Vulnerability of Groundwater Resources in Tongatapu

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Abstract: *Two thirds of the population of the Kingdom of Tonga, live on the small, South Pacific raised limestone island of Tongatapu. Groundwater is the principle source of reticulated fresh water both in the capital Nuku'alofa and in rural villages and is sourced from a relatively thin, fresh groundwater lens overlying seawater. This paper describes a comprehensive, integrated assessment of the vulnerability of fresh groundwater in Tongatapu. Water resources policy and legislation, and the organisation structures for regulating and managing of water were examined. Threats to groundwater from seawater intrusion, overpumping, agriculture, waste disposal, industry, quarrying, urban settlements, population growth, droughts and climate change were analysed using existing data and field measurements. The impact of pumping on freshwater salinity is clearly discernible within ENSO signatures. Suggestions are made for improving the protection of water resources, mitigating saline water impacts, enhancing freshwater supplies and for reforming regulation and management.*

Keywords: *Groundwater, vulnerability, water pollution, climate variability, water legislation.*

1. INTRODUCTION

Tongatapu, the main island in the Kingdom of Tonga, had 70.6% of the nation's population in 2006. It is blessed with reliable rainfall, fertile soils and has an adequate supply of groundwater, which with rainwater form the island's sources of freshwater. There are, however, increasing demands on, growing threats to, and public concerns about its groundwater, which require wise management and use to ensure adequate supplies of safe freshwater for current and future generations. Groundwater contained in Tongatapu's karst limestone aquifer is a valuable resource, particularly during dry seasons and periodic droughts. Unfortunately, the groundwater is both spatially and temporally of variable quality for drinking due to its mixing with underlying seawater and the impacts of overlying human settlements. There are, therefore, a range of natural, anthropogenic as well as institutional factors that contribute to the vulnerability of groundwater in Tongatapu. Over the past 40 years, investigations in Tongatapu have identified a number of natural and human-related factors that increase or have the potential to increase the vulnerability of fresh groundwater sources (summarised in Falkland, 1992; Furness and Helu, 1993; Douglas Partners, 1993; 1996; Furness, 1997; van der Velde, 2006). This study assessed the main factors and their impacts on groundwater using: "snap shot" measurements of groundwater taken in August and December 2007; a critical analysis of the valuable data bases of groundwater monitoring results dating back to 1959; interviews with government and non-government organisations and a range of techniques to predict possible future situations.

2. TONGATAPU

The Kingdom of Tonga lies in the southwest Pacific Ocean on the boundary between the Australian and Pacific Plates. Tongatapu, part of the southern-most group of islands is a tilted, raised limestone island 257 km^2 in area (Figure 1). It characterised by Pliocene and Pleistocene coral terraces unconformably overlying Miocene volcaniclastics (Furness, 1997). The limestone, which forms the unconfined aquifer, has a thickness of about 134 m around Nuku'alofa increasing to 247 m near Fua'amotu in the southeast (Lowe and Gunn, 1986). The maximum elevation of Tongatapu is 65 m above mean sea level (MSL) near Fua'amotu dipping down to sea level in the northwest. The island has a mantle of fine-grained, andesitic volcanic ash up to 5 m thick. This has produced extremely fertile and productive soils and agriculture is a fundamentally important activity.

Figure 1 Tongatapu island, Tonga, tilts generally from the higher southeast around Fua'amotu to the low northwest around Kolovai. The capital Nuku'alofa is in the central north. The Mataki'eua/Tongamai well field which supplies Nuku'alofa is circled in red.

Mean annual temperature in Tongatapu is 23°C and the mean annual rainfall in the capital Nuku'alofa, which is almost at sealevel (from 1945 to 2006) is 1,727 mm with a relatively small standard deviation of 423 mm. The five wet-season summer months of December to April have a mean combined rainfall of 962 mm which is 56% of annual mean rainfall. There is a small orographic effect with mean annual rainfall in the higher southeast Fua'amotu region being about 9% higher than that at Nuku'alofa, almost at sea level. Annual rainfalls are correlated with El Niño Southern Oscillation (ENSO) events with higher rainfalls tending to occur in the La Niña (SOI positive), phase (Hay *et al.,* 1993, van der Velde *et al.* 2006). Mean annual potential evaporation is around 1,460 mm (Furness 1997). Estimates of the mean annual groundwater recharge in Tongatapu vary between about 20 to 30% of annual rainfall with a value around 530 mm commonly accepted as a representative mean (Hunt 1979; Falkland 1992).

Groundwater for village use is extracted by pumps throughout the island and a reticulated water supply for Nuku'alofa is sourced from the Mataki'eua wellfield (Figure 1).

3. MAIN VULNERABILITIES

3.1. Groundwater salinity

Mapping of the salinity of groundwater in village wells showed seawater intrusion causes increased groundwater salinity in the Hihifo, northern Lapaha (around Kolonga) Districts and the Mu'a villages (Figure 2). Water supply quality in the Hihifo region needs to be addressed urgently. The freshest groundwater comes from the area around Fua'amotu in the southeast and should be considered as a future water supply source, particularly in droughts. The current distribution of groundwater salinity in Tongatapu is similar to the last survey mapped in 1990 (Furness and Helu, 1993).

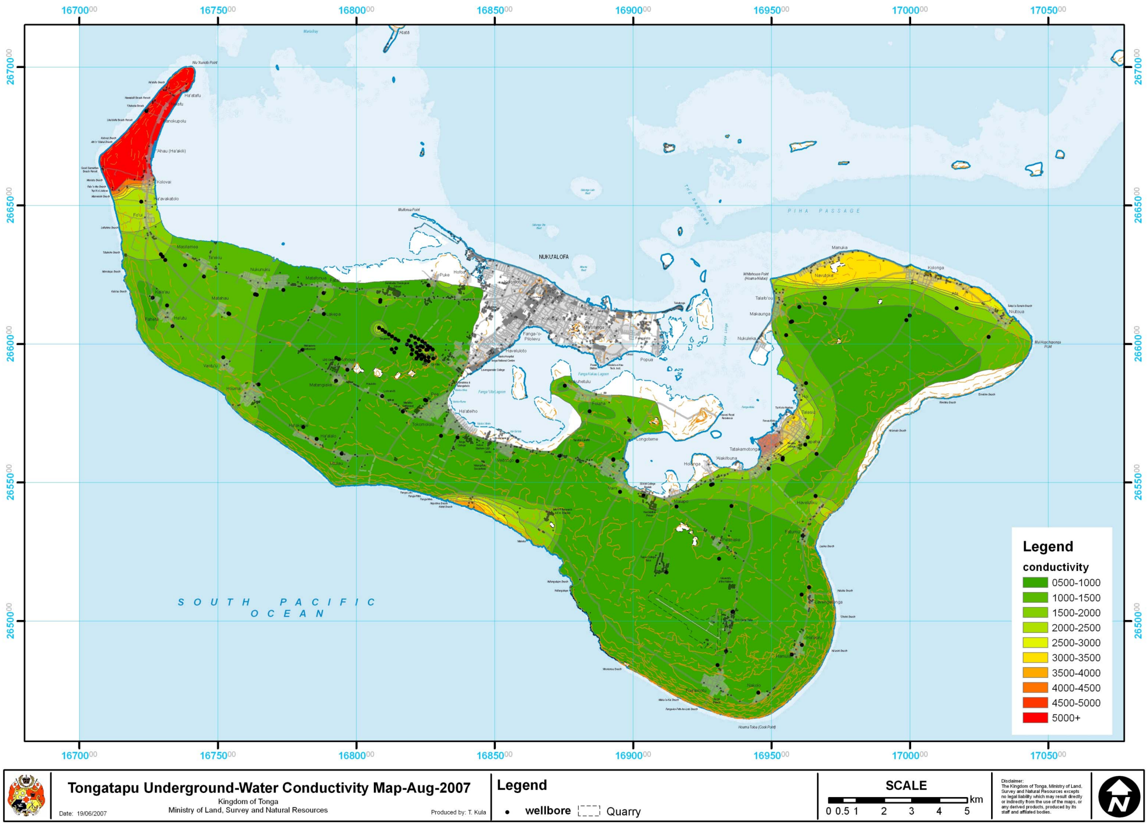

Figure 2 Groundwater salinity (EC) distribution map of Tongatapu in August 2007 as measured in this study from 55 pumping wells (GIS map produced by MLSNRE). Highest salinity in red near the northwestern Hihifo region.

The salinity of groundwater increases during droughts which are mostly related to El Niño events (van der Velde, 2006). It was found that number of droughts in Tongatapu has increased in the period 1975 to 2007 compared with those from 1945 to 1975. The average duration of droughts which most affect groundwater is 14 months and the average time between droughts is 7 years. These droughts were found to be highly correlated with sea surface temperatures, SSTs. Surprisingly wet season rainfalls were highly correlated with SST but dry season rainfalls were not.

Salinity of water from the Mataki'eua and Tongamai wellfield (Figure 1) is highest in wells closer to the lagoon, as expected, and depends on the rainfall over the past 12 to 18 months. Using the relation between rainfall and groundwater salinity, it was predicted that the groundwater salinity of the entire wellfield would exceed the salinity guideline limit for drinking water after four months without rain. Using the relationship between groundwater salinity and distance from the sea it was shown that vertical wells within 0.75 km of the sea would exceed the salinity guideline if pumped continuously. The results suggest a new groundwater extraction scheme from government land at Fua'amotu should be initiated to mitigate the impacts of droughts and seawater intrusion as population increases.

3.2. Groundwater pumping

It was difficult to assess the long-term sustainability of pumping from groundwater as there is no accurate metering of the rate at which water is being pumped from groundwater in Tongatapu. It was estimated that the total sustainable pumping rate for Tongatapu is between 54 and 72 ML/day. While the current extraction rate is uncertain, estimates suggest it could be as high as 13.4 ML/day or 19 to 25% of the sustainable yield. Approximately 10.7 ML/day, or 80% of this estimated total daily extraction, is sourced from the Liahona-Tongamai-Mataki'eua region due to the concentration of pumps at the Mataki'eua/Tongamai wellfield, while the remaining 20% is distributed over the rest of Tongatapu. This uneven distribution of pumping could be further exacerbated by proposals to increase the number of pumps at Mataki'eua/Tongamai by up to 60 and may create salinity problems in pumped water particularly during dry times. The household statistics show a dramatic increase in the number of household rainwater tanks since 1986, indicating a preference of rainwater for drinking.

The range of the maximum number of pumps, pumping continuously at rates of 216 to 260 m^3/day (2.5 to 3.0 L/s), that can be accommodated within the effective recharge zone of Tongatapu is between 210 and 330 pumps. It was concluded that all pumps should be metered and licensed to extract at a maximum of 3.0 L/s. To minimise upconing of the fresh/seawater interface it is desirable to have these pumps as evenly distributed as possible with spacing between pumps of 0.75 to 1 km. Spacing pumps closer than this will increase both local salinity of pumped groundwater, as observed at Mataki'eua/Tongamai wellfield.

Over two thirds of the water pumped from the Mataki'eua/Tongamai wellfield disappears as unaccounted-for losses. A large proportion of the good quality groundwater is therefore being pumped from Mataki'eua/Tongamai to be discharged from leaking pipelines into the polluted groundwater in Nuku'alofa were it discharges into the Lagoon or the ocean. Future water supply projects in Nuku'alofa should concentrate on reducing these losses.

3.3. Agricultural chemicals, heavy metals and nutrients

This study addressed increasing concerns about the quantity of agricultural chemicals used in Tongatapu and about leakage from septic tanks. Intensive sampling of 10 selected water supply wells across Tongatapu showed no detectable presence of harmful pesticides, petroleum products or most heavy metals. Species that were detected were well below the World Health Organisation (WHO) guideline values for drinking water except for lead at the Tapuhia Waste Management Facility (TWMF). The absence of pesticides, petroleum products or heavy metals found in this study agrees with three groundwater surveys undertaken by the Waste Authority between April 2006 and July 2007 around the TWMF and a survey conducted ten years earlier in the mid 1990s (Falkland, 1995).

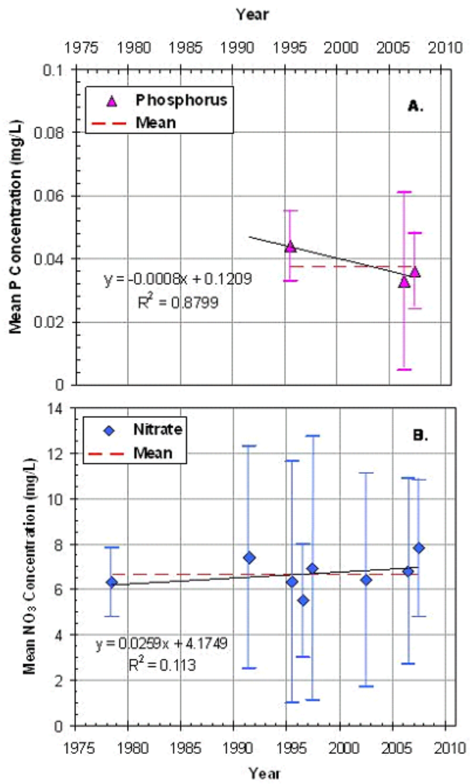

Figure 3 Trends in A. mean phosphorus and B. mean nitrate concentrations in groundwater in Tongatapu since 1978. Dashed lines are long-term means.

Nutrients such as nitrate were present in every sample but were less than WHO guideline values except for one measurement at the TWMF, close to a sewage sludge containment area. It was shown that nutrient levels have stayed remarkably constant since 1978 (Figure 3) despite the increase in nitrogenous fertilizer use since that time. The nitrate in groundwater is attributed to leakage from septic tank and pit latrines, human and animal wastes rather than agriculture fertilisers.

Continued monitoring of nitrate in groundwater and strategies for reducing nitrate inputs are required because of the increased use of nitrogen fertilisers, leakage from septic tanks and the health impact of high concentrations of nitrate in drinking water on young babies. Further use of hazardous agricultural chemicals requires continued monitoring of groundwater at selected sites. A data base showing where agricultural chemicals and fertilizers as well as industrial chemicals are being used across Tongatapu needs to be established to allow better targeting of sampling sites.

3.4. Faecal contamination

Indicators of bacterial contamination were found in 90% of the 19 water supply wells sampled and 24% of the wells had indicators of faecal contamination. Faecal contamination could be of human or animal origin. These results indicate that both the drilling of water supply wells away from faecal sources and treatment of all groundwater used for drinking in villages should be a priority. Control of leakage from septic tanks in and removing livestock from water source areas would decrease the threats to groundwater supplies.

3.5. Quarrying

Apart from the detailed measurements at the abandoned Tapuhia quarry now in use as the Tapuhia Waste Management Facility,TWMF, no detailed measurements were made on either the hydraulic gradients around or the water quality resulting from quarries, due to the absence of a groundwater monitoring borehole network. Because of this, we are unable to give recommendations on the safe distance between a quarry and a water supply well or wellfield. Nonetheless our observations and discussions with relevant agencies permit some general conclusions:

- Quarrying is largely unregulated.
- Current quarrying practice is to excavate material down to below the groundwater level. This exposes groundwater to direct evaporation losses and greatly increases the risk of groundwater contamination.
- Apart from the TWMF, there is no monitoring borehole network that can be used to determine the impacts of quarrying on groundwater hydraulic gradients or on the groundwater quality.
- Practices within quarries where the water table is exposed, such as disposal of industrial wastes and keeping of livestock, greatly increase the risk of groundwater contamination.
- Pre-existing lead and post-completion nitrate concentrations within monitoring boreholes around the TWMF warrant close attention and continued monitoring and reporting.
- Abandoned quarries could be used for locating infiltration galleries to produce lower salinity water from surface groundwater.

3.6. Population pressures

Shallow, unconfined groundwater in small islands is especially vulnerable to overlying settlements. It has been claimed that Tonga is also subject to a rapidly growing population with the number of people growing from around 20,000 in 1900 to around 100,000 in 2000 (van der Velde, 2006). The projected population of Tonga was expected to be 114,600 in July 2006 (Mafi and Crennan, 2007) with about 69% and 32% of the total population living in Tongatapu and Nuku'alofa respectively. In the past, Tongatapu and Nuku'alofa have experienced enhanced growth rates due to inward migration from outer islands to the main population centre. This has occurred in many small island countries in the Pacific (Ward, 1999). Figure 4 shows the population growth for the period 1956-2006.

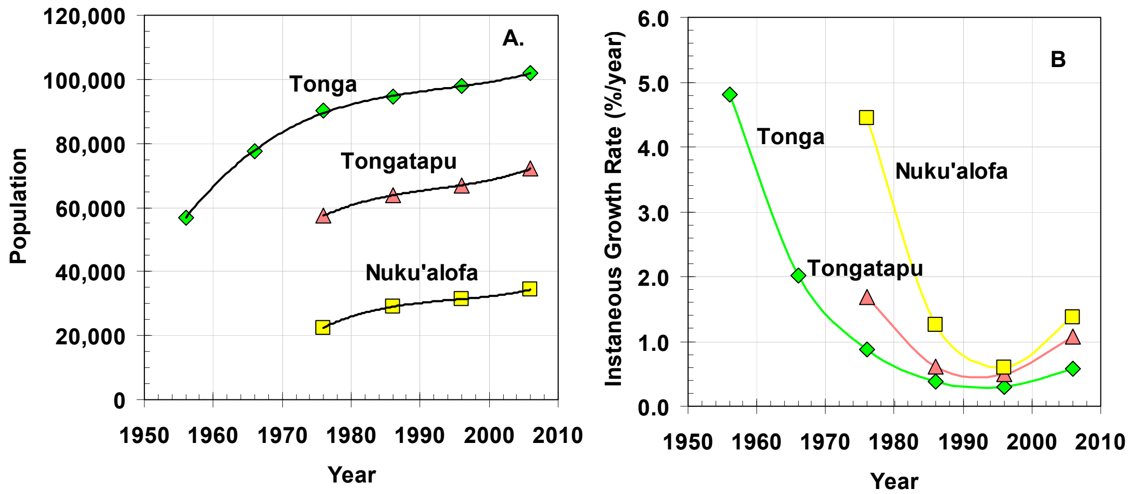

Figure 4 Population growth for Tonga, Tongatapu and Nuku'alofa A. Population numbers and B. Instantaneous rates of growth (Tonga Statistics Department)

The actual total population in 2006 was only 101,991 with 70.6% and 33.6% of the total population living in Tongatapu and Nuku'alofa, respectively.

It is clear that in the 1950's and 1960's, the population of Tonga was growing rapidly. Even in the 1970s and 1980s, the population growth in Tongatapu and Nuku'alofa was outstripping the growth in the Kingdom as a whole. The statistics in Figure 16 and Table 3, however, show a surprising slow down in the rate of increase in population numbers not only for Tonga as a whole, but for Tongatapu and Nuku'alofa, although they continue to increase at a faster rate than Tonga as a whole. This slow down appears not to be caused by a decline in fecundity but to migration to the United States, New Zealand and Australia.

While the population in the capital Nuku'alofa is a major contributor to pollution of the shallow groundwater and therefore of the Lagoon and northern sea coast, it is not a major threat to town water supplies since groundwater in Nuku'alofa is generally not used as a source of potable water. The more significant threat to local groundwater supplies comes from the 48% of residents in Tongatapu who live outside Nuku'alofa or from agricultural activities, aggregate mining and raising stock.

3.7. Climate change

The 23 coupled atmosphere-ocean global climate models, GCMs (selected from the IPCC, 2001a,b), run by CSIRO (Ian Macadam, CSIRO/BOM Climate Change Group, Pers. Com. 29 April, 2008) were used to predict possible changes to monthly rainfalls and potential evaporation for Tongatapu relative to the values for the period 1975 to 2004 for 4 scenarios of future green house gas, GHG, emissions, (IPCC, 2000) through to 2095. The 4 scenarios were: highest values for the SRES scenarios; best estimate values for the A1FI scenario; best estimate values for the B1 scenario; and lowest values for the SRES scenarios (IPCC, 2000). These were then used to estimate GHG-related changes in recharge. The models predicted widely divergent future monthly rainfalls in Tongatapu for the SRES selected. Some predict increases in rainfall; others predict decreases under the same SRES. This is worrying since a small, relatively low island embedded in a large ocean should be the simplest case. Here we have used the mean of all model predictions to arrive at a "consensus" value for the expected change in rainfall. These means have very large coefficients of variation.

For the period 1990 to 2095, the predicted increases in mean annual rainfall lie between 0.2 and 1.3 mm/year. Mean wet season rainfall is predicted to increase by between 0.4 and 2.1 mm/year, while mean dry season rainfall is predicted to decrease by 0.1 and 0.8 mm/year. These predicted trends are exactly opposite to the very weak trends found in actual historic rainfall from 1945 to 2007. Annual rainfall has a decreased by 2.3 mm/year while that for the wet season has decreased by 3.2 mm/year, while dry season rainfall, increased by 0.7 mm/year.

Only 14 of the 23 GCMs used can predict changes in potential evaporation. Their predictions for the 4 SRES scenarios give nearly an order of magnitude lower coefficient of variation in the mean predicted monthly potential evaporation than for predicted monthly rainfall. The mean predicted monthly changes in potential evaporation, E_0, all increased with increasing time beyond the reference period 1975-2004, irrespective of season or SRES scenario. This seems to be a consequence of the predicted increase in global temperature with increased GHG emissions. The increased predicted E_0 for the dry season were larger than those for the wet season. This differential increase in dry season E_0 over that for the wet season, coupled with predicted decreases in dry season rainfall, could increase seasonal differences in soil moisture and recharge.

Surprisingly, the predicted increasing trends in annual and wet and dry season E_0, between 1990 and 2095 are opposite to the trends in actual evaporation (ETa) estimated using recharge calculations for 1945 to 2006. For this period, estimated ETa decreased for annual and wet and dry seasons. The magnitude of the decrease of dry season ETa was less than that for the wet season. These trends are opposite to the predicted GCM trends, as was found for rainfall. Evaporation and its seasonal dependence appear more sensitive than rainfall to the expected impacts of increased GHG emissions. Monitoring of evaporation in Tongatapu should therefore recommence.

As a first approximation, the expected change in groundwater recharge resulting from continued GHG emissions has been estimated by assuming that the predicted percentage increases in potential evaporation also apply to ETa. We have then used the observed mean rainfalls for the period 1975-2004 and the mean ETa for the same period calculated for the recharge model together with the simplified long-term water balance to estimate changes in annual groundwater recharge. These first-order estimates suggest recharge will decrease by between 5 and 25% by 2095. The predicted increase in annual rainfall is offset by the predicted increase in evaporation, especially in the dry season which is coupled to the predicted decline in dry season rainfall.

When linear trends are fitted to the widely fluctuating annual recharge estimates for 1945 to 2006, annual recharge was found to decrease close to the rate predicted for the high SRES scenario. The trends for the wet and dry season recharges, however, are opposite in sign to those predicted from the GCMs with estimated wet season recharge decreasing and dry season recharge increasing. The coefficients of determination are very small indicating that the trends in the 1945-2006 recharge data are not significant.

Because recharge appears to be sensitive to climate change, it is important to monitor parameters indicative of recharge. The thickness of groundwater is clearly a sensitive parameter but one which is also influenced by the rate of withdrawal of groundwater and closeness to the sea. For this reason both profiles of salinity and pumping rates should be measured throughout Tongatapu. The predicted decrease in groundwater recharge rate with increasing GHG emissions, therefore reinforces the suggestion that pumping should be licensed and monitored.

GCMs are not good at simulating changes to the hydrological cycle and are notoriously bad on rainfall, especially in the tropics. There are two basic reasons for this: (i) they generally do not simulate tropical convection very well, and (ii) they can not reproduce some the major modes of current climate variability, including El Niño- Southern Oscillation (ENSO). The predictions here should therefore be treated with caution.

3.8. Institutional issues

The study found that the main threat to groundwater in Tongatapu is institutional. There is no legal basis for protecting groundwater from harmful activity or over use. The lead water resource Ministry, Ministry of Land Survey Natural Resources and Environment, MLSNRE, has no statutory basis for protecting, regulating, monitoring or reporting on groundwater resources. There are also conflicting ministerial roles in the water sector and no incentives for collaboration. Currently, there is little obligation for Ministries to report collectively to the Government on the state of the nation's water resources. The draft 2006 National Water Resources Bill addresses these issues but earlier versions of it have existed in draft form since 1983 without being submitted to government. A National Water Resources Committee, with members drawn from key water agencies and non-government organisations, as specified in the draft 2006 Water Resources Bill, should be established as a matter of urgency. Once established, this Committee will report regularly to Cabinet on the condition and use of water resources and on priority issues in the sector and will improve coordination and cooperation between agencies and help focus aid donor projects.

There is a serious need for continued recruitment and training of staff in water resource management agencies. Water agencies are operationally poorly resourced to conduct groundwater monitoring, analysis, assessment, reporting and community consultation. There are few incentives for cooperation between Ministries with responsibilities in water. The establishment of a modest environmental water abstraction charge on all groundwater pumped in Tongatapu to be totally allocated to water resource monitoring and assessment would provide operational resources to carry out this vital function and incentives for cooperation.

Village Water Committees manage water supplies for villages in Tongatapu but are under-resourced and largely untrained for this important technical task. Ways of improving the management and delivery of water supplies at the village level are needed. Institutional reform of the water supply sector through the formation of a single Tongatapu Water Authority for both urban and rural Tongatapu would address this problem and improve service in most rural areas, although it would require an increase in trained pesonnell. The village of Fua'amotu in the southeastern corner of Tongatapu has already taken action in this direction by inviting the Tonga Water Board to assume management of its groundwater supply wells.

4. CONCLUSIONS

Natural, anthropogenic, demographic and institutional factors were assessed for their impact on the vulnerability of groundwater in Tongatapu, the main island and population centre in the Kingdom of Tonga. Perhaps the greatest threat to groundwater that was identified came from the absence of any legal protection for groundwater resources, any legal definition of the responsibilities of management agencies, any licensing of groundwater drillers or any regulations on quarrying down to the groundwater. Passing of water resources legislation that has been in draft form for many years should help remove this threat.

The concentration of pumping in the Mataki'eua wellfield to supply the capital Nuku'alofa with reticulated water and the fact that much of the pumping throughout the island was unmetered is also a threat to groundwater. Leakage from the reticulation system is as high as 75%. Pumping good quality water and allowing it to leak into the contaminated groundwater in Nuku'alofa is not good practice.

Unlike some Pacific Island States, population growth rates in Tongatapu have decreased, lessening both the use of and impacts on groundwater. In addition, the community has shown a marked preference for rainwater and the use of rainwater tanks has expanded dramatically. Contamination of groundwater from septic tanks remains a threat and efforts should be made to identify groundwater protection zones. The difficulties global climate models have in predicting rainfall, especially in tropical areas, means that their use in predicting future changes in groundwater recharges are unreliable.

5. ACKNOWLEDGMENTS

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