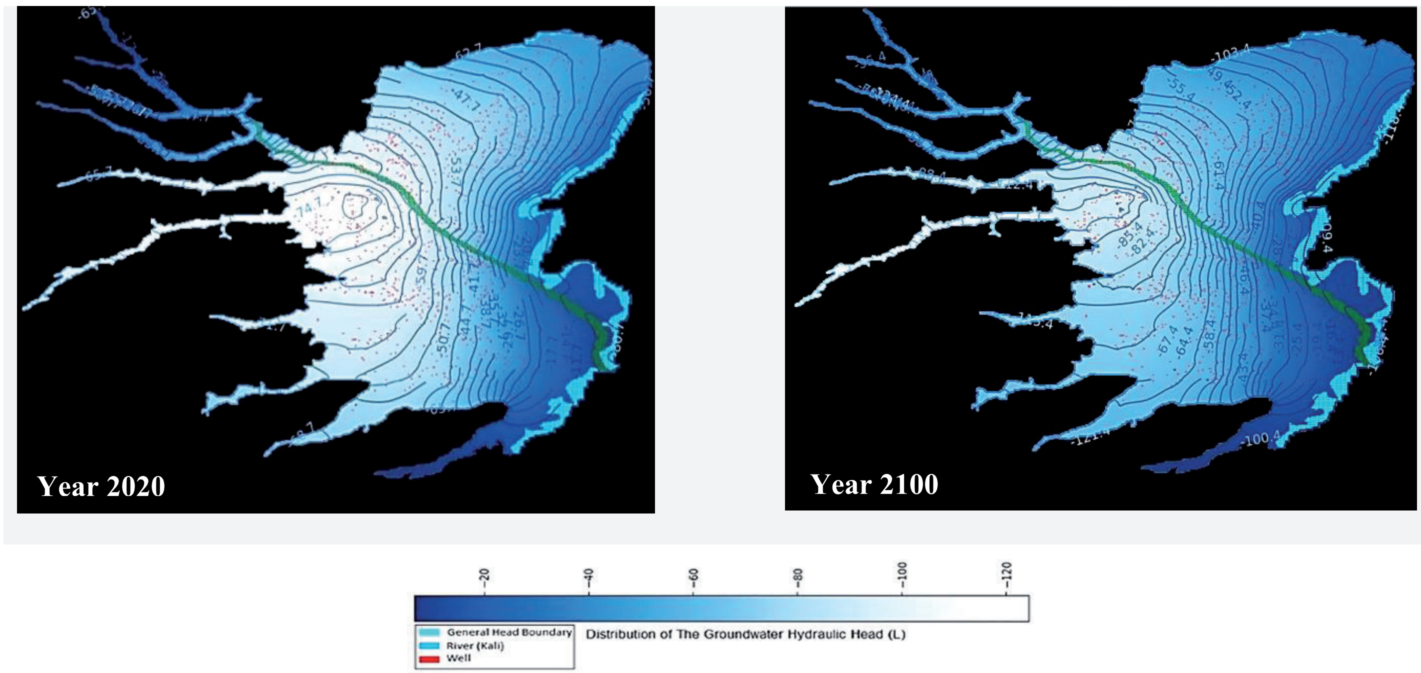


Figure 5

Continued

(b) Spatiotemporal Distribution of the Depth of Groundwater Level for the RCP8.5 Scenario



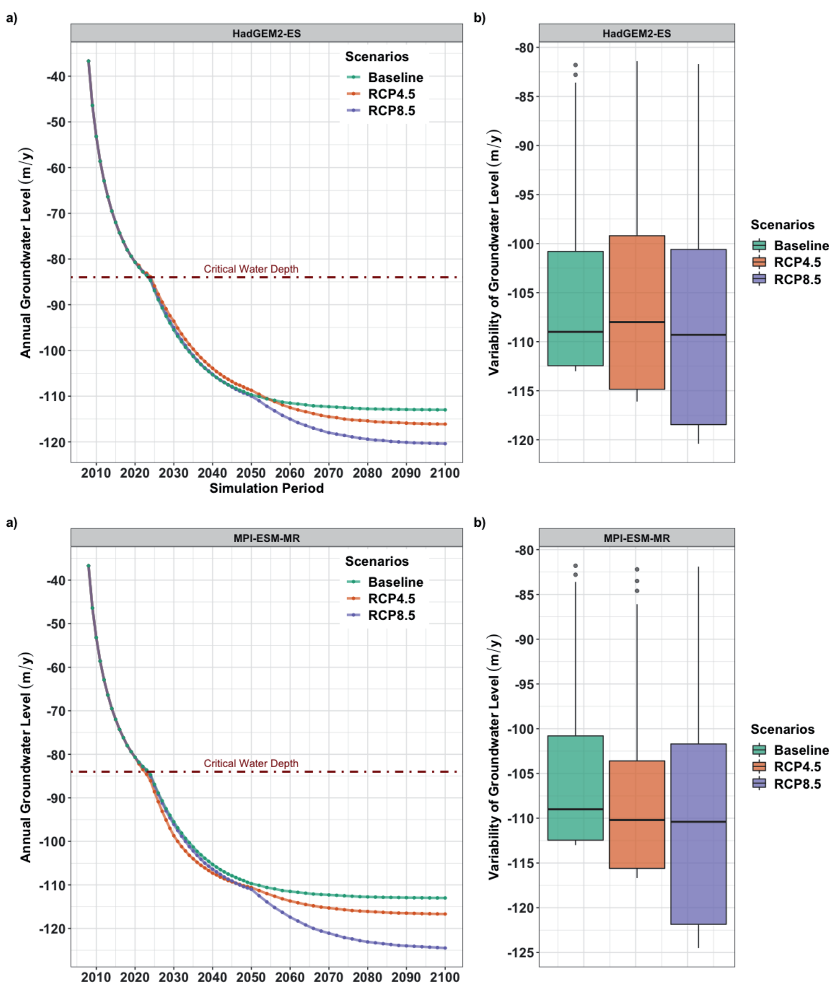
Note. Here, the simulations driven by climate outputs from the MPI-ESM-MR model are demonstrated.

Figure 6

The Model Simulations from HADGEM2-ES and MPI-ESM-MR over the period of 2008-2100

(a) The Annual Variability of the Simulated Groundwater Levels

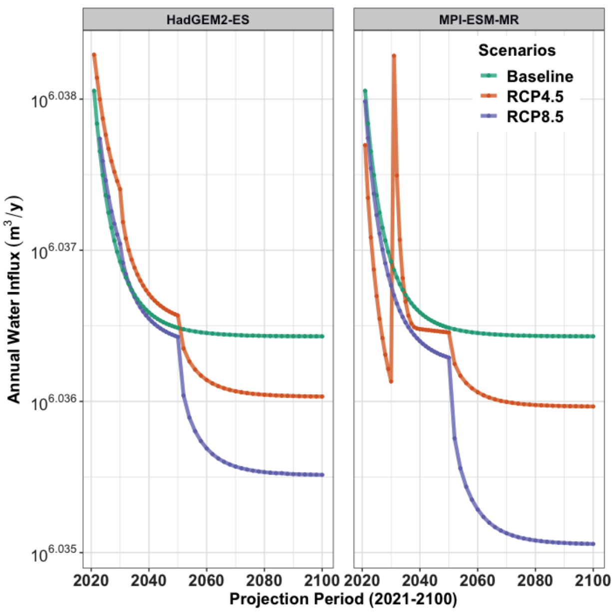
(b) The Box-and-Whisker Plots of the Simulated Groundwater Levels



Note. The horizontal dark red coloured line indicates 'critical water depth' (around -84 m for both model simulations) in which the drawdown of groundwater level starts to respond slowly to the variations in climate as compared to the reference period (2008-2020).

Figure 7

The Annual Anomalies of the Simulated Water Influx over the Projection Period (2021-2020).



The decreasing exponential behaviour of the water influx – it is also tracked over the simulation of groundwater level in Figure 6 – can also be seen in Figure 7. Here, the annual fluctuations in the water influx were characterized by a slowing downward trend after the year-2050 for both scenarios of the two climate models. Yet, the obtained annual values by the MPI-ESM-MR model still exhibited a strong decline, particularly for the RCP8.5 scenario. Therefore, the result verifies the fact that the hydrogeological model uses the precipitation input as a principal driver for the simulation of the hydraulic head even though the same exponential behaviour is not directly observed over the annual changes in the groundwater levels under the RCP4.5 scenario for the MPI-ESM-MR model.

Figure 8 demonstrates the temporal variability in the annual changes in water storage (*ΔS*, %) based on the climate change projections throughout the model projection period (2021-2100). Overall, *ΔS* varied primarily dependent on the climate models' outputs served as forcing inputs in the groundwater model. Here, *ΔS* was predominantly represented by the negative values in both cases, while the only exception is the positive value of *ΔS* accounted for by +2.85% (+30 mm for RCP4.5) and + 0.75 % (+10 mm for RCP8.5) for the HadGEM2-ES model.

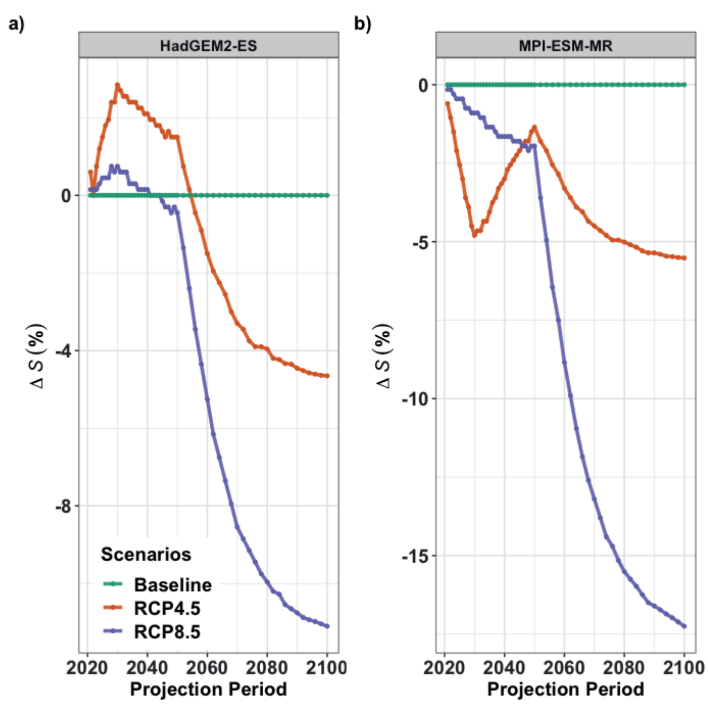
Figure 8 (b) also reveals that the storage depletion will be worsening by the end of 2100 according to the RCP8.5 scenario of the MPI-ESM-MR model in which the projected changes show a large range in the estimated values from -0.9 % (-10 mm decrease in precipitation amount over 2021-2030) to -17.25 % (-78 mm decline in precipitation amount over 2050-2100). Therefore, incompatible with the climate inputs for the hydrogeological model – decreased precipitation amount and increased temperature (see Table 1) –, the relative changes in the water storage based on the baseline scenario confirm that the climate-induced effect – especially the precipitation input – is of importance for the prediction of storage depletion.

Figure 8

The Temporal Variability of the ΔS (%) under the RCP4.5 and RCP8.5 for 2008-2100

(a) The Simulations Driven by the MPI-ESM-MR Model

(b) The Simulations Driven by the HadGEM2-ES Model



Note. Here, the baseline scenario corresponds to the absence of bias (0 %).

Conclusions

The study examines to what extent climate change influences groundwater depletion under the RCP4.5 and RCP8.5 scenarios of two GCMs. By implementing our experimental design into the Şuhut alluvial aquifer, we projected how groundwater level and storage vary over the projection time-period (2021-2100), thereby revealing the variability of the model results to the climate inputs obtained by two GCMs. The key findings from our research are as follows:

- A wide range of the projected annual groundwater level and storage changes reveals that the selection of climate models not only leads to different model predictions, yet also results in a different degree of confidence in the model simulations.

- The hydrological response of the groundwater depth over the model simulation period (2008-2100) is characterized by a decreasing exponential behaviour for the baseline scenario, whereas the slight deviations are observed under the climate-change projections for both GCMs. This hydrological response may indicate critical water depths in which the dramatic changes in hydrological and/or climatological conditions would not easily influence the aquifer hydrological conditions.

- As for the Şuhut alluvial aquifer, the climate change impact would have significant effects on the reduction of the groundwater depth and storage, especially in the western part of the aquifer system where the groundwater abstraction rate is rather higher. Furthermore, the substantial decline in the groundwater level is predicted by the near-future period (2021-2030), while the depletion in the water storage demonstrates a rather different response as compared to the groundwater depth in such that the substantial decline in the storage is projected throughout 2051-2100.

- The assessment of the model prediction uncertainty is not only essential to reliably interpret the model simulations under the climate change projections, yet it is also of importance to reveal the model prediction uncertainty caused by the climate outputs from the different GCMs.

The significance of this research is to assess the potential impact of climate change on groundwater level and storage while examining the model prediction uncertainty sourcing only from the selection of the climate models and their outputs –merely considering the precipitation and temperature variables–. However, it is worth noting that there are some limitations during the model experiment: (1) any further changes in the local water management for the experimental design were not considered after the reference period (2008-2020) to reveal the climate impact on the depletion of groundwater level and storage. For this reason, the aquifer boundary conditions were kept as identical as the reference period over the projection period (2021-2100). However, this assumption is not valid since climate change undoubtedly alters the hydrological and hydrogeological boundaries, as well. (2) the depletion of surface waters, the water transfers in/out the basin, and increased groundwater abstraction rates would be some reasonable examples under the changing hydrometeorological conditions. Henceforth, along with the prediction uncertainty coming from the selection of GCMs, it is important to consider that the complex hydro(geo)logical response of the aquifers to the variations of the hydrological and climatological conditions could also result in the model prediction uncertainty.

Acknowledgment

This research was carried out in the Republic of Turkey Ministry of Agriculture and Forestry, Directorate General for Water Management. The HİDROTÜRK hydrogeological model developed by the Republic of Turkey Ministry of Agriculture and Forestry, General Directorate of Water Management (GDWM) for the sustainable management of the water resources in Turkey was used in the modelling experiment. Kübra Özdemir Çallı (KÇ) and Yasemin Taşcı (YT) were involved in the model conceptualism and data preparation for the numerical model development and set-up. KÇ carried out the model experimental design while YT implemented the experiment in the model. KÇ performed the post-processing of the obtained model results, thereby visualizing the plots in R-studio. All authors have read and agreed to the published version of the manuscript.

The authors thank to Bilal Dikmen (General Directorate of Water Management), Mustafa Uzun (Deputy Director of General Directorate of Water Management), Nermin Anul (Head of Department of Monitoring and Water Information System), and Neşat Onur Şanlı (Supervisor of Modelling Working Group) for appreciating to carry out modelling studies in Turkey.

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Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Yeraltı Suyunun İklime Bağlı Azalışının Tahmini: Şuhut Alüvyon Akiferi Örneği

Su döngüsünün önemli ve kritik bileşenlerinden birisi şüphesiz yeraltı suyudur. Yeraltı suyu sadece insanlık için önemli değil, aynı zamanda ekosistemleri sürdürmek için de oldukça önemlidir. Ancak bu değerli hidrolojik sistemler iklim değişikliğinin tehdidi altındadır. Bu durum, özellikle Akdeniz bölgesi etrafındaki yarı kurak iklim koşullarına sahip bölgelerde bir tehdit unsuru haline gelmiştir. Bu bölgelerdeki birçok akifer, diğer pek çok su kaynağı gibi (dereler, akarsular, goller gibi) tarımsal sulama ve endüstriyel turizm sektörünün artan talebi nedeniyle hali hazırda zarar görmüştür. Bu nedenle, iklim kaynaklı etkilerin yeraltı suları üzerindeki doğrudan ve dolaylı etkilerinin ortaya çıkarılması zorunlu bir görevdir.

Değişen iklim koşulları yeraltı suyunun beslenmesini doğrudan etkilerken, artan su talebi dolaylı olarak yeraltı suyu depolaması üzerinde ciddi stres yaratmaktadır. Bu nedenle, yeraltısuyu kaynaklarının yakın gelecekte daha iyi planlanması ve yönetilmesi için, yeraltısuyu seviyesinde ve depolanmasındaki değişim dikkate alınarak yeraltı suyunun tepkisinin sayısal tahminine ihtiyaç duyulmaktadır. Bu bağlamda matematiksel modeller, değişen iklim ve/veya hidrolojik koşullar altında akifer sistemlerin hidro(jeo)lojik davranışları hakkında önemli bilgiler sağlamakta olup, yeraltı suyu akım ve davranış tahmininde önemli rol oynamaktadır.

İklim projeksiyonları ile ilgili olarak, iklim değişikliğinin potansiyel etkilerini ve tepkilerini incelemek için Temsili Konsantrasyon Yolları (RCP'ler) geliştirilmiştir. Buna temelde, öngörülen zaman dilimlerindeki iklim koşulları, gelecekte salınan sera gazlarının hacmine bağlı olarak açıklanmış ve her biri birbirinden oldukça farklı iklim koşullarını tanımlayan dört farklı sera gazı konsantrasyon eğrisine dayanan iklim senaryoları tanımlanmıştır. Örneğin, RCP2.6 ve RCP8.5 sırasıyla en düşük ve en yüksek sera gazı emisyonlarına sahip iklim senaryosunu temsil ederken, RCP4.5 ve RCP6.0 senaryoları ara stabilizasyona odaklanmaktadır.

Küresel İklim Modelleri olarak da bilinen Küresel Dolaşım Modelleri (GCM'ler), iklim göstergelerini elde etmek için kullanılan en güvenilir araçlar olarak kabul edilmektedir. Bu modeller ile, iklimdeki potansiyel değişiklikler farklı sınır koşullarına bağlı olarak simüle edilmektedir. Bu nedenle, farklı iklim modellerinin gerçek sistemin farklı özelliklerini tahmin etme konusunda birbirlerinden farklı güçlü yanları bulunmaktadır. Ancak, farklı iklim modellerinden elde edilen iklim tahminleri birbirinden farklı olmaktadır. Örneğin, GCM'lerdeki bazı iklim modelleri daha sıcak ve kuru iklim koşullarının öngörüsünü yaparken, bir diğeri nispeten daha soğuk ve yağışlı koşulları tahmin etmektedir. Bu nedenle, iklim modelleri sonuçlarında bir tahmin belirsizliği her zaman söz konusudur. Bu açıdan bakıldığında, iklim tahminlerini tek bir iklim modelinden ele almak, belirli bir derecede belirsizlik içerdiğinden, bir hidrolojik ya da hidrojeolojik çalışmada her zaman makul bir seçenek değildir. Bu nedenle, iklim projeksiyonları ağırlıklı olarak seçilen iklim modeline ve iklim senaryolarına bağlı olduğundan hareketle, GCM'lerden kaynaklanan olası belirsizlikleri ortaya çıkarmak amacıyla herhangi bir hidro(jeo)lojik modelleme çalışmasında farklı iklim modellerinin tahminlerini karşılaştırmalı olarak değerlendirmek önem taşımaktadır.

Yeraltısuyu kaynakları üzerinde iklim değişikliği etkilerini araştırmak için yapılan bu çalışmada, yeraltısuyu seviyesindeki ve depolanmasındaki olası azalışın tahmini yapılmıştır. Çalışmanın temel amacı şu şekilde özetlenebilir: *(i)* hidrojeolojik model simülasyonunun zaman dilimi boyunca (2021-2100) yeraltı suyun seviyesinin/derinliğinin konuma ve zamana bağlı değişiminin tahmin edilmesi, *(ii)* iki farklı Küresel Dolaşım Modelinin iki farklı iklim senaryosu gözetilerek yeraltısuyu tükenmesinin karşılaştırmalı olarak değerlendirilmesi, ve *(iii)* her bir iklim senaryolarına karşılık gelen yeraltısuyu azalışının değerlendirilerek, iklim modellerine dayalı model tahmin belirsizliğinin ortaya çıkarılması.

Çalışma alanı olarak, iklim değişikliği ile birlikte yağış miktarındaki azalmaya ve artan sıcaklığa karşı duyarlı bir yeraltı suyu kaynağı olan Akarçay Havzası'ndaki (Türkiye) Şuhut alüvyon akiferi seçilmiştir. Akiferin iklim etkilerine bağlı hidro(jeo)lojik davranışını tanımlamak ve ileriye dönük sayısal tahminlerde bulunmak amacıyla yeraltı suyu akım modeli kurulumu için HİDROTÜRK hidrojeoloji modeli kullanılmıştır. Hidrojeoloji modeline iklim girdilerinin (beslenme ve buharlaşma) tahmini için, iki farklı Küresel Dolaşım Modelinin (GCM) – HadGEM2-ES ve MPI-ESM-MR – RCP4.5 ve RCP8.5 senaryolarına karşılık gelen iklim çıktıları (yağış ve sıcaklık) kullanılmıştır. Yeraltı suyu akım modeli, 1997-2100 yıllarını arasında RCP4.5 (ara emisyon seviyesi) ve RCP8.5 (yüksek emisyon seviyesi) iklim senaryoları gözetilerek çalıştırılmış ve akiferdeki hidrolik yük dağılımı (yeraltı suyu seviyesi) simüle edilmiştir. Buna ek olarak, farklı iklim modelinin hidrojeolojik model sonuçlarında yarattığı tahmin belirsizliğinin ortaya çıkarılması amacıyla, HadGEM2-ES ve MPI-ESM-MR iklim modelleri ve bu modellerin ilgili iklim senaryolarına (RCP4.5 ve RCP8.5) göre yeraltı suyu seviyesi ve depolamasındaki değişim karşılaştırmalı olarak analizi gerçekleştirilmiştir.

Çalışma sonucunda, RCP4.5 ve RCP8.5 senaryolarının her ikisine göre, 2050'nin sonuna kadar yeraltı suyu seviyesindeki düşümlerin birbirinden çok farklı olmayacağı görülmüştür. Ancak RCP8.5 senaryosuna göre, bu yüzyılın sonuna kadar, özellikle yeraltı suyu pompaj oranının fazla olduğu akiferin batı kesiminde, oldukça yüksek bir hidrolik yük düşümüne (yaklaşık 114 m) ve depolama kaybına (%-17.25) neden olabileceği tahmin edilmiştir. Buradan hareketle, iklim değişikliği etkisinin özellikle Şuhut alüvyon akiferinin batı kesiminde önemli miktarda seviye düşümlerine ve depolama değişimine neden etkili olabileceği öngörülmüştür.

Sonuçlarımız, yeraltı suyunda öngörülen tükenmenin, tercih edilen küresel iklim modeli çıktılarına doğrudan ve büyük ölçüde bağlı olduğunu ortaya koymakla birlikte, yeraltı suyu seviyesinin kritik bir derinliğe ulaşması durumunda, akifer sisteminin iklim değişikliği etkilerine daha yavaş yanıt verebileceğini göstermektedir.