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Climatic variation, recharge and freshwater lens salinity of a coral atoll in the Pacific Ocean

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Abstract The El Niño-Southern Oscillation (ENSO) exerts a moderate control on the temporal fluctuations of the salinity of water pumped from the subterranean water resources of the raised coral atoll of Tongatapu (175°12′W, 21°08′S; Kingdom of Tonga). The lens reacts buoyantly to recharge events and the saltwater transition zone moves vertically with the buoyant response. Here we show, using data obtained at the main well field of Tongatapu, some preliminary observations that can be made on the combination of the travel time of water infiltrating through the vadose zone, coupled with the hydraulic buoyant response time of the lens in the aquifer, and the errors associated with the identification of the transfer function parameters identified with a simple inverse procedure from well salinity data.

Key words El Niño-Southern Oscillation; coral atoll; prediction; salinity; freshwater lens; salt water intrusion; Tonga; wells; pumping; climate change

INTRODUCTION

Coastal aquifers around the world suffer from salt water intrusion caused by natural as well as human-induced processes (Oude Essink, 2001). Human activities that threaten coastal lowlands include mining for natural resources (water, sand, oil and gas) and land reclamation that leads to subsequent subsidence. Coastal aquifers are affected by mean sea level (MSL). The Intergovernmental Panel on Climate Change (IPCC) estimates a global averaged sea-level rise of about 0.6 m in its present estimate for the coming century under the "Year 2000 constant concentrations" scenario, with a likely range of 0.3–0.9 m (IPCC, 2007). However, other scenarios predict increases that range from 1.1 to 6.4 m. It is thus expected that the salinization of coastal aquifers will accelerate. Consequently, the availability of fresh groundwater resources in coastal areas will decrease, putting serious constraints on present populations and future coastal development.

Seawater intrusion is reported for areas all around the world, including for example, Mexico (Halvorson *et al.*, 2003), Greece (Lambrakis & Kallergis, 2001), and Cypress (Ergil, 2000). Salt water intrusion is also a severe problem in several islands located in the Pacific region. Salt water intrusion has been reported for Kiribati, Kingdom of Tonga, Salomon Islands, Fiji, Hawaii, amongst others (see SOPAC website: http://www.sopac.org). One of the main reasons for salt water intrusion, or local upconing, is (over)pumping at well sites.

Logically, integrated coastal management plans are essential for small islands and they need to explicitly recognize the important links between geological setting, oceanographic conditions, reef health and the coastal zone (Solomon & Forbes, 1999). Solomon & Forbes (1999) further note that, although oceanographic hazards are often associated with catastrophic events, such as tsunamis and cyclones, they are also caused by processes that operate more slowly and over longer time scales, such as geological subsidence or uplift and regional and global sea-level changes with superimposed tides.

Although minimally responsible, small islands will be among the first to be struck by the effects of climate change and increased climatic variability. In particular, the availability of freshwater resources of low-lying atolls is vulnerable to climate change (Meehl, 1996). It is predicted that an increase in the frequency of El Niño events will occur in a warming global climate (Timmermann *et al.*, 1999; Tsonis *et al.*, 2005), although predictions remain uncertain (Cane, 2005). This may then lead to an increase in the occurrence of dry spells (Meehl, 1998).

Recently, the seasonality in the motion of the freshwater–saltwater interface has been shown to potentially have an important impact on the chemical loading of coastal waters (Michael *et al.*, 2005). In the South Pacific, rainfall exhibits seasonal as well as interannual variability related to the El Niño-Southern Oscillation (ENSO), with a consequent impact on the subterranean water resources (van der Velde *et al.*, 2006). It may be expected that interannual variability will have a comparable effect to that of seasonality on the temporal chemical loading of nearby coastal regions in areas affected by ENSO. For further understanding of small islands' marine ecosystems, and optimal water resources utilization on small islands, it is essential that a thorough understanding of the influence of climate variability on the interaction and water exchange between groundwater, surface water, lagoon, and seawater is obtained.

We studied the subterranean water resources of the raised coral atoll of Tongatapu (175°12′W; 21°08′S; Kingdom of Tonga). We will show some data on the freshwater lenses occurring in the atoll to deduce some preliminary observations that can be made on the combination of the travel time of water infiltrating through the vadose zone, coupled with the hydraulic buoyant response time of the lens in the aquifer, and the errors associated with the identification of the transfer function parameters identified with a simple inverse procedure from well salinity data.

METHODS

The water table of Tongatapu's freshwater lens is extremely flat. It is influenced by tides, sea-level change, barometric pressure, recharge, pumping and drought. Seawater level is mainly influenced by tidal processes, but is also affected by wind that causes build up of water masses of about 0.2–0.3 m at one side of the island and in the lagoon (Falkland, 1992). Furness & Gingerich (1993) showed that the water level of a well in Tonga showed a semi-diurnal response to the tidal constituents. Furness & Helu (1993) found that the barometric effect is of larger magnitude than the tidal pattern. Hunt (1979) presented 39 measurements of water table height in wells equally distributed over the island. Average water level above MSL was 0.32 ± 0.11 cm, or about 50% of the steady-state level presented by Pfeifer & Stach (1972).

In Tongatapu, the permeable limestone aquifer is overlain by a clay soil derived from volcanic ash with a variable thickness generally declining from 5 m in the west to 0.5 m in the east of the island (Cowie *et al.*, 1991). The filtering of the water that percolates towards the freshwater lenses depends on the hydraulic conductivity and the water holding capacity of the vadose zone. High values for saturated hydraulic conductivity were measured using disc permeates throughout a 1.2 m soil profile (van der Velde *et al.*, 2005).

Freshwater lens geometry is affected by recharge, hydrogeological characteristics of the aquifer and pumping well locations. Results from a sensitivity analysis by Griggs & Peterson (1993), show that the depth of the 50% salinity contour was most sensitive to permeability, and that the transition-zone thickness was most sensitive to dispersivity. The transition-zone thickness increases with increasing dispersivity values, and is most sensitive to changes in the transverse dispersivity. For a given recharge rate, the depth of the 50% salinity contour will decrease with increasing hydraulic conductivity.

Several authors have estimated the recharge towards the freshwater lens on Tongatapu (Pfeifer & Stach, 1972; Lao, 1978; Hunt, 1979 Kafri, 1989; Hasan, 1989; Falkland, 1992). The percentages of recharge these studies have estimated and calculated ranged from 5 to 35% with a generally adapted average estimation of 30%. Furness & Helu (1993) summarized the available recharge estimates (and also reported on the work of Kafri, 1989, and Hasan, 1989). Furness & Gingerich (1993) could not estimate the annual recharge due to a lack of rainfall during the measurement period. However, it was resolved from the residual fluctuation derived from the subtraction of the smoothed well water-level signal with the smoothed tide gauging signal, that an individual recharge event of less than 13 mm may pass undetected using water-level data.

Based on a pump test the saturated hydraulic conductivity (K) of the limestone was calculated by Hunt (1979) to be 1.5 cm s^{-1} (corresponding to 1296 m d^{-1}). This relatively large value of K related to the extremely porous nature of the coral limestone (especially since K was derived for the horizontal flow direction). Furness & Gingerich (1993) reported "from modelling of the aquifer and examination of drill-hole cores and exposures of rock in quarries, caves and cliffs it is apparent that the porosity and specific yield of the aquifer is very high. The latter probably averages as much as 0.4 (40%)". Limestone aggregate samples were obtained by Harrison (1993) to determine aggregate properties in relation to quarrying of the limestone for building and civil engineering purposes. Due to the weakness of the aggregates, and the ease by which they abrade, the limestone aggregates failed to meet specifications for concrete and road stone commonly used. Harrison (1993) further reports that the limestone is highly porous with a low density and that it contained large amounts of absorbed water. The physical quality (with respect to density, porosity, strength and durability) of the aggregates was also reported to be extremely variable. The limestone was found to be very pure, with percentages of $CaCO_3$ over 98.5%.

Wellfield salinity data

The data we present here are valuable, and obtained through the diligent monitoring efforts of the Tongan Water Board (TWB) and the Ministry of Lands, Survey and Natural Resources, from the well field of Mataki'eua. Because of its importance to the water supply for Nuku'alofa, the salinity measurements at the Mataki'eua well field have been carried out (although irregularly) over a long period of time. The data we use here include: (1) salinity measurements from three of 21 monitored and pumped wells; (2) several profiles of salinity through the freshwater lens, as measured at monitoring bores located in, or in the vicinity of, the well field; and (3) some information on the volumes pumped at several wells, as well as some water table heights. We use this information to derive transfer functions through the whole soil-limestone aquifer continuum for the pumped wells.

On the whole island of Tongatapu about 240 wells are in use. The depth has been measured for 90 of these wells and these depths generally increase from northwest to southeast, confirming the general tilt of the island's limestone. The wells on the island include: village wells with one or more wells in each village, which pump to an elevated water tank; and private wells which are mostly hand dug and not equipped with a motorised pump. However, most pumping is done at the main well field of Tongatapu, the Mataki'eua well field (see Fig. 1). The wells in Mataki'Eua well field are spaced approx. 150 m apart. Pumping is done from approx. 1–2 m below the average water level. Pumping data from the well site are scarce. The average pumping rate is about 3 L s^{-1}. Groundwater extraction from the Mataki'eua well field was approximated by Falkland (1992) to be 5.3×10^3 m^3 d^{-1}. Data from the TWB shows that monthly water production was quite stable, apart from a slight increase in 1998. The water production for 1996, 1997 and 1998 equalled 5.8×10^3 m^3 d^{-1}. However, leakage is reported to be high (above 30%) for the Tongan reticulation system. Also, when the water production is compared with the metered water, we find that roughly 50% of the pumped water is unaccounted for (JICA, 1999).

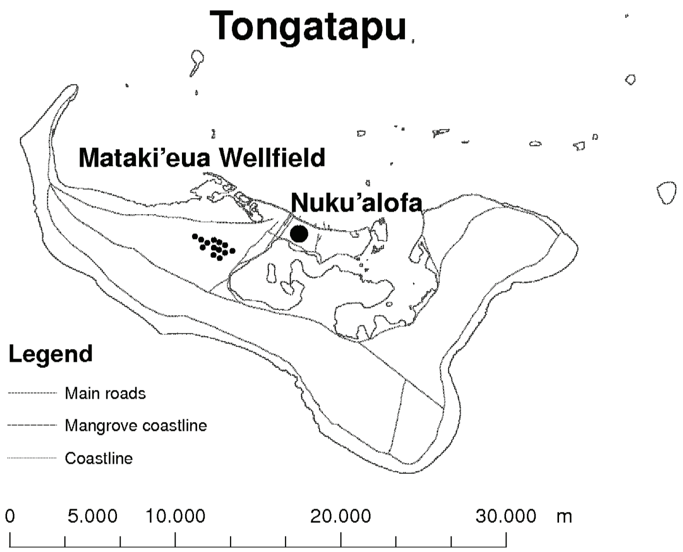

Fig. 1 The location of the Mataki'eua wellfield on Tongatapu.

Furness & Gingerich (1993) reported that the pumping at Mataki'eua has depressed the water table by about 0.25 m in the middle of the well field. According to Furness & Gingerich (1993) the water level in one individual well (105) falls about 0.1 m when the pump is operating. The electric conductivity of the water is inversely proportional to the height of the water table. The relation has a low correlation and conductivity is mostly affected by the time since the last heavy rainfall. In comparison, Furness & Gingerich (1993) noted that "it was surprising to see on Tongatapu falls of 0.3 m in the fresh water level without a drastic change in the conductivity of the water. Generally a rise of about 10% was noted in monitoring. It was concluded from this evidence that the movement of the transition zone from fresh to salty water is damped". We suggest that this delay mainly relates to the difference between vertical hydraulic conductivity and horizontal hydraulic conductivity (the latter being much higher in relation to the horizontal deposition of geologic layers). The relation between water table height and salinity was also investigated by Falkland (1992) with data taken during three days (6 August 1990, 11 January 1991 and 1 March 1991). As expected, increases in water table elevation were accompanied by expected decreases in salinity of the water at the water table. Falkland (1992) also reported on some of the uncertainty associated with the measurements. Most wells at the Mataki'eau well field show a decrease in salinity from 1990 to 1991 related to the high recharge during this period. However, it was reported by Falkland (1992) that "some wells (102, 106, 211 and 212) show an increase in salinity during this period".

Currently, about 30 wells operate at the well field. The salinity is estimated from electric conductivity (EC, $\mu S\ cm^{-1}$) measurements that were carried out sporadically since 1980 and approximately bi-monthly from January 1995 to June 2000. In this study we use measurements made since 1 January 1997 by the TWB. Twenty-one wells were monitored. The depth of the wells is influenced by the occurrence of relict coral patch reefs at the well field. The average salinity of each well shows the occurrence of a salt water wedge extending inland from the lagoon.

Monitoring bores and freshwater lens thickness

For a period of three years from 1997 to 2000 with an approximate 3-monthly time step the freshwater lens underneath the island was monitored for electric conductivity and temperature at different depths. Six points and later one additional point were monitored using 5–7 bore holes (MBs) at different depths to sample a profile of the freshwater lenses (see Fig. 2). One point (MB1) was located close to the lagoon. The other points are all located more inland. A polyethylene sampling tube with foot valve was used to obtain water samples from the monitoring tubes with an internal diameter of 38 mm. When approximately 5 L had been pumped the electric conductivity of the sample was measured, this was replicated three times, after which the temperature of the water was determined. A dipper was used to measure the depth to the water table. The depth to the base of the tube was determined and compared to the original depth measured after installation. The depth to the water level was also measured (Falkland, 1992).

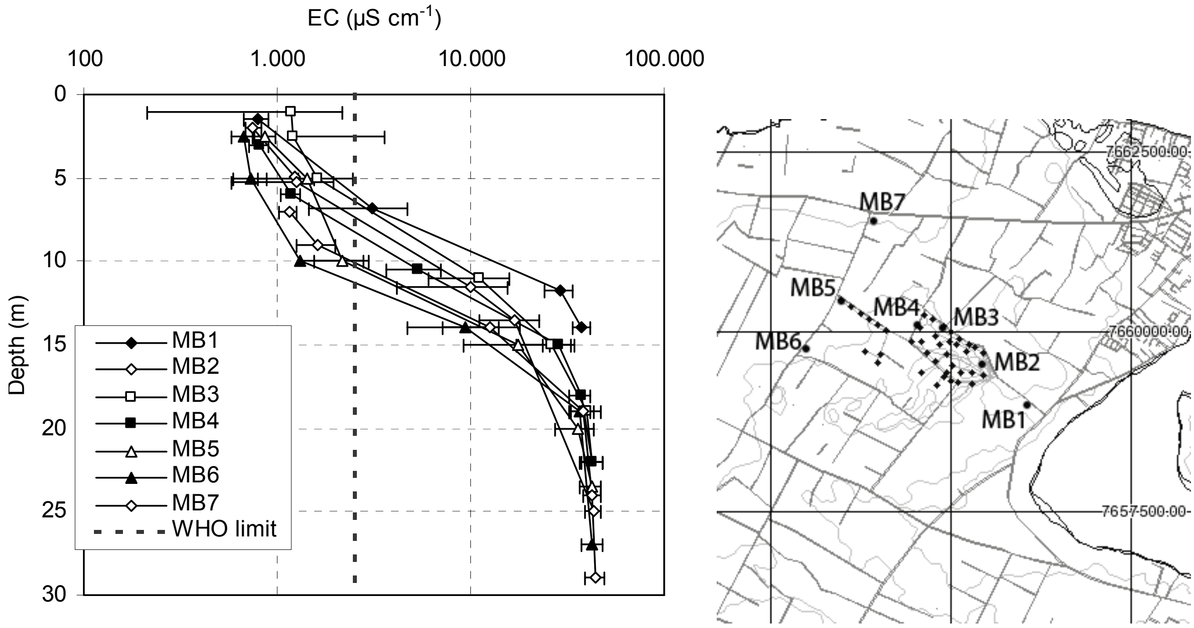

Fig. 2 Profiles of averaged conductivity measurements through the freshwater lens done at the monitoring bores (MB) located near or in the Mataki'eua well field, between May 1997 and July 2000 by the Tongan Waterboard. Error bars indicate standard deviation around the mean for the measurement period. The World Health Organization limit was defined at 2500 µS cm^{-1}. The right panel shows the location of the different MBs around the wellfield (cf. Fig. 1).

Temporal variations in salinity

From the measurements done in the MBs the depth of the freshwater lens can be inferred. The depth of the freshwater lens can be defined as the depth of potable water. defined by the World Health Organization (WHO) at 2000 µS cm^{-1}. From these measurements it can be shown that the thickness of the freshwater lens ranged between 5 and 12 m and that the lens becomes thinner towards the lagoon. The temporal variation in recharge of the lens relates directly to the temporal variations in rainfall. Mixing into the freshwater lens can be derived from the monitoring bores data (not shown). From these data, mixing into the lens can be observed deeper at 5–20 m below the water table, while at a certain depth (between 35–40 m) pure seawater is encountered. The TDS values from wells 102, 105 and 115, obtained by multiplying the EC data by a factor of 0.64, indicate a temporal pattern of the variation of TDS that relates to the amount of preceding rainfall (Fig. 3). It can be expected, however, that besides hydrogeological factors, pumping rates would also influence the fluctuations in salinity, especially if the pumps are not continuously operating.

Transfer functions

The salinity of the lens at a certain time is determined by the total mass of solute and the total mass of water in the pumped freshwater layer. If we consider that there exists an equilibrium state for the water lens corresponding to a continuous balance between averaged freshwater input and output and mean sea level, we then expect that every

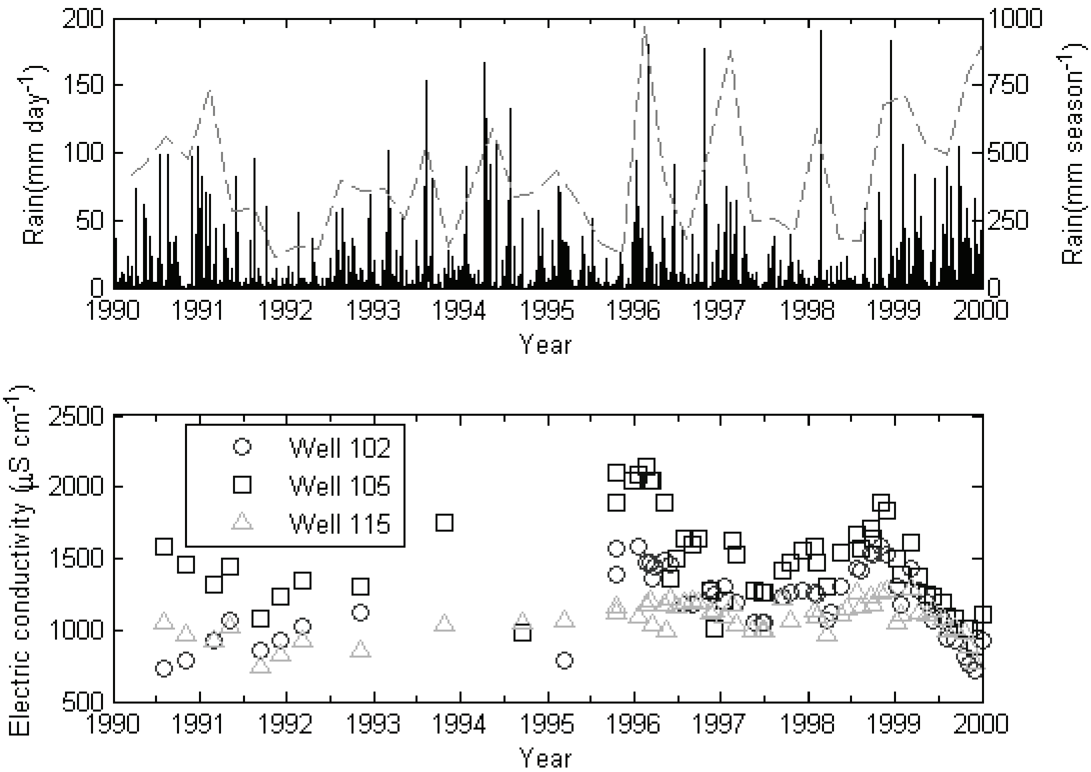

Fig. 3 Daily precipitation and three-monthly precipitation totals and total dissolved solids measured in 3 of 21 monitored wells on Tongatapu.

variation in the freshwater input from this equilibrium state will result in a change in the salt concentration. An increase in the rainfall rate would result in a decrease in salinity. Since the vadose zone between the surface and the aquifer smoothes out the variations of water flux, a transfer-function model can be used to describe the relation between the variation in rainfall and the variations in salinity. Transfer function theory was developed by Jury (1982) to simulate solute transport under natural field conditions where substantial variability exists in water transport properties. Jury's approach (1982) derives a distribution function based on the distribution of travel times of solutes from the soils' surface to a reference depth. Here we use the transfer function model in a slightly different setting then originally proposed. The transfer-function model describes the convolution of the variations in rain with the variations in the reciprocal of total dissolved solids (TDS) with a daily time step, so that

$$\mathrm{TDS}^{-1}(t) - \mu_{\mathrm{TDS}^{-1}} = \alpha \int_{-\infty}^{\infty} f(t) \cdot (P(t-\tau) - \mu_P)\mathrm{d}t + Z(t) \tag{1}$$

The integral in equation (1) expresses the convolution between the variations around the mean rainfall ($P(t) - \mu_P$) and the variations around the mean of the inverse of the total TDS ($\mathrm{TDS}^{-1}(t) - \mu_{\mathrm{TDS}}{}^{-1}$). Here t is time and τ the lag time between rainfall and dilution, α is a scaling factor, $f(t; \mu, \sigma)$ is the transfer function and $Z(t)$ is the residual error.

A lognormal probability density function was chosen for the transfer function $f(t)$ to reflect the transport and mixing of the percolating water as it moves through a porous medium exhibiting a log-normal distribution of pore-water velocities. Hence:

$$f(t) = \frac{1}{\sigma t \sqrt{2\pi}} \exp(\frac{-\ln(t) - \mu)^2}{2\sigma^2}) \tag{2}$$

where μ and σ respectively correspond to the mean and standard deviation of the log-normal distribution. The peak of the transfer function corresponds to the mode ($\exp[\mu - \sigma^2]$), the median is equal to ($\exp[\mu]$) and the mean to ($\exp[\mu + 0.5\sigma^2]$).

The use of a transfer function allows us to describe the whole system and the processes occurring in this system in a relatively simple way. Our system is a porous medium through which the infiltrated water moves and it includes the soil, the limestone, and the saturated limestone aquifer to a depth of 1–2 m below the water table. The processes in this system include the infiltration of rainwater in the soil, the downward movement of this water through the vadose zone, and the subsequent mixing of the drainage water into the freshwater lens to a depth of 1–2 m. The lens reacts buoyantly to recharge events, and the saltwater transition zone moves vertically with the buoyant response. Thus, the "response" or lag times we obtain with the transfer function encompass both the travel time through the vadose zone, and the hydraulic buoyancy response time.

The parameters α, μ, and σ in equations (2) and (3) were obtained by minimizing the sum of the sum of squared errors of simulations compared to the measurements available for each well. The objective function $\phi(\alpha, \mu, \sigma)$ was given by:

$$\varphi(\alpha, \mu, \sigma) = \sum_{i=1}^{N} (\mathrm{TDS}^{-1}_{i,\mathrm{simulated}} - \mathrm{TDS}^{-1}_{i,\mathrm{observed}})^2 \tag{3}$$

where N is the number of measurements in each well, $\mathrm{TDS}^{-1}_{i,\mathrm{simulated}}$ is the simulated variation of TDS^{-1} around the mean, and $\mathrm{TDS}^{-1}_{i,\mathrm{observed}}$ is the observed variation of TDS^{-1} around the mean. We used only the reliable data from the TWB obtained between January 1995 and June 2000 for 21 wells. The Nelder-Mead multidimensional unconstrained nonlinear minimization algorithm available in MatLab$^{\mathrm{TM}}$ was used to minimize the objective function.

RESULTS

Measured and modelled variations in TDS are given for wells 102, 105 and 115 in Fig. 4. Although differences between the three wells are apparent, it appears that the transfer function approach used here gives reasonable results. The transfer function model is in good agreement with the variation of the measured TDS. The information contained in the rainfall signal thus seems sufficient to reflect the variation in salinity. The errors of the objective function will be discussed later. The variation in salinity differs between the wells, and the optimal parameters obtained by minimizing the objective function therefore yields different probability density functions (pdf).

The pdfs for the individual wells are graphed in Fig. 5. The thick line represents the pdf that is obtained when all well data are combined and modelled with one transfer function model (cf. van der Velde *et al.*, 2006). The occurrence of the peak of

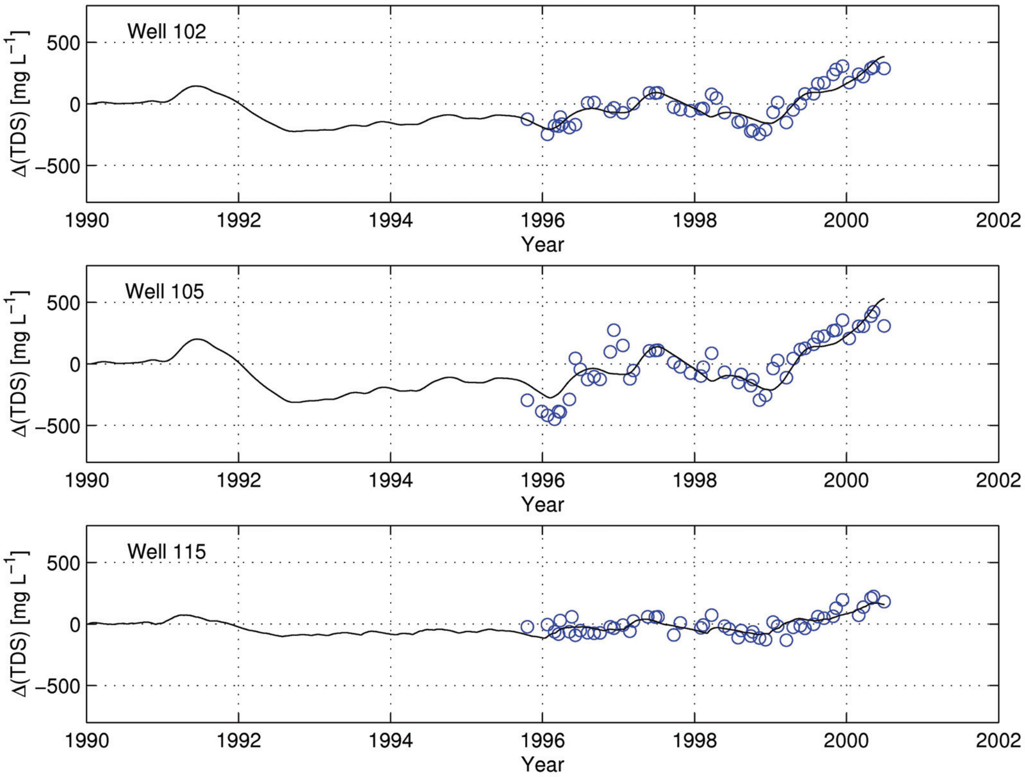

Fig. 4 Model and transfer function of wells 102, 105 and 115.

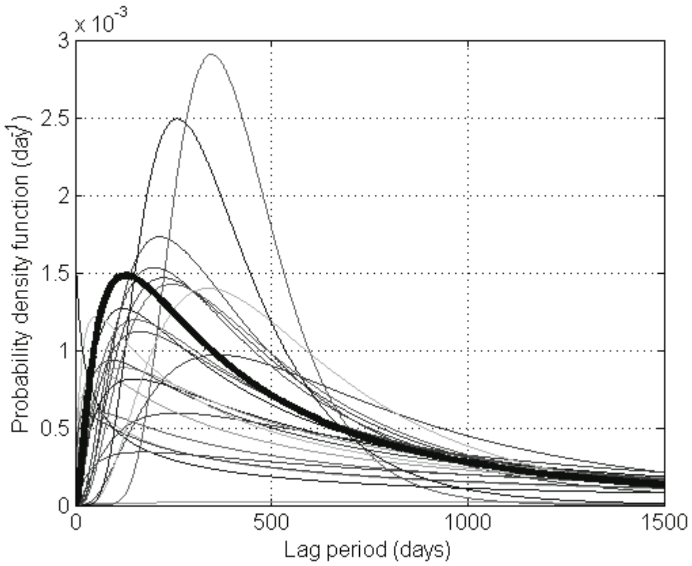

Fig. 5 The lognormal probability functions obtained for all the wells. The thick line is the probability density function obtained when all well data are combined with one transfer function model (cf. van der Velde *et al.*, 2006).

the pdf (corresponding to the mode) ranges between 8 and 305 days. The median and mean lag periods respectively range between 305 and 4912, and 383 and 11572 days. However, most wells have a lag or response time below 2000 days, and a median response time below 1000 days. These lag times thus relate to a combination of the travel time through the vadose zone, as well as the hydraulic buoyancy response time.

These transfer times are relatively large. Hydrographs of well-level response plotted against daily rainfall by Jocson *et al.* (2002) showed that "the rate at which water is delivered to the lens is a function of rainfall intensity and the relative saturation of the vadose zone". This determines the portion of fast flow through preferred flow-paths that bypass the bedrock matrix, with respect to the water that percolates more slowly through the bedrock matrix. Jocson *et al.* (2002) reported significant buffering of recharge to the freshwater lens of Guam, similar processes will influence the recharge here. Nevertheless, Jones & Banner (2003) showed a threshold of rainfall of 190–200 mm month^{-1} before recharge occurs for three different limestone aquifers, and attributed this to similar climate and geology that produce soils with similar hydraulic properties.

Larger travel times may also be associated with parameters that were obtained from erroneous data, or from wells that are more severely influenced by other processes. Therefore it will be necessary to stringently evaluate the accuracy of the minimum error obtained for the objective function by the inverse procedure.

Objective function

The uniqueness of the parameters was evaluated by plotting the error surface for a range of parameter value combinations around the minimum error obtained by the inverse procedure. Data are plotted in Fig. 6 for well 105. Values are shown for pairs of parameters and the associated objective function error, as well as the minimum error that was obtained. The range of parameter values encompasses a range of

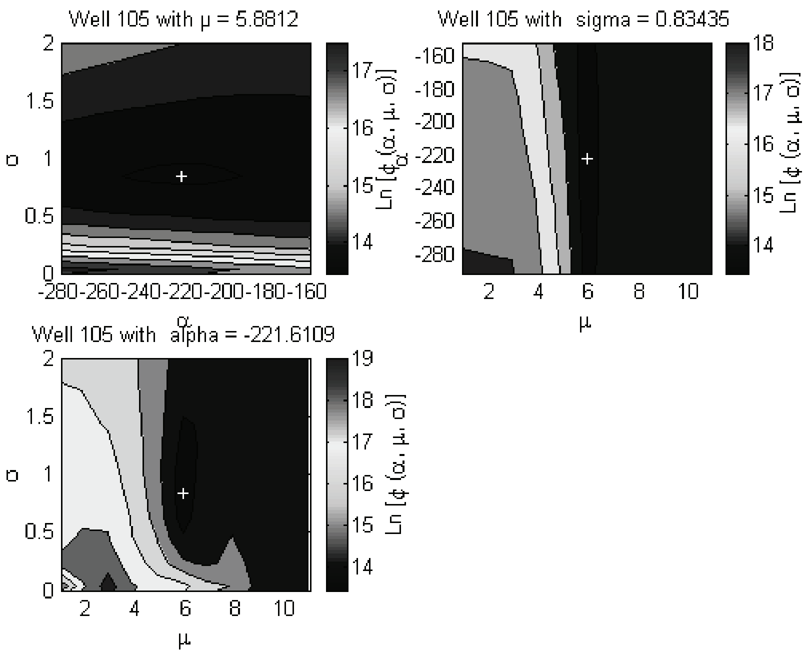

Fig. 6 Representation of the error surface of the objective function around the minimum error (white cross) obtained with the parameters for well 105.

probable parameter values. We find no artefacts in the objective function error surfaces. This shows that the minimum error was found by the inverse procedure. The value for μ is most clearly defined as indicated by the short range around the optimal value in both the μ vs α as well as the μ vs σ. μ relates strongly to the transfer times and corresponds directly to the median travel time (exp[μ]). A wider range around the optimal values for σ and α exists. Although for most wells the obtained model is in good agreement with the measurements (data not shown), differences between the error surfaces exist and problems of interpretation and fitting of the parameters give problems for some of the wells. We can choose an error threshold value of the objective function beyond which we would dismiss the obtained parameters, and thus the model for further analysis related to interpreting the influence on salinity variations of for example geographical location of the well with respect to topography and the coastal zone.

CONCLUSIONS

Two of the main issues that have to be dealt with by small islands that wish to sustain their water resources are intensification of agriculture (van der Velde *et al.*, 2007) and climate change and variability (van der Velde, 2006). Sustainable management of water resources must increasingly take into account human demands and pressures, and climatic influences upon these water resources. Sustainable water resource systems have been defined as "those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity" (UNESCO, 1999). An important aspect of this management is the understanding of climate variability and the influence on the freshwater resources of islands. This work and our previous work on the capability of the SOI to predict pumped water salinity may be beneficial for practical planning by water managers in similar environments.

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