



# Assessing sustainability of groundwater resources on Jeju Island, South Korea, under climate change, drought, and increased usage

Aly I. El-Kadi · Suzanne Tillery · Robert B. Whittier · Benjamin Hagedorn · Alan Mair · Kyoochul Ha · Gi-Won Koh

**Abstract** Numerical groundwater models were used to assess groundwater sustainability on Jeju Island, South Korea, for various climate and groundwater withdrawal scenarios. Sustainability criteria included groundwater-level elevation, spring flows, and salinity. The latter was studied for the eastern sector of the island where saltwater intrusion is significant. Model results suggest that there is a need to revise the current estimate of sustainable yield of  $1.77 \times 10^6$  m<sup>3</sup>/day. At the maximum extraction of 84 % of the sustainable yield, a 10-year drought scenario would decrease spring flows by 28 %, dry up 27 % of springs, and decrease hydraulic head by an island-wide average of 7 m. Head values are particularly sensitive to changes in recharge in the western parts of the island, due to the

relatively low hydraulic conductivity of fractured volcanic aquifers and increased groundwater extraction for irrigation. Increases in salinity are highest under drought conditions around the current 2-m head contour line, with an estimated increase of up to 9 g/L under 100 % sustainable-yield use. The study lists recommendations towards improving the island's management of potable groundwater resources. However, results should be treated with caution given the available data limitations and the simplifying assumptions of the numerical modeling approaches.

**Keywords** Groundwater management · South Korea · Numerical modeling · Climate change · Salt-water/freshwater relations

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## Introduction

In groundwater-resource assessments, terms such as sustainability, sustainable yield, sustainable pumping, sustainable development, and safe yield are often used interchangeably or with little distinction between the concepts. Definitions and approaches to assess sustainability of potable drinking-water resources are summarized by Bredehoeft (2002), Kendy (2003), Alley and Leake (2004), Maimone (2004), Devlin and Sophocleous (2005), Liu et al. (2006), and Bredehoeft (2007), among others. Sophocleous (2000), for instance, defines sustainable development, in general, as development that “*meets the needs of the present without compromising the ability of future generations to meet their own needs.*” Specifically, optimal or sustainable groundwater-resource use requires setting upper limits on water withdrawal (or sustainable yield) to avoid compromising the source (Mink 1992; Mink and Lau 1990; Takasaki and Mink 1985). Although the concept is widely practiced by state and federal government agencies, sustainable yield has come under heavy criticism for both theoretical and practical reasons. Sustainable yield is not always easy to estimate or utilize in practice. Estimation problems arise due to poor assumptions in models and the lack of reliability of available data. For example, although water

use in Hawaii is subjected to regulations regarding sustainable yield, studies have shown rising salinity and decreasing freshwater resources (Oki 2005).

On islands where potable water resources are limited, an accurate and reliable estimate of sustainable use or yield is critical. Estimates have to address not only decreasing water availability, as manifested by declining water levels, but also deterioration of water quality caused by, e.g., seawater intrusion (Kim et al. 2006) or agrochemical use (Koh et al. 2007).

On Jeju Island, as is the case for many islands, sustainability of groundwater resources is especially important given the increasing water demands from urban and agricultural development and the island's lack of reliable surface-water resources (Hagedorn et al. 2011; Won et al. 2006). The island has experienced tremendous growth over the past 30 years and now supports a residential population of 583,000 and 8.7 million visitors annually. Groundwater aquifers supply 92 % of freshwater consumed on Jeju (Kim et al. 2003a, b). Because of the rapid growth and increased demand for potable water, saltwater intrusion has become a persistent problem, particularly in the eastern portion of the island (Kim et al. 2003a, b, 2006).

Examples of approaches to define and estimate sustainable aquifer yield are those implemented in Hawaii and Jeju. On the Hawaiian Islands, the sustainable yield of an aquifer is defined by the Hawaii State Water Commission (1979) as the “*water supply that may normally be withdrawn from a source at the maximum rate, which will not severely impair source utility.*” Mink (1980) notes that the clearest expression of sustainable yield is that of allowable net draft for a selected equilibrium head. In a subsequent publication, Mink (1981) developed the robust analytical model (RAM) for estimating the sustainable yield of a basal aquifer. However, the model does not take into account the effects of transport processes due to saltwater–freshwater interaction. The analytical RAM2 model was developed as an extension of the original RAM model to include the simulation of the salinity distribution in a transition zone (Liu 2007). The RAM and RAM2 models are currently used to estimate the sustainable yield of basal aquifers in the Hawaiian Islands (Wilson Okamoto Corporation 2008). However, these analytical models are limited in their ability to evaluate spatio-temporal effects of climate and withdrawal scenarios on groundwater resources.

Based on detailed analysis of aquifer testing data on Jeju Island, Hahn et al. (1997) estimated sustainable yield by combining mass balance with Darcy's law. In this regard, the authors set an upper limit for the ratio between the equilibrium water level to be maintained and the initial water level in the pre-development time for each area under consideration. While this approach is very useful for providing a cursory estimate, it is subjected to significant uncertainty due to data limitations, considering that initial water-level data for pre-development times are rarely available. A need exists for a more comprehensive, physically based approach that utilizes site-specific data.

Hahn et al. (1997) and the Korean Water Resources Corporation (KOWACO 2003a) used a set ratio of 80 % between the equilibrium water level to be maintained and the initial water level in the pre-development time to estimate the sustainable yield of Jeju's aquifers. Koh et al. (2006b) reported the most recent estimate of sustainable yield by KOWACO as  $1.77 \times 10^6$  m<sup>3</sup>/day. KOWACO also specifies a maximum allowable aquifer withdrawal rate (MAWR) of  $1.48 \times 10^6$  m<sup>3</sup>/day for domestic, industrial, and irrigation purposes (KOWACO 2003a), which is roughly 84 % of the estimated sustainable yield. Estimates of groundwater recharge on Jeju range from  $4.09 \times 10^6$  to  $4.80 \times 10^6$  m<sup>3</sup>/day (Hahn et al. 1997; KOWACO 2003b; Koh et al. 2006b; Won et al. 2006). Thus, the limits on aquifer pumping as a percentage of groundwater recharge range from 37 to 43 % for the sustainable yield and from 31 to 36 % for the MAWR. By 1993, total daily pumping averaged  $0.66 \times 10^6$  m<sup>3</sup>/day from all of Jeju's domestic, municipal, and irrigation water-supply wells (Hahn et al. 1997). The data implies that pumping from Jeju's aquifers by the mid-1990s was already at 37 % of the sustainable yield and 45 % of the MAWR. Although accurate estimates of pumping rates from all sources on Jeju in recent years are lacking, it is highly likely that total pumping now exceeds the rate in 1993 of 37 %. Based on discussion with various government groups, a value of total use of 64 % of the sustainable yield was adopted in the current study based on a best estimate.

In recent years, hydrological models, with various degrees of sophistication, have been used in various settings to evaluate water budgets under various climate or land-use scenarios (e.g., Mink 1981; Gingerich 2008). The report by the Minnesota Department of Natural Resources (2010) evaluates models and tools needed for assessing water availability and sustainability. In general, a water-budget model is used in estimating recharge, which is used as input to groundwater models. Sustainability indicators such as acceptable head or water-quality levels, are examined based on climate and management decisions affecting water extraction and land use. Due to limitations in models and data availability for model calibration, field monitoring of sustainability indicators should be an important part of any sustainability planning effort.

The objective of this study is to assess sustainable groundwater use for Jeju Island under projected climate, land use, and increased-pumping conditions. Numerical modeling is used in assessing the sustainability by evaluating the response of the groundwater system to different climate, land use, and pumping scenarios. The results for each scenario are evaluated by assessing negative effects on groundwater sustainability indicators, namely, hydraulic head, spring flow, and salinity.

## Study site

Jeju Island is a mid-latitude volcanic island located about 140 km south of the coast of South Korea in the

transitional region between the temperate and subtropical climate zones (Park 2010) (Fig. 1). About half of the mean annual rainfall occurs in the summer monsoon between June and September, with average monthly rainfall higher than 200 mm (KOWACO 2003b). Winters are dry and cold, with occasional snowfall at the higher elevations. About half of the island is covered with natural forest vegetation, while other areas are covered by pasture, grassland, cropland, and increasing urban development along the coastline (KOWACO 2003b). As a Quaternary shield volcano, Jeju is mainly composed of basaltic and trachytic lavas and associated sediments (Won et al. 2006). In addition, nearly 400 scoria cones and tuff rings are scattered across the island. According to Sohn (1996), the major geologic units for Jeju Island are subdivided from top to bottom as follows (Fig. 2):

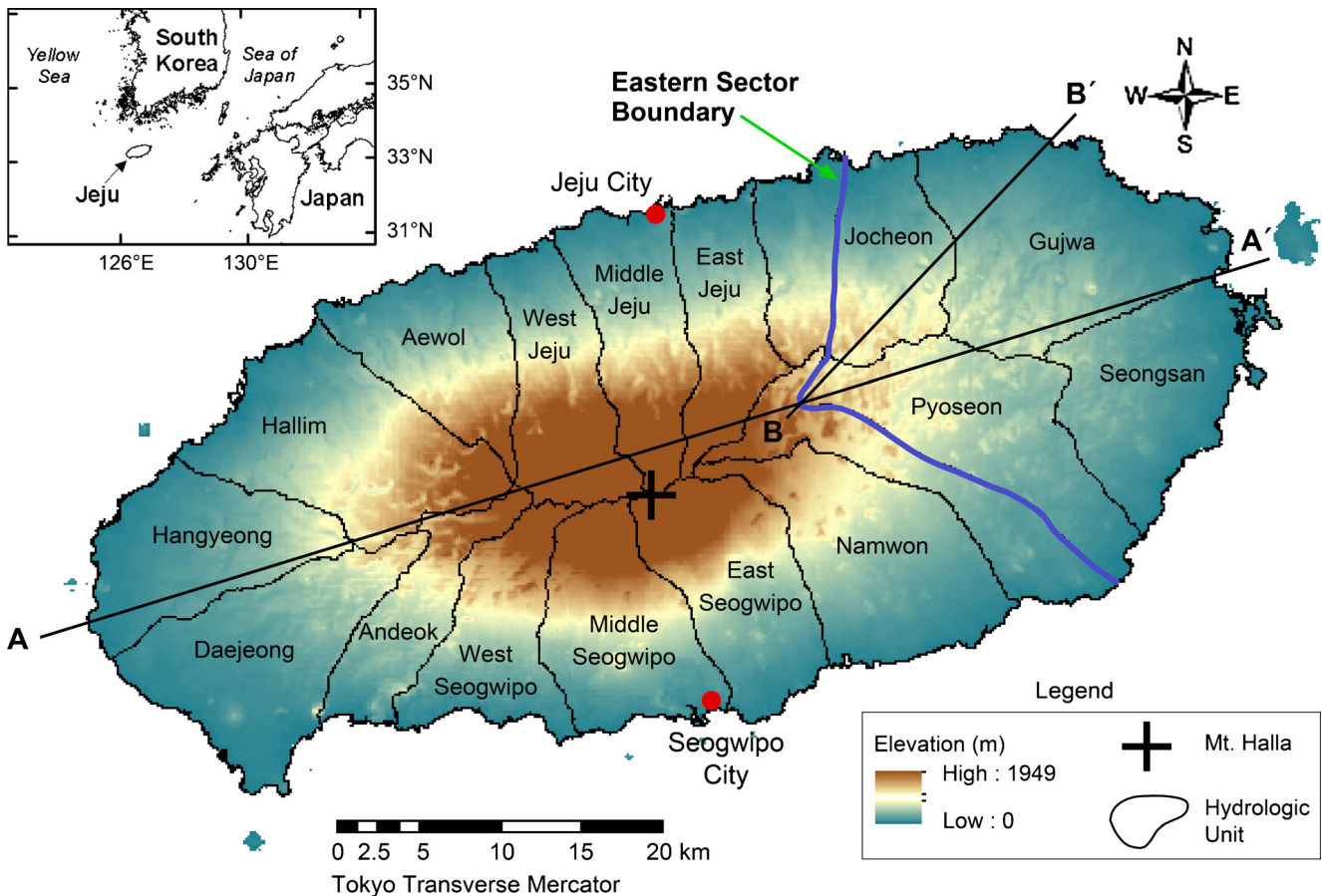
1. The main volcanic lithologies consisting of permeable basalt, andesite, and trachyandesite lavas, with numerous flow units and abundant fractures
2. The Seogwipo Formation, comprising low permeability volcanic sediments with an average thickness of about 100 m (Nam et al. 2009)
3. The U-Formation, including low permeability unconsolidated silt and sand deposits with an average thickness of approximately 150 m (Nam et al. 2009)

4. The relatively impermeable basement, which is mainly composed of welded tuffs and granite, occurring at depths of about 250–300 m below sea level (Nam et al. 2009)

Recharge occurs predominantly in the high rainfall inland areas of the island (Mair et al. 2013a, b), whereas volcanic lithologies (i.e., basalts, andesites, and trachytes) comprise the main aquifers (Hahn et al. 1997; Won et al. 2005). Groundwater flow occurs mainly through rock fractures and along interflow structures (Hamm et al. 2005). Groundwater level contours roughly follow the topography with highest values in the interior (about 300 m asl) and lowest levels towards the coast (about 2 m asl).

## Methods

The numerical groundwater models MODFLOW (Harbaugh et al. 2000) and SEAWAT (Langevin et al. 2007) were applied to assess groundwater-resources sustainability criteria under various climate and groundwater-withdrawal scenarios. MODFLOW was used to develop an island-wide model to evaluate water levels



**Fig. 1** A map of Jeju Island showing the hydrologic districts and the boundary of the eastern sector. Lines A–A' and B–B' illustrate the location of cross sections displayed in forthcoming figures

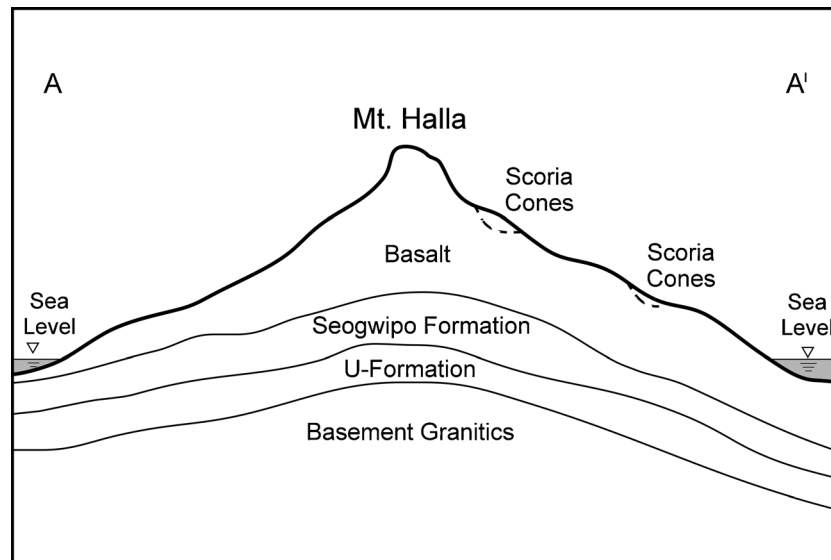


Fig. 2 Lithologic cross-section and groundwater occurrence for Jeju Island (modified from Koh et al. 2006b)

and spring flows, assuming saturated flow and constant water-density conditions. Applicability of this widely used model in island modeling is limited due to the lack of density-change accountability; however, the model can be reasonably calibrated for sites that are farther away from the shoreline (e.g., Whittier et al. 2010). More recently, the SWI2 Package (Bakker et al. 2013) has been added to MODFLOW, which makes the model more appropriate by including variable-density groundwater flow.

SEAWAT combines MODFLOW with MT3DMS (Zheng 2006; Zheng and Wang 1999) in simulating three-dimensional (3D) variable-density groundwater flow. SEAWAT has been applied to saltwater intrusion and up-coning (Shoemaker and Edwards 2003; Masterson 2004; Masterson and Garabedian 2007; Dausman and Langevin 2005; Heywood and Pope 2009; Sanford et al. 2009; Hughes et al. 2009), and it has been also utilized in assessing submarine groundwater discharge (Langevin 2001, 2003; Dausman et al. 2007).

In this study, SEAWAT was used to incorporate the effects of density-driven groundwater flow to assess salinity for the eastern sector of the island where significant saltwater intrusion has been reported (Koh et al. 2006a). MODFLOW and SEAWAT were applied within the groundwater modeling system (GMS) graphical user interface (Aquaveo 2011).

Spatially distributed estimates of groundwater recharge computed by Mair et al. (2013b) were input into the numerical groundwater model. These authors used a deterministic, quasi-3D physically based soil-water balance model developed by Westenbroek et al. (2010) and inputs of soil, land cover, topographic, and climatic data to estimate potential groundwater recharge at a daily time step and 100-m-grid cell size. They estimated potential recharge for baseline, drought, and future climate-land-use scenarios. The baseline scenario was comprised of an

18-year period during 1992–2009, while the drought scenario was developed for a 10-year historical drought during 1963–1972 as identified by Mair et al. (2013a). A future climate-land-use scenario was created to simulate projected changes in surface temperature and land use. Projected future increases in average temperature during 2070–2099 under an A2 emission scenario as reported by Min et al. (2004) were simulated by adjusting the 18-year-baseline-scenario temperature dataset using a seasonally variable change factor approach. Based on a comparison of historical trends with projected changes in rainfall, Mair et al. (2013b) made no changes to the 18-year precipitation dataset for the future climate-land-use-change scenario. Land-use change was incorporated by increasing the urban-residential land-use type by 46 %; henceforth, the term climate scenario will be used to describe future climate-land-use changes.

The models were calibrated for the baseline recharge scenario to match average island-wide water levels, average spring flows at selected locations near the coast, and groundwater salinity. The calibration was done under a pumping rate at the 64 % of sustainable yield. Following calibration, simulations were run for the three groundwater-recharge scenarios—namely, baseline, drought, and climate—each under a number of pumping scenarios for MODFLOW. A total of seven pumping scenarios were considered for each recharge scenario by adjusting pumping to 18, 34, 51, 64, 67, 84, and 100 % of the estimated sustainable yield. The pumping rate at the 84 % level approximates the reported groundwater MAWR, which is the maximum amount of pumping allowed on Jeju (KOWACO 2003a). For this specific study, SEAWAT was not practical for a full-scale analysis, due to its computational burden. Hence, the model was only run for a worst-case scenario of withdrawals at 100 % of sustainable yield.



### Conceptual model

Groundwater on Jeju is classified into four general categories: high level, parabasal, basal, and basement (Won et al. 2006 and references therein; Fig. 3). It is postulated that high-level groundwater is perched by low-permeability volcanic layers at high levels in the mountainous interior of the island without a direct hydraulic connection to the other types of groundwater. Modeling the dynamics of this type of groundwater is complicated by the following factors.

1. The lack of understanding of the spatial distribution of low permeability volcanic sequences that may impede vertical flow and perch groundwater at high levels
2. The lack of information on the subsurface distribution of the Seogwipo Formation in that region
3. The lack of detailed water elevation data needed for calibration

Given these issues, the analysis was simplified by excluding the area of the island above the 600 m asl from modeling (Fig. 4). The choice of this 600 m elevation line was somewhat arbitrary; however, generally, no perched groundwater has been observed beyond that contour line (Koh et al. 2006c). Total recharge over this area as computed by Mair et al. (2013b) within each hydrologic district (Fig. 1) was integrated and routed to the modeled area through the boundary of the excluded area where a specified flux condition was applied. Gingerich (2008) adopted a similar approach for an area on the island of Maui (Hawaii) for a similar situation.

Basal groundwater occurs near the coast and floats on the denser seawater, whereas parabasal groundwater is separated from the seawater interface by the low permeability Seogwipo sediments (Fig. 3). Because the

Seogwipo Formation occurs at the greatest depths in the eastern section of the island (Koh et al. 2006b), basal groundwater extends farthest inland along the eastern coast (Hagedorn et al. 2011) where typical mixing and water-circulation patterns develop (Kim et al. 2006).

The ratio of head above sea level versus the depth of the freshwater lens below sea level at the midpoint of the transition zone averages 1:23 in the eastern area of Jeju (Won et al. 2006), which is significantly different from the typical 1:40 Ghyben-Herzberg ratio (Freeze and Cherry 1979). Such a deviation can be due to many factors including the effects of anisotropy and vertical flow components (Gingerich 2008). The transition zone is thin in this area and is virtually non-existent in other parts of the island (Won et al. 2006). The relatively minor observed effects of saltwater intrusion and mixing for most of the island justified the use of MODFLOW for an island-wide model and the application of SEAWAT to the eastern sector of Jeju.

Basement groundwater occurs in fractures and joints of the basement rocks at depths of  $-300$ – $400$  m or more. The granitic basement is relatively impermeable with a uniform estimated conductivity of 0.01 m/day (Kim et al. 2009). Basement groundwater does not currently comprise a significant potable water source for Jeju, and no basement specific groundwater data was available for model calibration in this study.

Groundwater discharge mainly takes place as submarine groundwater discharge (SGD) to the ocean, spring flow above sea level, water withdrawal from wells, and evapotranspiration at the water table (Hahn et al. 1997; Koh et al. 2006a; Won et al. 2005). Kim et al. (2003a) assumed that freshwater discharge is approximately equal to recharge and estimated a submarine discharge rate at

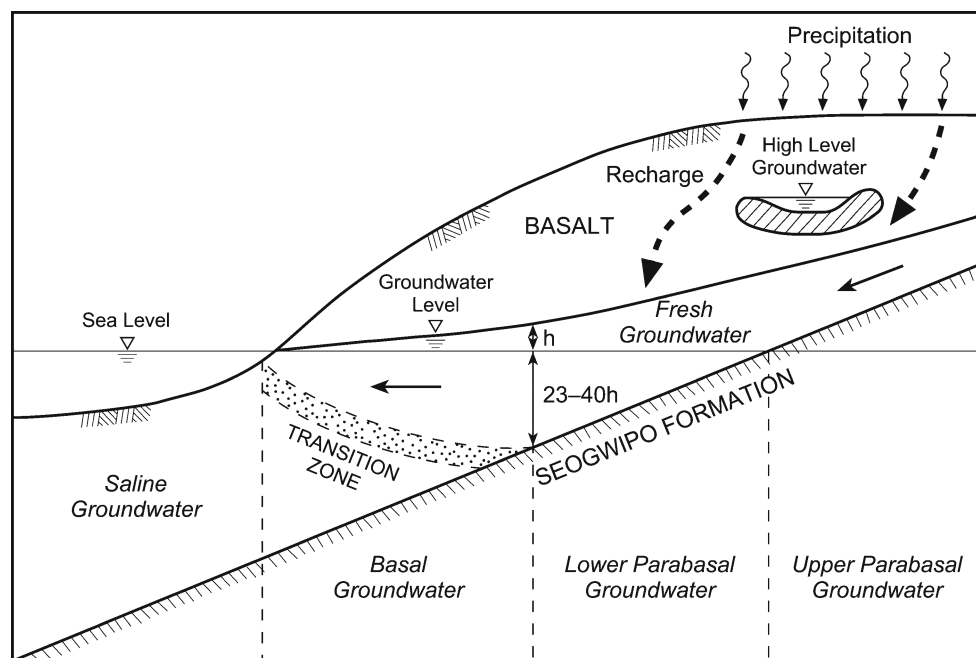
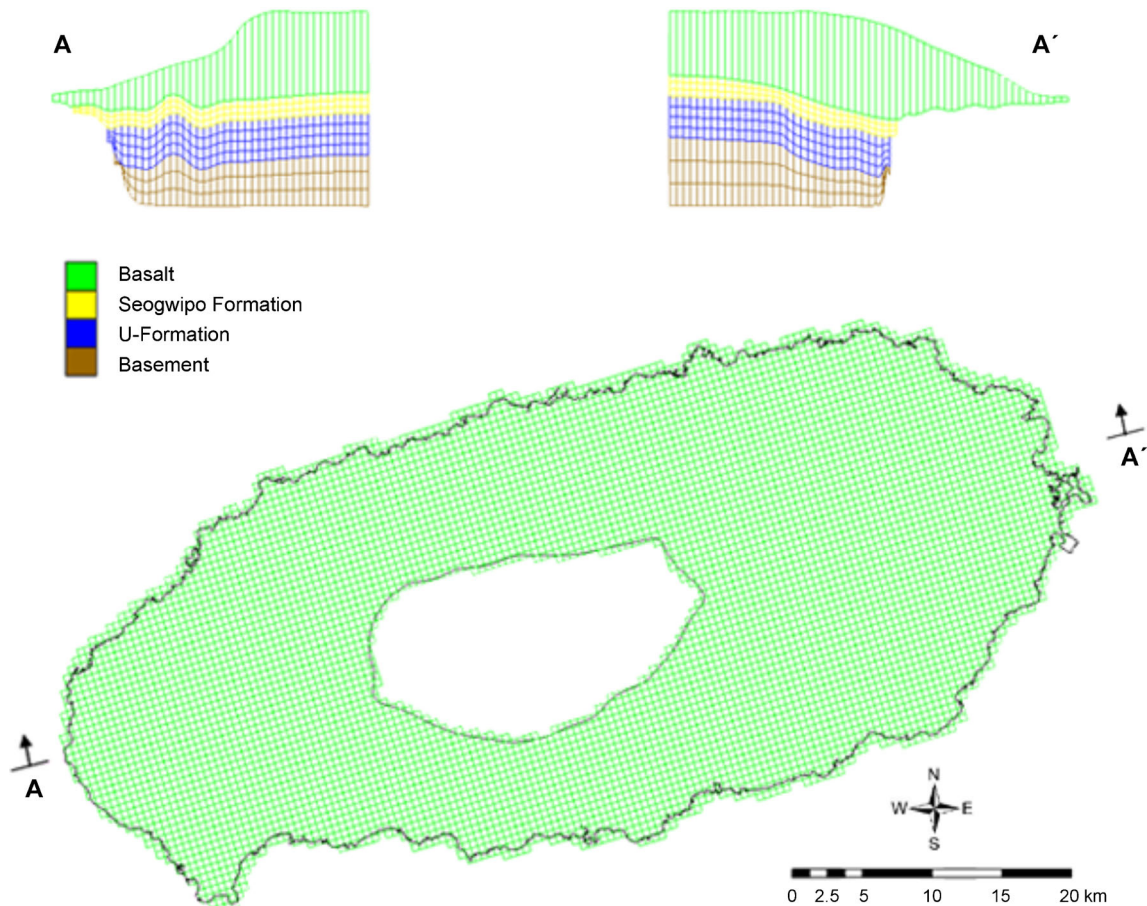


Fig. 3 Simplified conceptual model of the hydrogeologic system of Jeju Island (from Won et al. 2005)



**Fig. 4** MODFLOW grid for cross-section *A–A'* in Fig. 1 through the Jeju Island. The *white area* in the center of the island is excluded from modeling

about  $1.5 \times 10^9$  m<sup>3</sup>/year. Also according to Kim et al. (2003a), in the eastern region, almost all groundwater below a few meters of the water table is essentially comprised of re-circulated seawater, whereas in the west, freshwater accounts for 20 % of the SGD. In the north and south, there is less SGD, but rather there are a large number of coastal springs (Koh et al. 2006a). Obviously ignoring density driven and saltwater flow in the MODFLOW model is expected to introduce errors in estimating SGD.

A total of 911 springs have been mapped on Jeju Island (Koh et al. 2006a) and spring flow commonly occurs along streambeds, lava flow boundaries, and scoria cones. Hahn et al. (1997) provide estimates for average discharge from the springs around the coast.

## MODFLOW

### *Spatial discretization and layering*

The flow domain is 78-km long, 37-km wide, and up to 800-m deep, rotated counter-clockwise by 17.6° to

minimize the number of inactive numerical cells (Fig. 4). Spatially, the model cells are uniform at 500 m by 500 m, resulting in 156 columns and 74 rows. Vertically, the domain was divided into 11 layers: (1) volcanics material assigned as a single layer, (2) the Seogwipo and basement granite each was divided evenly into three layers, and (3) the U-Formation was evenly divided into four layers (Fig. 4). Since the model is only simulating interactions from the water-table downwards, the elevations were truncated at around 325 m asl, which is above the maximum water level reported by Won et al. (2006). The elevations for the top of the layer representing the Seogwipo Formation were based on a co-kriging interpolation of borehole data compiled throughout the island (K. Ha, KIGAM, personal communication, 2010).

### *Boundary and initial conditions*

Bathymetric data are typically used to extend the model boundary beyond the coastline and assign specified head or head-dependent flux conditions. However, in this study, the external model boundary was set at the coastline of the

island to reduce the computational burden due to the large area of an island-wide model. A constant head boundary of zero meters was set at the boundary for the basalt layers and a no-flow boundary was assigned for the other layers. The centerline of the saltwater–freshwater mixing zone was set as a no-flow boundary representing the bottom of the model. The location of such a boundary was based on available data on vertical salinity profiles (Kim et al. 2006; Fig. 4).

Because the models were not used to simulate water flow in the unsaturated zone, it was assumed that potential recharge computed from the soil-water balance modeling represents actual recharge at the water table. For the internal model boundary, the areal recharge above the 600-m elevation contour was accumulated and distributed as constant fluxes along that contour.

MODFLOW modeling was completed for steady-state conditions for the baseline and climate scenarios, representing presumed permanent management decisions. Although not required for the steady-state simulations, but to achieve faster convergence, the initial conditions of head for the models were assigned based on average water levels reported by Won et al. (2006). Drought was assessed for a transient condition at the end of 5- and 10-year duration periods, with the baseline-calibrated head-values representing the initial condition. The transient simulations were done for variable time steps starting at about 2 days with an expansion by a factor of 1.05 for the duration of the simulation. All cases were run with constant recharge at the pertinent average daily rate computed for each of the three recharge scenarios.

#### Recharge conditions

Grid-cell values of recharge for each of the three recharge scenarios as computed by Mair et al. (2013b) were transformed into an average recharge rate within the hydraulic-conductivity calibration zones (Fig. 5). The greatest recharge occurs under a baseline scenario during 1992–2009 ( $883$  or  $1,605 \times 10^6$  m<sup>3</sup>/year) followed by the climate scenario ( $788$  or  $1,432 \times 10^6$  m<sup>3</sup>/year) and drought scenario ( $591$  or  $1,073 \times 10^6$  m<sup>3</sup>/year).

#### Parameters and calibration

For calibration, which was done through an iterative procedure, volcanic hydraulic conductivity ( $K$ ) values were constrained in the range of 0.5–2,000 m/day (Won et al. 2006). The calibrated values are generally higher towards the eastern coast ( $K=75$ – $1,275$  m/day) and are lower in the interior of the island ( $K=0.75$ – $75$  m/day). This trend relates to the spatial distribution of the volcanic lithologies on the island with more conductive basalts occurring along the western and eastern coastlines and less conductive trachytic rocks prevailing in the inner portions of the island (Won et al. 2005, 2006). Relatively low conductivities also correlate with the locations of tuff cones on the island (Kim et al. 2007). Vertical conductivity for the basalt has been reported to vary between 3 and

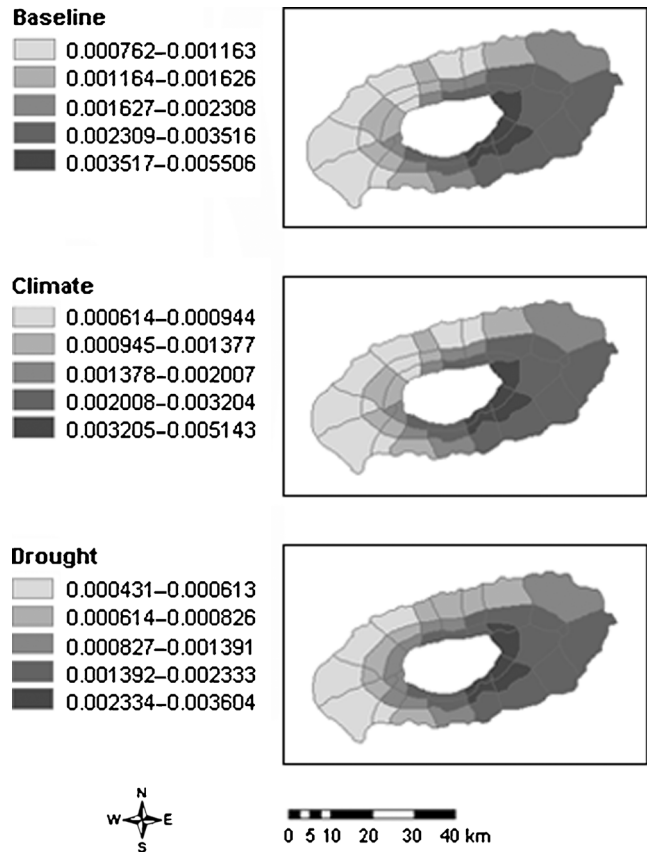
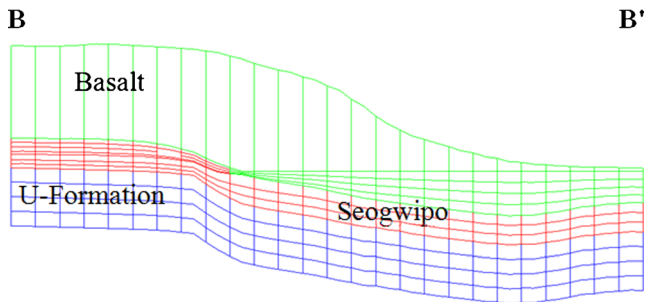


Fig. 5 Scenario recharge-values assigned as averages to each of the hydraulic conductivity calibration zones. Average groundwater recharge rates within the portions of each respective hydrologic district (Fig. 1) above 600 m (i.e., center of the island) were routed to the inland boundary of the adjacent hydraulic conductivity zone

28 m/day (Kim et al. 2003a). The Seogwipo Formation was assigned a uniform horizontal conductivity of 1.0 m/day, while the U-Formation was assigned a slightly lower conductivity of 0.1 m/day (Won et al. 2006).

MODFLOW calibration was done through matching the simulated hydraulic heads to contour values taken from Won et al. (2006), and matching average spring flows at the coast, for which each spring should be treated as a point drain. Modeling parameters for a drain include drain-bed elevation and a conductance parameter, which is combined with the groundwater elevation to compute the amount of spring flow. Hence, the drain acts as a head-dependent source that will dry up if the water table declines below a certain level. Calibration was done by the tedious process of adjusting the drain-bed elevation of each drain until the resulting simulated spring flow approximately matched the average value. However, due to the large number of springs, only springs with flows larger than 1,000 m<sup>3</sup>/day were treated as drains. The springs with flows less than 1,000 m<sup>3</sup>/day (with total flow of about 10 % of the total) were simulated as constant flux sources, which always withdraws their specified amount of water from the system.





**Fig. 6** SEAWAT grid for a cross-sectional section *B–B'* in Fig. 1 through the eastern sector of Jeju Island

## SEAWAT

### *Spatial discretization and layering*

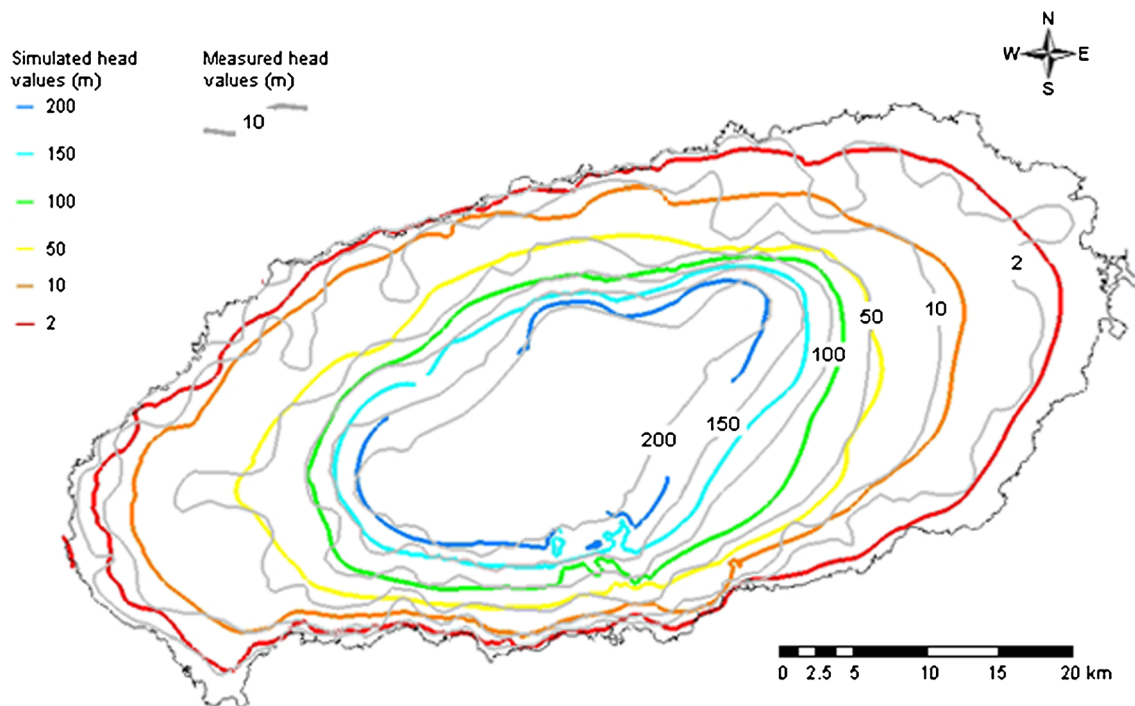
The inland boundary of the eastern sector of Jeju was delineated from MODFLOW's baseline run by using the model MODPATH (Pollock 1994). Assigning particles at the center of the island, MODPATH delineated streamlines, or groundwater divides, which were used as the sector's boundary (Fig. 1). The SEAWAT model was divided into  $50 \times 30$  uniform cells, each of the size of about 900 m by 600 m, with a grid that was rotated  $45^\circ$ . The layer thickness ranged between 9 and 37 m near the ocean where

saltwater and freshwater interact (Fig. 6). The domain was divided into three layers—basalt, Seogwipo, and U-Formation—considering that there is no significant flow in the basement; these layers were further divided into sub-layers of 5, 3, and 3 sub-layers, respectively.

### *Boundary and initial conditions*

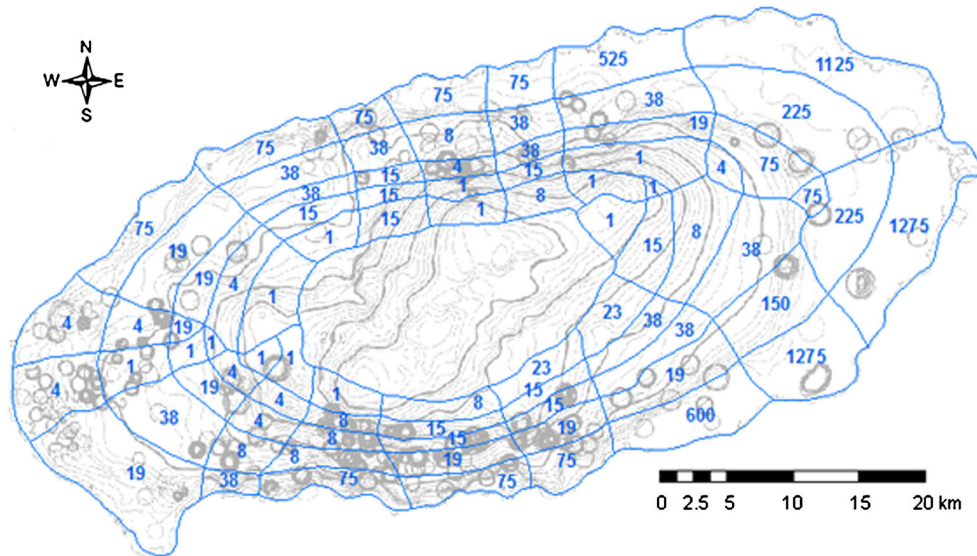
As was the case with MODFLOW, the ocean-side boundary corresponded to the coastline to reduce the computational burden caused by the need for a refined grid for the model and by non-linearity of the problem. Salinity at the shoreline was set as 19 g/L. A specified-head condition was set for the top layer (above the mean sea level), while a head-dependent flux was assigned to cells below the mean sea level. The latter is a general boundary condition that allows accounting for a variable flux, and thereby is more appropriate in the absence of an accurately defined physical boundary. Conductance, a parameter needed at the head dependent flux boundary, was estimated through an iterative trial and error approach in the calibration process. The bottom of the U-Formation was assigned a no-flow boundary, assuming negligible flow in the basement rocks.

As was the case with MODFLOW, it was assumed that potential recharge represents actual recharge at the water table. However, and due to the use of groundwater divides, a no-flow condition was assumed at the upper



**Fig. 7** Comparison between contours of measured head levels (from Won et al. 2006; gray lines) and calibrated model head values (colored lines)





**Fig. 8** Calibrated values for basalt’s horizontal hydraulic conductivities (to the nearest 1 m/day) superimposed on a map of the locations of tuff cones (modified from Kim et al. 2007)

boundary (i.e., flux condition approach for recharge used at inland MODFLOW model boundary was eliminated).

All scenarios were simulated as transient and the results were assessed after 5 and 10 years. A pseudo steady-state simulation was completed first for the baseline case and used as the initial condition for all scenarios. SEAWAT simulations were done for variable time steps starting at about 2 days with an expansion by a factor of 1.05 for the duration of the simulation. All cases were run with constant recharge at the pertinent average daily rate computed for each of the three recharge scenarios.

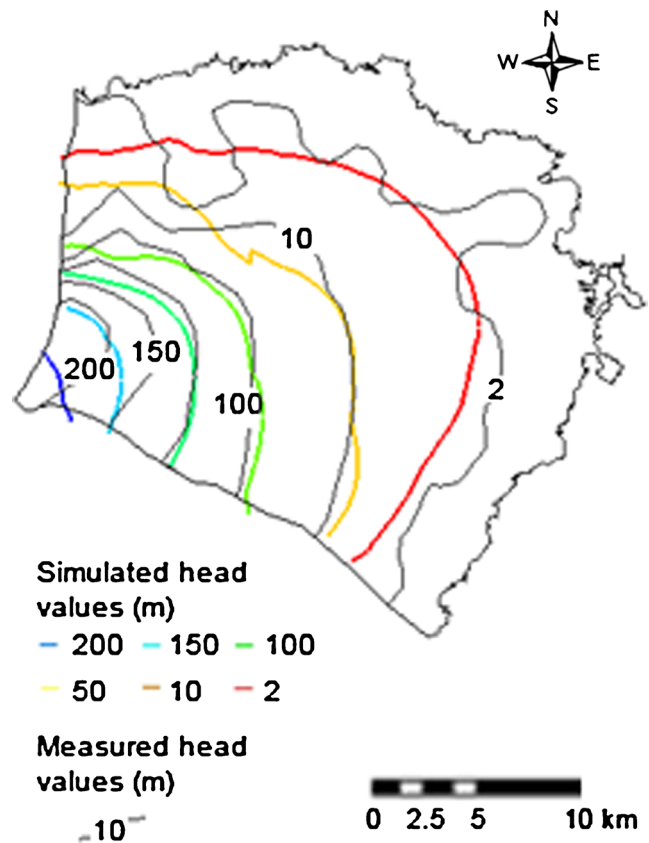
*Recharge conditions*

The SEAWAT model utilized the recharge rates used in the MODFLOW model as described in the preceding. The recharge maps were clipped to cover the eastern sector’s area.

*Parameters and calibration*

Minimum calibration was done regarding MODFLOW parameters to test whether their values, especially hydraulic conductivity, were independent of the model used. Calibration was mainly related to parameters controlling solute transport and the transient condition—that is, dispersion and storage parameters. The values of these parameters were adjusted for the volcanics within ranges set by Oki (2005). Results were not sensitive to values assigned for other layers considering their relatively low conductivity. Final values used for the longitudinal and transverse dispersivities were 20 and 2 m, respectively,

while values for the specific yield and specific storage were 0.1 and 0.001 m<sup>-1</sup>, respectively.



**Fig. 9** SEAWAT simulated hydraulic head values (colored) compared against data from Won et al. (2006; gray) for the eastern sector (see Fig. 1)

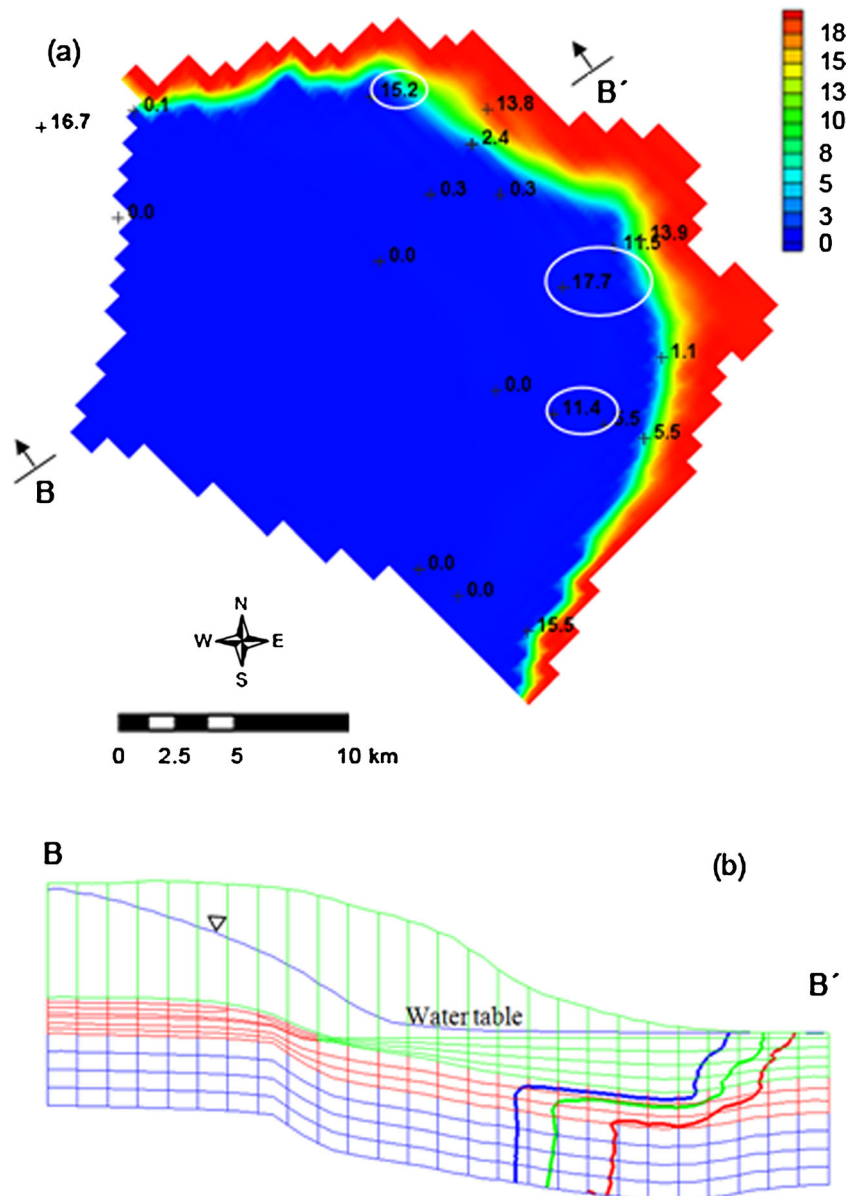
## Results and discussion

### Baseline case

#### MODFLOW

The baseline case, representing the groundwater withdrawal and other related conditions for 2009, was used to calibrate the models and as a basis for assessing the likely effects of various scenarios. Changes in values of various sustainability indicators, i.e., spring flow, head, and salinity, were compared against the respective values for the baseline case.

The calibrated MODFLOW head results are shown in Fig. 7 compared against measured values reported by Won et al. (2006). Reasonable match can be seen, despite the lack of closer match around the 2 m contours in some locations. Such deviations are most likely due to variability of hydraulic conductivity values at a smaller scale than that represented in the simulations. However, it is believed that the model was reasonably calibrated as evident by the reasonable head match and the spatial distribution of hydraulic conductivity values that correlated with various geological features of the island. As shown in Fig. 8, relatively lower values for hydraulic conductivity appear



**Fig. 10** SEAWAT's salinity results (in g/L) for the eastern sector: **a** Plan view at the bottom layer of the basalt formation compared against measured maximum values. Areas of inaccuracies are marked with *white ellipses*, **b** Cross sectional view with the 1, 10, and 18 g/L contour values (*blue, green, and red*, respectively). Also shown are the layers of the numerical models with colors reflecting the material shown in Fig. 6

**Table 1** Values of spring flow and their percentage changes relative to average values. Values are estimated at various pumping–sustainable yield (P–SY) ratios. The row with *italics* represents results for the current (baseline) pumping. The percentage is based on the simulated average flow (749,621 m<sup>3</sup>/day). Note that such a value differs from the measured average value of 789,075 m<sup>3</sup>/day. The difference is due to about –5 % for model estimate

P–SY ratio (%)	Values of spring flow (m <sup>3</sup> /day)				Percentage change in spring flow relative to the average of 749,621 m <sup>3</sup> /day			
	Baseline	Drought 5 years	Drought 10 years	Climate change	Baseline	Drought 5 years	Drought 10 years	Climate change
18	1,026,971	810,808	786,618	894,169	37	8	5	19
34	933,558	745,975	713,112	800,650	25	0	–5	7
51	835,348	693,831	653,651	702,132	11	–7	–13	–6
64	<i>749,621</i>	<i>647,042</i>	<i>607,588</i>	<i>647,042</i>	<i>0</i>	<i>–14</i>	<i>–19</i>	<i>–14</i>
67	743,312	640,694	595,315	618,773	–1	–15	–21	–17
84	654,489	589,452	537,982	540,037	–13	–21	–28	–28
100	578,869	542,606	486,318	483,929	–23	–28	–35	–35

to coincide with the locations of the cinder cones found on Jeju that may represent lower permeability barriers to groundwater flow.

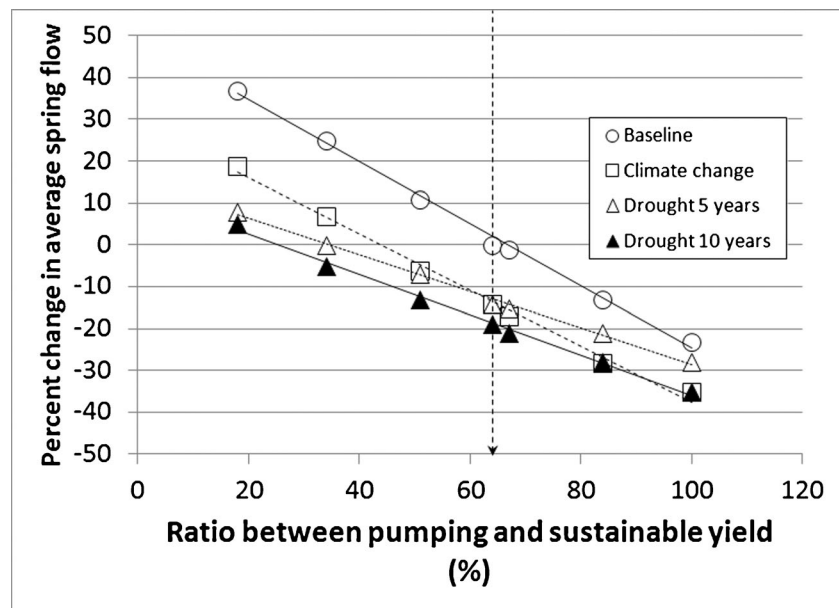
Island wide, the total measured average spring flow is 992,512 m<sup>3</sup>/day. Among these, there are about 200 springs with flows that are larger than or equal to 1,000 m<sup>3</sup>/day, with an average flow of 789,075 m<sup>3</sup>/day. Based on calibration, the model estimated an average flow of 749,621 m<sup>3</sup>/day, with a calibration error of about –5 %.

#### SEAWAT

SEAWAT was run first to simulate 2,000 years to obtain a pseudo steady-state solution, which required a relatively large execution time due to non-linearity of the problem. Figure 9 compares the simulated hydraulic-head values against the measured values reported by Won et al. (2006).

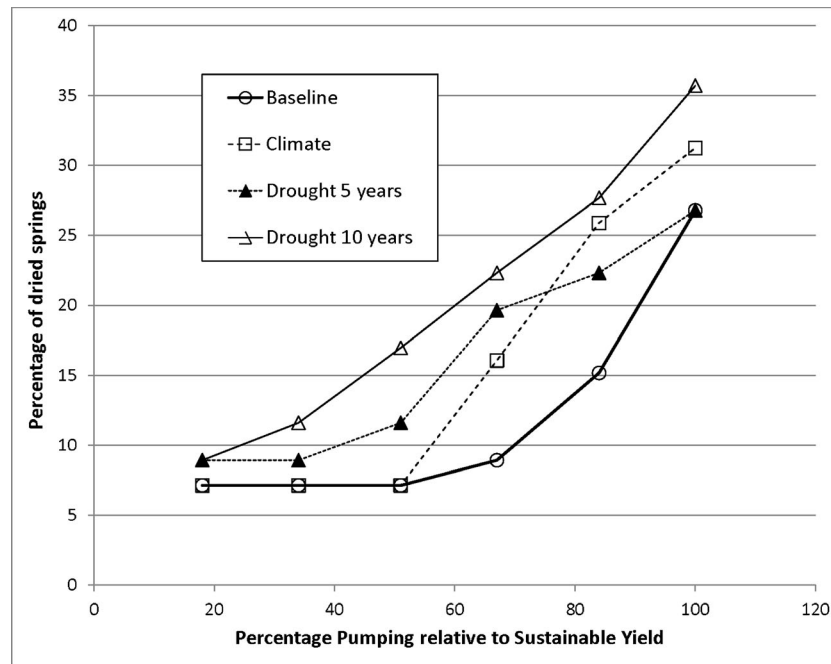
Overall, the match is reasonable, but the model underestimates the head values at the 2-m contour lines, compared to the MODFLOW results in Fig. 7. Simulations showed sensitivity of the solution regarding numerical scheme concerning advection. Such an assessment is beyond the scope of this study.

Inaccuracies also are evident in the high-elevation area due to the assumption of no-flow conditions along the boundary treated as divides. Certainly, as was the case with the MODFLOW's simulation, additional calibration could have produced closer results. However, in the absence of a clear basis for parameter adjustments, calibration by refining spatial distribution of parameters is merely a fitting process. Factors contributing to uncertainty of results are related to the limited information regarding (1) the elevation of the top of the Seogwipo Formation, (2) the complex flow paths associated with



**Fig. 11** Spring flows percent change displayed against ratio between pumping rates and sustainable yield (%). Trend lines are also shown. The vertical dotted line represents the baseline pumping rates at 64 % sustainable yield





**Fig. 12** The minimum number of springs with average flows greater than 1,000 m<sup>3</sup>/day that are expected to dry-up under the various recharge and pumping scenarios. The expected percentage of dried springs, based on the current use, can be estimated from the intersection of the vertical dotted line with the plotted percentage dried-up spring lines

fractured aquifer settings, (3) detailed lithology information, especially at the coast, (4) groundwater flow in the interior of the island, and (5) the large range of hydraulic conductivities of the volcanic lithologies (Hahn et al. 1997; Won et al. 2006). The discrepancy between the simulated and measured head values in some areas clearly emphasizes the need for more detailed hydrologic and lithologic data.

Figure 10(a) illustrates SEAWAT's salinity results for the bottom layer of the basalt formation compared against measured maximum values (KIGAM, personal communication, 2010), which are expected to occur in such a layer. Reasonable match can be seen in most areas. Exceptions are evident in the three marked locations, which are consistent with areas of inaccuracies in hydraulic head estimates (Fig. 9). Figure 10b illustrates the simulated vertical profile of salinity, which is typical of a saltwater intrusion in an aquifer bounded at the bottom by a no-flow condition (e.g., Fetter 2001). Saltwater intrudes into the aquifer with distance corresponding to the position of an intrusion toe, with a location that depends on recharge rates, aquifer parameters,

and well pumpage (e.g., Izuka and Gingerich 1998), with highest concentrations near the bottom of the formation. Effects of aquifer stratification and the low conductivities of the Seogwipo and U-Formations are evident.

### Scenario simulations

In this study, sustainability of groundwater resources was assessed for various recharge scenarios, each under a number of pumping–sustainable yield (P–SY) ratios ranging between 18 and 100 %. The results are compared to those predicted at the baseline pumping (64 % P–SY) and baseline recharge, which will be termed the baseline pumping–recharge (BPR) case. MODFLOW was used to evaluate water levels and spring flows, while SEAWAT was used to assess salinity.

### Spring flow results

Table 1 lists the values and the respective percentage changes in the larger spring flows for various scenarios.

**Table 2** Average and standard deviations (*between parentheses*) for change in water-table elevation island wide (m) for various scenarios and pumping as a percentage of sustainable yield (*negative numbers denote decrease*). The column with *italics* represents results for the current (baseline) pumping

Scenario	P–SY ratio (%)	18	34	51	64	67	84	100
Baseline		3.89 (5.69)	2.42 (3.61)	0.80 (1.23)	–	–0.81 (1.28)	–2.52 (3.84)	–4.17 (6.47)
5-year drought		–1.20 (1.51)	–1.21 (1.75)	–1.40 (1.80)	<i>–1.65 (1.70)</i>	–1.80 (1.76)	–2.54 (1.66)	–3.83 (2.22)
10-year drought		–1.99 (2.40)	–2.12 (2.77)	–2.50 (2.80)	<i>–2.90 (2.55)</i>	–3.00 (2.70)	–4.25 (2.67)	–6.47 (3.89)
Climate change		0.12 (5.26)	–1.44 (3.96)	–3.19 (3.73)	<i>–4.78 (4.86)</i>	–4.83 (5.03)	–6.66 (7.33)	–7.88 (8.96)

The percentage changes were estimated relative to the baseline pumping–recharge (BPR) value of 749,621 m<sup>3</sup>/day. Figure 11 illustrates the percentage change of spring flows versus the P–SY ratio, and shows strong linear relationships, with  $R^2$  exceeding 0.99 for all cases. The results show that, overall, drought has the most negative effect on spring flows, except for the 5-year case, which is exceeded by the climate change case. The slope of the trend-lines indicates that higher P–SY ratios speed up spring-flow reduction due to imposing a steady-state condition in the model. At the BPR, there is an expected reduction in spring flows by up to 19 % under a 10-year drought scenario, whereas at the admittance level, the likely reduction is 28 % under either the climate or the 10-year drought scenario.

Figure 12 shows the minimum number of larger-flow springs that are expected to dry up under various recharge and pumping scenarios. This figure refers to a ‘minimum’ number of springs, because multiple springs located in the same model cell were combined into a single representative drain. Again, the 10-year drought has the most negative effect followed by the 5-year drought scenario, except at higher pumping rates, above the P–SY ratio of 75 %, for which climate change has more negative effects. At the BPR, it is expected that between 8 and 22 % of springs would dry up under various scenarios. The respective range for the admittance level is between 15 and 27 %.

#### Water-level results

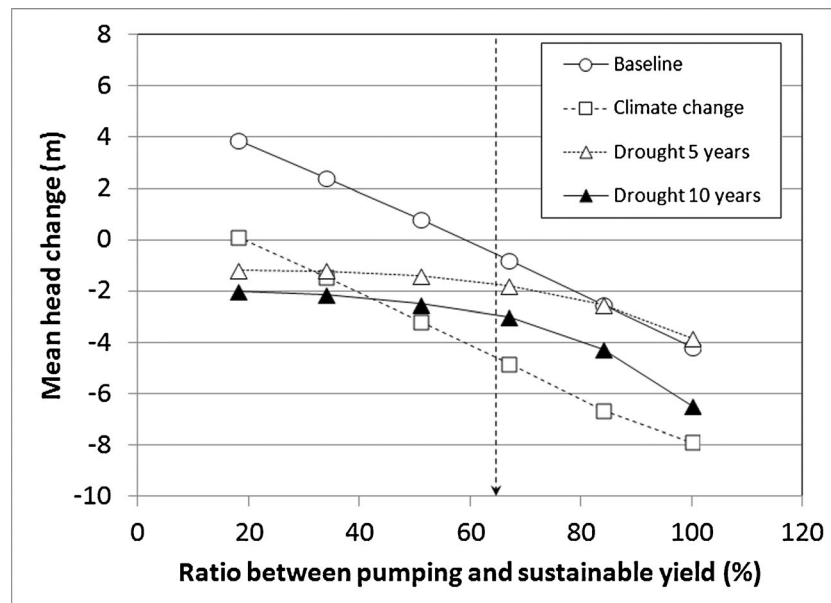
Table 2 lists the values of the mean and respective standard deviation for changes in hydraulic head for

various scenarios, while Fig. 13 displays the mean values against the P–SY ratios. At the BPR, and depending on the scenario, the average head is expected to decline between about 1 and 5 m (the dotted line in Fig. 13). For the admittance case, the decline is between about 3 and 7 m. The worst-case scenario would be related to the 5 or 10-year droughts at a P–SY ratio less than about 35 %. Under higher P–SY ratios, the climate-change scenario has the largest negative effect (up to 8-m decline).

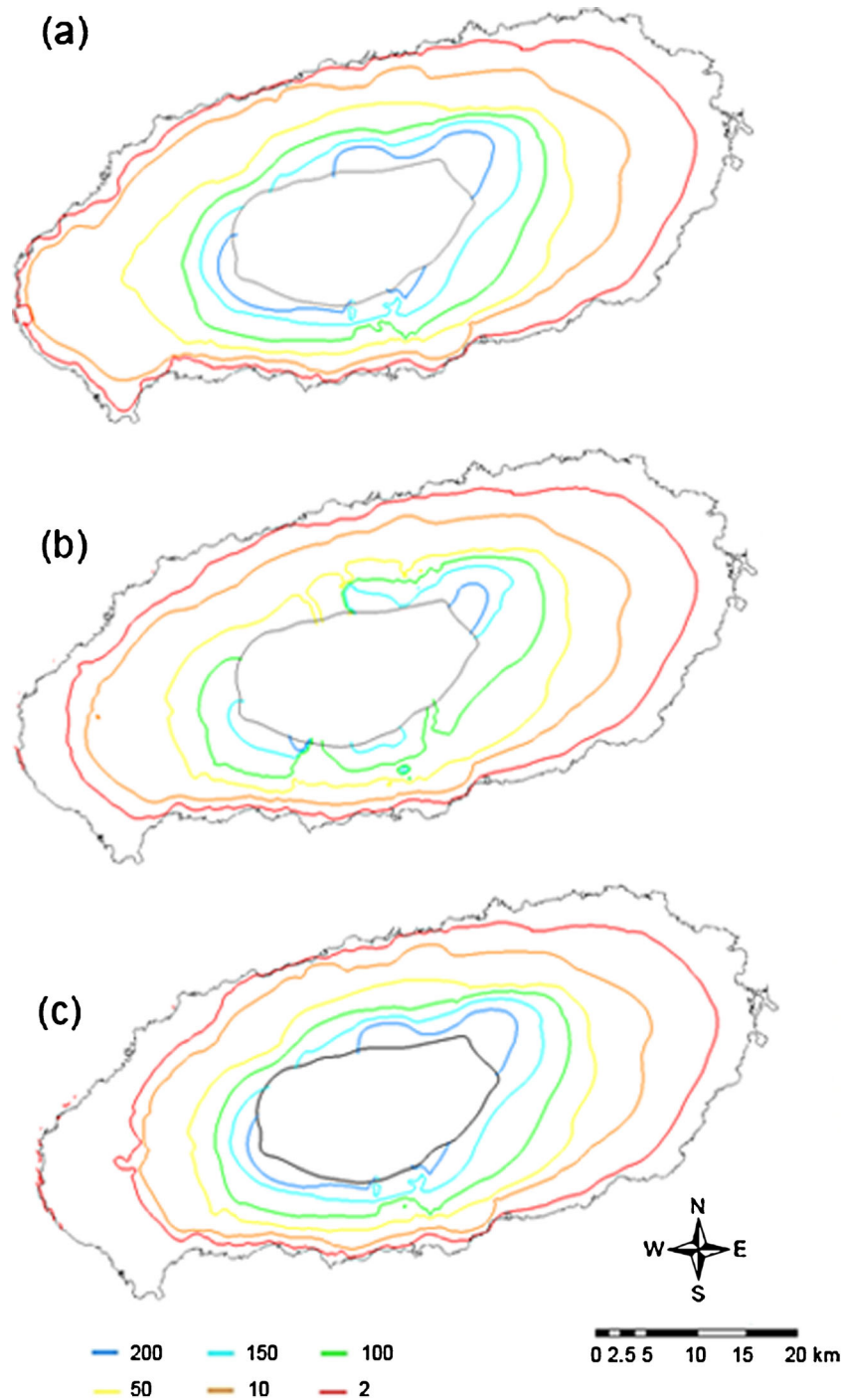
An example of spatial patterns of results is shown in Fig. 14, which depicts contour maps of the head-distributions for the climate-change case for a number of P–SY ratios. As should be expected, the decline in water-table elevations increases as well-pumping increases. Various scenarios predicted more pronounced head declines in the western parts of the island, based on the values of decline and the respective size of the area bounded by the shoreline and the 2-m contour, similar to that shown in Fig. 14. Such declines are most likely related to the relatively lower hydraulic conductivity, lower recharge, and higher pumping in the area, when compared to the other regions; thus, this study suggested using the location of the 2-m contour line as a criterion in assessing the sustainability of resources regarding water elevations.

#### Salinity results

Figure 15 illustrates the expected changes in salinity for various scenarios after 10 years for the case of 100 % P–SY ratio. The largest increases in salinity values occur under a drought condition, followed by the climate and the baseline cases. The respective maximum increases are



**Fig. 13** Hydraulic head mean change (m) for different scenarios under different ratios between pumping rates and sustainable yield (percent). The expected change in head, based on the current use, can be estimated from the intersection of the vertical dotted line with the plotted mean-value lines



**Fig. 14** Hydraulic head contours (m asl) for the climate change case under pumping scenarios of a 18, b 51, and c 84 % of sustainable yield

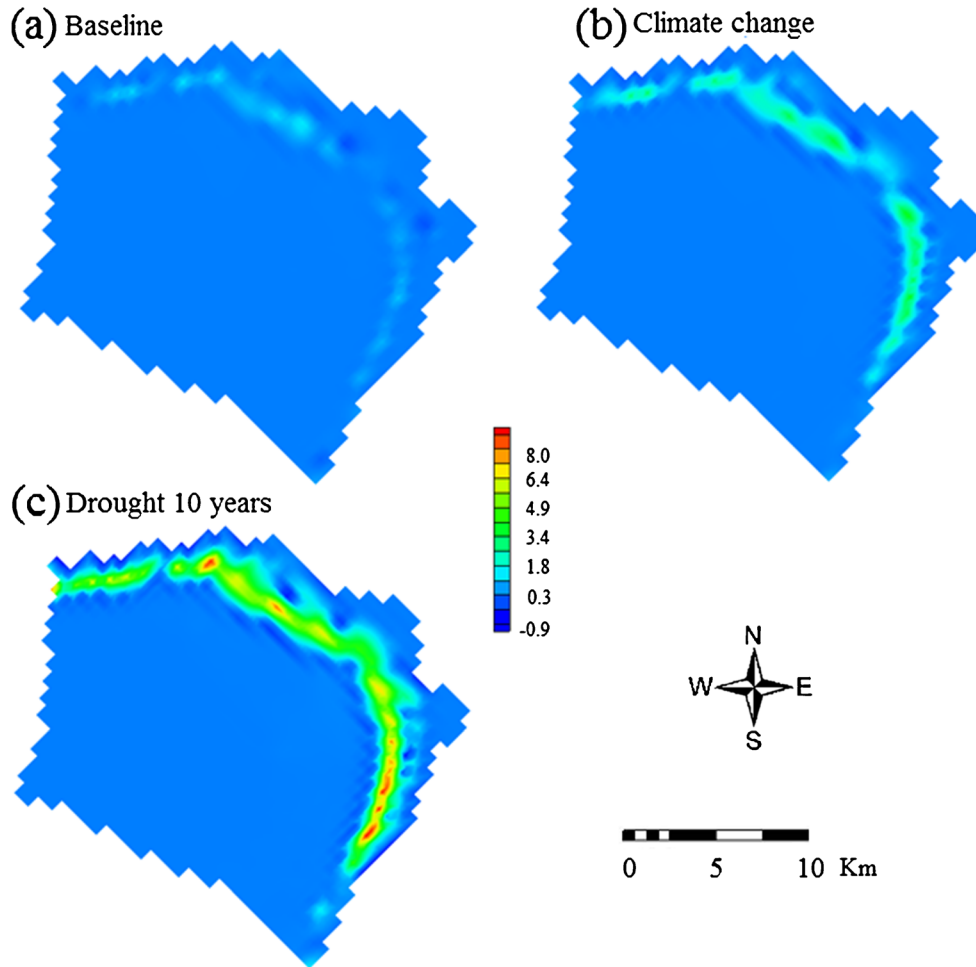
about 8.7, 3.6, and 1.0 g/L. After a 5-year drought condition, the maximum increase is still significant at about 5 g/L. The largest increases are confined to the salt-intrusion toe area where the head value is near 2 m. Such changes emphasize the need for developing strong monitoring strategies and restrictive management practices in such areas.

#### **Sustainable management of groundwater resources**

Results of this study provide the following guidelines towards the sustainable management of groundwater resources on Jeju Island.

1. Future management decisions should take into consideration the fact that long sustained drought and climate





**Fig. 15** Expected changes in salinity (g/L) for the three scenarios after 10 years: **a** baseline, **b** climate change, and **c** drought 10 years

change has serious adverse effects on sustainability indicators.

2. Without even drought or climate change, the current estimated P–SY ratio of 64 % can cause long-term strains on groundwater resources.
3. A strong linear relationship exists between values of spring flow and pumping as shown in Fig. 10. Such a representation can provide appropriate total pumping rates based on a certain acceptable total spring flow. Similarly, Fig. 11 can provide suitable total pumping rates based on acceptable number of dried-up springs.
4. New water-use policies should be implemented in the western part of the island where head declines can be excessive under various scenarios of recharge and water use.
5. The location of the 2-m head contour should be adopted as an indicator of sustainability, regarding both its relative location from the shoreline and salinity level near such a line. Collection of lithologic data and monitoring information should be emphasized in the relevant areas for future model refinement. In addition, restrictive management practices should be developed

in such areas to avoid further head decline and seawater intrusion.

## Summary and conclusions

The models MODFLOW and SEAWAT were used to assess the sustainability of Jeju Island's groundwater resources. Due to complex challenges in modeling the central part of the island, the analysis was simplified by excluding the area above 600-m ground elevation from modeling. Flow to the model was estimated as precipitation-induced recharge in addition to that routed from the excluded center area of the island. The models were calibrated against hydraulic head data, average spring-flow estimates, and groundwater salinity measurements. Reasonable matches were obtained despite uncertainties in the model data and the absence of detailed characterization of parameter variability. Other factors contributing to the uncertainty are the lack of information concerning the elevation of the top of the low-permeability Seogwipo

Formation, the complex migration behavior of groundwater in crystalline-fractured aquifers, data related to spring flows, coastal stratigraphy, vertical migration of perched groundwater in the interior of the island, and the large possible range of hydraulic conductivities of the island's volcanic lithologies.

MODFLOW was calibrated to match the average spring-flow values by treating larger-flow springs as drains, with a calibration error of about 5 %. Reasonable calibration of hydraulic head was evident by the fact that spatial distribution of hydraulic conductivity values were correlated with various geological features of the island such as areas with lower conductivities correlating to the locations of tuff cones around the island.

SEAWAT was used to address potential salinity effects on sustainability in the eastern part of the island where saltwater intrusion is significant. Hydraulic conductivity estimates based on MODFLOW's calibration seems reasonable for use in SEAWAT; however, additional data collection is needed for a closer match of both hydraulic head and salinity.

A number of scenarios were developed to test the sustainability of groundwater resources, and the results were evaluated based on comparison to a baseline simulation. For MODFLOW, a range of pumping rates from 18 to 100 % of the sustainable yield was used with each of the three recharge scenarios. The aquifer sustainability was assessed based on the decrease in head and spring flows.

At the baseline pumping, drought has the most pronounced negative effect on spring flows, with a decrease up to 21 % relative to average condition at the BPR. Up to 22 % of large-flow springs dried up under these conditions. The deterioration is worse with the admittance-value rates, with decline of spring flows up to 28 % and a dried-up percentage of 27 %. Climate change has lower impact on spring flows considering that the change was mostly related to recharge redistribution from the baseline recharge case; however, climate change has the most significant influence on head decline, probably due to the same reason by causing significant local effects. At the baseline pumping, the average head declines between about 1 and 5 m, while for the admittance case, the decline is between about 3 and 7 m.

The west side of Jeju Island is the most sensitive to recharge decline, which is most likely related to the relatively lower hydraulic conductivity and higher pumping rates, when compared to the other regions. The location of the 2-m contour can be used as a criterion for assessing the decline in head under changing recharges.

Drought simulations showed the most increase in salinity when compared to other scenarios. Largest increases are mainly confined around the 2-m head-contour line. As with any modeling studies, it should be stressed that the results are subjected to uncertainty due to model and data limitations. In addition, calibration was done using a snapshot of hydraulic head; therefore, and considering the non-uniqueness inherent in modeling, such a calibration should be considered incomplete.

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