ORIGINAL ARTICLE

Regional and well-scale indicators for assessing the sustainability of small island fresh groundwater lenses under future climate conditions

Roshina Babu[1,2] · Namsik Park[1] · Byunghee Nam[1]

Abstract

Salinization of the freshwater lens and well fields under future climate and groundwater demands threaten the sustainability of groundwater abstraction in small islands. In this paper, two simple indices are proposed for a comprehensive assessment of freshwater salinization in small islands. Values of these indices are computed based on a sharp-interface finite element numerical model with the interface matched to the lower limit of freshwater. The first index relates rainfall percentiles with the computed freshwater volume and provides regional assessment of changes in the volume stored in the freshwater lens over time. The second is a sustainability index, based on computed saltwater ratios in pumping wells as the performance indicator, which represents the well salinization risk at a spatial scale. The proposed methodology is illustrated with the example of Tongatapu Island. Freshwater lens dynamics and well salinization under various scenarios of dry, median, and wet general circulation model predictions-based unsteady recharge, sea level rise, and pumping demands were evaluated for the period 2010–2099. The freshwater lens of Tongatapu is dependent on rainfall, and the 60-month rainfall percentile is highly correlated with the total freshwater volume. Public well field indicates sustainability indexes of 45% and 100% under the current pumping conditions for the driest and the wettest scenarios, and with increased pumping and sea level rise, they reduce to 30% and 90%, respectively. Thus, management of pumping rates is essential for future freshwater sustainability. This methodology can be used for first-hand temporal and spatial estimations of small island freshwater lens salinization considering both the regional and well scales.

Keywords Sharp-interface numerical model · Freshwater lens · Saltwater intrusion · Tongatapu · Sustainability index · Small islands

Introduction

Many small islands across the world have a unique form of groundwater system where the fresh groundwater floats as a relatively thin lens above the denser seawater in highly

permeable aquifers (Falkland and Custodio 1991). Salinization of the thin freshwater lens can occur under future climate conditions like changes in rainfall patterns and sea level rise (Ketabchi et al. 2014; Holding et al. 2016; Werner et al. 2017). As small island communities rely mostly on groundwater for municipal, agricultural and tourism demands, overabstractions can also lead to saltwater upconing below pumping wells (White and Falkland 2010). The total volume of fresh groundwater is an important parameter representing the state of island groundwater resources and reflects the long-term and regional-scale behavior of these groundwater flow systems. Concomitantly, saltwater upconing under the pumping wells is a short-term localized behavior which can abruptly contaminate the well field (Werner et al. 2011) and critically affect the sustainability of the freshwater lens. These parameters are certainly related, as decreasing volume indicates thinning of the lens. However,

✉ Namsik Park
  nspark@dau.ac.kr

[1] Department of Civil Engineering, Dong-A University, Busan, Republic of Korea

[2] Present Address: Department of Civil and Environmental Engineering, The University of Utah Asia Campus, Incheon, Republic of Korea

they are not necessarily proportional as the impacts of volume changes can affect a large number of pumping wells in a region, while saltwater upconing affects a small number of wells (Tarbox and Hutchings 2008). Therefore, joint evaluation of regional-scale seawater intrusion and well-scale salinization is required for developing sustainable adaptive plans for small island freshwater lenses under future climate conditions.

First-hand assessments can help water resource decision makers to assess the risks and plan for the future. Various approaches are available for a quick and regional assessment of saltwater intrusion vulnerability in coastal aquifers. These include tools like GALDIT (Chachadi and Lobo-Ferreria et al. 2007) or GIS-based risk evaluations (Klassen and Allen 2017; Eriksson et al. 2018) which propose subjective indexes based on a subset of factors that contribute to saltwater intrusion. For example, a comprehensive salinity index was proposed combining two such subjective index-based methods (GALDIT for saltwater intrusion and TAWL-BIC for saltwater upconing vulnerability mapping) and was applied to the Ghaemshahr-juybar aquifer (Motevalli et al. 2018). However, the above index-based methods often lack a theoretical basis (Werner et al. 2012), and hence steady-state sharp-interface analytical equations were employed to provide a quantitative assessment of saltwater intrusion (SWI) vulnerability in a hypothetical strip island (Morgan and Werner 2014). Though the above methods can rapidly assess the long-term vulnerability of freshwater lenses to saltwater intrusion, the assessment of how these risks vary over time still remains a challenge.

Numerical groundwater flow models, which include freshwater–saltwater dispersion, are currently the most physically appropriate mathematical models for assessing saltwater intrusion phenomena (Werner et al. 2013). The correlation of the freshwater volume indicator from SEA-WAT simulations with the 3-month reconnaissance drought index (RDI) was suggested as an early warning for droughts in a two-dimensional hypothetical island aquifer with no groundwater pumping (Kopsiaftis et al. 2017). The development of dispersion-based models is a challenge in data-scarce regions like real islands (White and Falkland 2010), as they require extensive field data for detailed calibration of freshwater heads and salinities (Ghassemi et al. 2000; Sanford and Pope 2010). Furthermore, the prediction of well salinities requires a very fine discretization of space and time to meet the numerical stability criteria (Sanford and Pope 2010; Sulzbacher et al. 2012; Werner et al. 2017). Despite the advances in hardware technology, dispersion modeling of real islands is challenging, especially when simulations over a broad range of spatial and temporal scales are attempted (Mahmoodzadeh et al. 2014). Thus, there is a lack of assessment methodologies that can provide quantitative estimates of freshwater salinization in small islands that consider how the volume of the freshwater lens varies over time and how individual wells are subject to salinization. Moreover, real island applications of quantitative assessment methods are absent in the literature.

The objectives of this study are to address the above-mentioned research gaps by: (1) proposing two simple indexes to represent the comprehensive state of health of an island groundwater system considering a temporal index to reflect changes in the total freshwater volume and a spatial index for assessing saltwater intrusion in each pumping well; and (2) verifying the functionality of the proposed indexes by applying it to the island of Tongatapu using sharp-interface numerical simulations under future climate change and groundwater pumping scenarios.

A sharp-interface numerical modeling approach was used to assess these factors in this study. This is because, despite the obvious limitations of this assumption, this methodology allows models to be developed and run over a large range of scales without excessive numerical difficulties (Dausman et al. 2010; Llopis-Albert and Pulido-Velazquez 2014). Consequently, the steady-state freshwater lens of the island of Tongatapu was simulated using a sharp-interface numerical model with the interface matched to the freshwater limit (Babu et al. 2018).
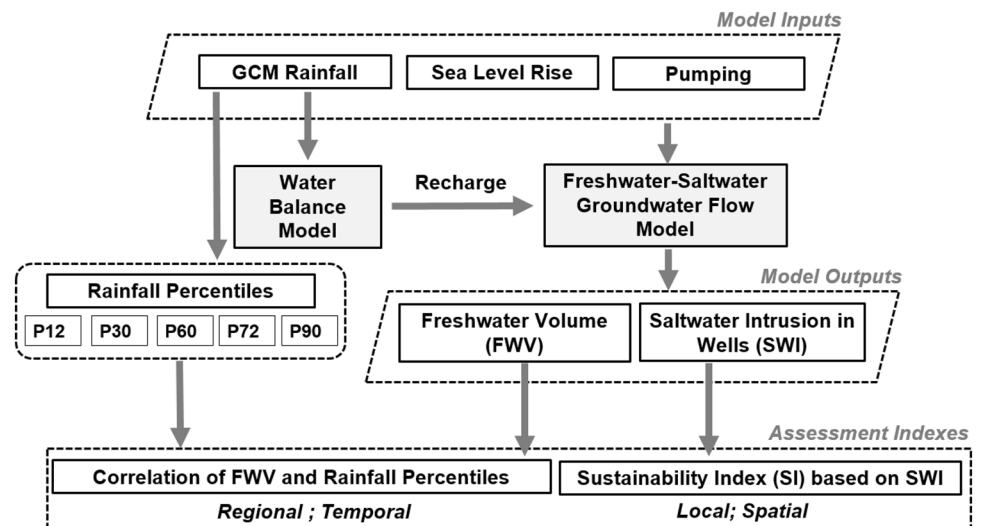
The public water supply for Tongatapu is sourced from vertical wells concentrated in a single well field which covers an area of about 1 sq. km (Nath 2010). Recently, an additional 12 wells were constructed in the existing well field of 38 wells. The increased abstraction from a single well field poses an increased risk of saltwater upconing (White et al. 2009) which could be aggravated by future changes in rainfall patterns and sea level rise. Hence, the island of Tongatapu serves as a good case study to explore the effects of localized abstractions on the sustainability of island freshwater lenses in the future.

Materials and methods

Outline of methodology

The outline of the methodological approach is presented in Fig. 1. This study uses the sharp-interface numerical model (Huyakorn et al. 1996) for simulation of freshwater–saltwater groundwater flow in a small island freshwater lens (Babu et al. 2018) and validates it against the transient field observations of freshwater thickness in monitoring wells. Recharge estimates for the lens were obtained from a water balance model (Falkland and Woodroffe 2004). The validated numerical model was used for simulating the freshwater lens until 2100 using future rainfall predictions from general circulation models (GCMs), estimates of sea level rise and predicted future water demands.

Various scenarios considered include combinations of low-rainfall, median-rainfall and high-rainfall conditions from GCM models under different representative concentration pathways (RCPs) of RCP 4.5 and RCP 8.5, high and medium emission sea level rise along with the current and increased rates of groundwater pumping. The simulated changes in the freshwater volume in the lens were correlated with rainfall percentiles at a temporal scale to develop a regional freshwater volume assessment index. The degree to which well salinization was predicted by the model was used as an indicator to assess the reliability, resilience and vulnerability of groundwater pumping to salinization, and to develop a sustainability index (SI) for each well at a suitable spatial scale.

Future rainfall scenarios

Due to the inherent uncertainty and limitations in downscaling of climate models to small island grid sizes (Karnauskas et al. 2016), multiple GCMs may have to be used for future groundwater modeling (Holman et al. 2012). Previous studies (Deng and Bailey 2017; Alusmaiei and Bailey 2018) considered different statistical approaches to select one or more GCMs and conducted groundwater modeling for each of the selected GCMs individually. With the increasing number of GCMs and scenarios, groundwater modeling for each GCM prediction may not be feasible. As first-hand water management planning requires the range of expected freshwater resources under climate change (Alsumaiei and Bailey 2018), this study uses the selection criteria as described by Rossman et al. (2018) where median, wet and dry GCMs are selected with the uncertainty bounds defined by the standard deviation specific to the projection period. The GCM which indicates the cumulative potential groundwater recharge closest to

the median of all cumulative potential recharges at the end of the projection period is designated as the median GCM. The wet and dry conditions are represented by GCMs that indicate ± 1 standard deviations (SD), respectively, from the median. Since both positive and negative standard deviations are included, the selected GCMs can represent the range of increases and decreases in recharge predicted by the ensemble of GCM projections despite their inherent variability (Rossman et al. 2018).

Assessment indexes

Rainfall percentiles and freshwater volume

Rainfall percentiles have been widely used for drought identification in the Pacific Islands (White et al. 1999). In this study, the functionality of rainfall percentiles in the assessment of total freshwater volume is explored. The use of rainfall percentiles (White et al. 1999, 2007) is a method of ranking the rainfall accumulated over a period of interest relative to all the recorded rainfall values during the same summation period in the past. The total rainfall for the kth month with a summation period of n months $(\mathrm{TP}_n)_k$ is calculated as follows.

$$(\mathrm{TP}_n)_k = P_k + \sum_{i=1}^{n-1} P_i, \tag{1}$$

where P_k is the rainfall for the current month and P_i is the rainfall for the previous ith month. The computed value $(\mathrm{TP}_n)_k$ is compared with other total rainfall summations and a percentile value $(P_n)_k$ is assigned to indicate the rainfall percentile for month k for a summation period of n (White et al. 1999) as shown below:

$$\left(P_n\right)_k = \frac{\text{Number of values below } (TP_n)_k}{m} \times 100, \tag{2}$$

where m is the integer (N/n); N is the number of months with past rainfall records.

Rainfall percentiles with different summation periods are evaluated and the correlations with freshwater volumes predicted by the numerical model are computed. The model results of freshwater volume computed at the end of the ith month (FWV$_i$) are normalized by removing the mean (μ_{FWV}) and dividing by the standard deviation (σ_{FWV}) of freshwater volumes at the end of all months in the entire simulation period to calculate the normalized freshwater volume (NFWV$_i$) for that month.

$$NFWV_i = \frac{FWV_i - \mu_{FWV}}{\sigma_{FWV}}. \tag{3}$$

The temporal evolutions of normalized freshwater volume (NFWV) are compared to the time series of well salinization to explore the relation of rainfall-based indicator (volume indicator) to well salinization.

Sustainability index (SI) of pumping wells

A simple approach based on a single performance indicator has been widely used to make a preliminary assessment of sustainability in water resources planning and management (Sandoval-Solis et al. 2010; Mays 2013). Targeted groundwater heads at various monitoring wells were used as the performance indicator for continental aquifers by Mays (2013).

However, as the critical condition affecting pumping sustainability in small islands is saltwater intrusion, this study proposes the use of a numerical model-predicted saltwater ratio (SWR) in pumping wells as the performance indicator. A satisfactory condition is defined as when the saltwater ratio at any time t is zero (SWR$_t$=0) in the well. An unsatisfactory condition is defined as SWR$_t$>0. The time base can be adapted according to the total simulation period. In this study, as future simulations till 2100 are considered, the time base selected is a month. Hence if the saltwater ratio exceeds zero at any point of time during a month, it is considered as an unsatisfactory condition.

Based on the value of the performance indicator, the reliability, resilience, and vulnerability (Mays 2013) of the pumping well can be evaluated. The reliability (REL) of well i is defined as the ratio of number of months with SWR$_t$=0 to the total number of months, and it indicates the probability of freshwater supply during the target period.

$$REL_i = \frac{\text{Number of months with } SWR_t = 0}{\text{Total number of months}}. \tag{4}$$

The resilience (RES) of well i as defined as the ratio of number of months for which the satisfactory condition of SWR$_t$=0 follows an unsatisfactory condition of SWR$_{t-1}$>0 to the total number of months with SWR$_t$>0. It measures how quickly the system returns to normal condition after a failure (Hashimoto et al. 1982).

$$RES_i = \frac{\text{Number of months with } SWR_{t-1} > 0 \text{ and } SWR_t = 0}{\text{Total number of months where } SWR_t > 0}. \tag{5}$$

Vulnerability (VUL) accounts for the probability of occurrence of saltwater intrusion in the pumping well. It is calculated as the ratio of unsatisfactory conditions of SWR$_t$>0 to the total number of months and is inverse of resilience.

$$VUL_i = \frac{\text{Number of months with } SWR_t > 0}{\text{Total number of months}}. \tag{6}$$

Using the above measures, the SI for well i is defined (Loucks 1997; Mays 2013) as follows:

$$SI_i = \left[REL_i \times RES_i \times \left(1 - VUL_i\right)\right]^{1/3}. \tag{7}$$

The SI value can quantify the sustainability of the groundwater pumping system and can aid in comparing various water management policies (Sandoval-Solis et al. 2010). The overall SI can be calculated as the average sustainability of all wells.

$$SI = \frac{\sum_{i=1}^{n} SI_i}{n}. \tag{8}$$

Water balance model

In this study, a simple water balance model WATBAL (Falkland and Woodroffe 2004) was used for the estimation of monthly recharge based on inputs of monthly rainfall and temperatures. Water balance models based on the same approach have been used for estimation of recharge inputs to numerical groundwater models for the Republic of Maldives (Alsumaiei and Bailey 2018; Deng and Bailey 2017) and Kiribati (Post et al. 2018).

Sharp-interface groundwater flow numerical model

The groundwater in Tongatapu is conceptualized as being a two-phase flow system that occurs in an unconfined aquifer, and was simulated using a sharp-interface numerical model (Huyakorn et al. 1996). Details on the development of the numerical model for the island are provided in Babu et al. (2018) and only a brief description is presented here. The flow dynamics of both freshwater and saltwater are

considered by two vertically integrated governing equations for freshwater and saltwater, respectively.

$$\frac{\partial}{\partial x}\left(K_x^f b^f \frac{\partial h^f}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y^f b^f \frac{\partial h^f}{\partial y}\right) = S_y^f \frac{\partial h^f}{\partial t} - \theta \frac{\partial \xi}{\partial t} - Q^f, \quad (9)$$

$$\frac{\partial}{\partial x}\left(K_x^s b^s \frac{\partial h^s}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y^s b^s \frac{\partial h^s}{\partial y}\right) = S_y^s \frac{\partial h^s}{\partial t} + \theta \frac{\partial \xi}{\partial t} - Q^s, \quad (10)$$

where freshwater and saltwater are referred to by the superscripts f and s, respectively, and the vertically averaged hydraulic head for the aquifer is h. The thickness of each fluid in the aquifer is b and K_x and K_y are the x and y direction hydraulic conductivities for each fluid, θ is the effective porosity of the unconfined aquifer, and ξ indicates the location of saltwater–freshwater interface above the datum. S_y is the specific yield of aquifer in zones of each fluid. The pressure at the interface boundary is equated to obtain the relationship between freshwater and saltwater heads (Bear 2007) as given below:

$$\xi = \frac{\rho_f}{(\rho_s - \rho_f)}\left[(\rho_s/\rho_f)h^s - h^f\right], \quad (11)$$

where ρ_f and ρ_s are the freshwater and saltwater densities, respectively.

Pumping wells are represented by point locations of specified flux. Water is extracted from a pumping well at specified rates irrespective of saltwater or freshwater. When the freshwater–saltwater interface is within the well screen, the total pumping rate Q^T at a well is the sum of Q^f and Q^s, the volumetric fluxes of freshwater and saltwater per unit volume of aquifer due to pumping.

$$Q^f = \left(\frac{K^f L^f}{K^f L^f + K^s L^s}\right)Q^T, \quad (12)$$

$$Q^s = \left(\frac{K^s L^s}{K^f L^f + K^s L^s}\right)Q^T, \quad (13)$$

where L is the total length of the screen, L^f and L^s is length of screen exposed to freshwater and saltwater, respectively. $K^f L^f$ and $K^s L^s$ represent transmissivities of freshwater and saltwater regions, respectively. The saltwater ratio at a pumping well i (SWR$_i$) is the ratio of saltwater pumped to the total pumping at the well as given below:

$$SWR_i = \frac{Q^s}{Q^f + Q^s}. \quad (14)$$

Further details on the application of the numerical model can be found in Park and Lee (1997) and Han et al. (2004) for groundwater development, and Shi et al. (2009) and Shi et al. (2011) for the estimation of salinity at pumping wells.

Example application

Study area

Tongatapu Island (Fig. 2) is located in the southwest Pacific Ocean about 3000 km off the southern coast of Australia at 21° 03′ to 21° 16′ S latitude and 175° 02′ to 175° 21′ W longitude. It has an area of 259 km^2 and is the largest among all islands of the Kingdom of Tonga. In 2011, the population of the island was 75,600 and about 30% of the population was concentrated in the capital city Nuku'alofa (SPC 2011). The highest location rises about 65 m above the mean sea level. In general, the climate is tropical and is characterized by a wet season (November–April) when much of the annual rainfall occurs and a dry season (May–October). The average annual rainfall is 1746 mm. Groundwater occurs predominantly as a freshwater lens contained within an unconfined aquifer (Furness and Helu 1993) composed of limestone which was reported to be karstic in nature (White et al. 2009; Hyland 2012). Hydraulic conductivity estimates of the limestone aquifer vary between 500 and 3600 m/day (Falkland 1992; White et al. 2009). Previous groundwater monitoring studies estimated the average freshwater head to be in the range of 0.3–0.41 m (Hunt 1979; White et al. 2009). The maximum freshwater thickness, defined by groundwater with electrical conductivity (EC) less than 2500 μS/cm (White et al. 2009), was estimated to be about 14 m (Furness and Helu 1993; White et al. 2009).

Groundwater is the primary source for urban, rural and agricultural water demands, as there are no perennial surface water sources in Tongatapu (van der Velde 2006). Public wells managed by the Tonga Water Board (TWB) supply groundwater to the capital city of Nuku'alofa and are concentrated in the Mataki'eua/Tongamai well field (Fig. 2). There have been no reported management measures for groundwater pumping from public wells. Village wells distributed over the island supply the domestic and agricultural water demands of each village. Groundwater monitoring data from sixteen salinity monitoring boreholes (SMB) provide a basis for interpreting the freshwater lens thickness of the island. Nested wells with screens at different depths are used for monitoring temperature, EC and water levels in the aquifer. More information on geography, hydrology, hydrogeology, water supply, salinity monitoring and other characteristics of this island are available in (Babu et al. 2018) and are not repeated here.

Conceptual hydrogeological model

In this study, some simplifying assumptions were used to develop the conceptual hydrogeological model for the

Fig. 2 Island of Tongatapu
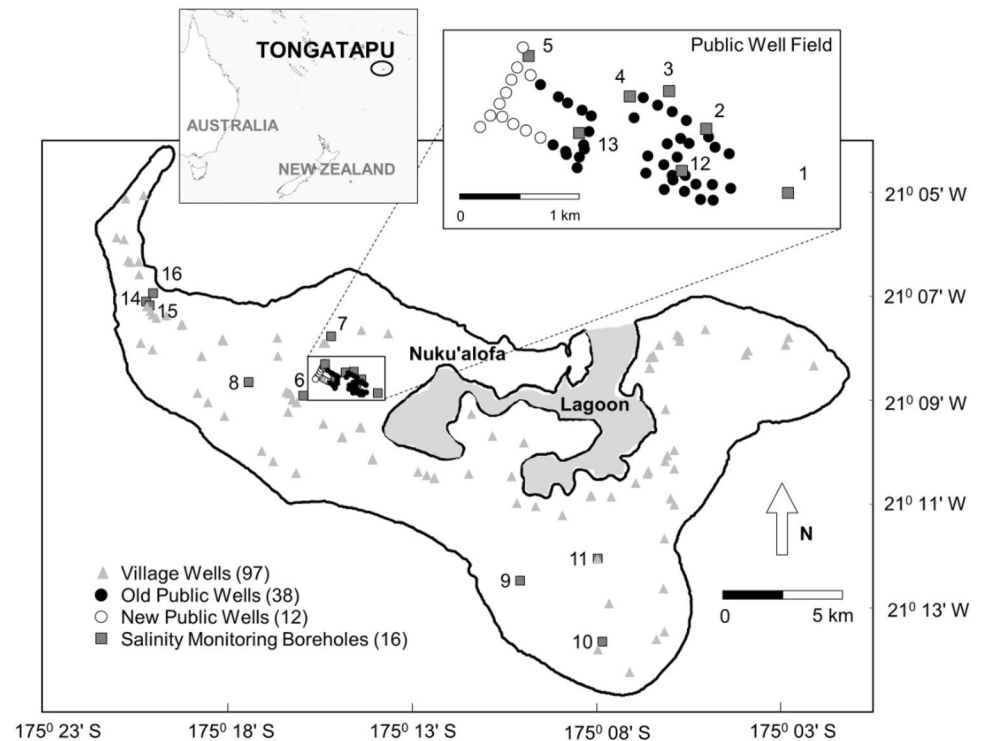
island of Tongatapu. The geology of the island as observed from drill logs (Hyland 2012) consisted of limestone which was reported to be karstic in nature (White et al. 2009; Waterloo and Ijzermans 2017). However, detailed hydrogeologic characteristics of the karst geology were not investigated. Observed freshwater thickness values (Babu et al. 2018) from 16 salinity monitoring boreholes (SMBs) dispersed throughout the island did not show any obvious irregularities despite the karstic nature of the aquifer. Hence, in this study, the unconfined aquifer was assumed to be represented by a single porous continuum that is homogeneous and isotropic with a uniform porosity of 0.3 (White et al. 2009). These assumptions were used as the overall objective of this study to conduct a preliminary assessment of the island-wise groundwater lens.

Model development

A sharp-interface finite element numerical model for Tongatapu Island was constructed similar to that described by Babu et al. (2018). The model domain consists of the entire island, and was discretized to contain 89,200 rectangular elements with 89,824 nodes. Elements with 25 m sides were used for the central part of the island where the public wells are concentrated, and 100 m elements were used for other areas. A grid convergence test was conducted to check the mesh. The freshwater density of 1000 kg/m^3 and saltwater density of 1024 kg/m^3 were assumed in the model.

A no-flow boundary condition was assumed at the base of the aquifer 40 m below mean sea level and was located based on trial and error simulations to ensure that the freshwater lens was unaffected by the selected boundary (Schneider and Kruse 2006). A groundwater efflux-only third-type boundary condition was specified for the freshwater equation, and a first-type boundary condition was specified for the saltwater equation at the nodes along the coastline and lagoon. Recharge was applied as a time-varying flux boundary condition at all interior nodes on the surface of the island. Groundwater recharge was estimated using the water balance model WATBAL using the parameters (Table 1 of Online Resource 1) which are based on the sensitivity analysis by White et al. (2009).

Information about groundwater use on the island was obtained from a number of sources. Groundwater abstraction records were obtained from the Tonga Water Board (TWB). The number of wells and screen locations were adapted from information provided in a previous model (Babu et al. 2018) with the availability of more field data. The locations of 50 public wells and 97 village wells were included in the model, and hence a total of 147 pumping wells have been considered (Fig. 2). The screened intervals for all wells were assumed to extend from 0 to − 2 m above mean sea level (AMSL) for all types of wells.

Abstraction records (TWB 2018) indicate that the total groundwater pumping from the 38 existing public wells on the island was 11,950 m^3/day in 2017. It is planned to increase the groundwater abstraction from public wells

to 17,000 m^3/day with the addition of 12 new wells by 2018–2019. Pumping from village wells is estimated based on the rural population to be 6300 m^3/day (Waterloo and Ijzermans 2017; Babu et al. 2018). Individual abstraction rates are unavailable for all wells due to lack of adequately maintained flow meters (Waterloo and Ijzermans 2017) and hence total pumping rates were equally distributed in all wells according to the type of well. The steady-state sharp-interface numerical model was calibrated for horizontal hydraulic conductivity with the sharp interface corresponding to the average freshwater thickness observed in salinity monitoring wells (Babu et al. 2018) and the parameter value obtained was 3600 m/day.

Validation of transient numerical model

A transient groundwater model was developed to simulate historical groundwater abstraction on the island for the period 1966–2016. This was undertaken using the historical rainfall data supplied by the Tonga Meteorological Services (TMS 2018) and records of total groundwater abstraction from public wells (TWB 2018). The steady-state predevelopment model was used as the initial condition for the above transient simulation. The groundwater model was validated for the transient state for the period from January 2010 to December 2016 due to the availability of more frequent monitoring data in the sixteen salinity monitoring boreholes (SMBs). The model inputs of recharge and pumping for the validation period are given in Fig. 1 of Online Resource 1. The freshwater thickness in each of the sixteen monitoring wells was compared to the freshwater thickness simulated by the groundwater model.

Future modeling scenarios

Modeling scenarios

The transient groundwater model discussed above was extended to explore the sustainability of the freshwater lens in the future by considering the impact of changes in recharge, sea level rise, and groundwater pumping. To determine the state of the freshwater lens under different future conditions and to verify the functionality of the suggested assessment indexes, the twelve simulation scenarios indicated in Table 1 were considered. For all twelve scenarios, the model parameters (other than recharge, sea level, and pumping) were identical to those used in the historic scenario simulation.

Recharge was considered under three rainfall scenarios (wet, median and dry), whereas sea level rise and pumping were considered for "low impact" and "high impact" conditions. The "low impact" condition of sea level changes corresponds to the sea level rise projections made under

Table 1 Future scenarios considered for simulation

Scenarios	Factors			RCP
	Pumping	Sea level Rise	Recharge	
1	Current	Medium	Dry	RCP 4.5
2			Median	
3			Wet	
4		High	Dry	RCP 8.5
5			Median	
6			Wet	
7	Increased	Medium	Dry	RCP 4.5
8			Median	
9			Wet	
10		High	Dry	RCP 8.5
11			Median	
12			Wet	

the medium emission scenario of RCP 4.5, and the "high impact" case corresponds to the projections under the high emission scenario of RCP 8.5. The current pumping represents low impact groundwater development, and the increased or projected future groundwater development corresponds to high impact scenario.

Inputs for future modeling scenarios

Projections of changes in rainfall and temperature were obtained from 29 statistically downscaled GCM predictions provided by the APEC Climate Center (APCC). The model name and institute are given in Table 2 of Online Resource 1. The GCM-predicted monthly rainfall and temperature values were input to the water balance model (WATBAL) to obtain the potential recharge under all 29 GCMs for the projection period 2010–2099. The GCMs selected were INMCM4 (dry), HadGEM2-AO (median) and MIROC5 (wet) under RCP 4.5 and MRI-CGCM3 (dry), INM-CM4 (median), and IPSL-CM5A-LR (wet) under RCP 8.5 (Fig. 2 of Online Resource 1). The detailed statistics of the GCMs are provided in Table 3 of Online Resource 1.

Table 2 indicates the historical, current and future pumping rates used in this study. The low impact groundwater development scenario assumed that the current pumping rates as of 2018–2019 in public wells and village wells remained constant until 2099. The high impact scenario assumed a stepwise increase in future pumping rates. The historical pumping rates in public wells were linearly extrapolated to obtain the future pumping rates for climate periods of 2010–2039, 2040–2069 and 2070–2099. Village water demands were projected based on future population estimates (UN 2017) and the rural per capita water demands of Tongatapu (PCCSP 2014). The total groundwater abstraction

Table 2 Historical records and future estimates of total groundwater abstraction in Tongatapu

Time period	Year	Groundwater abstraction (m³/day)		
		Public wells	Village wells	Total
Historical records	1966	1300	No data	–
	1995	5800	No data	–
	2010	10,890	5400	16,290
	2017	11,950	7050	19,000
Current	2018–2019	17,000	7050	24,050
Future climate period estimates	2010–2039	17,000	8650	25,650
	2040–2069	23,000	10,050	33,050
	2070–2099	28,000	10,250	38,250

Table 3 Maximum predicted sea level rise (m) for Tongatapu (TMS)

Emissions	2030	2055	2090
Medium	0.16	0.31	0.59
High	0.17	0.31	0.62

rate was equally divided among the existing wells according to the type of wells as public or village well.

Sea level rise predictions as in Table 3 were provided by Tonga Meteorological Services (TMS). Linear interpolation was adopted to estimate values in between the predictions and instantaneous rise in sea level was considered at the end of each 10-year period during the simulation period of 2010–2099. Sea level rise was simulated by increasing the coastal head boundary condition without change in the coastal node. Hence in this study, the effect of land surface inundation due to sea level rise was not considered.

A predevelopment steady-state simulation was followed by a transient simulation for 1966–2009 using historical records of rainfall and groundwater abstraction. The simulated heads and interface positions at the end of 2009 served as the initial condition for future scenario simulations during 2010–2099. The model output of freshwater thickness was used for the computation of freshwater volume. Monthly freshwater volume values were calculated by the summation of the product of freshwater thickness at each node at the end of the month and area of influence and porosity. Another major model output is the saltwater ratio (SWR) at each pumping well, which is a measure of well salinization.

Results

Validation of the transient model

Figure 3a shows the plot of simulated versus observed freshwater thickness values in all salinity monitoring boreholes during the validation period of January 2010 to December 2016. The average of the 431 freshwater thickness

observations from all SMBs during the above period is 10.97 m, and the corresponding value from the simulated model is 11.47 m. The overall correlation coefficient of simulated versus observed freshwater thickness in all 16 salinity monitoring wells is 0.82 and root mean squared error is 1.88 m. Table 4 indicates the root mean squared error, bias (the difference between simulated and observed mean freshwater thickness), and number of field records in each of the 16 SMBs during the validation period.

In the absolute hydrographs of various SMBs, the bias varies from 4.41 to − 1.84 m, with an average of 0.6 m. The positive bias indicates an overestimation of freshwater thickness by the model. The largest positive bias is observed at SMB08 and the largest negative value at SMB07. The simulated and observed absolute hydrographs of freshwater thickness for six representative SMBs (Fig. 3b) are shown in Fig. 3c. The SMBs are selected such that (1) they represent monitoring wells located throughout the island, (2) wells with longer and shorter period of observation data availability are included and (3) they indicate various degrees of the model and observation misfits.

Groundwater resources under future climate conditions

The time series of monthly freshwater lens volume computed under the future scenarios are shown in Fig. 4a, b. The volume of freshwater at the end of the year 2009 based on historic rainfall is selected as the base condition. Due to the large variability in GCM-based recharge values, significant variations occur in the freshwater volume predictions for the future. As observed from the time series data, the freshwater lens is highly dynamic with frequent depletion, especially for model scenarios where rainfall in the future is reduced. However, the simulations indicate that under median and wet future rainfall scenarios, the volumes of freshwater stored in the lens will be larger than that of the selected base condition for most of the simulation period under both RCP 4.5 and RCP 8.5. The impact of increased groundwater withdrawals is less evident on the total freshwater volume predictions (Fig. 4a, b). The basic statistics of future freshwater volume with respect to base condition, under different scenarios, are given in Table 4 of Online Resource 1 for climate periods of 2010–39, 2040–69 and 2070–99.

The minimum monthly freshwater volume indicated during the entire simulation period was 59% of the base condition under scenario 7 which represents a dry GCM under RCP 4.5 with a moderate sea level rise and increased groundwater abstraction. Scenario 6 showed the maximum increase in monthly freshwater volume as 98% of the base. At the end of the year 2099, the predicted freshwater volumes in the lens are − 18% and + 59% of the base condition for the worst and most favorable scenarios, respectively. Increase in pumping decreased the freshwater
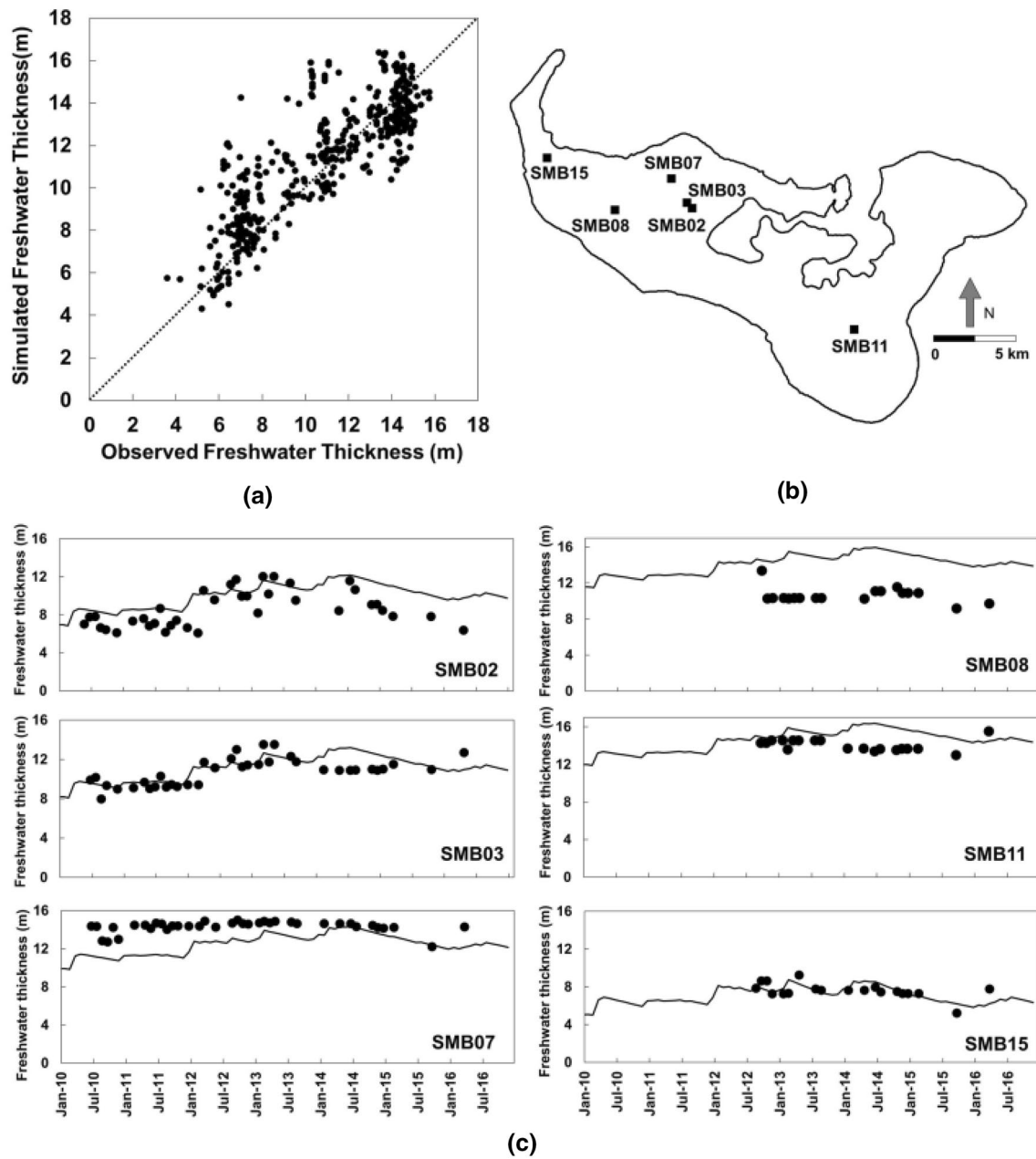
Fig. 3 Validation of transient model **a** simulated versus observed freshwater thickness in all SMBs, **b** location of six representative SMBs, **c** simulated (continuous line) versus observed (dots) freshwater thickness in the six representative SMBs

volume by an average of 1.1% for 2040–69, and 2.3% for 2070–99 compared to that of current pumping conditions under RCP 4.5 for medium sea level rise. The above values were 1.8% for 2040–69 and 2.8% for 2070–99 under RCP 8.5 for high sea level rise. The coefficient of variation (CV) for the freshwater volume predictions is in the range of 10–20%. The results indicate freshwater volume in the lens is more sensitive to changes in rainfall than to the effects of groundwater pumping, sea level rise or differences in RCPs.

The maximum number of wells that indicate saltwater intrusion (SWI) and the maximum predicted saltwater ratio (SWR) at any time during the future scenarios are given in Table 5. It is observed that the SWI and SWR are closely related to the recharge pattern and the pumping rates. About 94% of the public wells are vulnerable to salinization for the RCP 4.5 dry GCM scenario, and 98% are vulnerable under the same recharge conditions with increased pumping rates, as the increase in pumping increases the risk of well salinization. Due to the saltwater upconing beneath the wells, the

Table 4 Model performance in predicting freshwater thickness for validation simulation period 2010–2016

SMB	RMSE (m)	Bias (mean simulated − mean observed) (m)	Number of observations
SMB01	2.07	1.87	39
SMB02	2.58	1.41	38
SMB03	1.05	0.39	37
SMB04	1.14	− 0.09	38
SMB05	1.03	0.19	39
SMB06	1.09	− 0.07	38
SMB07	2.10	− 1.84	38
SMB08	4.50	4.41	18
SMB09	1.66	− 1.06	14
SMB10	1.31	− 1.12	19
SMB11	1.76	1.44	19
SMB12	4.13	3.53	18
SMB13	1.86	0.37	19
SMB14	1.07	0.49	19
SMB15	0.74	0.07	19
SMB16	0.76	− 0.45	19

maximum saltwater ratios are higher when a large number of wells are intruded by saltwater. The modeling results show that all scenarios except the wet GCMs under the current pumping conditions can possibly lead to saltwater intrusion in the pumping wells.

Regional freshwater volume assessment index

Estimates of how the volume of the freshwater lens beneath Tongatapu changes with time in response to rainfall variations were calculated with the model to evaluate the relation between rainfall percentiles and freshwater volume predictions. The summation periods of 12, 30, 60, 72 and 90 months were selected based on previous studies (White et al. 1999, 2007).

Figure 5a–e show the plots of monthly freshwater volume under scenario 1 along with the rainfall percentiles with summation periods of 12 months (P12), 30 months (P30), 60 months (P60), 72 months (P72), and 90 months (P90). Similar plots can be obtained for other scenarios. It is observed that as the summation periods increases, the effect of seasonal variations of rainfall is greatly reduced (Fig. 5). The correlation coefficient (R^2) of freshwater volume and rainfall percentiles under future scenarios is obtained as in Fig. 6. The increase in pumping does not significantly affect
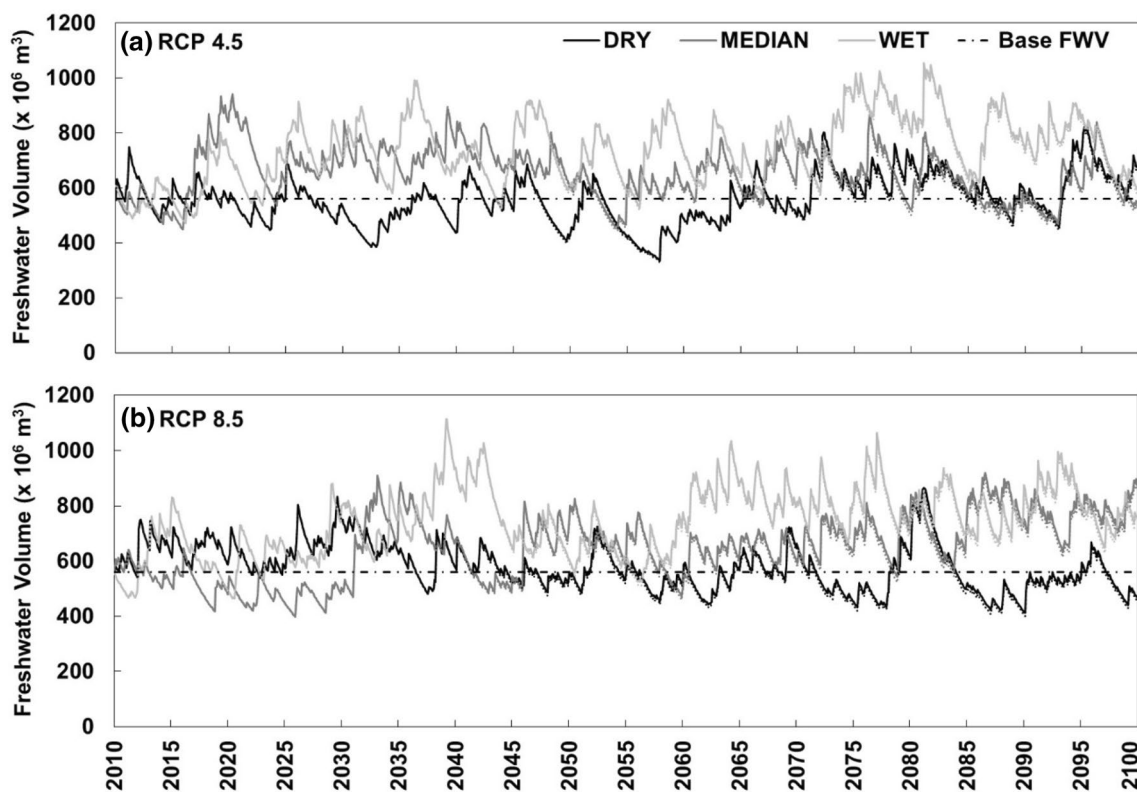

Fig. 4 Simulated freshwater volume under various GCM-predicted recharge conditions; continuous lines indicate monthly freshwater volume under current pumping and dotted lines indicate monthly freshwater volume under increased pumping conditions for **a** RCP 4.5 and **b** RCP 8.5

Table 5 Maximum well salinization of public wells at any time under various scenarios

Emission/sea level rise	GCM	Pumping			
		Current pumping		Increased pumping	
		Max. % of SWI wells	Max. SWR	Max. % of SWI wells	Max. SWR
RCP 4.5/medium	Dry	94	0.84	98	0.91
	Median	22	0.39	92	0.80
	Wet	0	0.00	28	0.51
RCP 8.5/high	Dry	70	0.71	96	0.88
	Median	72	0.74	72	0.76
	Wet	0	0.00	30	0.53

the correlation coefficients. Though the correlation coefficients between rainfall percentiles and freshwater volume are highly dependent on the rainfall patterns, the average correlation coefficient is the highest for the summation period of 60 months under all scenarios.

The relation of normalized freshwater volume (NFWV) to the percentage of saltwater intruded wells (SWI) is explored in Fig. 7. Time series of monthly freshwater volume, monthly pumping rates, and percentage of saltwater intruded wells (SWI) are indicated against the normalized freshwater volume (NFWV). Scenarios 1 and 7 indicate relatively lower freshwater volumes and higher well salinization than other scenarios and are represented in Fig. 7a, b, respectively. Results for other scenarios are provided as Fig. 3 of Online Resource 1. The dark gray areas indicate periods when the freshwater volume is below the average conditions (negative NFWV) and light gray areas indicate higher than average conditions (positive NFWV). It is seen that under current pumping conditions (scenario 1), well salinization occurs during negative NFWV with a response time of about a year between negative NFWV and well salinization and the response time depends on previous recharge conditions. However, the response time decreased and at times is completely absent during dry periods with increase in groundwater abstraction (scenario 7) for the same recharge conditions. The results indicate that for the current pumping rates, possible well salinization occurs during dry periods with some response time. However, when the pumping rates are increased, well salinization occurs even for above-average freshwater volume conditions and almost immediately during dry periods.

Sustainability index (SI) of pumping wells

The variations in saltwater ratios with time in each pumping well were used to calculate the reliability (REL), resilience (RES), vulnerability (VUL) and the SI of each pumping well for future scenarios. The spatial distribution of the wells together with the average of SI values under all 12 scenarios is shown in Fig. 8. The freshwater thickness in 2099 for

scenario 7 is indicated as the filled contours. Lower values of SI indicate a high risk of saltwater intrusion. Public wells near the center of the well field and village wells near the coast were found to have a low sustainability. Most of the public wells indicate possible saltwater intrusion under worst conditions, whereas most village wells are relatively sustainable.

The overall SI values for public wells and village wells were computed separately, as their pumping characteristics are different. The overall SI values and average values of reliability, resilience and vulnerability under various for groundwater pumping from public wells are given in Table 6. For the current pumping conditions, the freshwater lens is quite reliable under future rainfall patterns considering that the lowest reliability of the freshwater lens is 0.9. However, the above value decreases to 0.69 with an increase in pumping. The resilience of the system is notably low under dry recharge conditions (< 0.10) for current pumping rates, and it would be further reduced if the current pumping rates were to increase. Vulnerability under dry recharge conditions increases over three to six times that of current pumping when groundwater abstraction is increased. The SI of the public well system is 0.45 and 1.00 under current pumping conditions and under a scenario of a moderate sea level rise for the driest and wettest recharge conditions and the above values reduced to 0.30 and 0.90, respectively, under increased pumping and high sea level rise. The village wells showed SI values of 0.95–0.97 under various future scenarios (Table 5 of Online Resource 1).

Discussion

The freshwater lens of small islands is highly dependent on recharge from rainfall (Bailey et al. 2016; Werner et al. 2017) and the present study has demonstrated that rainfall percentile with the appropriate summation period can be used as a regional index for the assessment of the volume of freshwater stored in a groundwater lens. Among the various summation periods used for calculation of rainfall percentiles,

Fig. 5 Monthly freshwater volumes (FWV) simulated under scenario 1 along with rainfall percentiles of summation periods **a** 12 months (P12), **b** 30 months (P30), **c** 60 months (P60), **d** 72 months (P72) and **e** 90 months (P90)
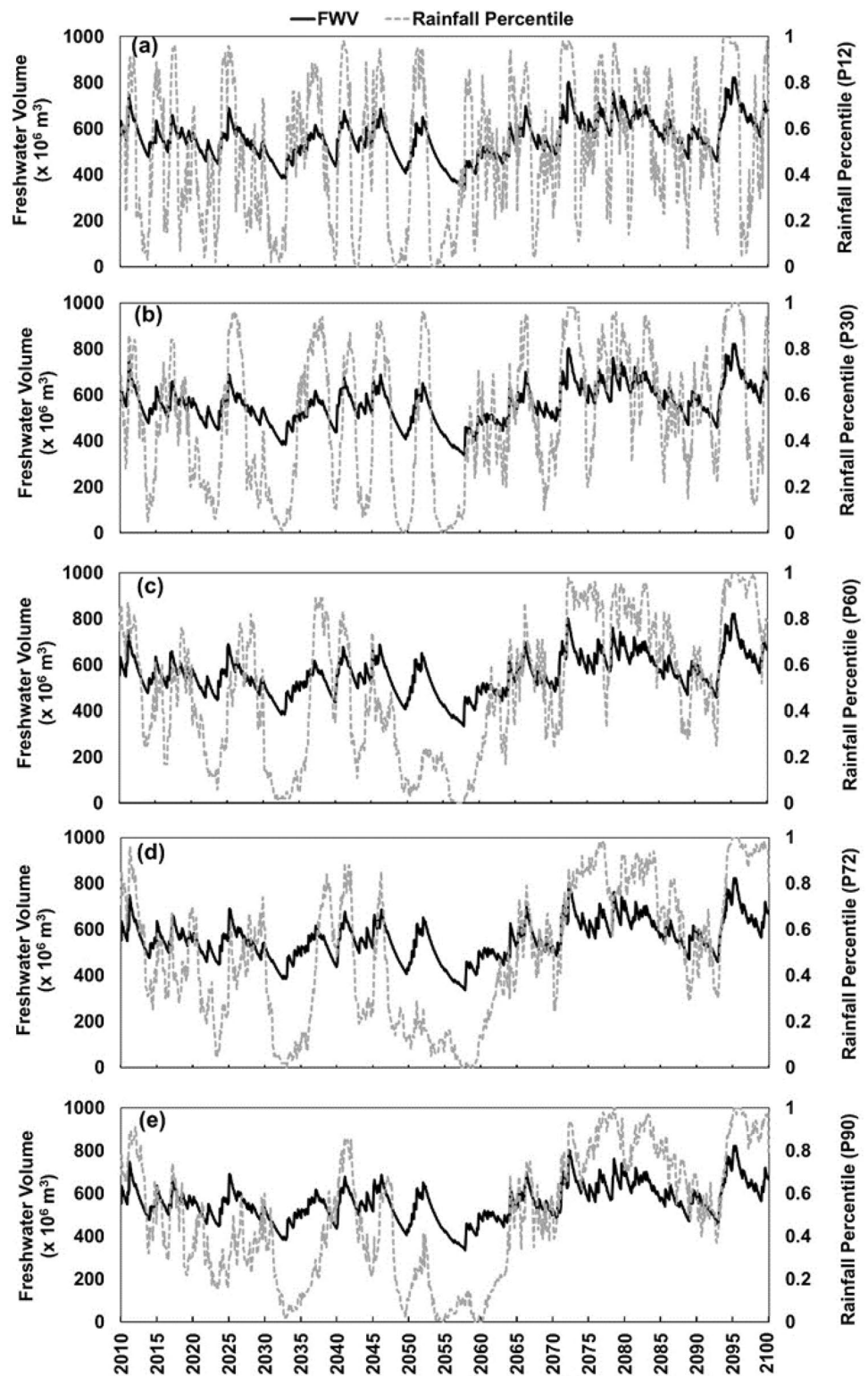
the 60-month summation period (P60) showed the strongest correlation with the freshwater lens volume (Table 6) of Tongatapu Island. Incidentally, the estimated groundwater residence time is about 5–5.5 years (White et al. 2009). White et al. (1999) observed from field measurements that

the maxima and minima of freshwater lens thickness of Bonriki freshwater lens, with an estimated 5.5-year groundwater residence time, best corresponded with rainfall percentiles of 60-month summation period. However, the seasonality of the freshwater volume change can be captured with shorter
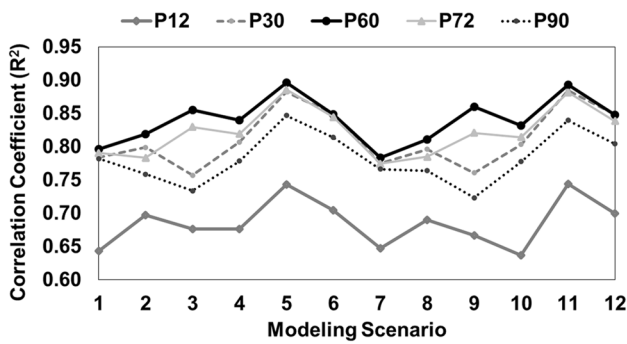
Fig. 6 Correlation coefficients of freshwater volume and rainfall percentiles with different summation periods (P12, P30, P60, P72, P90) under future scenarios

summation periods of about 12 months. Hence, water managers can use a combination of P60 and P12 to plan for the long-term and short-term conditions, respectively.

The simulated variations of normalized freshwater volumes (NFWV) over time indicated that there are storage deficiencies in the aquifer that could lead to well salinization (Fig. 7). Whether the NFWV time series can adequately predict well salinization depends on the mean and standard deviation of the time series. Under wet GCM rainfall conditions, the predicted mean values of the volume of freshwater stored in the aquifer would be much higher than base conditions, and hence a negative NFWV would not necessarily lead to well salinization as shown in Fig. 3 of Online Resource 1. However, under general dry and median rainfall conditions, changes in the NFWV could be an early estimation of well salinization. In Tongatapu, varying response

times could occur under current pumping conditions from the time of deficit freshwater volume to first well salinization (Fig. 7). Well salinization can occur even for higher than average freshwater volume under high abstraction rates and previous occurrences of saltwater intrusions can leave the freshwater lens highly vulnerable to future droughts.

Scenario 7 indicated the worst conditions of freshwater lens volume (Fig. 4). The pumping sustainability of village wells which are distributed across the island is observed to be the least for scenario 7 (Table 5 of Online Resource 1). However, the least favorable scenario for pumping sustainability in public wells is scenario 10, representing a dry GCM of RCP 8.5 with high sea level rise and increased pumping, and has an overall SI of 0.3 (Table 6). The average number of public wells intruded by saltwater under scenario 10 is about 2% higher than that of scenario 7. This indicates the importance of joint evaluations of well-scale and regional-scale risks.

Wells that are vulnerable to salinization can be identified by calculating their SI values (Fig. 8) based on the simulated saltwater ratios. In Tongatapu, the locations of wells that are vulnerable to salinization correspond to regions where the freshwater lens is thin and when the wells are spread out, and in the center of the well field when the wells are clustered. The SI values of each well can be integrated into optimization network and the objective function could be designed so as to maximize the SI (Mays 2013), however, further study is warranted.

The present study improved the understanding of the transient nature of the freshwater lens of Tongatapu by combined regional- and well-scale modeling. Previous modeling studies on Tongatapu (Hunt 1979; Bobba and Singh
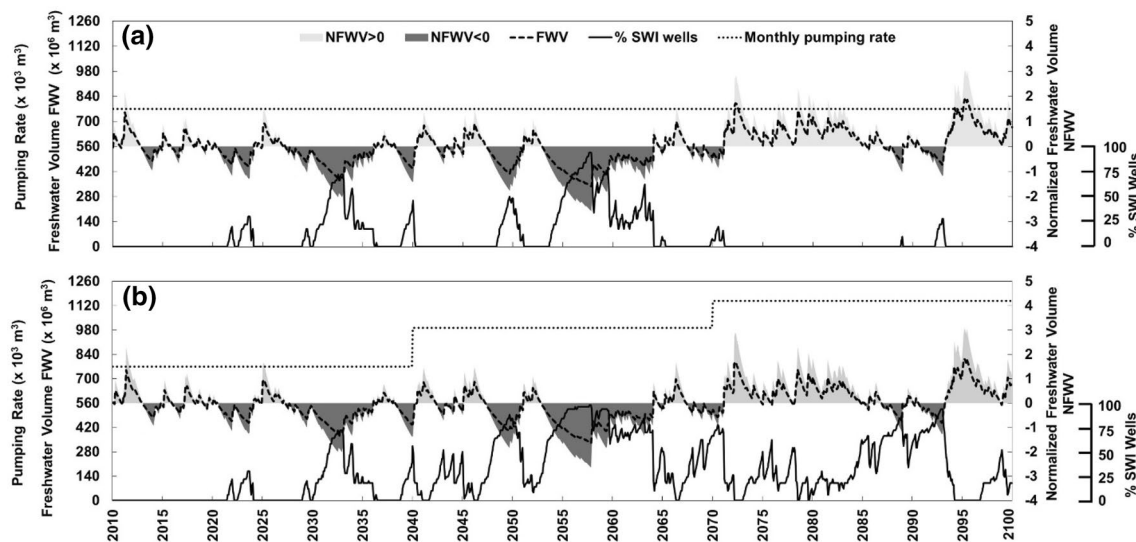

Fig. 7 Normalized freshwater volume related to the percentage of saltwater intruded (SWI) wells along with monthly freshwater volume (FWV) and pumping rates for **a** scenario 1, **b** scenario 7
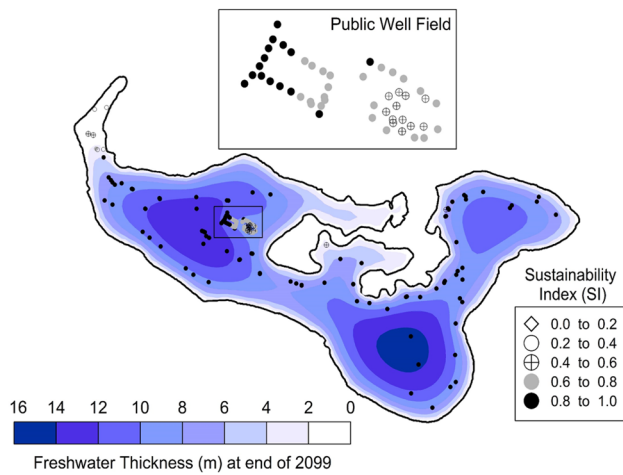
Fig. 8 Average sustainability index (SI) of each well for future scenarios along with the freshwater thickness at the end of 2099 for scenario 7

1999) used steady-state conditions, with large grid size and neglected the effects of groundwater pumping. Despite the simplification, the model was able to predict the overall transient nature of the freshwater lens thickness with a scaled root mean square error of 14.8% during the validation period. By comparison, Alsumaiei and Bailey (2018) calibrated the numerical models for atoll islands of Republic of Maldives against the field measurements of freshwater lens volume with a target of less than 1% discrepancy in freshwater lens volume from field estimations and numerical model. Similarly, the elevations of measured EC levels were reproduced within a few meters for dispersion-based numerical modeling of the freshwater lens of Bonkiri Island (Post et al. 2018) when calibration and validation were done using observed salinity at monitoring wells.

Though there are deviations between the observed and simulated freshwater thickness depending on the locations of SMBs, the present model is able to predict the general freshwater lens dynamics of the island. The standard deviations of predictions for individual SMBs are within 1.88 m for

the validation period which includes a relatively dry period of 2015. The manual calibration of the steady-state model (Babu et al. 2018) could have resulted in an overestimation of the freshwater thickness. The total overestimation for all SMBs was 9.6 m, while that of SMB08 and SMB12 together contributed 7.9 m (Table 4). The average discrepancy in freshwater thickness reduces to 0.12 m in the remaining SMBs, and which is not a grave overestimation considering the simplified hydrogeological model. The lack of data regarding the locations of all wells near agricultural fields and actual pumping rates in each of the public wells (White et al. 2009; Waterloo and Ijzermans 2017) also could have caused deviations in the prediction of freshwater thickness in SMBs near the agricultural fields (SMB08) and the public well field (SMB05, SMB07, and SMB12).

The cumulative recharge at the end of the century predicted by the ensemble of 29 GCMs ranges from a minimum of 0.432 m/year to a maximum of 1.069 m/year for RCP 4.5, and from a minimum of 0.378 m/year to a maximum of 1.322 m/year for RCP 8.5, indicating a large variability in GCM predictions (Table 3 of Online Resource 1). Due to the variability of the selected GCMs within the simulation period, a projection designated as median may have periods of wet or dry conditions. The frequent dry periods are observed in most GCM predictions and can lead to a significant decrease in freshwater volume, with the worst dry condition potentially causing a 40% decrease in freshwater volume compared to the base condition.

The impact of groundwater pumping on the total freshwater lens volume is less than 2.5%, even for the worst conditions. This is mainly due to the relatively large size of Tongatapu and the localized nature of groundwater abstraction on the island. Groundwater pumping from the vertical wells that are concentrated in a single well field increases the risk of well salinization. Previous estimates of sustainable yield on Tongatapu considering distributed abstraction was 54,000–72,000 m^3/day (White et al. 2009). The present study shows that even about 27,000 m^3/day can cause 94% of the public wells to be salinized under the worst conditions (Table 5).

Table 6 Overall sustainability index (SI) of public wells and average reliability, resilience and vulnerability under various scenarios

Emission/sea level rise	GCM	Pumping							
		Current pumping				Increased pumping			
		REL	RES	VUL	SI	REL	RES	VUL	SI
RCP 4.5 medium	Dry	0.901	0.145	0.099	0.445	0.691	0.086	0.309	0.325
	Median	0.995	0.823	0.005	0.902	0.870	0.169	0.130	0.424
	Wet	1.000	1.000	0.000	1.000	0.997	0.823	0.003	0.897
RCP 8.5 high	Dry	0.946	0.458	0.054	0.674	0.686	0.087	0.314	0.300
	Median	0.958	0.418	0.042	0.637	0.916	0.435	0.084	0.648
	Wet	1.000	1.000	0.000	1.000	0.995	0.771	0.005	0.869

The model assumed homogeneous and isotropic aquifer, and the spatial variation of recharge was not considered. The use of sharp-interface assumption and idealized aquifer conditions could have caused some regional discrepancies between the simulated and observed freshwater thickness. For example, though the aquifer was reported to be karstic in nature, the hydrostatic assumptions in the sharp-interface model restricted the implementation of anisotropy in the hydraulic conductivity of the aquifer. Additionally, applying empirical mixing-zone correction factors to account for dispersion in sharp-interface models (Werner 2017) could be attempted to reduce the discrepancy between the simulated and actual lens thickness. However, in this study, the sharp interface was assumed to correspond to the upper limit of electrical conductivity of freshwater, hence the saltwater considered by the model included the dispersion zone (Babu et al. 2018).

Though all the 50 existing public wells in Tongatapu were included in the model, only 50% of the village wells known to exist (van der Velde 2006) were included in the model as a detailed inventory of all wells was absent (Waterloo and Ijzermans 2017). The results of well salinization can be improved if all wells are represented with correct locations, screen depths, and pumping rates. Kopsiaftis et al. (2019) and Mehdizadeh et al. (2015) reported that saltwater intrusions predicted by sharp-interface model differed from those of dispersion model in aquifers exposed to pumping. However, both studies indicated that the sharp-interface model results were more conservative than the dispersion model results, hence the results obtained in this study can be used for long-term island-wise preliminary planning of groundwater resources.

As potential groundwater recharge is used in this study, the time lag due to unsaturated flow needs to be included in both the recharge prediction model and the groundwater flow model. The factors that affect the selection of GCMs (Rossman et al. 2018) can possibly lead to uncertainties along with those of recharge simulation model (Werner et al. 2017). The sea level rise considered in this study ignored land inundation effects. There could be possible additions of new pumping wells at other locations in the future, which is beyond the scope of the present study. The calculation of SI values based on a single indicator is not the only measure of the long-term viability of water supply wells, and hence other aspects like water quality and economy need to be considered for a better understanding of groundwater sustainability on oceanic islands.

Conclusions

The vulnerability of the small island freshwater resources to changes in rainfall caused by climate change can be intensified by excessive groundwater abstraction. Hence, it is important to assess both the regional- and the well-scale risks of saltwater intrusion taking place for groundwater resource planning and management.

This was carried out in the present study through the development and field application of indicators for a combined assessment of the regional- and well-scale vulnerability of an island freshwater lens to saltwater intrusion using a numerical modeling approach. This study also indicated that a sharp-interface numerical model calibrated with freshwater thickness could be used (Babu et al. 2018) for the transient modeling of a small island freshwater lens. The study utilized freshwater thickness, the most critical parameter for water resource management on islands (Werner et al. 2017), for the validation of the transient model which to the knowledge of the authors has not been attempted in previous studies on small islands. This study also utilized GCM predictions of rainfall patterns together with predictions of sea level rise and groundwater pumping rates to predict well-scale saltwater intrusions in Tongatapu Island.

This study has shown that rainfall percentiles with a summation period equal to the groundwater residence time of the freshwater lens (about 60 months for Tongatapu) can be used to represent the evolution of freshwater lens volume. The normalized freshwater volume can also be used as an advance indicator of the risk of well salinization. Values of the SI of wells computed based on numerical model results can also be used to identify wells with a high risk of salinization which require close monitoring. Values of this index can also be used to assess the sustainability of groundwater abstraction under different climate and pumping conditions.

The results of the numerical modeling indicate that the freshwater lens of Tongatapu is highly dependent on recharge rates and abstraction rates. About -18% to $+56\%$ of the base conditions of freshwater volume in the groundwater lens beneath the island in 2009 is predicted by 2099 under the worst and the most favorable scenarios, respectively. Uncertainties associated with GCM predictions considered in this study, make it difficult to make definite conclusions regarding the trend of freshwater volume change. Sustainability indexes of the public well system are 45% and 100% for the driest and wettest recharge, respectively, for current pumping conditions and medium sea level rise. The above pumping sustainability values reduced to 30% and 90%, respectively, under increased pumping and high sea level rise. From a water management perspective, it is imperative to explore additional well field locations for public wells and control pumping rates to ensure the sustainability of groundwater pumping in the future. The methodology suggested in this study can be adopted for first-hand temporal assessment of regional freshwater lens volume and spatial assessment of well-scale saltwater intrusions in other small islands with comparatively lesser data and computational resources, for water management planning and preparedness.

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