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Research papers

Evaluation of management scenarios for potable water supply using script-based numerical groundwater models of a freshwater lens

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ABSTRACT

Challenges in balancing freshwater demands and the long-term availability of freshwater from small island aquifers warrants responsive management, whereby groundwater conditions guide decisions about pumping rates to avoid well salinization. We evaluate responsive freshwater lens management for the first time, through transient, three-dimensional, dispersive modelling of Bonriki Island (Kiribati). Both responsive- and fixed-management scenarios are explored, including a novel pumping redistribution strategy. Modelling results reveal that responsive management offers superior lens protection, particularly during droughts. Pumping redistribution produced lower salinities but greater lens depletion. All scenarios indicate that the Bonriki lens will continue to decline, consistent with previous shorter-timeframe projections. Lower lens storage losses are attainable by abstracting groundwater at the maximum acceptable salinity, contrary to traditional strategies of seeking the lowest available salinities. The methodology developed in this research provides a blueprint for investigating responsive, "monitor-and-react" management scenarios, which we advocate as best practice for balancing freshwater demands with long-term lens security.

1. Introduction

Fresh groundwater in islands is stored in lenses that float above underlying saltwater and are held in delicate balance by buoyancy forces, freshwater-seawater mixing and aquifer inflows and outflows. On small islands, freshwater lenses and rainfall are the two main sources of water for human consumption (White and Falkland, 2010; Werner et al., 2017). The main threats to freshwater lenses are pollution by anthropogenic contaminants and salinization by seawater. Safeguarding the available freshwater resources calls for water management strategies that are tailored towards the unique physiographic conditions encountered on islands.

The abstraction of fresh groundwater from islands results in thinning of the lens, widening of the transition zone between the fresh groundwater and seawater, and in many cases, up-coning (e.g., Werner et al., 2017). Due to the increasing demand for water, mainly driven by population growth, the withdrawal of groundwater has increased in many islands (e.g., Ibrahim et al., 2002), and future changes in rainfall patterns are expected to affect freshwater availability (Alsumaiei and Bailey, 2018). Without sufficient knowledge of the groundwater system and recharge rates, there is a serious risk of over-exploitation. Much effort has therefore been devoted to determining the sustainable yield of freshwater lenses. Broadly defined as the rate at which groundwater can be extracted without adverse effects, the sustainable yield is often expressed as a percentage of the recharge, for example ranging between 25–50% for atoll islands (Hunt and Peterson, 1980; White and Falkland, 2010).

Numerical groundwater models play a key role in water management decision making and have been applied to a number of islands (see Werner et al. (2017) for a recent overview of atoll island examples). They provide a versatile tool for the comprehensive assessment of factors that may impact the sustainable yield of island aquifers, such as transient recharge and pumping variability, and solute mixing processes. The latter is particularly important, given the greater thickness of the transition zone relative to that of the freshwater lens in many cases (e.g., Buddemeier and Oberdorfer, 2004). Therefore, numerical models that simulate dispersive mixing may be the only appropriate tool to assess abstraction effects in the context of the island's

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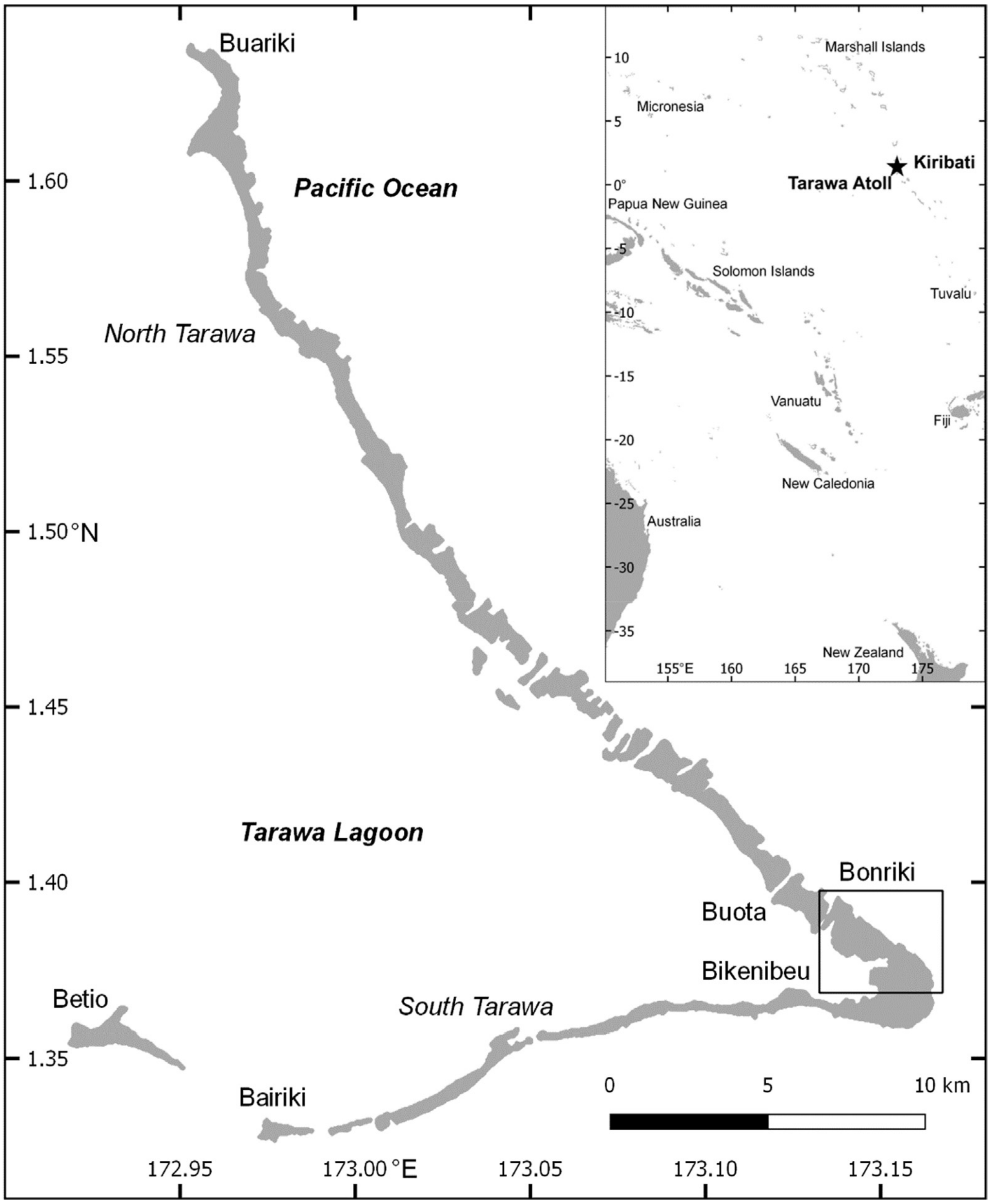

Fig. 1. Locality map of Tarawa Atoll and Bonriki Island (taken from Post et al., 2018).

sustainable yield. Their application for sustainable yield estimation is limited though to islands where sufficient hydrogeological data are available.

Several studies have adopted numerical models to design groundwater supply systems for atoll islands. Griggs and Peterson (1993) modelled the freshwater lens of the Laura area on the Majuro Atoll, Marshall Islands. They varied design criteria such as abstraction rate, number of wells, and well depth. It was concluded that the sustainable yield of horizontal galleries was roughly double that of individual pumping centres (i.e., drilled vertical wells). They also noted the absence of steady-state conditions due to the high temporal variability of recharge rates, and contended that a higher sustainable yield would be calculated when monthly recharge rates were modelled instead of yearly averages, as the latter underestimated actual recharge. Ghassemi et al. (1999) found that using monthly recharge rates instead of quarterly averages led to improvement in their model's ability to simulate observed groundwater salinities. They concluded that it is vital to consider the transience of the system at an appropriate temporal resolution during calibration.

Post et al. (2018) investigated the long-term effects of abstraction from the freshwater lens of Bonriki Island, Tarawa Atoll, Kiribati. Groundwater is withdrawn using a network of infiltration galleries, which has been in operation since 1987. Growing water demand and upward revisions of the sustainable yield estimates have led to the abstraction of ever-greater amounts of groundwater. Water balance calculations by Post et al. (2018), based on a calibrated SEAWAT model, showed that nearly 80% of the total abstracted volume since the start of operations is made up by freshwater that would have otherwise discharged into the ocean. The remainder was removed from storage within the freshwater lens, which consequently decreased in volume. Post et al. (2018) found that the storage volume decrease is almost linearly dependent on the total volume abstracted and showed no signs of abatement after 27 years. The salinity of the abstracted water on Bonriki Island has become much more responsive to droughts, as the transition zone has migrated upward and moved closer to the screens of most of the wells than in the past.

These negative developments call for a reassessment of the management of the Bonriki Water Reserve. The current water demand appears to exceed the capacity of the freshwater lens according to Post et al.'s (2018) results, but a reduction in abstraction is not considered a feasible option for the short-term, as there are no alternative water sources on the island to meet the possible water deficit (Jolliffe, 2017). Therefore, a strategy is needed to minimise freshwater lens vulnerability to salinization while maximising the provision of fresh groundwater to the island's populace. This paper presents a methodology to explore groundwater reserve management strategies applied to Bonriki Island (Kiribati) including several options, such as redistribution of pumping and land use management to increase recharge. This allowed the effectiveness of dynamic management of the lens based on drought indicators to be investigated

The principles of dynamic management scenarios are predicated on adaptive management concepts (e.g., Williams, 2011). Specifically, the approach to managing the Bonriki lens adopted in this investigation is a form of trigger-level management (Werner et al., 2011), in that meteorological indicators and salinity levels are used to set the allowable abstraction volumes. Standard groundwater modelling codes are not well-suited to test the effectiveness of such operational management processes, because the rate of pumping over time is not known a priori to simulation, and instead depends on the model outcomes. That is, to properly assess the anticipated mode of management, feedback mechanisms are required whereby pumping is moderated by lens behaviour. Enabling dynamic simulation of pumping rates based on management rules is an extension to previous modelling investigations of coastal aquifers (e.g., Ghassemi et al., 1999; Werner and Gallagher, 2006; Post et al., 2018). The calibrated numerical model of the Bonriki lens was implemented as a script-based model using the FloPy library (Bakker et al., 2016), which enables the execution of a MODFLOW-based model in a Python programming environment. The objective of this article is to demonstrate the applicability of such models to design and evaluate the effectiveness of dynamic management procedures for fresh groundwater resources, in particular, where saltwater-freshwater interactions are critical.

2. Study area

The island of Bonriki is part of the Tarawa Atoll in the Republic of Kiribati, located near the equator in the western part of the Pacific Ocean (Fig. 1). The surface elevation is between 2 and 4 m above mean sea level. It is separated from the neighbouring Buota Island to the northeast by a tidal channel. On the ocean side is a beach on a rock platform from which a reef flat extends into the ocean. The island is located on the south-eastern tip of the atoll's lagoon. An aquaculture facility with approximately east-west oriented saltwater ponds is located in the southern part of the island. Bonriki International Airport is located centrally on the island, and the fringes contain residential areas.

Together with the smaller lens of the adjacent Buota Island, Bonriki Island's freshwater lens constitutes Tarawa's National Water Reserve. Due to limited water resources on the island, land use is regulated; however, law enforcement is problematic. Extensive vegetation, primarily coconut trees and pandanus (Jolliffe, 2017), covers the lens area. Groundwater is abstracted by a system of infiltration galleries in the form of horizontal wells that are a few hundred metres in length just below the water table. These wells feed water into a central vertical shaft from which the water is pumped. After chlorination, the water enters the reticulated water system, through which the majority of water is provided to the high population density regions of South Tarawa (notwithstanding significant leakage problems with the reticulation network). In 2014, groundwater was being abstracted at a rate of 1362 m^3/day (Post et al., 2018).

The subsurface lithology is made up of Holocene clastic sediments that cover the underlying Pleistocene limestone. The latter was subjected to weathering during ocean low stands of the earth's glaciations. The erosive surface that forms the boundary between the Holocene sediments and the underlying limestone is uneven and its depth varies by 3 to 6 m between drill holes. The Holocene material transitions from the lagoon to the ocean from (i) unconsolidated sand and gravel, into (ii) poorly cemented hard coral fragments, into (iii) consolidated coral deposits. Detailed descriptions of the geology of Bonriki Island are provided by Falkland and Woodroffe (2004) and Jacobson and Taylor (1981).

Tarawa's hot tropical climate is strongly influenced by El Niño-Southern Oscillation (ENSO) cycles, and thus the Southern Oscillation Index and Tarawa's annual rainfall are strongly correlated (White et al., 2007). The period between May and November tends to be the driest, while most rainfall occurs from December to April. Daily rainfall observations have been made on Betio Island (see Fig. 1 for location) since 1947. The average annual rainfall based on the measurements between January 1947 and December 2013 was 1998 mm. Daily rainfall has been recorded at Bonriki Airport since 2009. Pan evaporation data collected on Betio Island between 1981 and 1991 yielded a mean pan evaporation rate of 6.15 mm/d, with a minimum of 5.5 mm/d in July and a maximum of 6.9 mm/d in September and October (Falkland, 1992).

Increases in seawater temperatures due to future global warming are expected to lead to an increase in rainfall averages in the Pacific. Predictions of future rainfall as well as drought frequency and duration are based on global atmospheric circulation models. Drought periods are strongly correlated with the inter-annual La Niña cycles and sea surface temperatures (White, 2010). While the representation of ENSO cycles in such models has improved, different models still produce diverging projections of changes in frequency, intensity and patterns of future El Niño and La Niña events (BoM and CSIRO, 2011). For Kiribati, BoM and CSIRO (2014) indicate with medium confidence that the annual as well as the seasonal mean rainfall will increase, and that the incidence of droughts will decrease.

3. Methodology

The modelling technique adopted in assessing the efficacy of management scenarios on the Bonriki freshwater lens involved the development and application of a novel feedback mechanism, whereby pumping was restricted according to aquifer conditions. The rules for modifying pumping in simulations of future lens behavior are considered representative of the operational procedures that are expected to be adopted by water managers. A suite of future scenarios was considered, and the corresponding simulated management practices were evaluated, in terms of their effectiveness, based on the predicted salinities (expressed as the water's electrical conductivity, EC) of the abstraction wells. From these, management rules were formulated that aim to minimise the long-term effects of abstraction on the freshwater lens while optimising the access to fresh groundwater (i.e., EC below 1.5 mS/cm) for the population of South Tarawa. This was achieved through the placement of constraints on the abstraction rates during droughts so that unacceptable negative impacts from prolonged periods of low recharge are minimised. Firstly, a calibrated numerical model was developed for this purpose using the SEAWAT code. The calibration procedures and results are described in detail in Bosserelle et al. (2015), Galvis-Rodriguez et al. (2017) and Post et al. (2018). The design of management procedures took into consideration various aspects that determine the condition of the lens, i.e., rainfall, land use and abstraction regimes, as will be detailed in the following subsections.

3.1. Rainfall

The spatially distributed and transient recharge required for the numerical model was determined using the WATBAL code, which has formed the basis for estimates of rainfall recharge to the Bonriki lens in several previous modelling studies (Alam et al., 2002; Falkland and Woodroffe, 2004; Post et al., 2018). Rainfall inputs to WATBAL were required for future scenarios, which were developed for an evaluation period spanning the years 2015 – 2044 (i.e., 30 years). This was preceded by simulation of the conditions occurring during January 1997 – December 2014, which encompassed the calibration period for the transient model and represents the historical period with the most intensive abstraction.

Uncertainty in future predictions of changes in inter-annual rainfall variability, as mentioned above, as well as the unknown response of evaporation to changes in climatic variables such as temperature, form an obstacle in parametrising the recharge to the freshwater lens for predictive model scenarios (White, 2010). Therefore, instead of relying on uncertain projections, the daily measured rainfall data from January 1986 to December 2014 were used as input for the recharge calculations for the period January 2016 to December 2044. The selected historical rainfall record includes 5 years of high rainfall (1990 – 1994) as well as a three-year drought (1998 – 2000), which was the severest event since measurements started in 1947. This three-year drought occurs during the years 2028 – 2030 in the rainfall time series adopted for scenario analyses. Actual measurements were used for the year 2015.

The unmodified historical rainfall as a proxy for the future rainfall is referred to as rainfall scenario S1. Additionally, two scenarios were designed in which different drought characteristics were considered. In rainfall scenario S2, a six-year drought was implemented by replacing the daily data for the relatively wet year 2027 (which maps onto 1997 in the historical record) with the averages of the years 1995, 1996, 1998, 1999 and 2000. By doing this, the rainfall of 2025 – 2030 was lowered from 1213 mm/y to 808 mm/y (on average). In rainfall scenario S3, a repeated drought is considered by using the 1996 – 2014 rainfall observations for the period 2016 – 2034, and the 1996 – 2005 data for the years 2035 – 2044, which means that the 1998 – 2000 dry years are repeated twice in the future scenario, i.e., during the years 2018 – 2020 and 2037 – 2039. The monthly rainfall values are displayed graphically in Fig. 2.

3.2. Land use

The original calibrated model adopted five recharge zones and considered the period 1997 – 2014. In 2015, the vegetation was cleared in a significant part of the Bonriki Water Reserve for the installation of solar panels. The modified land use of this zone was included in the model during the years 2015 – 2044 (Fig. 3), with the effect of vegetation clearing on recharge evaluated using WATBAL.

3.3. Abstraction

Three future abstraction regimes were considered, referred to as Q1 to Q3 in the following. In the first (Q1), it was assumed that the total abstraction rate becomes 1660 m^3/d as of July 2014, which is the first month for which no actual, measured abstraction rates were available at the time of this analysis. The abstraction rate is kept steady and is distributed in relative proportions over the 21 operational galleries based on the original design-yield of each of the pumping galleries (Alam et al., 2002; Falkland, 2003) (Fig. 3). This abstraction regime represents a no-management approach to drought, with abstraction for each pumping gallery at its original design rate.

The second regime that was considered (Q2) involved redistributing the abstraction rates between individual galleries based on a sensitivity ranking. The ranking was determined by repeatedly running the model with rainfall scenario S1 and abstraction regime Q1, but with abstraction at each gallery increased by 80 m^3/day one gallery at a time. The sensitivity was measured by the resulting increase of the salinity of the water at the trunk main, which collects the water from all galleries. The salinity increase was taken as the average EC value over the years 2029 – 2031, i.e., following the 2028 – 2030 drought by a lag time of 12 months to account for the delayed response of the abstraction water salinity to low-recharge conditions. The abstraction rates of the four most sensitive galleries (i.e., 1, 17, 2 and 20) were scaled back by 45, 45, 22.5 and 22.5 m^3/day, respectively, while the abstraction rates of the six least sensitive galleries (i.e., 7, 9, 11, 12, 13 and 22) were each

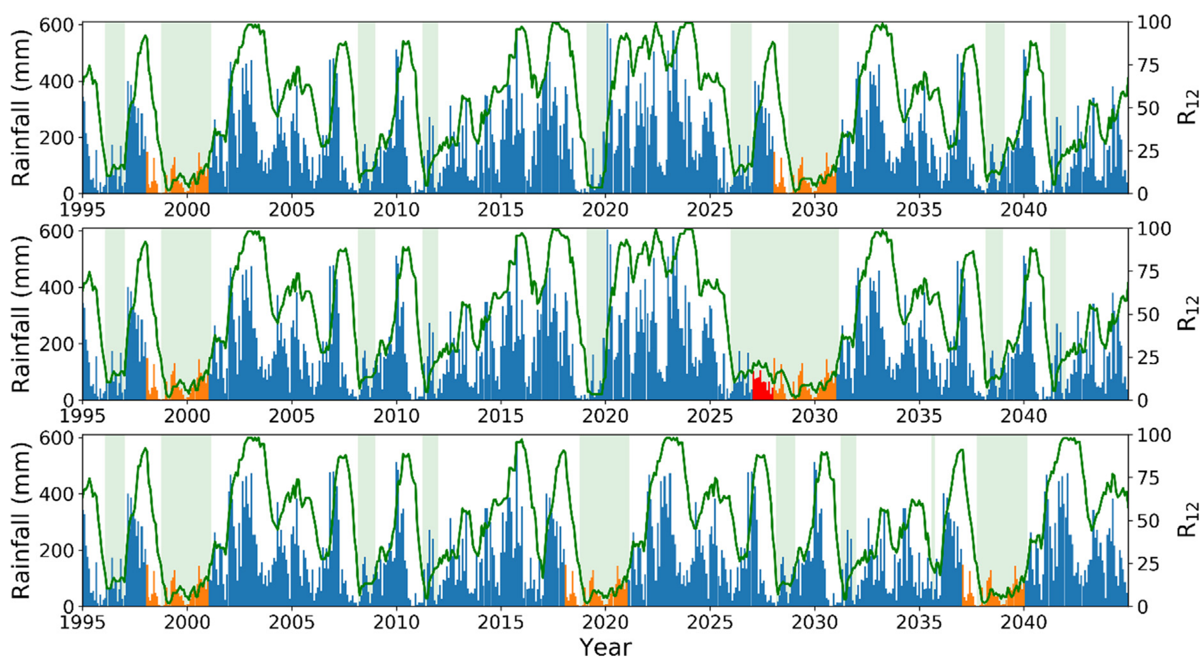

Fig. 2. Monthly rainfall for the period January 1995 to December 2044 for rainfall scenarios (a) S1, (b) S2, and (c) S3. The green line shows the R_{12} trends for the rainfall time series, where R_{12} is obtained by first summing the month's rainfall and that of the preceding 11 months, and ranking this relative to other 12-month sums (with the same start and end months; Post et al., 2018). The green shading indicates periods with $R_{12} < 25\%$. The orange bars are used to highlight the replicated 1998 – 2000 drought period. The red bars indicate the values used for the year 2027 in rainfall scenario S2, in which each month was the average of the corresponding month in the years 2025, 2026, 2028, 2029 and 2030. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

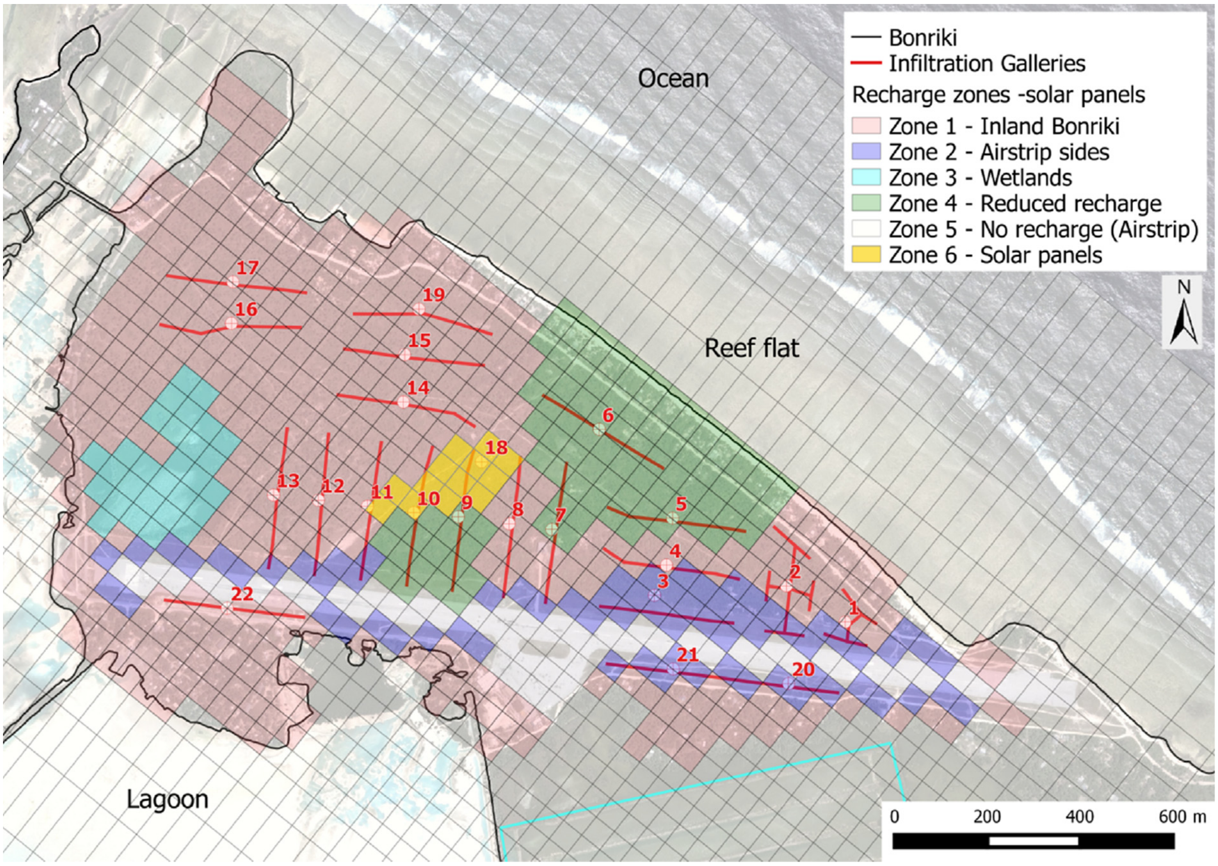

Fig. 3. Zonation of recharge in the numerical simulations and the location of infiltration galleries, overlain on a close-up of the model grid. The yellow area indicates zone 6, which experienced higher recharge rates since September 2015 when the vegetation was cleared and solar panels were installed. Prior to this, it was part of recharge zone 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increased by 22.5 m^3/day. The total abstracted rate thus remained constant at 1660 m^3/day.

The third abstraction regime (Q3) built upon Q2, in that the redistributed pumping rates from Q2 were used as the target (or starting) values in Q3. The sensitivity analysis that was run prior to Q2 (see above) was re-run to recalculate the sensitivities with Q2 pumping rates in place. The results are provided in Table 1, which lists the wells with the highest/intermediate/lowest sensitivities; noting that these have changed compared to sensitivities used to determine the pumping redistribution in Q2 (see above). Relative to Q2, an additional set of more sophisticated rules was adopted to minimise the impact of drought on the lens (i.e., in the form of trigger-level management). A period during which $R_{12} < 25\%$ is called a warning period under this regime. The rules tested were formulated as follows:

1. If $R_{12} < 25\%$ and the EC at the trunk main exceeds 1 mS/cm at any stage in a 3-month period, the abstraction rates of galleries with EC > 1 mS/cm are reduced by a predetermined level at the end of that 3-month time-step (Table 1). Galleries with EC > 2.5 mS/cm are switched off. The reduction becomes effective during the subsequent 3-month period.
2. If $R_{12} \geq 25\%$ and the EC at the trunk main exceeds 1.2 mS/cm at any stage during a 3-month period, the abstraction rates of galleries with EC > 1 mS/cm are subsequently reduced for three months as indicated in Table 1, and galleries with EC > 2.5 mS/cm are switched off.
3. While the conditions under 1 or 2 are in effect, a gallery can only be restored to its full pumping capacity if the EC of the water it abstracts falls below 0.9 mS/cm at the end of each 3-month period. Once these conditions are no longer in effect, the relevant galleries are restored to their full capacity.

For abstraction regime Q3 (i.e., “responsive abstraction”), the 30-year future simulation period was subdivided into 120 sequential model runs of 3-months duration. The first 3-month period, starting on 1 July 2014, used the calculated heads and concentrations of the calibrated model as starting conditions. A central control program, written in the Python programming language, runs the SEAWAT model and reads in the concentrations at the end of each 3-month period using the FloPy library (Bakker et al., 2016). It implements the above management rules to decide for which galleries the abstraction rate will be reduced during the subsequent 3-month run. The main program sequence is

Table 1
Reduction in abstraction from individual galleries based on their sensitivity, as part of the responsive management rules simulated in abstraction regime Q3.

Sensitivity	EC change at the trunk main (mS/cm)[a]	Galleries	Reduction in Q3 abstraction (m^3/d)
High	> 0.4	4, 7, 8, 9, 10, 11 and 19	50
Medium	0.1–0.4	3, 5, 6, 12, 14 and 15	30
Low	< 0.1	1, 2, 13, 16, 17, 20, 21 and 22	20

[a] Average change in EC over the years 2029 – 2031 in response to a pumping increase of 80 m^3/day for simulation S1Q1.

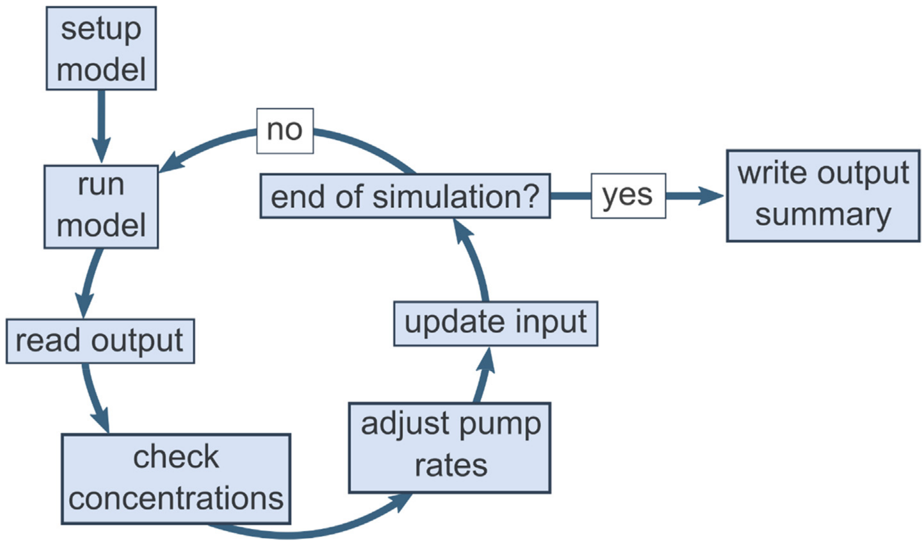

Fig. 4. Schematic diagram showing the main program flow used in the script-based approach to evaluate management scenarios. In this study, the loop depicted by the circle was executed 120 times and each model run lasted 3 months, bringing the total simulation period to 30 years.

displayed graphically in Fig. 4. The heads and the concentrations at the end of a 3-month model run are used as initial conditions for the subsequent model run. The program also calculates the freshwater lens volume (V_f) and other water balance components at the end of each model run, and the numbers for the entire 30-year period are recorded in spreadsheet files for post-processing. This on-the-fly processing of model outcomes (requiring minimal extra computation time) has the additional advantage that the size of the output files remains small, as the results of 3-month simulations keep getting overwritten.

Model simulations are denoted by a label that is composed of the rainfall scenario and abstraction regime. For example, model simulation S2Q3 is for the responsive abstraction regime (Q3) applied to rainfall scenario S2. The third abstraction regime was not implemented for rainfall scenario S1, but otherwise all combinations of rainfall scenario and abstraction regime were considered, resulting in eight simulations (Table 2). A no-abstraction regime (Q0) was also run with each rainfall scenario, bringing the total number of simulations to eleven.

3.4. Model output

The effectiveness of management scenarios was evaluated from model outputs of: (1) the freshwater lens volume (V_f), (2) pumped water volumes (Q_A), and (3) the salinity of pumped groundwater. Modelled concentrations were used to determine V_f, which was calculated by summing saturated volumes in cells containing groundwater with EC < 2.5 mS/cm, at the end of each stress period. The effect of pumping on the size of the freshwater lens was assessed in terms of the difference between modelled freshwater volumes without abstraction ($V_{f,na}$) and with abstraction ($V_{f,a}$), as $\Delta V_f = V_{f,na}$ - $V_{f,a}$. The total abstracted volume of groundwater ($V_{abs,tot}$) was defined as:

Table 2
Model simulation names.

Abstraction regime	Rainfall scenario		
	S1	S2	S3
Q0 (no abstraction)	S1Q0	S2Q0	S3Q0
Q1 (original)	S1Q1	S2Q1	S3Q1
Q2 (redistributed)	S1Q2	S2Q2	S3Q2
Q3 (responsive)		S2Q3	S3Q3

$$V_{abs,tot} = \sum_{1}^{N} Q_{A,i} \Delta t_i \quad (1)$$

where $Q_{A,i}$ is the volumetric abstraction rate for month i (m^3/d), and Δt_i is the length of month i in days ($28 \le \Delta t_i \le 31$). The total number of months since the start of pumping on 1 January 1987 was $N = 696$.

The model results were compared to R_{12} (see Fig. 2), which is a drought index used in Kiribati's water management and drought response plans (e.g., White et al., 2008). R_{12} represents the rank of the 12-month rainfall total relative to other 12-month sums (for the same month) for the rainfall scenario being evaluated. That is, an R_{12} value of 100% means that the current month and previous 11 months were wetter than any other 12-month period with the same start and end months.

4. Results

4.1. Effect of rainfall scenarios

Fig. 5 shows the development of the abstracted water EC at the trunk main for rainfall scenarios S1, S2 and S3 (July 2014 to December 2044), and for the three abstraction scenarios Q1, Q2 and Q3. The difference in the calculated EC between the rainfall scenarios demonstrates how sensitive the lens condition is to changes in recharge. This is borne out especially by the difference between rainfall scenarios S1 and S2, which are identical except for the year 2027, which was much dryer in scenario S2 than in scenario S1. The effect on the salinity of the abstracted groundwater is substantial: while the EC only just exceeded the critical limit of 1.5 mS/cm for two brief periods of a few months in simulation S1Q1, the 1.5 mS/cm limit was well exceeded for a period of about 3 years in simulation S2Q1. Even more remarkably, the exceedance of the 1.5 mS/cm EC limit in 2043 and 2044 in S2Q1, but not in S1Q1, is the result solely of the year 2027 being drier in rainfall scenario S2 than in S1.

During and after the first 3-year drought (2018 – 2020), the trunk main EC in simulation S3Q1 reaches levels of over 2 mS/cm for several consecutive months. Bearing in mind that the 2035 – 2044 sequence is the same as the 2006 – 2015 in scenario S3, it is interesting to note that the same 3-year drought (now spanning the years 2037 – 2039) provokes a much stronger salinity response (Fig. 5c). EC values reach over 4 mS/cm and the 1.5 mS/cm threshold is exceeded for a continuous period of about 4 years, and even persists during the first months of the following above-average rainfall period.

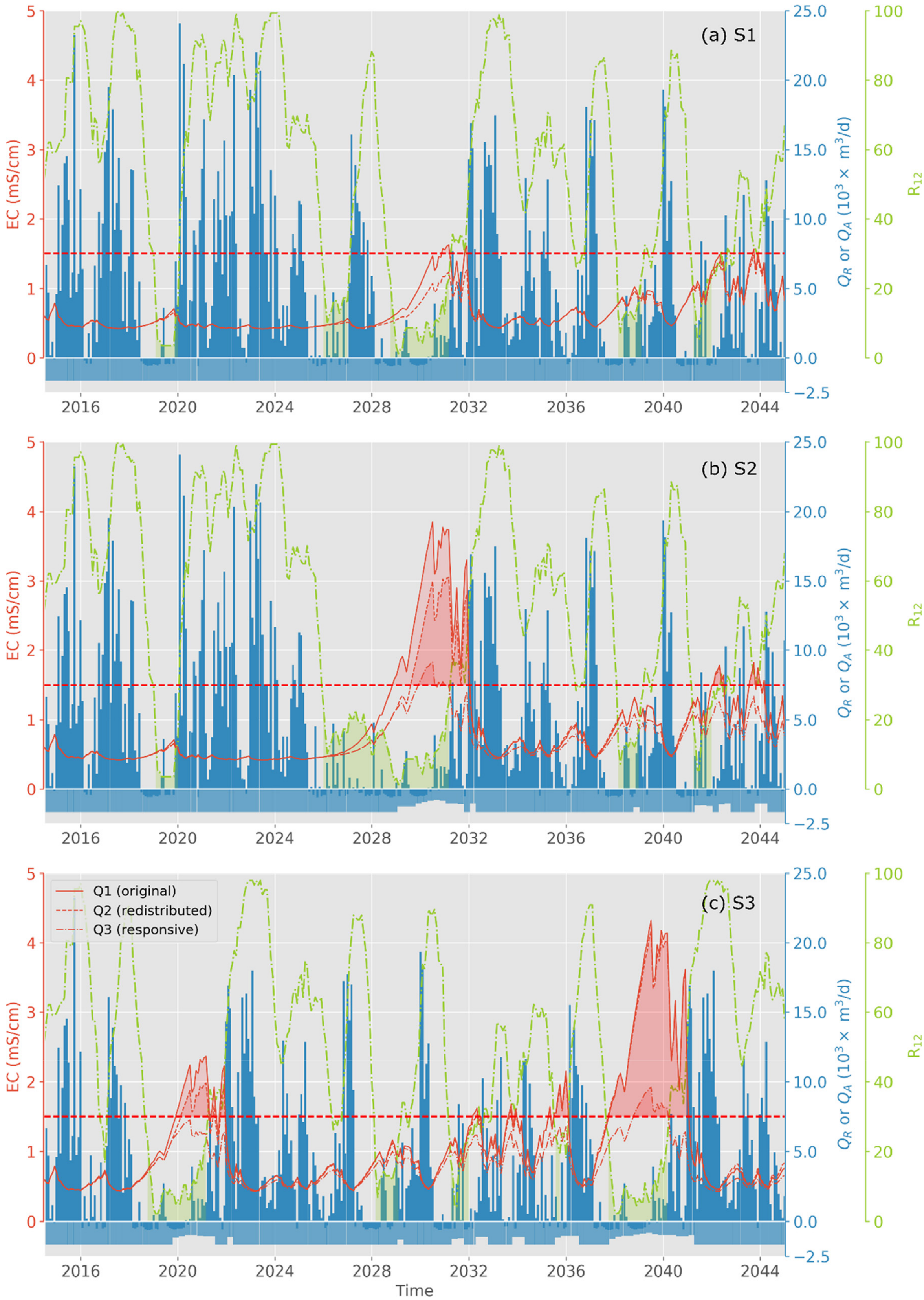

Fig. 5. Results of model simulations for rainfall scenarios: (a) S1, (b) S2, and (c) S3. The EC is shown in red, whereby solid lines, dotted lines and dashed lines are for, respectively, the abstraction regimes of pumping at the original design yield (Q1), pumping redistribution (Q2), and pumping restrictions based on aquifer response and occurrences of drought (Q3). Red shaded areas show regions of EC variation between abstraction scenarios when EC $>$ 1.5 mS/cm. The green line shows the R_{12} trend for the rainfall time series and green shaded areas indicate warning periods (i.e., $R_{12} < 25\%$). Light blue bars show pumping for pumping regime Q3 (negative values) and dark blue bars shown recharge rates (i.e., Q_R). The EC limit of 1.5 mS/cm is indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

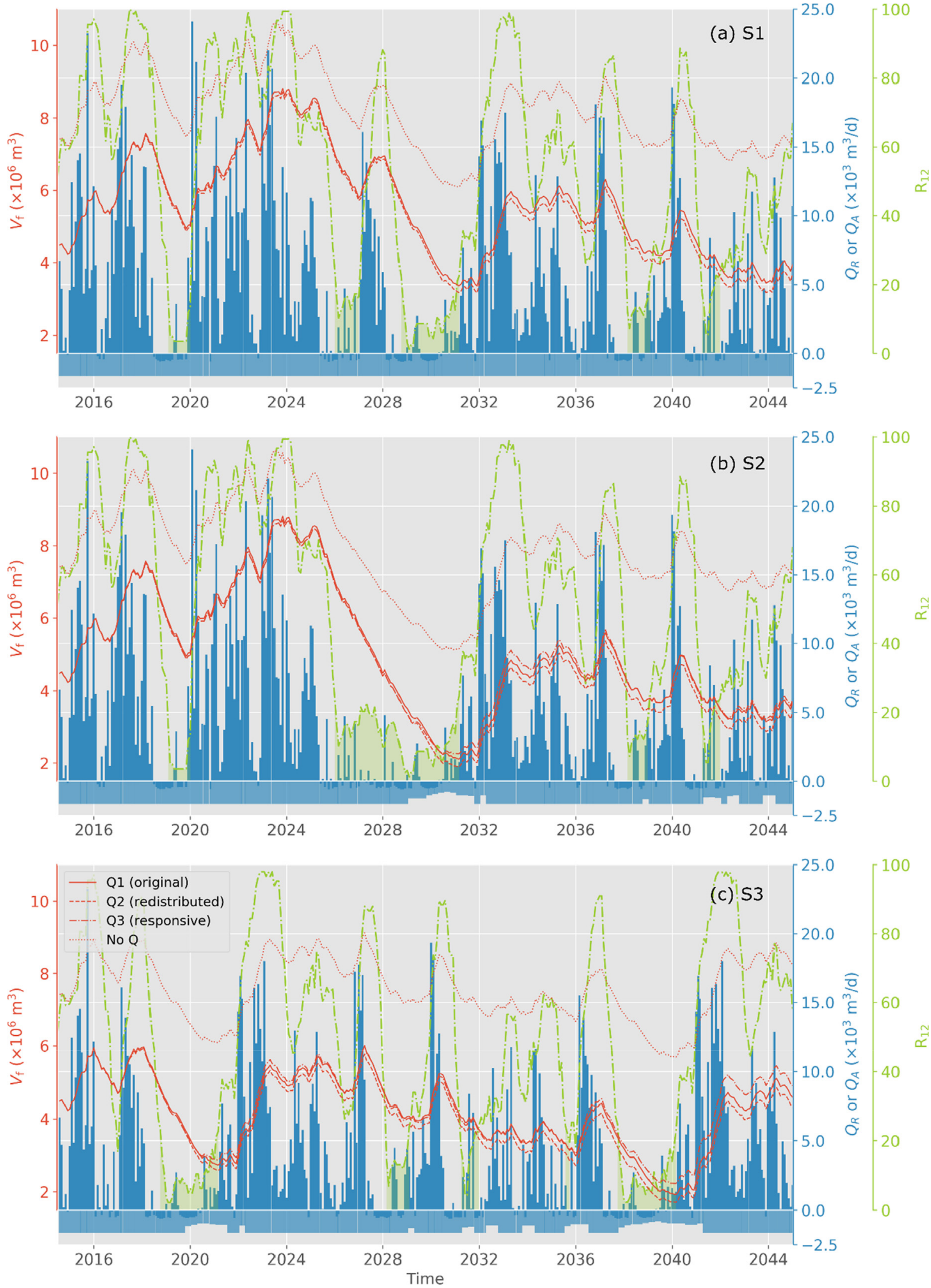

Fig. 6. Results of model simulations for rainfall scenarios: (a) S1, (b) S2, (c) S3. The lens volume (V_f) is shown in red, whereby solid lines, dotted lines and dashed lines are for, respectively, the abstraction regimes of pumping at the original design yield (Q1), pumping redistribution (Q2), and pumping restrictions based on aquifer response and occurrences of drought (Q3). The green line shows the R_{12} trend for the rainfall time series and green shaded areas indicate warning periods (i.e., $R_{12} < 25\%$). Light blue bars show pumping for pumping regime Q3 (negative values) and dark blue bars shown recharge rates (i.e., Q_R). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This behaviour can be better understood by observing the temporal variability of V_f, which is shown in Fig. 6. The main difference between rainfall scenarios S1 and S2 is that in scenario S1, the persistent decrease in V_f during the years 2025 – 2031 of scenario S2 is interrupted by a circa one-year period of recovery in 2027. This means that in simulation S1Q1, V_f only drops below a value of $4 \times 10^6\,m^3$ during the years 2030 and 2031, which is when the salinities are at their highest. In simulation S2Q1 on the other hand, V_f falls to values of just over $2 \times 10^6\,m^3$ during those same years, which indicates that the lens is in a poorer condition overall and explains why the salinities rise much higher and for a much longer period of time. The same reasoning applies to explain the difference in the response to the 3-year droughts in rainfall scenario S3. While the lens is in a relatively poor state during the 2018 – 2020 drought, its condition is worse during the drought of 2037 – 2039. This is reflected in simulation S3Q1 by much higher salinities of the abstracted water during the latter compared to the former (Fig. 5c).

Post et al. (2018) noted that the historical pumping regime of the Bonriki lens caused ΔV_f (i.e., the "lens storage deficit") to increase virtually unabated as a function of V_{tot}, indicating that the stressed system had not yet reached a new (dynamic) steady state. The assumed future rainfall scenarios in the current study allow for an extended period of analysis of EC and V_{tot} trends relative to that of Post et al. (2018), as shown in Fig. 7. The lens storage deficit appears to level off in all rainfall scenarios, at least temporarily, in 2015, soon after the 1948 – June 2014 period considered by Post et al. (2018). In rainfall scenarios S1 and S2, there is even a reversal of the trend, which indicates a phase of lens recovery that persists, with a brief interruption during the years 2018 – 2021, until the 2025 drought sets in. The wetter year of 2027 in rainfall scenario S1 leads to a brief pause of the increase ΔV_f, while ΔV_f continues to increase unabated at a rate of approximately $0.3 \times 10^6\,m^3/yr$ in scenario S2. In rainfall scenario S3, there are no prolonged periods of high enough rainfall for the lens to recover, except for the periods 2023 – 2028 and 2043 – 2044, when a slight decrease of ΔV_f can be observed for simulations S3Q1 and S3Q2 (Fig. 7).

The total recharge over the simulation period is larger in rainfall scenarios S1 and S2 than in scenario S3 (by $8.76 \times 10^6\ m^3$ and $5.67 \times 10^6\ m^3$, respectively), and as a result, V_f is lower on average in scenario S3 than in the other two rainfall scenarios (Fig. 6). Moreover, the variability of ΔV_f is smaller in rainfall scenario S3 than in S1 or S2 (Fig. 7). By the end of the simulation period (December 2044), the lens is in a better state in terms of V_f for simulation S3Q1 ($V_f = 4.59 \times 10^6\,m^3$), than for S1Q1 ($V_f = 3.94 \times 10^6\ m^3$) or S2Q1 ($V_f = 3.67 \times 10^6\,m^3$). The simulated EC values of simulation S3Q1 are also favourable compared to those from S1Q1 and S2Q1 during the last two, high-rainfall years of the simulation, even though EC values reached the highest levels of all simulations in S3Q1 during the 2037 – 2039 drought.

4.2. Effect of abstraction regimes

A positive effect on the salinities is achieved by the redistribution of the abstraction (abstraction regime Q2) between the individual galleries in all three rainfall scenarios (Fig. 5). However, contrary to the reasoning applied above to explain the differences in the EC response to droughts, the lower EC values of the abstracted water at the trunk main is accompanied by a lower V_f for abstraction regime Q2 compared to Q1 (Fig. 6). These results show that the same total abstraction rate, distributed differently across the island's wells, can modify the groundwater flow regime so that the lens shrinks in size, but at the same time, the water supply system becomes more resilient to droughts in terms of the abstraction water salinity. In other words, lower salinity groundwater can be pumped from a smaller lens with alternative pumping strategies.

Abstraction regime Q3 (responsive management) has a positive effect on the EC of the salinity of the distributed water, albeit at the expense of reduced water availability for the residents of South Tarawa. For simulation S2Q3, the EC remains markedly lower than in simulations S2Q1 or S2Q2 during the 2025 – 2030 drought, although, there is still an exceedance of the 1.5 mS/cm threshold from January 2029 to December 2030. With the defined management rules, the model reduces abstraction between January 2029 and April 2032. The maximum decrease of the total abstraction rate is $877\,m^3/day$ (i.e., 53% of $1660\,m^3/day$) during the period July to December 2030. It can also be seen from Fig. 5b that there are four one- to three-month intervals between 2038 and 2044 when abstraction is not at its full capacity, which is because the salinity of individual galleries is above the EC threshold. In the latter two of these four cases, this occurred outside a warning period.

For simulation S3Q3, the management rules result in prolonged reduction of abstraction during the years 2019 to 2021 (by up to $680\,m^3/day$) and 2037 to 2040 (by up to $802\,m^3/day$), see Fig. 5c. These significant reductions are effective in keeping the EC below 1.5 mS/cm during the first drought but fail to accomplish this target during the second drought. There are six periods of reduced abstraction (ranging in length from 3 to 6 months) during the years 2029 to 2036, which do not all coincide with R_{12} warning periods.

As expected, the reduction of the freshwater volume during a drought is not as severe when abstraction is reduced (simulations S2Q3 and S3Q3) compared to the scenario in which the galleries are redistributed (simulations S2Q2 and S3Q2). Since the duration of the reduced-abstraction periods is short though, the magnitude of the difference is small relative to the total reduction of V_f brought about by pumping (Fig. 6). In simulation S3Q3 (contrary to S3Q1 or S3Q2), there is a prolonged decrease of ΔV_f during the last 8 years of the simulation period, which already sets in during the 2037 – 2039 drought. It thus seems that a reduction of the abstraction rates during droughts is effective in preventing further harm to or even restoring the health of the lens.

5. Discussion

The investigation of coastal groundwater management, including the dynamic pumping-response methodology applied in this study, is an improvement on previous island modelling investigations in which the pumping rates of management scenarios are pre-set (e.g., Alam et al., 2002). Management scenarios are tested that follow the recommendation of Werner et al. (2011) to combine elements in flux-based (i.e., rainfall- or recharge-based) and trigger-level (i.e., head and/or salinities) management. Specifically, a rainfall-based index (R_{12}) and salinity thresholds were used as indicators for hydrological drought and freshwater lens stress, respectively, in abstraction regime Q3. These were used in combination to initiate management responses in the form of reduced abstraction. The current study adds to Werner et al.'s (2011) evaluation of coastal groundwater management by adopting a more sophisticated modelling platform, rather than the simple quasi-steady-state, sharp-interface evaluation of their case study. Furthermore, we report on a novel approach to redistributing the pumping rates to coastal aquifers, using sensitivity analysis of the pumped water salinity versus pumping rate changes. Comparisons between the responsive pumping regime (Q3), redistribution regime (Q2) and original design yield regime (Q1) reveal important insights regarding management of the Bonriki lens, as discussed below. The results of the current research has already been taken into account by the Government of Kiribati, who have updated their operational rules in their drought response policies, aimed at maximising the availability of water without causing detrimental salinization of the freshwater lens during periods of reduced recharge.

The script-based numerical model developed for responsive pumping scenarios requires the modeller to specify only the pre-defined rules for the management scenario, and all the pre-and post-processing

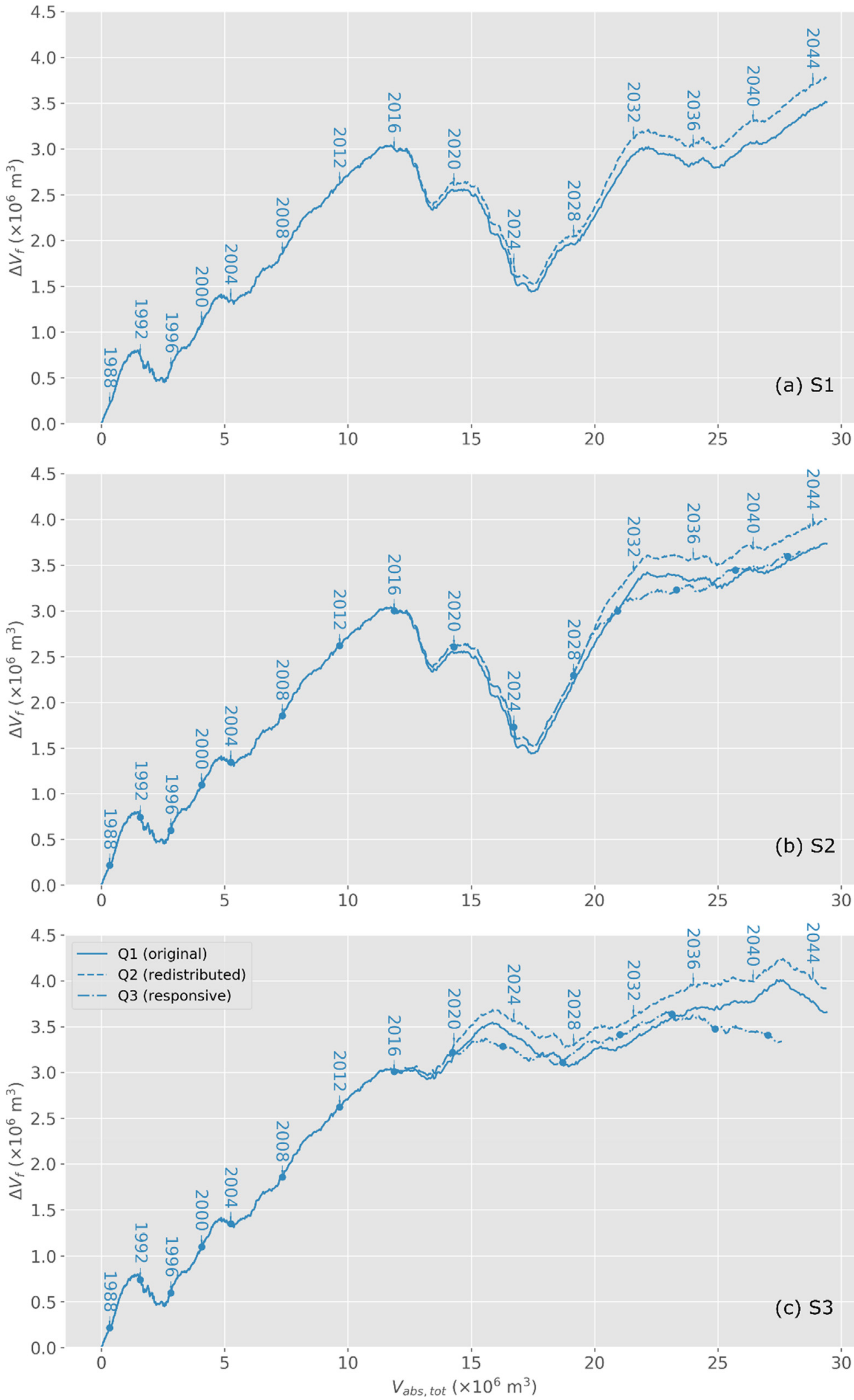

Fig. 7. Graph showing the pumping-induced depletion of the lens (ΔV_f) plotted versus the total volume of pumped groundwater ($V_{abs,tot}$) for rainfall scenarios: (a) S1, (b) S2, and (c) S3. The last 27 years of the calibration period (1987–2014) is also shown. The blue arrows mark the start of years for pumping regimes Q1 and Q2, with arrows placed every four years. For pumping regime Q3 in (b) and (c), the arrows have been replaced by circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of model files is fully automated. This enables rapid evaluation of different management responses, or variations of a response, and avoids the need for tedious preparation of input and analysis of output files. In the context of Williams' (2011) definition of adaptive management, this is effectively a single cycle in what would otherwise be, under an adaptive management philosophy, itself a repeated cycle of re-setting the management rules themselves. For example, the use of R_{12} to designate drought periods could be adapted or the salinity thresholds for management actions might be redesigned after a period of testing of the management rules. These types of scenarios are plausible adaptations to the current approach, albeit, stakeholder consultation would be integral to management protocol redesign, and the outcomes of consultation processes are practically impossible to predict and thereby challenging to implement into responsive groundwater modelling scenarios.

Post et al. (2018) concluded that lens shrinkage is likely to continue to occur under the pumping rates of recent years. The modelling results support that finding by revealing that for all three rainfall scenarios and for the three abstraction regimes, it holds that while wet phases bring some relief, the overall decadal trend of ΔV_f is to increase, i.e., lens shrinkage caused by abstraction is set to progress with time. This means that the freshwater buffer zone below the abstraction galleries is expected to continue to thin, increasing the sensitivity of the abstracted water salinity to droughts. There are notable differences between the abstraction regimes (i.e., original, redistributed and responsive) in terms of the absolute value of ΔV_f, but the rising trend is obtained in all three regimes.

The difference in the simulated abstraction water salinities between rainfall scenarios S1 and S2 (for abstraction regime Q1) testify to the long-lasting consequences of a single year with lower recharge: The lower recharge in 2027 in scenario S2 compared to S1 leads to higher modelled EC values 15 years later. The brief recovery of the lens as indicated by the increase of V_f in scenario S1 in 2027 (Fig. 6a) provides just enough buffer to maintain abstraction water salinities below the threshold during the years that follow. On the other hand, the continual depletion of the lens in scenario S2 during the years 2025 – 2031 (V_f in Fig. 6b) destroys the lens' buffer capacity, which can only be restored when abstraction is severely reduced, or during periods of extraordinarily high recharge. The latter effect is exemplified by the strong recovery of EC values and V_f from their extreme values in simulation S3Q1 during the period from 2040 when above-average R_{12} values are sustained for multiple years in a row. Hence, whilst R_{12} is a predictor of short-term (on the order of one year) salinity trends, monitoring of the trends of V_f (and ΔV_f), based on model simulations that assimilate the latest observed rainfall and salinity data, may support management in that it can provide an indicator of the long-term (on the order of a decade) future salinity trends (under a constant abstraction regime).

The differences between abstraction regimes Q1 and Q2 indicate that if higher salinities are accepted from the abstracted water, the lens volume is likely to be higher, because in effect some proportion of the water supplied through the trunk main is in fact brackish or seawater. Conversely, the fresher the trunk main water, the larger the relative draw of the lens storage, notwithstanding the impact on discharge to the sea of alternative pumping regimes. This suggests that pumping lower quality water leaves a greater provision for future extraction, through larger lens storage. Thus, island lens management could consider providing the highest tolerable salinity of groundwater rather than the freshest water possible. Identification of highest tolerable salinity of groundwater would need to be agreed through community and stakeholder consultation to ensure that the salinity of supplied water is acceptable for its intended purpose, and considering other social, economic, health and environmental factors. The objective of seeking to pump the highest "tolerable" salinity groundwater presents as a paradoxical management ideology, relative to traditional approaches of seeking to extract the lowest salinity groundwater. Further exploration is warranted to examine the practicalities and true benefits of this management philosophy.

Declines in freshwater storage under dynamic conditions are rarely analysed in atoll environments and other freshwater lens settings, with often steady-state conditions, constant recharge or constant pumping assessed. Our modelling results reinforce the importance of using transient recharge for freshwater lens analysis (Griggs and Peterson,1993; Ghassemi et al., 1999), because the Bonriki lens condition appears to be highly dynamic, and only by capturing the transient behaviour of V_f can lens recovery during high rainfall periods and its decline under drought be properly interpreted. This is critical for the assessment of responsive management. Groundwater abstraction systems in atoll environments are typically developed as 'pump-and-forget' management strategies. These approaches focus on maintaining abstraction at a constant rate over time to maintain water supply, but tend to overlook the capacity of water managers to modify their operation of the system in response to its condition dynamics (e.g., Sinclair et al., 2014). The long-term implications of this approach is that frequently the freshwater quality decreases, limiting the use of groundwater to washing, bathing or toilet flushing applications, and alternate (and often less reliable) water sources such as household rainwater harvesting are needed to meet potable water needs.

In this study, we advocate for and test an active management regime that embraces the dynamic nature of the groundwater system. Different levels of salinity and the corresponding available volumes of water that a community may be prepared to accept under different climate and water security situations can be evaluated, with a particular focus on the conditions experienced under drought conditions. Communities and groundwater custodians may be willing to accept higher salinity levels during drought periods in order to maintain a particular level of supply. The current methodology allows for assessment of these sorts of trade-offs, including under various plausible future climate regimes. The conditions that signify a return to pre-drought salinity conditions, following higher rainfall rates that allow for recovery of the lens, can also be tested. These will be significant additional factors for groundwater stakeholders, and are also plausibly assessable using the current methodology.

The social and economic costs of maintaining an acceptable salinity or 'freshness' of the supplied water, compared with the costs of providing an alternate water source (e.g. desalination), are an important consideration. The reduction of abstraction during droughts to safeguard acceptable salinity levels creates a mismatch in the supply and demand of freshwater, because demand is highest, and other sources of freshwater (i.e., from rainwater tanks) are lowest, during drought periods. In these cases, the community may be willing to accept higher levels of salinity in the reticulated water for a period rather than incur the cost of desalinated water to meet the freshwater demand. In addition to the supply management that we have assessed, demand management can assist in abating the degradation of fresh groundwater resources during periods of lower recharge. For example, pre-drought periods, declared based on R_{12} (e.g., $25\% < R_{12} < 40\%$), can be used to alert the community and bring water restrictions into effect. Additionally, access to potable water could be limited to strategically located and controlled standpipes. This regulated-access approach would not only lower demand by requiring householders to retrieve low salinity potable water from discrete locations, but would also reduce potential losses from leaking household distribution systems and encourage the use of water supply from domestic wells for non-potable needs, such as washing and toilet flushing. Various other forms of demand management are possible, and are essential elements in determining development and management strategies for the groundwater system.

This study did not consider the option of abstraction reduction during periods of ample rainfall. It is conceivable though that a significant part of the demand can then be met by rainwater harvesting, allowing temporary relief of the pressure on the lens. Reducing the abstraction when recharge is high might be an effective way to promote the recovery of the freshwater volume (i.e., a reduction of ΔV_f) as a larger fraction of the recharge remains available to add to the storage. Without numbers on the rainwater storage capacity, this option could not be considered in our numerical simulations. Yet this might constitute another form of dynamic abstraction management, aimed at preserving as much of the freshwater volume as possible.

6. Conclusions

This study provides a rare example of physically based, density-dependent simulation to examine possible future behaviour of an atoll island lens (Bonriki Island, Kiribati) subjected to high levels of abstraction. In addition to traditional fixed-pumping scenarios, this study investigated the applicability of responsive management, whereby pumping was adjusted according to aquifer conditions, which were assessed from system variables that are historically monitored on Bonriki Island.

The salinity of the abstracted water was found to depend strongly on the assumed temporal distribution of groundwater recharge, with relatively small differences between rainfall scenarios yielding large differences in salinity. It was found that antecedent differences in recharge as far back as 15 years can lead to important differences in salinity of the pumped water during a drought. Because projected future rainfall, and especially its temporal distribution, is inherently uncertain, this high sensitivity of the model outcomes forms a severe impediment to assessing the future development of the water resource and the sustainability of abstraction regimes. Therefore, rather than forecasting future water availability using a deterministic approach, modelling efforts are best aimed at developing management responses to events that are likely to occur under future conditions. This has important ramifications for the interpretation of sustainable yield of freshwater lenses and water supply systems more generally. The traditional construct of sustainable yield refers to the maximum amount of water that can be taken from the system without causing adverse effects, which in the context of island water supply translates to an abstraction rate that is invariably related to the amount of rainfall recharge. We propose a more dynamic interpretation, in which the abstraction amount is time-variant and depends on drought conditions and the maximum salinity a community is willing to accept. Perhaps a temporary degradation of the resource can be accepted in order to meet the water needs during a drought, as long as the recovery during the subsequent wet phases is sufficient to ensure the long-term sustainability of the water supply. Assessing the lens' ability to supply water under likely scenarios of reduced rainfall conditions allows estimating the required capacity and costs of alternative water supply options, which can be presented to the community to support the decision-making process. The proposed responsive management, and the indicators used here, can strengthen Tarawa's adaptive water management process, and should be evaluated and potentially modified after a period of testing. This facilitates the development of optimal solutions that ensure the sustainability of the lens and that provide maximum benefit to stakeholders and the community. The departure from a sustainable yield concept that is static (i.e., fixed pumping rates) in lieu of one that is more dynamic (based on rainfall history and salinity thresholds) entails both opportunities and risks. Future research could be aimed at mapping these, not just for atoll islands but for water supply systems under pressure more generally.

The methodology to evaluate various responsive management simulations adds to the existing suite of groundwater modelling tools by exploiting the flexibility of script-based numerical modelling. By breaking up the simulation into a series of short-duration intervals (120 intervals of 3 months duration in our case), the model output after one interval can be used to decide how the model input variables must be changed for the next interval. While we used the Python-based FloPy library (Bakker et al., 2016) in this study, any programming language could be used for this purpose. Also, the approach is easily transferrable to other applications, such as the simulation of artificial storage and recovery schemes where injection and abstraction cycles are dependent on the hydraulic head or a chemical concentration threshold level.

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