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Research papers

Impact of historic and future climate on spring recharge and discharge based on an integrated numerical modelling approach: Application on a snow-governed semi-arid karst catchment area

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ABSTRACT

Flow in a karst system in Lebanon (Important water supply source; Assal Spring; discharge 0.2–2.5 m^3/s yearly volume of 22–30 Mm^3), which is dominated by snow and semi-arid conditions, was simulated using an integrated numerical model (Mike She, 2016). The calibrated model (Nash–Sutcliffe coefficient of 0.77) is based on high resolution input data (2014–2017) and detailed catchment characterization. A sensitivity analysis of individual climatic parameters shows that spring hydrograph characteristics are most sensitive to temperature.

A forward simulation using the IPS_cm5 model with the RCP6.0 scenario for future climate change (Global Climate Models GCM; daily downscaled bias and altitude corrected time series for Lebanon 2020–2099) unravel that precipitation, recharge, and discharge have moderate to highly significant decreasing trends with time over the 21st century. Moreover, recession flowrates are expected to drop drastically starting in the year 2070 to 1 l/s with shortage periods reaching up to six months. The latter is due to a temperature rise of +1.5–2.5 °C and subsequent shrinking of snow cover by almost 100% (e.g., 2073–2074). Furthermore, this is accompanied by a decline in annual spring volume by 73% with respect to the current status, with real evapotranspiration consisting of up to 50% from total water budget (currently around 12–17% in 2014–2017). Moreover, decreasing snow accumulation and a more prominent flushing of precipitation event waters into fast preferential pathways will lead to peak spring discharges. This study allows decision makers to implement best informed practices for future water resources management especially for karst systems under semi-arid conditions in the regions.

1. Introduction

Freshwater has been under stress in recent decades due to climate change and increasing water demands (Kløve et al., 2014). In response, numerous water management methods have been developed (Iglesias et al., 2007) to overcome water shortage, prevent further degradation of groundwater quality and quantity, and ensure sustainable water supply in the future (Taylor et al., 2013). Several studies aimed at highlighting the impact of climate change on groundwater resources (Gleeson et al., 2012; Green et al., 2011; Goderniaux et al., 2015) to assess the extent of the problem and to ensure that management and sustainable exploitation practices account for future climatic variability and increasing demand (Hartmann et al., 2012; Lauffenburger et al., 2018; Loaiciga et al., 2000; Neves et al, 2016; Samuels et al., 2010).

Fresh water availability and recharge is affected by climatic parameters; namely precipitation, temperature, and evaporation (Bates et al., 2008) in addition to land use and land cover, as well as the response of specific types of aquifer. The development and application of integrated groundwater flow and solute transport models are ideal tools for decision makers to predict the transient behavior of aquifers under various stress conditions such as decrease of precipitation, increase of temperature (Christensen et al., 2007; Hartmann et al., 2014) and increased likelihood of floods or droughts (Hartmann et al., 2017; Taylor et al., 2013).

Several previous studies have simulated groundwater responses (water availability, total recharge, water table fluctuations) to various future climatic scenarios in different climate regions (Bliss et al., 2014; Hartmann et al., 2014; Khadka et al., 2014; Stigter et al., 2014; Yang et al., 2014; Mountain Research Initiative EDW Working Group, 2015; Beniston and Stoffel, 2016; Kopsiaftis et al., 2017). For example, the Mediterranean region is expected to undergo pronounced droughts periods and a subsequent unusual decline of groundwater resources

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(Giorgi and Lionello, 2008). Additionally, other studies have taken into account the effect of the anthropogenic activities such as over-pumping and increase in population and water demand on future groundwater resources (Dar et al., 2014; Gurdak, 2017; Sapriza-Azuri et al., 2015; Sharma et al., 2015; Hartmann et al., 2016; Shrestha et al., 2016). In another example from a catchment in the Mediterranean region, hydrological model simulations to future climate change and increase in pumping predicted a 3-month extended dry period in the future, in addition to a 50% decline in groundwater recharge and a 20% increase in evapotranspiration (Sapriza-Azuri et al., 2015). Other parameters such as groundwater- surface water exchange, stream flow, and runoff generation were also expected to decrease by 60% (Sapriza-Azuri et al., 2015). While the future variation in precipitation patterns negligibly affects stream responses to precipitation, a considerable increase in evaporation and decrease in rainfall amount is to be expected in the future (Samuels et al., 2010). Sharma et al. (2015), shows that the estimated change in temperature (an increase of 0.32–1.28 °C) in years 2021–2051 will result in an annual decline in groundwater level by 4.6% and 17.8% in 2021 and 2051, respectively. It was also noted that climate variation might become more pronounced in the future, which may have escalating effects on groundwater sustainability (Sharma et al., 2015). Moreover, rainfall under tropical conditions is thought to decrease in the dry season and to increase in the wet season (Shrestha et al., 2016). An application using projections based on future Representative Concentrating Pathways (RCPs) scenarios (Van Vuuren, et al., 2011), shows that the expected change in temperature by the end of the 21st century ranging between +1.5 °C and +4.9 °C, will yield an important decrease in groundwater recharge and therefore water level and storage (Shrestha et al., 2016).

In such groundwater and climate change simulations, the validity of the predicted output depends to a large extent on the resolution, uncertainty, and uniqueness of the base hydrological model. Unlike most porous unconsolidated systems, the selection and construction of a hydrological model for future projections is particularly challenging in highly responsive karst aquifers systems due to their duality of infiltration and flow (Kiraly, 2002; Geyer et al., 2008). The duality of flow requires the simulation of both fast (high response to precipitation events) and slow flow components (Birk et al., 2004; Geyer et al., 2008). Moreover, as karst aquifers have been known to be highly impacted by environmental changes (Butscher and Huggenberger, 2009; Ravbar et al., 2017), their sensitivity to climate change has been recently given particular attention (Hartmann et al., 2014; Charlier et al., 2015; Chen et al., 2017; Hao et al., 2006; Loaiciga et al., 2000; Samuels et al., 2010). Hartmann et al. (2014) used a combination of spatially distributed recharge as percentage of precipitation (Andreo et al., 2008) and a process based lumped model and others such as Hao et al. (2000) applied a gray-box model to simulate variation of recharge rate, discharge and their relationship to precipitation under future climatic variability in a Mediterranean karst region (Hartmann et al., 2012; Samuels et al., 2010). It is worth noting that simulation of this type of aquifer requires both high resolution time series and detailed catchment characterization (Ranjan et al., 2006) to account for the spatial distribution of point source fast infiltration, land use, and soil type distribution, which are key parameters in climatic components such as evapotranspiration (Manrique-Alba et al., 2017). Such information may be scarce and unavailable at the scale of a catchment, but is needed to set up and calibrate a representative integrated hydrogeological model valid for future climate scenarios simulations (Taylor et al., 2013).

The aim of this study is to use a spatially distributed model to simulate the response of an important karst spring in Lebanon to future climatic scenarios based on bias corrected downscaled projected climatic data for the region. Flow in the small-scale pilot catchment (influenced highly by snowmelt in a semi-arid region) was simulated with an integrated process based hydrological model MIKE She (DHI, 2016) to account for the atmosphere, unsaturated zone, and saturated zone, and depict the variation of response signals in each of these layers. Snow melt was regarded as an important factor controlling recharge processes in snow dominated areas (Chen et al. 2017). The calibrated and validated model is based on high resolution collected data for spring discharge and climatic parameters (2014–2017) and detailed catchment characterization from tracer experiments and soil sampling. The influence of climate change is evaluated using two approaches. First, we evaluated the sensitivity of spring discharge to historical climate data, such as precipitation (P) and temperature (T), etc. Second, we conducted future flow simulations using downscaled data from the IPSL_CM5 global climate model (GCM) with Representative Concentration Pathway (RCP) 6.0 scenario to depict the daily variation of discharge in 2021–2099. The study further highlights the variation of recession coefficients with time that is indicative of the flow pathways, duration of the recession periods below a specific threshold, and the lag of spring response to snowmelt under future climatic conditions. These findings have important implications for water management decisions and policy in similar catchment types across the greater Mediterranean region.

2. Methodology

In the framework of a monitoring project funded by USAID since 2014, a full climatic station (Campbell-Scientific-Alpine type) with a heated gauge mounted with a data logger was installed at about 1700 m above sea level to record climatic parameters such as precipitation, temperature, humidity, wind direction and speed, and radiation at an hour interval. Additionally, a multi parameter probe (Insitu-Troll 9500) measuring parameters such as water level, electrical conductivity, temperature, turbidity, chloride, pH and Redox potential at a 30-min interval. Daily data for these parameters was obtained/ purchased from local authorities for the period extending from 2010 till 2013. A rating curve (polynomial relationship) between water level and discharge was constructed based on bi-monthly measured discharge rate over a period of two years. The error of the measurement is about 8–10% during recession. The methods to develop a calibrated integrated hydrological model to simulate spring responses to future climatic scenarios use the following three consecutive steps (Fig. 1):

(1) Construct an integrated numerical model with MIKE She (DHI, 2016) with high resolution time series data (2010–2015) based on detailed geological characterization, calibrate the model based on spring discharge data, and to validate it (2015–2017);
(2) Perform sensitivity analysis on single climate parameters such as precipitation and temperature to evaluate their impact on the modelling results; and
(3) Conduct future simulations (2020–2099) based on time series of forecast climatic data downscaled from a GCM, apply different statistical tests for distribution and significance, and highlight the impact of climate change scenarios on spring discharge and on different signals within the various hydrologic compartments in the karst system and other spring characteristics.

2.1. Set up and calibration of an integrated hydrological model

In this work, the simulation of flow in a karst system at a catchment scale was done using MIKE She (DHI, 2016). The catchment area of a karst spring is sub-divided spatially into a 33 × 33-m cell size grid and vertically into three main compartments: atmosphere (A), unsaturated zone (UZ), and saturated zone (SZ). The development of the model and its parametrization was based on a similar approach used in Doummar et al. (2012) with the same set of calibration parameters (fitted and physically based parameters).

The A compartment includes climatic processes (rainfall, snow, evapotranspiration) and interception by vegetation. The snow model used for the purpose of this study is a simple one governed mostly by air temperature (DHI, 2016). If air temperature is above the threshold