Assessing vulnerability and adaptation to sea-level rise: Lifuka Island

Ha'apai, Tonga

B 1: Physical resources

1.1: Shoreline assessment

SPC Secretariat of the Pacific Community

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Contents

List of technical report titles for the project:
Assessing vulnerability and adaptation to sea-level rise: Lifuka Island, Ha'apai, Tonga

The Australian Government's Pacific Adaptation Strategy Assistance Program (PASAP) aims to assist the development of evidence-based adaptation strategies to inform robust long-term national planning and decision-making in partner countries. The primary objective of PASAP is: 'to enhance the capacity of partner countries to assess key vulnerabilities and risks, formulate adaptation strategies and plans and mainstream adaptation into decision making' (PASAP, 2011). A major output of PASAP is: 'country-led vulnerability assessment and adaptive strategies informed by best practice methods and improved knowledge'.

The Lifuka project was developed in conjunction with the Government of Tonga Ministry for Lands, Survey, Natural Resources, Environment and Climate Change (MLSNRECC), PASAP and the Secretariat of the Pacific Community (SPC) to develop an evidenced-based strategy for adapting to sea-level rise in Lifuka Island.

Rising oceans, changing lives: Final report is the overview report in a series of technical reports that have been written for the project on Lifuka Island. Accordingly the section titles in the final report correspond with the names of the respective technical reports. The full series of technical reports is listed below.

A: Rising oceans, changing lives: Final report

B: Mapping the Resources

B 1: Physical resources

- 1.1: Shoreline assessment
- 1.2: Groundwater resources assessment
- 1.3: Oceanographic assessment
- 1.4: Benthic habitat assessment
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B 2: Community assessment

- 2.1: Community engagement strategy and community assessment manual
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D: Adaptation options and community strategies

Abbreviations and symbols

E. coli	*Escherichia coli*
FAC	Free available chlorine
GPS	Global positioning system
HD	Horizontal Dipole
LIF	Lifuka salinity monitoring bore
MLSNRECC	Ministry of Lands, Survey, Natural Resources and Environment and Climate Change -
PASAP	Pacific Adaptation Strategy Assistance Program
PVC	Polyvinyl chloride
SPC	Secretariat of the Pacific Community
TWB	Tonga Water Board
UNESCO	United Nations Educational, Scientific and Cultural Organization

Measurements

KL/day	Kilo litres per day
L	Litres
L/sec	Litres per second
m^3	Cubic metres
ML/day	Mega litres per day
μS/cm	Microsiemens per centimetre

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Executive summary

This report is the output from the groundwater resource assessment carried out on Lifuka in September 2011, as part of the project Assessing Vulnerability and Adaptation to Sea-Level Rise: Lifuka Island, Ha'apai, Tonga. It captures information on the extent and thickness of the freshwater lens, the impact on the lens from a sudden increase in sea level related to subsidence caused by the 2006 earthquake, groundwater contamination threats and impacts, and the potential exposure of the freshwater lens and abstraction infrastructure to inundation.

The freshwater lens on Lifuka is naturally very dynamic and fragile. It is very responsive to rainfall events and begins to thin within a few months when there is little or no rainfall. Projected climate scenarios of longer dry periods and wetter wet seasons suggest that Lifuka's communities will have a greater reliance on groundwater in the future.

The subsidence and the associated rise in sea level on Lifuka have affected the fresh groundwater lens, with the lens having been 'lifted' by an observed 0.45–0.55 m in monitoring bores. In some cases, this appears to have increased the thickness of the freshwater lens and the storage.

Mapping shows that the freshwater lens is thickest in the area around Hihifo Gallery East. Geophysics indicates a lens up to 9 m thick, but of limited extent. The sustainable yield for the fresh groundwater in the area is conservatively estimated to be 159,989 m^3/year.

Abstraction rates for some bores are too high, causing localised increased salinity during dry periods. There is limited potential for increased development of the freshwater lens due to existing land-use activities and infrastructure. The area of the existing Pangai High School offers greatest potential for development of a horizontal infiltration gallery. Additional investigation is recommended to confirm the optimal location in this area.

Inundation modelling shows that all existing Tonga Water Board (TWB) infrastructure, including the production bores and galleries and the treatment plant, are at risk of some level of inundation from a 1:100 year inundation event.

Water resource adaptation options

It is recommended that TWB undertakes several actions, described below.

1. Introduce groundwater protection setback zones around TWB infrastructure to reduce contamination risks. A setback area of 100 m from groundwater capture zones and well heads should be applied. The setback zone would restrict land-use activities, including housing of pigs and storage and use of chemicals and fuels. Consideration should be given to providing support to households within the setback zone to replace or improve their on-site wastewater disposal to reduce the risk of contaminating groundwater.

2. Build bunds around water supply infrastructure as protection against inundation and surface-water ingress. This would include all TWB pump installations and the treatment plant.

3. Fence well heads to provide a 10 m setback distance from the well head, and restrict access in order to reduce contamination risks. This includes fencing TWB well 4, adding a bund and improving surface drainage to direct surface water away from the well head.

4. Undertake additional investigation on the construction of a horizontal gallery in the area near the Pangai High School playing fields. As this area is outside the area that modelling shows would be inundated in a 1:100 year event, it would provide additional security and a greater quantity of water for Lifuka.

5. Adjust abstraction rates based on production-well salinity, reducing the pumped abstraction when salinity is high.

6. Reduce the high rate of lost and unaccounted-for water.

7. Improve water-quality sampling and adopt a pro-active response to results.

'No-regrets' options

'No-regrets' options are activities that should be pursued, regardless of the impacts of coastal inundation, as they ensure the safety and quality of water supply. In general, they are straightforward tasks that can be carried out by householders themselves.

It is recommended that householders be encouraged to consider:

1. **boiling** or chlorinating drinking water;

2. improving gutter maintenance to ensure adequate rain is being captured;

3. installing first-flush systems and screens at tank openings to reduce the risk of contamination (a first-flush device is a system of pipes that diverts the first rain that falls on the roof after a dry period, reducing the amount of dust, bird droppings, leaves and debris that flows into the tanks); and

4. installing plastic tanks to replace leaking cement tanks.

1. Introduction and background

1.1 Pacific Adaptation Strategy Assistance Program

The Pacific Adaptation Strategy Assistance Program (PASAP) aims to facilitate the development of evidence-based adaptation strategies in partner countries. The programme is implemented by the Government of Australia. The primary objective is to enhance the capacity of partner countries to assess key vulnerabilities and risks, formulate adaptation strategies and plans, and mainstream adaptation into decision-making.

PASAP was conceived by the Government of Tonga's Ministry for Lands, Survey, Natural Resources and Environment and Climate Change (MLSNRECC) in consultation with the Government of Australia. It responds to coastal erosion issues that accelerated following a May 2006 earthquake in the Ha'apai island group, which resulted in subsidence along the island chain. There is some suggestion of coastal erosion occurring prior to the earthquake (Cummins et al. 2006).

The Government of Australia and MLSNRECC approached the Secretariat of the Pacific Community (SPC) to assist in the development of a project to investigate the causes of coastal erosion and the impacts of sudden sea-level rise on the coastal environment and the communities of Lifuka. The project was nested within a community-focused framework to promote the selection of suitable mitigation and adaptation strategies in a context of adaptation to expected future impacts of climate change.

SPC, through its Human Development Programme and Applied Geoscience and Technology Division, developed a proposal that identified climate-change adaptation strategies appropriate to Lifuka with application to other parts of Tonga and the Pacific. The project is formally referred to as the *Assessing Vulnerability and Adaptation to Sea-Level Rise: Lifuka Island, Ha'apai, Tonga* and is intended to develop an evidence-based strategy for adapting to sea-level rise while supporting the capacity of the Government of Tonga and relevant non-governmental organisations to conduct similar assessments of coastal and social vulnerability and adaptation to sea-level rise in the future. The overall project design is based on an earlier draft proposal developed by the Government of Australia, MLSNRECC and Melbourne University.

The project consists of a sequence of activities that includes a scientific analysis of coastal process dynamics and inundation modelling, topographic and groundwater resource mapping, analysis of community social and environmental values, and analysis of community exposure to risk. Outputs from the project consist of reports from each of the project steps that serve as primary inputs into the project's final report. The final report draws important conclusions across related pieces of work, and captures lessons learned.

This report is the output from the groundwater resource assessment carried out on Lifuka in September 2011 and quarterly monitoring undertaken during 2012. The groundwater resource assessment captures information on the extent and thickness of the freshwater lens, the impact on the lens from a sudden increase in sea level related to subsidence from the 2006 earthquake, groundwater contamination threats and impacts, and the potential exposure of the freshwater lens and abstraction infrastructure to inundation.

This document outlines the methods used for assessment of the groundwater resources and reports on the preliminary findings.

1.2 National context

Tonga is a small island developing state located in the Central South Pacific. It lies between 15° and 23° 30' South and 173° and 177° West. Tonga has a combined land and sea area of 720,000 km². There are 36 islands that are inhabited, with an area of 670 km². Tonga had a total population of 103,000 in 2011 (Tonga Department of Statistics 2013).

Tonga has a typical South Pacific island economy. It has a narrow export base in agricultural goods. Successful exports include squash pumpkin. Agricultural exports, including fish, make up 73% of total exports. Tonga imports a high proportion of its food from New Zealand. The country remains highly dependent on external aid and remittances from Tongan communities overseas to offset its trade deficit. Tourism is the second-largest source of hard currency earnings after remittances. The government is emphasising the development of the private sector, especially the encouragement of investment, and is committing increased funds for health and education (CIA 2013).

Crops are grown for subsistence, for sale at local market and, in recent years, for export. The majority of Tongans are Christians, with the main faiths the Free Wesleyan Church (37%), the Church of Latter-Day Saints (Mormon) (17%), the Roman Catholic Church (16%) and the Free Church of Tonga (11%) (PASAP document 2011).

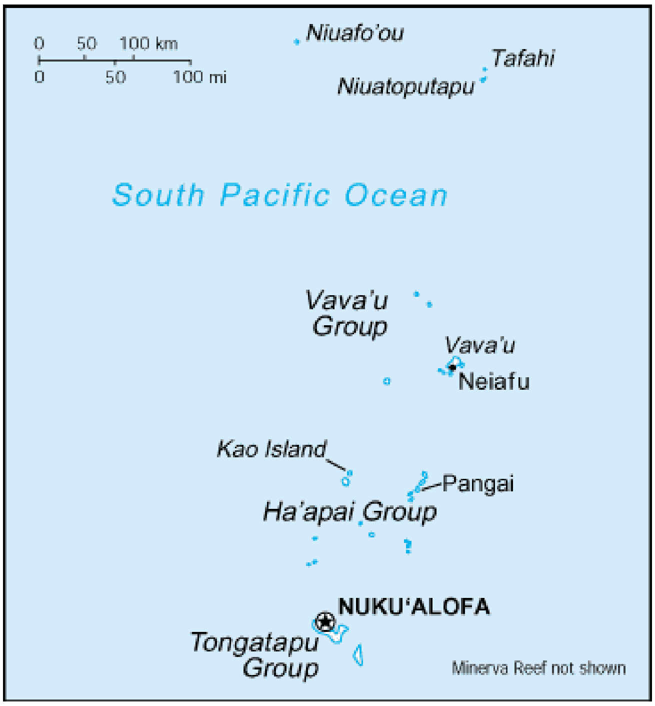


Figure 1: Map of Tonga (Source: CIA 2013)

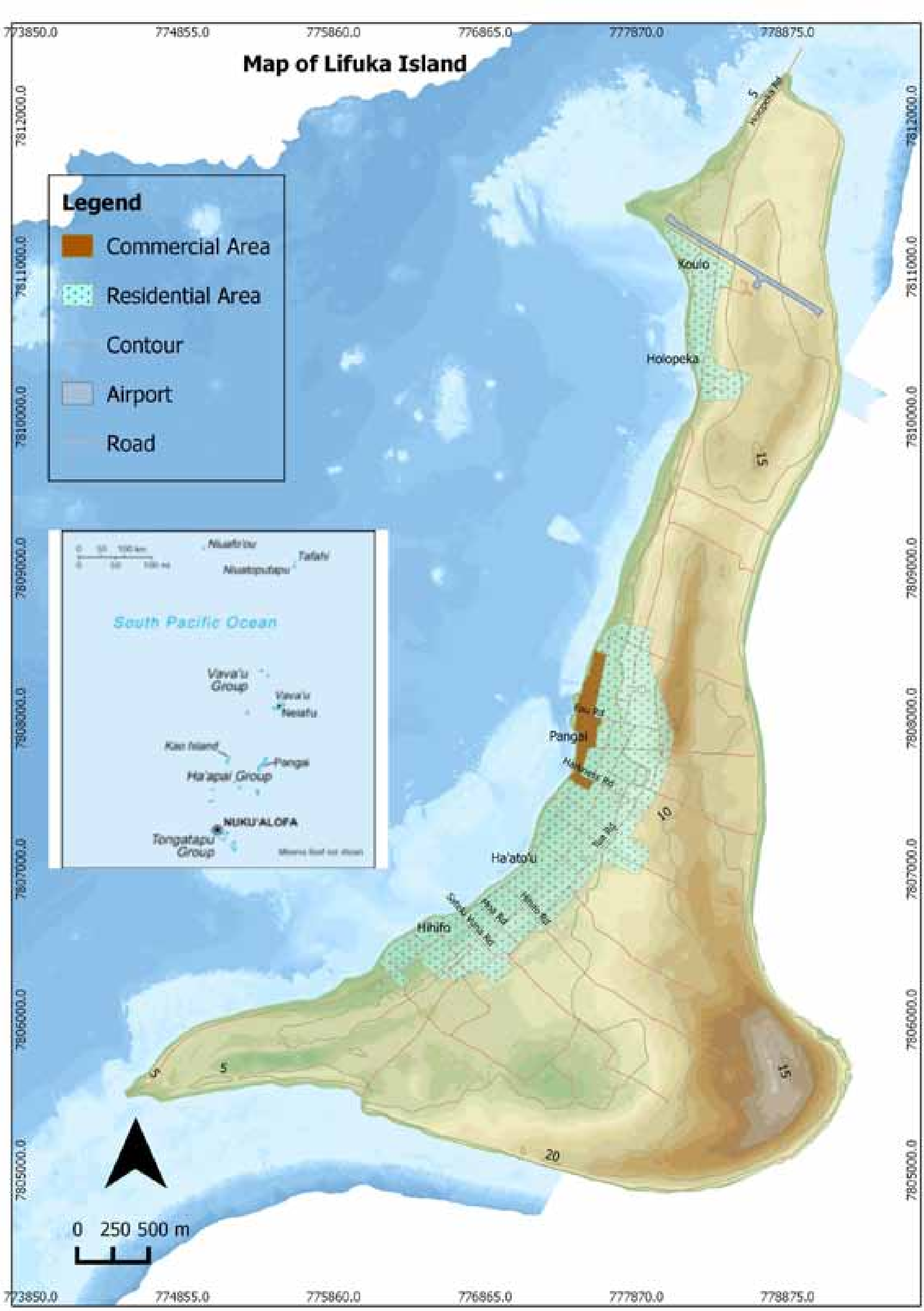


Figure 2: Map of Lifuka

1.3 Geological setting

The Tongan archipelago lies along the boundary of the Pacific and Indo-Australian tectonic plates. The 800 km archipelago lies along a NE–SW axis and consists of two parallel belts, with volcanic islands found in the western belt, called the Tofua Arc, whilst the eastern belt, the 'Tonga Platform' located closer to the Tonga Trench, consists of fertile low-lying uplifted limestone coral (Furness 1997).

The limestone islands of Tonga are characterised by Pliocene and Pleistocene coral reef terraces. Wilson and Beecroft (1983) report that the uplifted reef material on Lifuka is covered by andesitic tephra of an approximate thickness of 2.5 m, possibly originating from near volcanic activity along the Tofua Arc. The tephra deposits reveal at least two related ash-fall depositions, distinguished by weathering-related colouration. The younger tephra layer, moderately weathered to reddish-brown soil, is approximately 1.5 m thick, while the underlying, older layer is more strongly weathered to yellowish-brown tints (Wilson and Beecroft 1983). Other soils, which include calcareous sandy soils derived from the weathering of the coral reefs, form an unconsolidated mantle on the leeward sides of the islands. Refer to Annex 1 for a soil map of Lifuka. Maximum elevation on Lifuka does not exceed 20 m above mean sea level, and elevations in excess of 15 m are limited to the highest parts of the island (eastern side).

On 3 May 2006 the Ha'apai group experienced a 7.9 magnitude earthquake, resulting in subsidence measured at 23 cm on Lifuka (Cummins et al. 2006). Coastal erosion has greatly damaged infrastructure along the western coastline, including the harbour, residential dwellings, a broadcasting tower, a church and the Lifuka hospital; locals attribute this to the earthquake and subsidence. It has been reported that the coastline has receded between 2 m and 11 m at some specific locations. During daily high tides, some the homes are within 2 m of the water and face inundation during strong on-shore winds (Figure 3).

Figure 3: A house that is inundated by waves at high tide

1.4 Climate

Tonga's climate is dominated by south-easterly trade winds. Rainfall is moderate and variable, influenced by the El Nino–Southern Oscillation (ENSO), the South Pacific Convergence Zone (SPCZ), and tropical cyclones. The SPCZ is a low-level wind convergence extending from the West Pacific warm pool south-eastwards towards French Polynesia. Low-latitude easterly trade winds and the higher latitude south-easterly trade winds meet, with associated rainfall. The location of the SPCZ is affected by large-scale atmospheric circulation patterns, ENSO and the Interdecadal Pacific Oscillation.

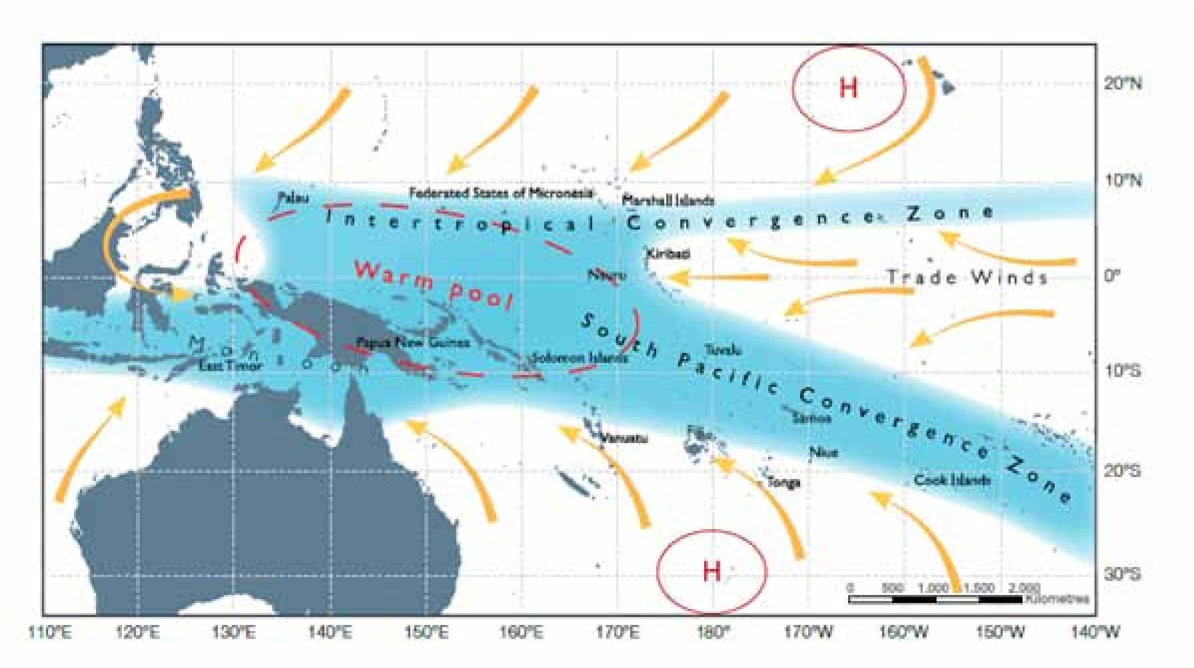


Figure 4: The average position of the major climate features, including the SPCZ, November to April. The yellow arrows show near surface winds, the blue represents the bands of rainfall (convergence zones with relatively low pressure), and the red dashed oval indicates the West Pacific Warm Pool (PCCSP 2011).

Tonga experiences a wet season (November–April) and a dry season (May–October), with about 60%–70% of the rain falling during the wet season (data provided by Tonga Meteorological Services, March 2012). The variation of monthly and annual rainfall over Tonga shows the influence of the SPCZ. The most northern islands of Tonga receive more rainfall (approximately 2,500 mm a year) due to the seasonal proximity of the SPCZ, while the southern islands received about 1,700 mm of rainfall a year.

The Ha'apai group of islands sits in a relatively dry zone and receives less rainfall than southern Tonga – refer to Figure 5. Rainfall in the islands of the Ha'apai group averages about 1,706 mm per year (1947–2011). The rainfall is variable from year to year, ranging from 826 mm to 2,664 mm. Persistent prolonged periods of low rainfall in Tonga are associated with El Niño events. Drought-like conditions can result, and can be severe if the event is strong. The 1997/1998 a strong El Niño event caused drought conditions that affected Tongatapu and Ha'apai.

Records of average monthly rainfall for different islands in Tonga over a 30-year period (1971–2000), show the pattern and variation of rainfall experienced across the island groups (Figure 5). Note that Lifuka (Ha'apai) has the lowest overall average rainfall and correspondingly some of the lowest monthly averages, indicating that it sits in a rain shadow relative to other locations in Tonga.

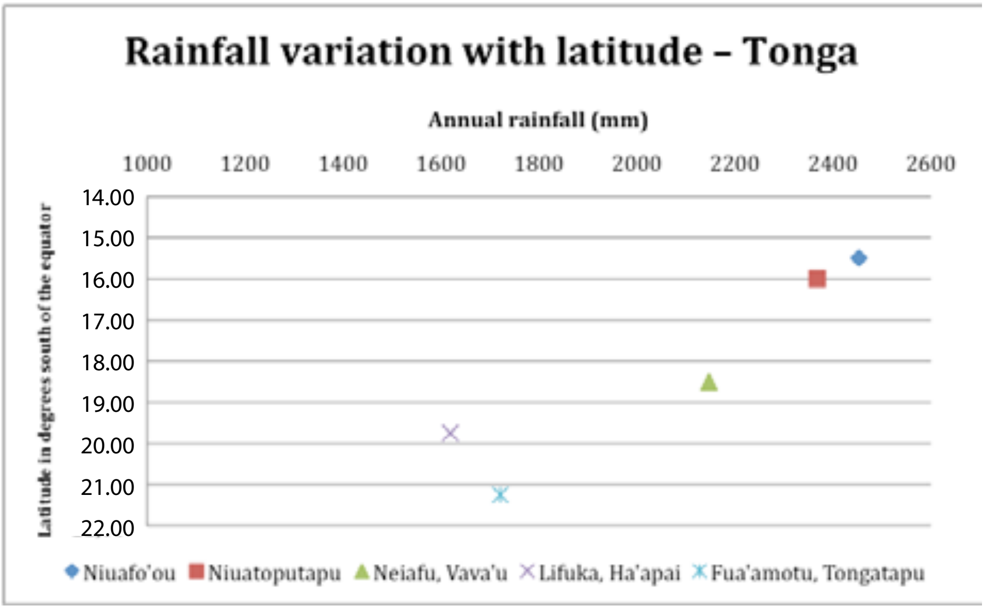


Figure 5: Average annual rainfall for selected stations in Tonga and the variation associated with latitude. Note that Lifuka has the lowest annual rainfall of the stations and is somewhat of an anomaly in an otherwise linear relationship between average annual rainfall and latitude (source: Tonga Meteorological Services, 2013).

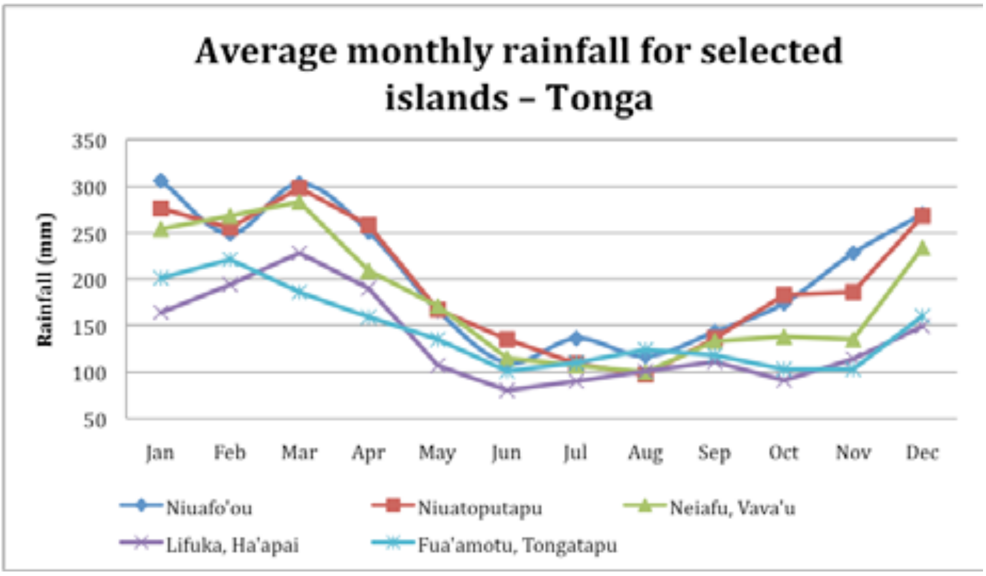


Figure 6: Monthly average rainfall for selected stations in Tonga, 1971–2000 (source: Tonga Meteorological Services, 2013)

Groundwater is used throughout Tonga, and comes from either a relatively thin freshwater lens in the limestone, such as on Tongatapu and Vava'u, or a thin freshwater lens in unconsolidated sediments, such as on Lifuka, Ha'apai.

Rainwater harvesting systems are used to complement groundwater sources; the groundwater has high 'hardness' associated with Tonga's carbonate geology. In most cases, rainwater is preferred for drinking, cooking and washing (Sinclair et al. 2013), with groundwater used for most other purposes and relied on for all needs during extended dry periods.

1.5 Water supply infrastructure

In March 2012, a house-to-house survey of water supply infrastructure was undertaken as part of the Lifuka project. Details on the infrastructure for rainwater harvesting and groundwater abstraction can be found in the report published as part of this series, B 1.6: *Household Survey to Assess Vulnerabilities to Water Resources and Coastal Erosion and Inundation, Lifuka, Ha'apai, Tonga* (Sinclair et al. 2013).

In summary, 92% of households rely on rainwater as their primary drinking-water source. The Tonga Water Board (TWB) provides treated piped groundwater to 68% of all households, mainly for non-potable needs, including toilets, gardening and washing clothing. This highlights the importance of groundwater on Lifuka.

TWB has four sites constructed and equipped to abstract groundwater. Horizontal galleries are found at the Pangai North, Hihifo North (both located in rugby fields), and Hihifo East sites, and a well is located near Hihifo at a site referred to as TWB4. Locations are shown in Figure 7.

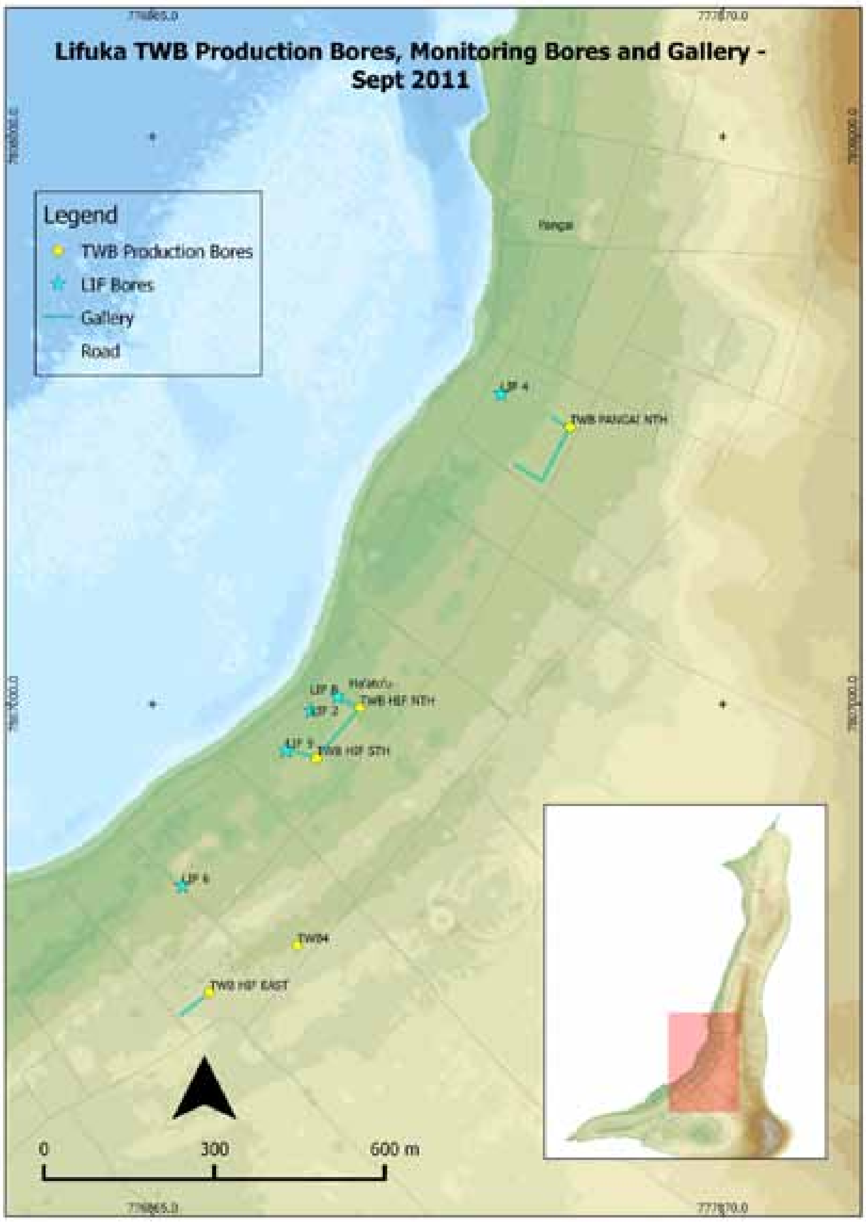


Figure 7: Location of TWB production bores and galleries and LIF salinity monitoring bores

Two of the horizontal galleries (Pangai North and Hihifo North) were completed in 1999, and the Hihifo East gallery was completed in mid-2000 (Falkland 2000). Both the Pangai North and Hihifo North galleries were constructed with two abstraction wells and were originally equipped with a pump for abstraction from each well. Only one of the two original pumps is currently operational at either site, limiting the volume of water abstracted. There is a solar pump operating at Pangai North and an electric pump operating at Hihifo North. The other pumps for these sites have been decommissioned and are awaiting replacement or refurbishment.

A diesel pump is used for abstraction from Hihifo East and an electric pump is used for abstraction at TWB4. At the time of the fieldwork, only one production well site, TWB4, had a working water-flow meter attached for measuring abstraction (Figure 8). Instantaneous abstraction rates from the working meter for TWB4 were measured at 0.46 L/sec., equivalent to an estimated 39.7 KL/day. Water-flow meters purchased under PASAP were fitted to the three unmetered raw groundwater abstraction points to provide information on future abstraction. A flow meter measuring the volume of water leaving the treatment plant was also installed to improve water supply budgeting and to assist in leak detection.

Usage data provided by TWB from the recently installed water meters indicates that a total of 269 KL/day is abstracted from the four TWB abstraction wells. Households are metered for TWB piped water, and they indicate usage of 131 KL/day. This suggests that 51% of total water production is unaccounted for.

Using the metered outflow from the installed bulk meter at the treatment plant, it is estimated that there is a loss of 33% of the total water abstracted. It is calculated that a loss of 13% of total production occurs between the production wells and the treatment plant and a loss of 20% occurs between the bulk meter and the household, with an additional 18% of total production considered unaccounted for at the household level (Table 1).

Table 1: Abstraction data from installed meters

	Volume abstracted, litres					
Pump	**15–16/10/12**	**16–17/10/12**	**17–18/10/12**	**Average/day**	**average L/s**	**% of total abstraction**
Solar Pangai 121	46,774	31,700	39,797	39,424	0.46	16%
Electric pump Hihifo (school) 114	41,539	43,113	40,728	41,793	0.48	17%
Diesel pump Hihifo Gallery East 118	90,126	170,902	135,267	132,098	1.53	52%
TWB4 electric pump 104	40,106	39,216	37,784	39,035	0.45	15%
Total	**218,545**	**284,931**	**253,576**	**252,350**	**2.91**	**100%**

Salinity readings for the piped TWB water received at the tap vary seasonally in response to rainfall and the volumes of water abstracted from each gallery (Table 2). Salinity readings taken during a dry period in September 2011 indicated relatively high salinities at the production wells and at the treatment plant. Salinity readings taken again six months later, in March 2012, indicated a reduction in salinity in response to rainfall. One notable exception is Hihifo Gallery East 118, which is identified as abstracting 52% of the total water abstracted for TWB treatment plant. Salinity levels recorded in the production well for this gallery in September 2011 were 1,758 µS/cm, whilst in March 2012 salinity was reduced to 1,697 µS/cm, a smaller reduction than experienced at the other production galleries and wells. This would suggest that the abstraction rate of 1.5L/s from the gallery may be causing the introduction or upconing of more saline water. Further observation of salinity and usage data is recommended for the production galleries to improve understanding of rainfall and abstraction impacts on the salinity of the water supplied. Consideration should be given to reducing the abstraction rate of Hihifo Gallery East 118 to improve the salinity of the water at the treatment plant at times when salinity is high.

Table 2: Salinity readings from TWB production wells.

Pump	Solar Pangai 121	Electric pump Hihifo (school) 114	Diesel pump Hihifo Gallery East 118	TWB4 electric pump 104	Treatment plant
Salinity Sept 2011 (electrical conductivity [EC] taken at bottom of production well)	3,430 µS/cm	822 µS/cm	1,758 µS/cm	2,436 µS/cm	2,820 µS/cm
Salinity March 2012 (EC taken at bottom of production well)	1,583 µS/cm	669 µS/cm	1,697 µS/cm	1,257 µS/cm	1,565 µS/cm

Figure 8: TWB production well, TWB4, in Hihifo

The water from the four pumping sites is piped to the TWB treatment plant in Hihifo, where it is stored in three 45,000 L fibreglass tanks.

The standard operational procedure for treatment of groundwater is to mix 500 ml of chlorine granules daily into each of the three 45,000 L raw water storage tanks. There are times when the treatment of the water with this volume of chlorine appears insufficient, as indicated by the March 2012 water quality sampling (Sinclair et al. 2013).

The treated water from the connected storage tanks is then pumped via the No. 1 storage tank to the 20 m elevated header tank (22,000 L), which then distributes the treated water via gravity to connected households. The bulk water outflow meter from the header tank was replaced under PASAP, as it was previously non-operational.

Operating procedures at the treatment plant (TWB, Lifuka, personal communication, 2011) require that water-quality samples be taken monthly by TWB staff from operating abstraction wells, the treatment plant, and along the distribution line, to test for levels of free available chlorine (FAC), noting that FAC should be greater than 0.6 mg/L. These collected samples are then analysed in Tongatapu by the TWB water quality officer, who informs Lifuka TWB staff when samples do not meet FAC requirements. We suggest that efficiencies and improved response could be achieved if FAC analysis is performed by Lifuka-based staff. Each household connected to the piped water supply has a water meter, with meters read monthly. TWB charges households a monthly TOP 12.70 service fee and TOP 2.11 for each m^3 of water used. Non-payment can result in disconnection.

1.6 Climate change scenarios predicted for Tonga

The Pacific Climate Change Science Program funded by the Australian Government undertook comprehensive research into the climate and ocean projections for 14 Pacific nations. The projections for temperature, rainfall, and sea-level rise are based on the output from 24 global climate models and the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al. 2007), and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007), focusing on projections for 2030, 2055, and 2090 under high, medium and low greenhouse gas emissions scenarios. The projections and predictions are the result of joint research by the Australian Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (Australian Bureau of Meteorology and CSIRO 2011).

The summary predictions for Tonga indicate the following:

- annual average air temperatures will increase. By 2030 they are predicted to increase by 0.3°–1.0° C (high confidence);
- there will be a general decrease in dry-season rainfall, and an increase in wet-season rainfall (moderate confidence);
- little change is projected in total annual rainfall (low confidence);
- intensity of extreme rainfall and frequency of days on which it occurs are projected to increase (high confidence);
- drought projections are inconsistent;
- tropical cyclones will be less frequent but more intense (moderate confidence).
- Sea levels will continue to rise. By 2030, sea-level rise is expected to be 5–15 cm (moderate confidence). A rising sea level will increase the impact of storm surges and coastal flooding.

With respect to water resources, the most obvious concern is the projected decrease in rainfall during the dry season. This is very likely to result in people relying more heavily on groundwater during dry periods. With corresponding increased temperatures, there is potential for increased usage of groundwater for garden irrigation and non-potable needs.

The rainfall prediction is for little change in rainfall totals, but increased intensity and frequency. The impact on households may therefore include shorter periods in which rainwater can be harvested to be stored, requiring consideration of infrastructure needs such as increased storage capacity or increased guttering and downpipe sizes.

Groundwater recharge is unlikely to be affected if the total volume of recharge is the same – that is, if annual average rainfall remains unchanged. However, the timing of recharge will have an impact on the shape and dynamics of the freshwater lens. If higher recharge is experienced during the wet season then higher discharge can also be expected, and whilst increases to storage will occur, rainfall increases may not be directly proportional to recharge increases. Similarly, reduced rainfall during the dry season will result in reduced recharge, coupled with an expected increase in abstraction. This will have the effect of causing greater draws on the limited groundwater in the lens and increased frequency of periods of higher-salinity water being delivered through the piped TWB system during dry periods.

1.7 Previous investigations

There have been a number of water resource investigations on Lifuka: Pfeiffer and Stach (1972), Waterhouse (1984), and Lao (1986).

In 1984, Waterhouse commented on the limited water supplied from the limestone using the existing TWB wells, and the potential for groundwater contamination from land-based activities. Lao (1986) undertook a more comprehensive assessment of the groundwater resources on Lifuka. He found that, on pumping the TWB wells in the limestone, the groundwater in these wells quickly became brackish. His investigation of some of the domestic wells in the unconsolidated sediments indicated different tidal responses in wells, which led him to propose a two-aquifer system, a limestone or 'basal aquifer' and a shallow unconsolidated 'coastal aquifer'. He concluded that the limestone aquifer has meagre potential for supplying low-salinity water for distribution, and recommended a moratorium on the development of groundwater from the limestone, with additional monitoring to determine the impact of the abstraction and how to optimise this abstraction without compromising water quality. He suggested the use of a horizontal infiltration gallery to skim the fresh water from the very top of the lens.

Stoll (1987) drilled three test wells to assess the thickness of the freshwater lens, concluding that over the main part of the island, the lens was either a few metres thick or entirely absent. Stoll's monitoring of water levels in the water supply well in the limestone showed a tidal response of 0.3 m. However, in a private well in the village close to the sea, within the sediments, the fluctuation was only 0.2 m. Stoll's results indicate that different hydraulic parameters and geology were present, with implications for groundwater development.

Falkland (1992) carried out a comprehensive water resources report as part of the Tonga Water Supply Master Plan Study. His report detailed previous investigations and provided a useful assessment on recharge using a water-balance approach. For Ha'apai, Falkland (1992) estimated recharge to be 28% of annual rainfall (478 mm), and provided a preliminary sustainable yield estimate. Falkland referred to investigations, including geophysics undertaken by Furness and the Tonga Hydrogeology Unit in 1991, with a comment on future investigations.

Furness, 1993, using the results of electromagnetic conductivity surveys using an EM34 instrument in 1991, and including comparisons with a study by Vacher (1978), concluded that a two-aquifer system was present: the coral limestone and the weakly lithified sand aquifer, with each aquifer having markedly dissimilar properties. Sand, being less permeable, is able to generate a thicker lens of fresh water. EM34 traverses across the island allowed the delineation of a dual aquifer system, and mapped the extents and boundaries of sands and coral limestone which corresponded to the soil mapping of Wilson and Beecroft (1983). Furness went on to recommend that a series of 12 wells be developed in the coastal sand aquifer to provide up to 528 KL per day. Even at this stage, Furness was concerned about the potential for contamination from pit latrines and rubbish dumping, and recommended the installation of wells at the periphery of the villages near the aquifer boundary. These 12 wells were drilled and installed on his recommendations (Figure 9).

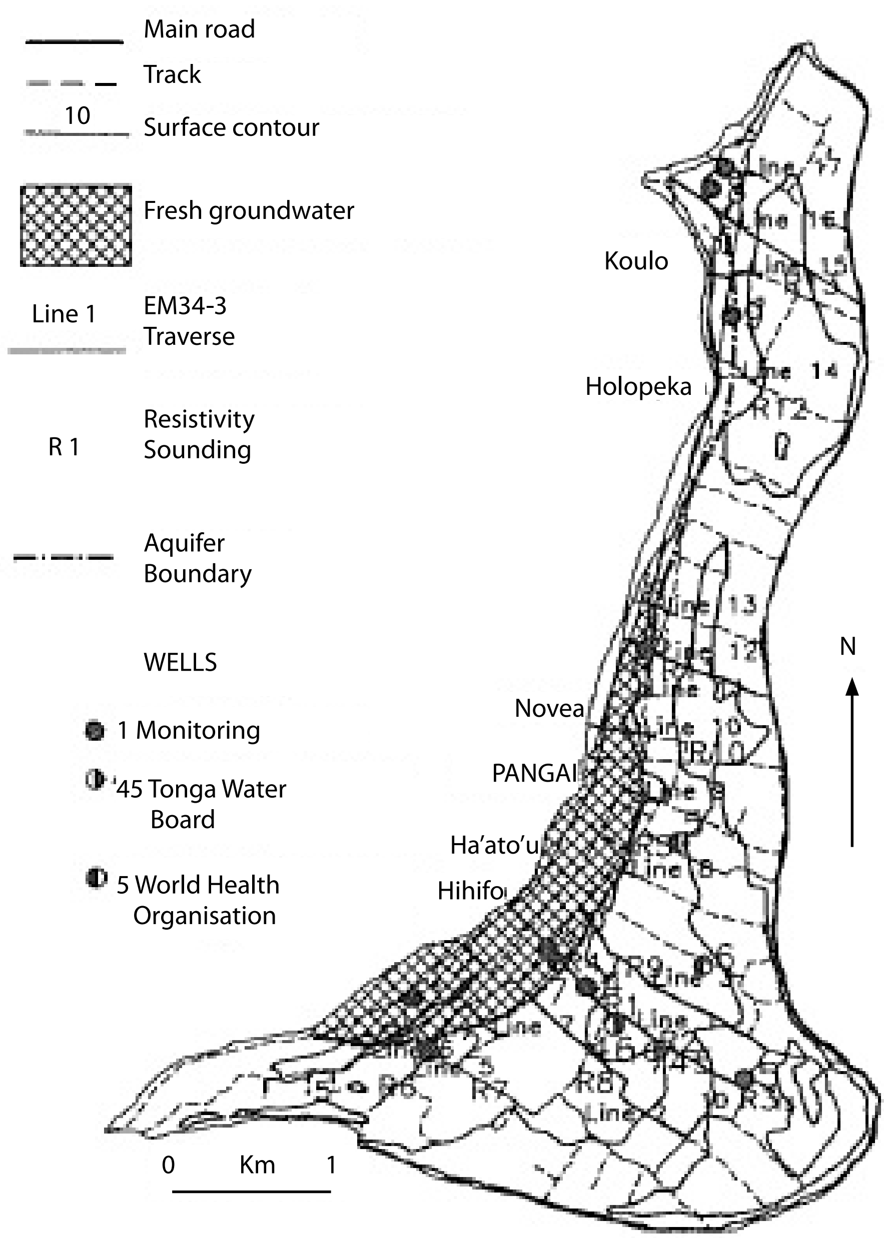


Figure 9: Hydrogeology of Lifuka Island (modified from Furness 1993)

Falkland (1997, 1999) undertook further groundwater investigations, confirming the freshwater lens and its potential as a water supply, which resulted in a water supply improvement project in the late 1990s. This included the construction of two 200 m-long, 4 m-deep U-shaped infiltration galleries at Pangai and Hihifo and the installation of nine monitoring bores for salinity monitoring (Turner 1998).

Figure 10: Location of old and new production wells and galleries (Falkland 1999)

Crennan (2001) undertook investigations into groundwater pollution on Lifuka, using tracers to investigate contamination and determine a safe distance for wells from possible contamination sources such as septic tanks. Crennan concluded that faecal contamination was present in most wells and that there was no safe distance between wells and toilet facilities; rather, she concluded that the density of toilet facilities or effluent loading was an important consideration in terms of contamination.

2. Field Investigations

This section presents the results from water resource assessment investigations using geophysics and bore monitoring. Investigations were undertaken jointly by SPC and MLSNRECC geology staff between September 2011 and October 2012.

2.1 Objective

The 2006 earthquake and subsequent subsidence of Lifuka provides a unique opportunity to assess the impact of a sea-level rise of 23 cm on the groundwater water resources in a low-lying atoll-type island setting. It is worth noting that this subsidence caused a relative sea level rise on the island equivalent to 39% of that predicted to result from climate change by the year 2100 (based on IPCC 2007 estimates).

The fieldwork was designed to investigate:

- how the groundwater responded to this apparent rise in sea level;
- the potential impact of the rise in sea level on the use of the freshwater lens, including effects on existing groundwater abstraction infrastructure, infiltration galleries, and wells;
- the potential for additional groundwater resources and future groundwater abstraction; and
- the impact of contamination from current land-use activities.

The investigation drew on the resources and staff of SPC, MLSNRECC and TWB. The objective was to provide technical information to the government and the community on the vulnerability of the groundwater resources of Lifuka to sea-level rise and other impacts, and to identify adaptation options to reduce this vulnerability.

2.2 Investigation approach

The proposed investigation techniques to assess the impact on the freshwater resources from the rapid rise in sea level and the projected climate changes included:

- a review of existing investigations and information sources;
- geophysics, including electromagnetics, and electrical resistivity;
- salinity monitoring on existing boreholes;
- installation of flow meters for groundwater abstraction galleries; and
- a survey of rainwater and groundwater infrastructure to meet potable and non-potable water needs.

Electromagnetic (EM) surveys that measure ground conductivity have been successfully used on Lifuka and other atoll islands to assess the thickness of the freshwater lens and to map the freshwater and saltwater boundary (Furness 1993; Falkland et al. 2003). Vertical electrical resistivity soundings (VES) have also been used with some success in the past (Scott 1999).

An EM34 conductivity instrument, in combination with a SuperSting resistivity meter, was used to determine the freshwater/saltwater boundary and freshwater lens thickness to identify extents of the resource boundaries.

Monitoring bores installed in 1999 that had not been sampled since 2001 were used to guide the calibration of the geophysics and to monitor the changes in salinity of the lens over time.

Flow meters purchased under the project were installed on all TWB pumping wells and galleries to measure the rate of abstraction and the volume of water abstracted, and to identify the reliance of the overall water supply on each well and gallery and its potential impact on the lens.

A survey and review of existing rainwater harvesting and domestic wells, and of water quality, was useful to determine reliance, preference and potential impact of sea-level and climate changes and inundation events.

2.3 Geology – Lifuka

A review of the available literature allowed a geological conceptual model to be constructed during the investigations.

Furness (1993) described the geology of Lifuka. He wrote that it is: ‘low-lying and consists of a highly porous, uplifted coral ... the higher parts of the island is a volcanic ash soil (andesitic tephra), up to 3 m thick … the western coast area has a younger deposit of shelly, coral sand which is weakly consolidated to a maximum thickness of about 5 m.’

Dickinson et al. (1994) suggest the originally subhorizontal reef flats are now tilted locally to slopes of 0.005–0.01 (5–10 m per km).

Uplifted reef material is covered by a blanket of andesitic tephra. The tephra deposits include at least two thick ash falls, or two groups of related ash-fall deposits. The younger tephra layer, weakly or moderately weathered to reddish-brown soil, is approximately 1.5 m thick in the study area (Foa and Lifuka islands), while the underlying older tephra layer is more strongly weathered to yellowish-brown tints (after Wilson and Beecroft 1983).

Dickinson et al. (1994) propose a model of uplift, erosion and sea-level changes to account for the erosive and accretionary geological setting found on Lifuka. A conceptual diagram of the processes proposed by Dickinson et al. is presented in Figure 11.

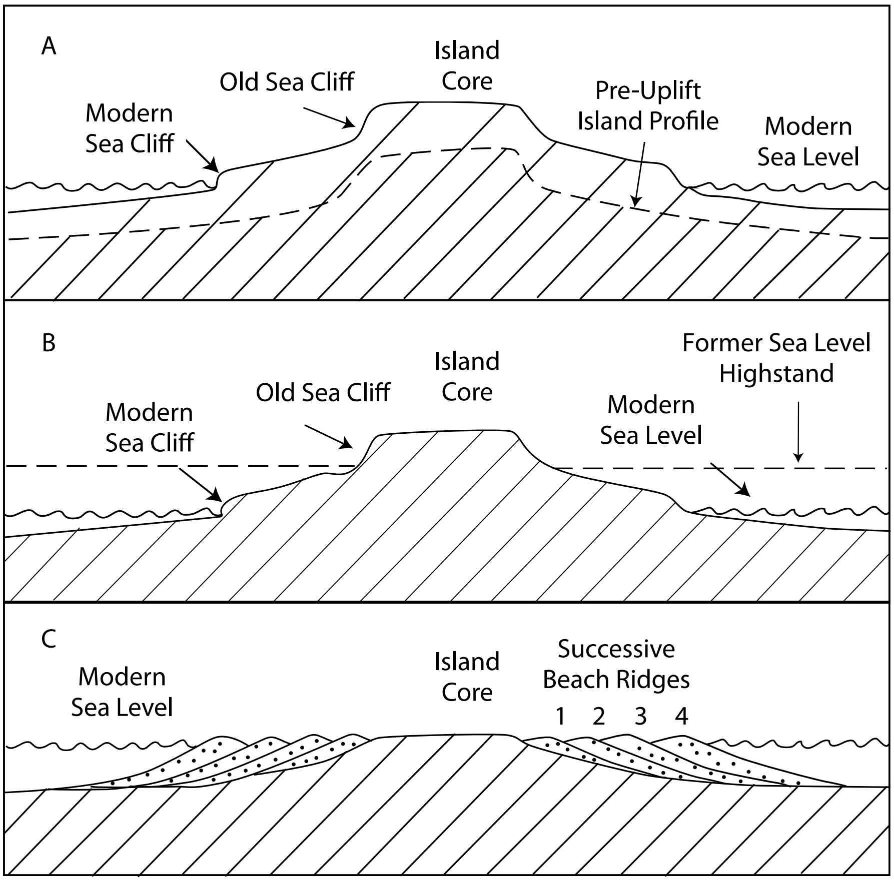


Figure 11. Schematic of potential geologic processes proposed by Dickinson et al. (1994). A and B indicate uplift and relative sea-level decline, resulting in an exposed old sea-level bench and an erosive exposed reef flat (Holocene). C indicates accretion with or without sea-level change. It is suggested that this model of tectonic uplift and subsidence with relative changes in sea level would help account for the geology and the accretion of the sediments in the western portion of Lifuka.

Dickinson and Burley (2007) provide a model in which the estimated uplift of the islands along the Tonga platform took place in response to the subduction of the Louisville Ridge. It suggests that uplift of Lifuka occurred about two million years ago (Ma) (Figure 12).

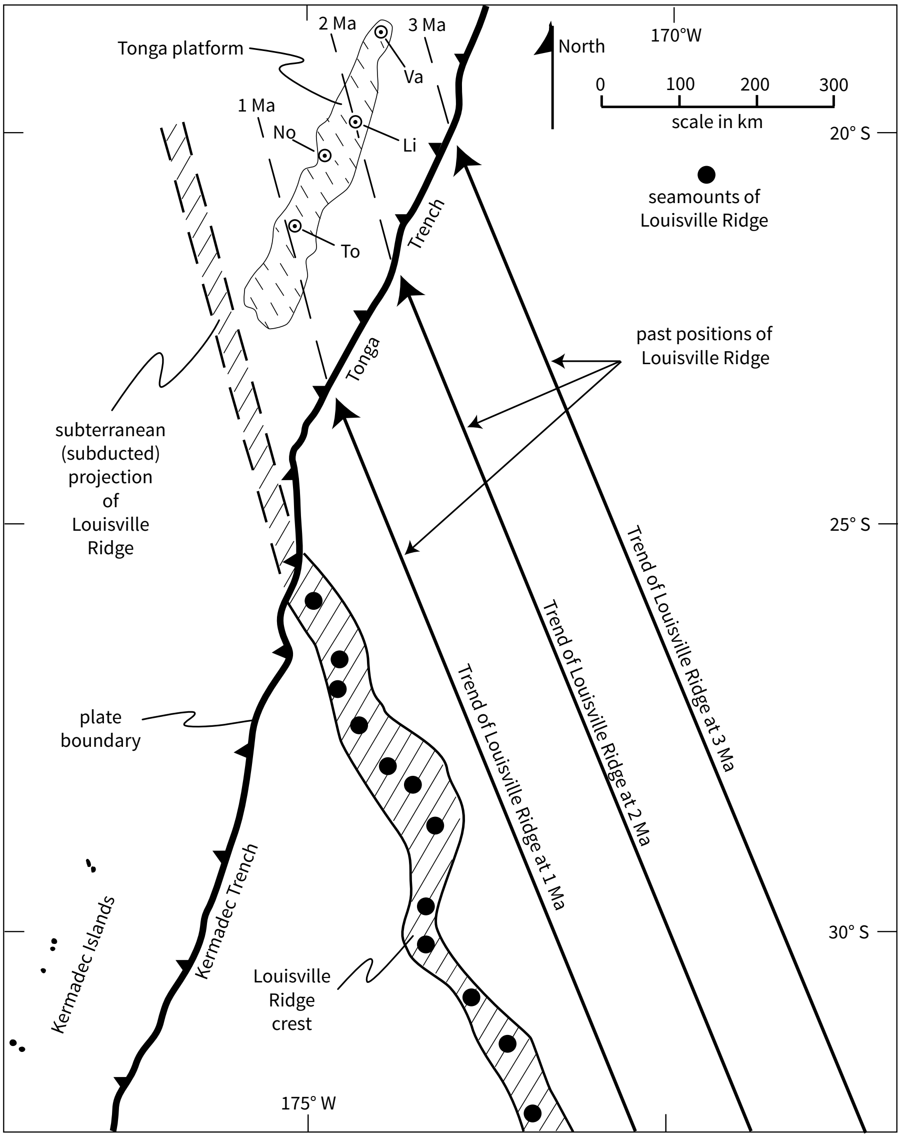


Figure 12: Relation of forearc uplift of Tonga platform to subduction of Louisville Ridge at Tonga Trench, proposed by Dickinson and Burley 2007. Selected islands and estimated timing of their uplift due to subduction of Louisville ridge. Va = Vava'u; Li = Lifuka; No = Nomuka; To = Tongatapu (Dickinson and Burley 2007).

Drill logs from Turner (1998) indicate that the sediments in the western portion of Lifuka extend down to 19 m in some areas (LIF1) before intersecting the limestone.

There is also some evidence of the tephra deposits in Turner's drill logs. The younger tephra deposits found on the surface (Dickinson et al. 1994; Wilson and Beecroft 1983) with depths in the coralline sands of 0.5–2 m thick are underlain by silty gravelly sands. The older tephra deposits referred to by Dickinson et al. (1994) are indicated to be about 1 m thick at a depth of about 12 m below the surface (LIF 6, LIF 1, LIF 2). Beneath the older tephra deposits are silty gravelly to silty clayey sands, which continue down to the limestone. These silty gravelly sand sediments contain the freshest and thickest groundwater resources located on Lifuka and are underlain by weathered limestone. Drill logs from Turner are found in Annex 2.

Using bore logs from Turner (1998) in combination with topographical data derived from LiDAR (light and radar – a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light), a schematic conceptual cross-section for Lifuka has been constructed (Figure 13).

Schematic geological cross sections

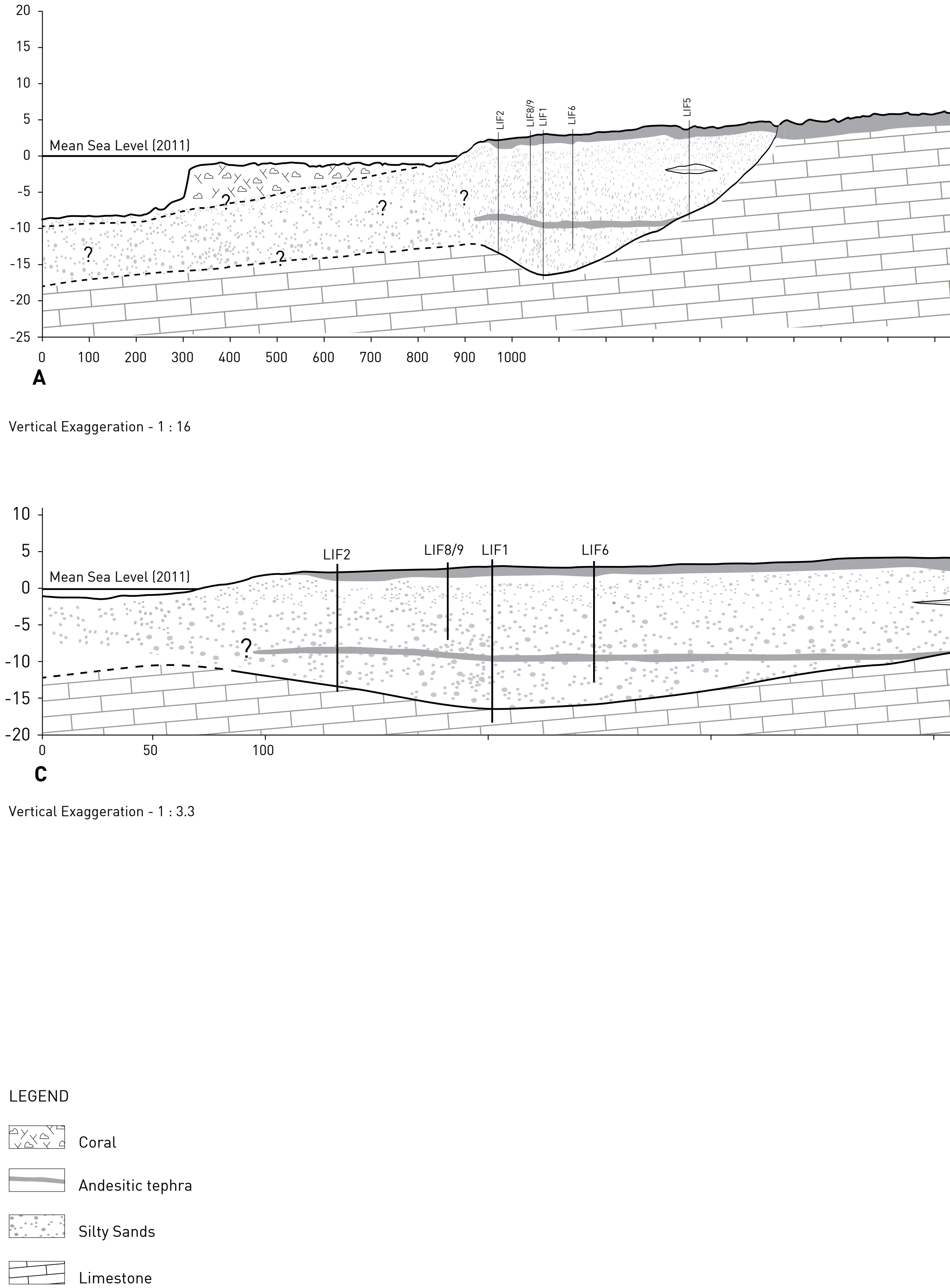
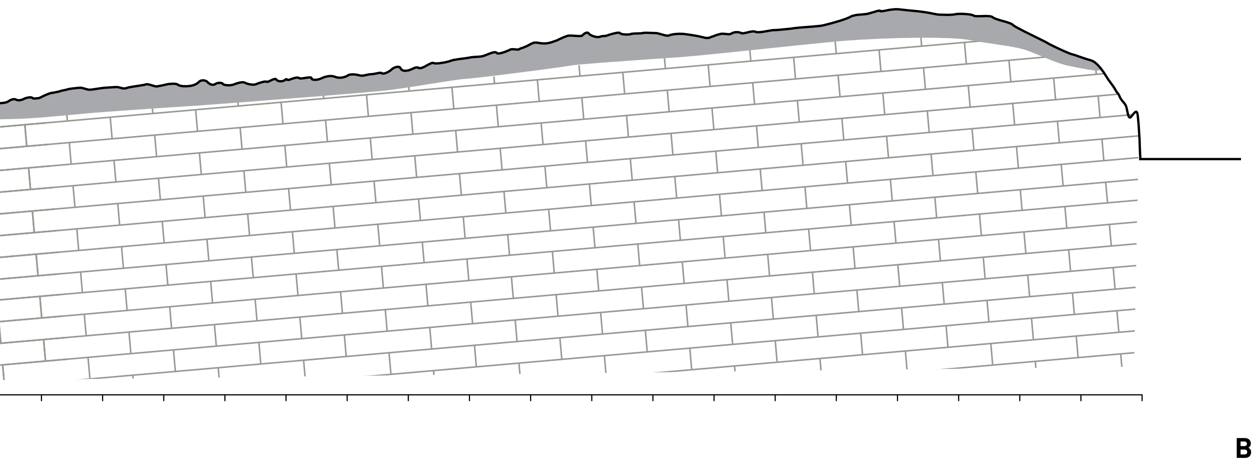
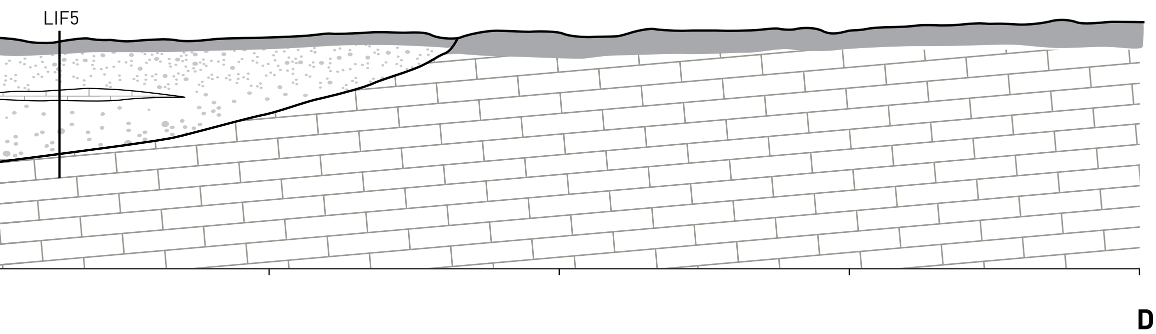
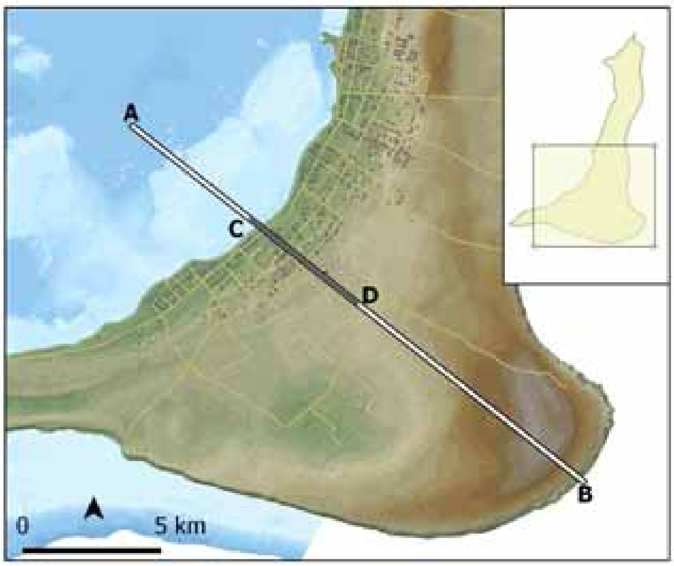


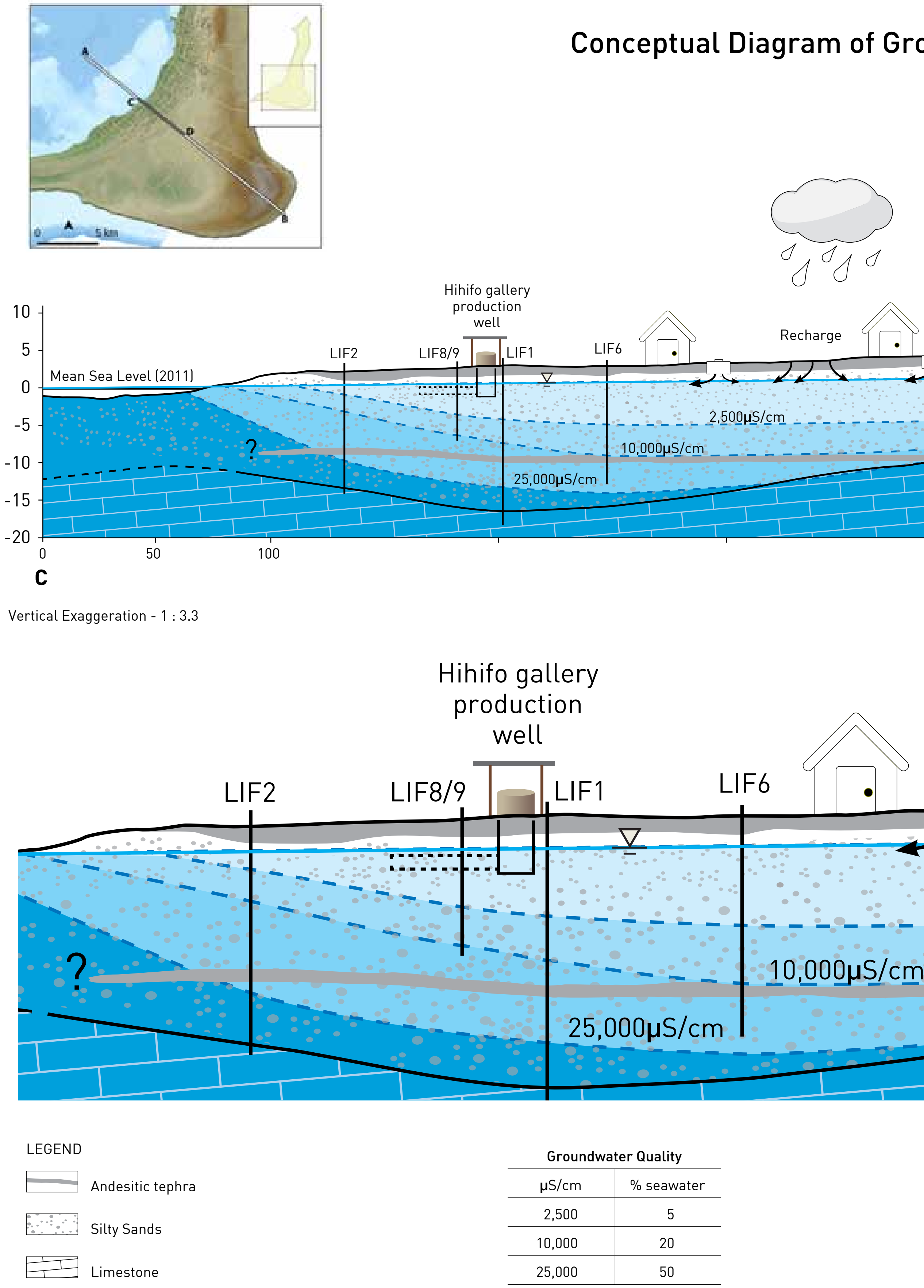
Figure 13: Schematic geological cross-section of Lifuka

Lifuka – Northwest - Southeast







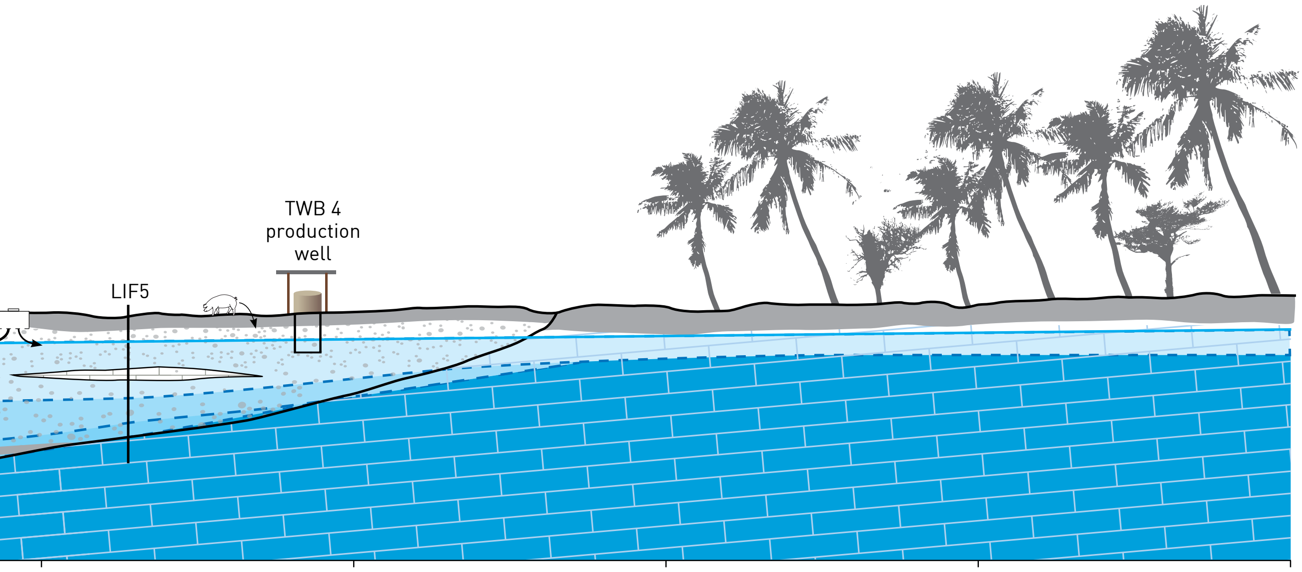


Groundwater Quality

µS/cm	% seawater
2,500	5
10,000	20
25,000	50

Figure 14: Conceptual diagram of groundwater resources on Lifuka

oundwater Resources, Lifuka



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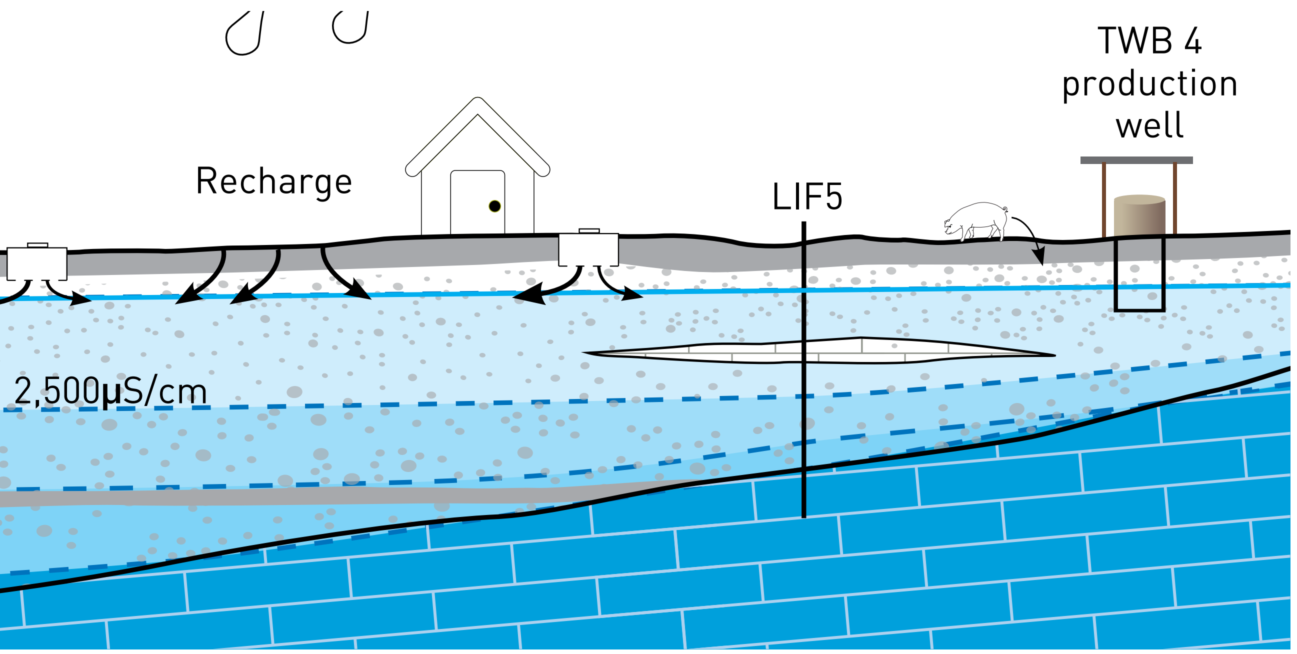


The work of previous investigators has been used to construct a geological history and cross-section for the sequencing of the tectonics and sedimentation.

- Tongan islands formed in between the Tofua volcanic arc and the Tonga Trench are composed of Quaternary limestone (Dickinson and Burley 2007).

- In response to the subduction of the Louisville Ridge, approximately 2 Ma, the atoll of Lifuka was uplifted (Dickinson and Burley 2007) by an estimated 15–20 m (current high point), with development of a wave-cut cliff on both the eastern and western sides. It is suggested that the tilting of the island to the west occurred over a period of time, allowing the development of the wave-cut profile proposed for the western side of the island.

- During the mid-Holocene, in a context of retreating sea levels globally and highstands for the South Pacific, sea levels were estimated to be 1–2 m above modern mean sea level before they began to retreat. This suggests that the multiple accretionary beach ridges of sandy silt sediments occurred during the middle to late Holocene, according to Dickinson et al. (1994). The periods of discrete accretion of sediments are supported by the discrete tephra and andesitic ash deposits present as horizontal marker beds in the drill logs. Dickinson et al. (1994) refer to the two tephra deposits, the younger deposits being found on the surface across much of Lifuka, the older being found in the middle to late Holocene sediments.

2.4 Hydrogeology - Lifuka

Previous investigators established that the most promising groundwater resources are to be found in the sediments on the western portion of Lifuka, under the existing township. The focus of the groundwater investigations for this study was constrained to the thicker unconsolidated sediments found on the western side of Lifuka, where geological conditions provide the greatest potential for fresh groundwater resources.

The limestone of the island, with observed fresh groundwater restricted to a thickness of 1–2 m, indicates high permeability and may be karstic in places, as indicated by the observed high connectivity with the ocean and the lack of any significant fresh groundwater lens.

The Holocene sediments appear to be up to 19 m thick in places and composed of fine to coarse coralline sands with some larger coralline gravels within. Silty or clayey sediments associated with the andesitic tephra ash falls are observed 10–12 m below the surface. The borehole logs of Turner (1998) and the relative thinness of the freshwater lens suggest that the sediments are moderately permeable, which can restrict the formation of a freshwater lens. Highly permeable sediments allow for greater hydraulic connection and mixing of the freshwater with the underlying seawater, resulting in a thinner freshwater lens.

A conceptual diagram of groundwater resources for Lifuka was constructed to indicate the lens thickness and the processes (Figure 14).

2.5 Electro Magnetic Survey Investigations – EM34

EM34 surveys are an efficient way to survey a relatively large area to identify brackish and freshwater boundaries and estimate freshwater lens thickness on atolls. A detailed description of the EM34 methodology is provided by Falkland (2004). The measured apparent conductivity is related to an effective freshwater thickness by calibrating the EM data against measured freshwater thickness using multi-level salinity monitoring bores, as found on Lifuka, allowing an estimation of the freshwater lens thickness to be determined. The principles of EM34 are described in Annex 3.

The EM34 surveys on Lifuka used the transmitter and receiver coils in the horizontal dipole mode (vertical coil orientation) using coil spacing of 10 m and 20 m. The effective depths of exploration at these coil separations are approximately 7.5 m and 15 m respectively (McNeill 1980).

A total of approximately 20 surveys were completed predominantly in Hihifo and Pangai to help map the current extents of the groundwater resource and investigate areas considered favourable for future groundwater abstraction (Falkland 2011, pers. comm).

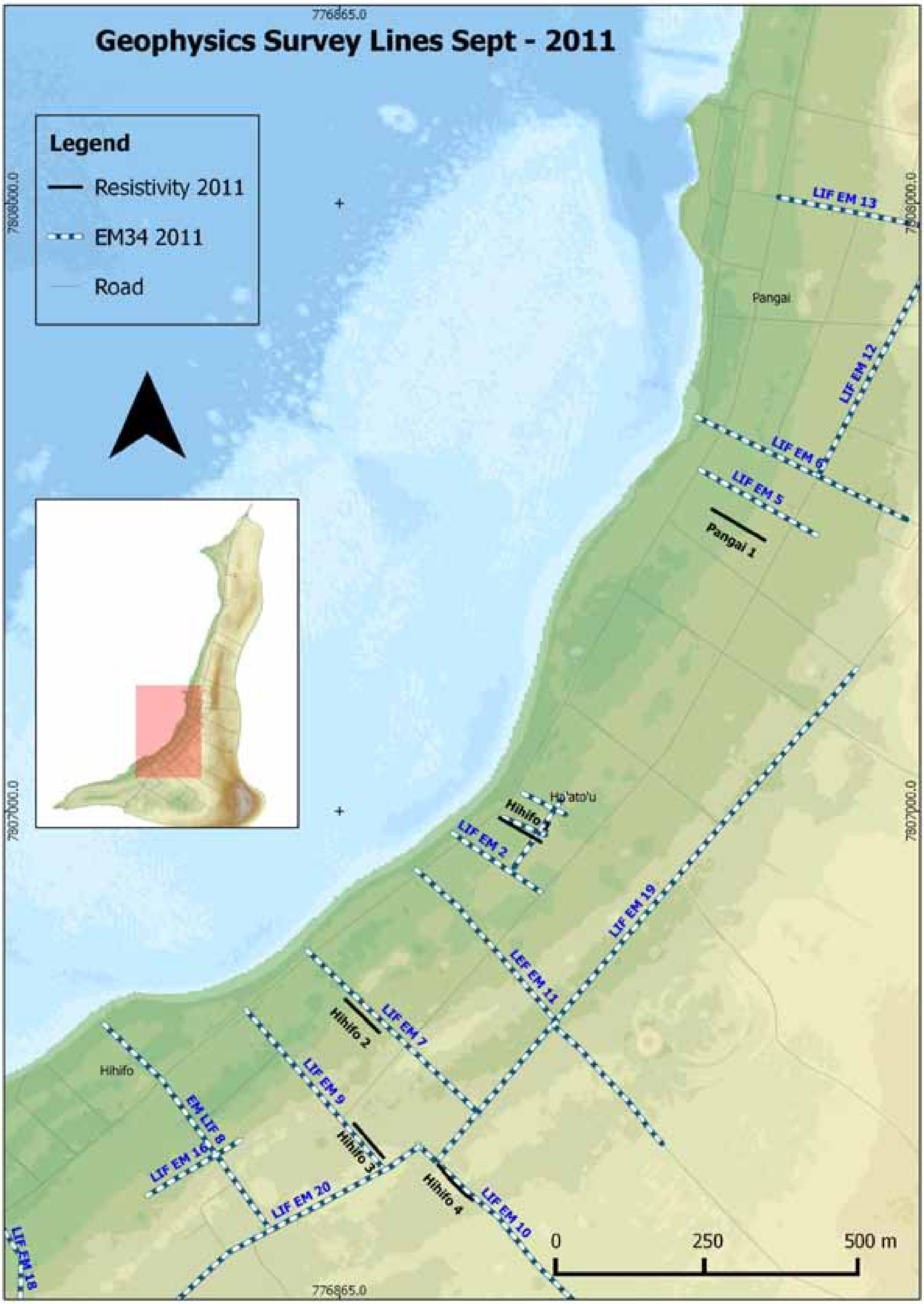


Figure 15: Location of geophysical surveys in Hihifo, Lifuka.

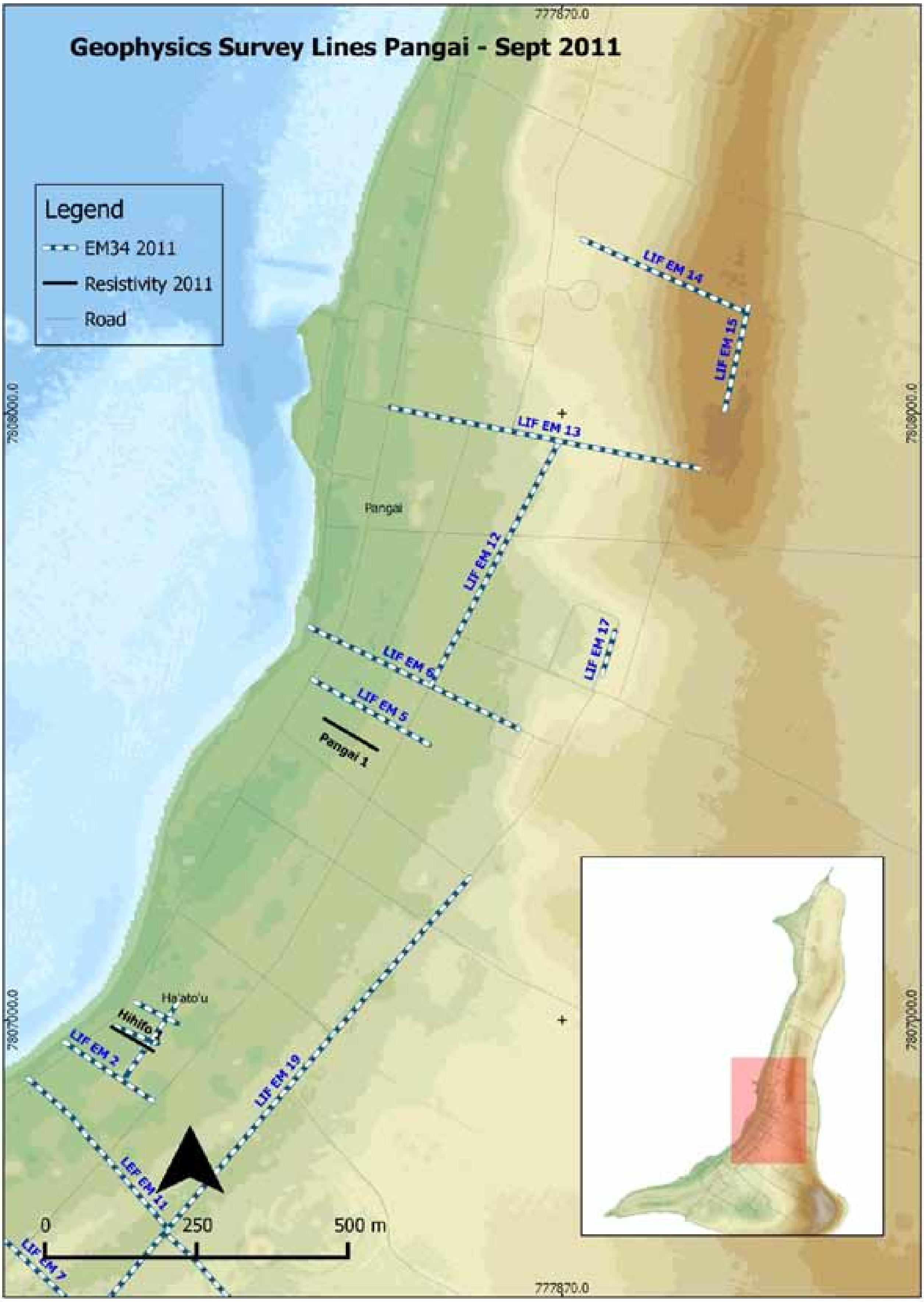


Figure 16. Location of geophysical surveys in Pangai, Lifuka.

The locations of the geophysical surveys undertaken in Hihifo and Pangai are shown in Figures 15 and 16. The surveys were conducted along roads or open spaces that were accessible (Figure 17).

The EM conductivity results for the two preferred spacings (10 m and 20 m) are presented in Annex 5.

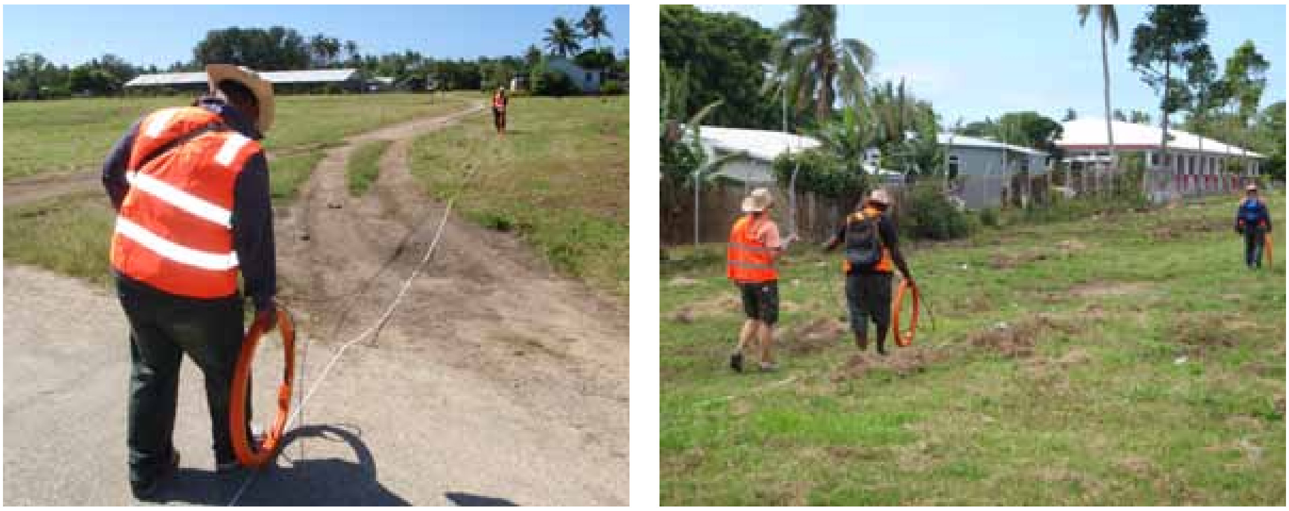


Figure 17: EM transect across the Hihifo oval (left) and across the Pangai rugby field (right).

2.5.1 Methodology

To improve the confidence in the interpretation of the EM34 readings, the resulting conductivity data are calibrated against known ground conditions. Data from monitoring bores with salinity information at different depths were used to help guide the interpretation of the EM34 readings.

A relationship between EM34 conductivity readings and freshwater lens thickness measured from the multi-level monitoring borehole on Lifuka can be made, based on a depth to known salinity (2,500 µS/cm freshwater limit) and the conductivity reading for the 10 m and 20 m horizontal dipole coil spacings. The resulting relationship can be used to then estimate the freshwater lens thickness in other survey lines for similar ground conditions. It should be noted that, due to the relatively thin nature of the freshwater lens, these calculations are estimations only.

The relationship between EM34 readings for both 10 m and 20 m coil spacings for the horizontal dipole, adjacent to the salinity monitoring bores, and the freshwater lens thickness obtained from salinity monitoring are shown in Table 3.

Table 3: Comparison of EM results and freshwater lens thickness.

Date	Borehole	Borehole monitoring data	EM conductivity (mS/m)	
		Freshwater lens thickness (m)	10 m coil spacing (HD)	20 m coil spacing (HD)
Sep-11	LIF2	2.1	54.9	120
Sep-11	LIF4	1.20	62.8	116
Sep-11	LIF6	4.1	39.5	73
Sep-11	LIF8	3.9	30.9	71
Sep-11	LIF9	4.1	28	89

Figure 18 plots the points, curve and the equation of best fit to the data (using logarithmic relationships). The (R^2), measure of the 'goodness of fit', is also shown for each spacing. The curve for the 10 m coil spacing gives a better fit to data than the curve for the 20 m coil spacing data, as shown by the R2 values of approximately 0.89 and 0.74 respectively.

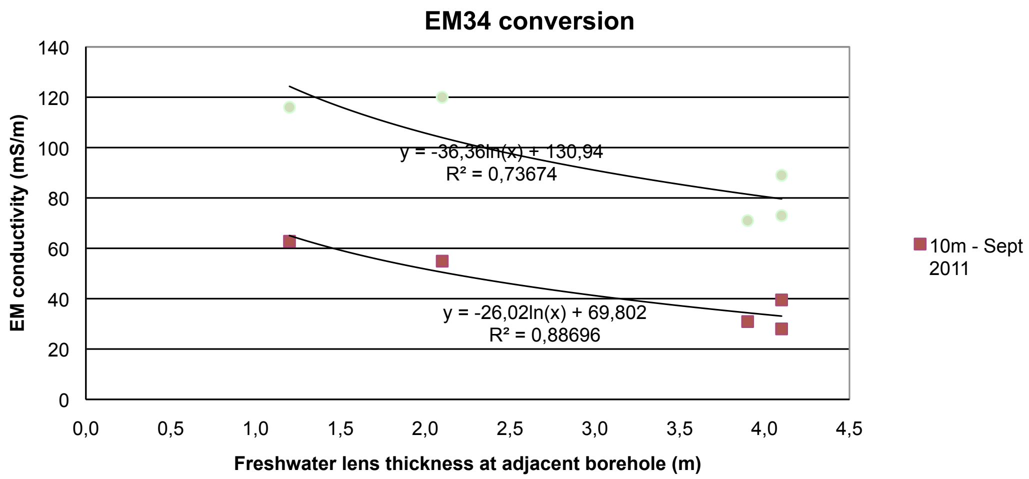


Figure 18: Relationship between EM readings (mS/m) and freshwater lens thickness (m).

Using the curves of best fit in Figure 18, the approximate thickness of freshwater lenses can be estimated from the EM survey data. These are summarised in Table 4 for the selected freshwater zone thickness. Due to the limited number of calibration points and the thin nature of the lens, extrapolation of the EM34 readings was required for the lower conductivity values from the EM34 and thicker parts of the lens.

Table 4: EM conductivity for selected freshwater zone thickness.

Freshwater zone thickness	EM conductivity (mS/m)	
(m)	10m coil spacing	20m coil spacing
1	70	131
2	62	120
4	54	109
6	50	103
8	46	98

2.5.2 Results

The results from the EM34 survey, which are presented in Annex 5, were hand-contoured to produce a freshwater lens thickness plan for the area showing the estimate of fresh groundwater resources (Figure 19). The survey was taken in September 2011 towards the end of a dry period when the lens was thin, and therefore it is likely to be conservative. Due to the dynamic nature of the groundwater system and the observed response to rainfall, the thickness of the lens will vary over time.

The conductivity readings from the EM34 survey are higher than expected, suggesting some concern over the calibration of the instrument at the time of the survey. The readings from Lifuka did not correlate as well as was expected with other sites of similar geology and hydrogeology, such as Bonriki, Tarawa. Whilst the readings provide a relative assessment of conductivity between sites within the study area and are correlated against known boreholes, they may underestimate the freshwater lens thickness and therefore be conservative.

The resulting map of freshwater thickness (Figure 19), whilst conservative, remains a useful guide for future groundwater development and protection. The area to the north of Pangai near the high school playing fields holds promise for additional groundwater development. Consideration should be given, after supplementary investigation, to constructing an additional horizontal gallery here for groundwater abstraction.

It is noted that a conductivity high was identified during the EM34 survey, as indicated in Figure 19. This anomaly is not easily explained and could be the result of a geological or hydrogeological feature – possibly raised limestone, which has resulted in a thinning of the freshwater lens, or is possibly due to instrument calibration issues. It is recommended that prior to the construction of a gallery in this area this high conductivity anomaly be accounted for with additional investigation.

The northern area of Pangai is also favourable from the perspective that the current land-use activities, a high school and playing fields, are considered to present a low contamination risk and are more easily managed with regard to contamination risk than other areas of Lifuka.

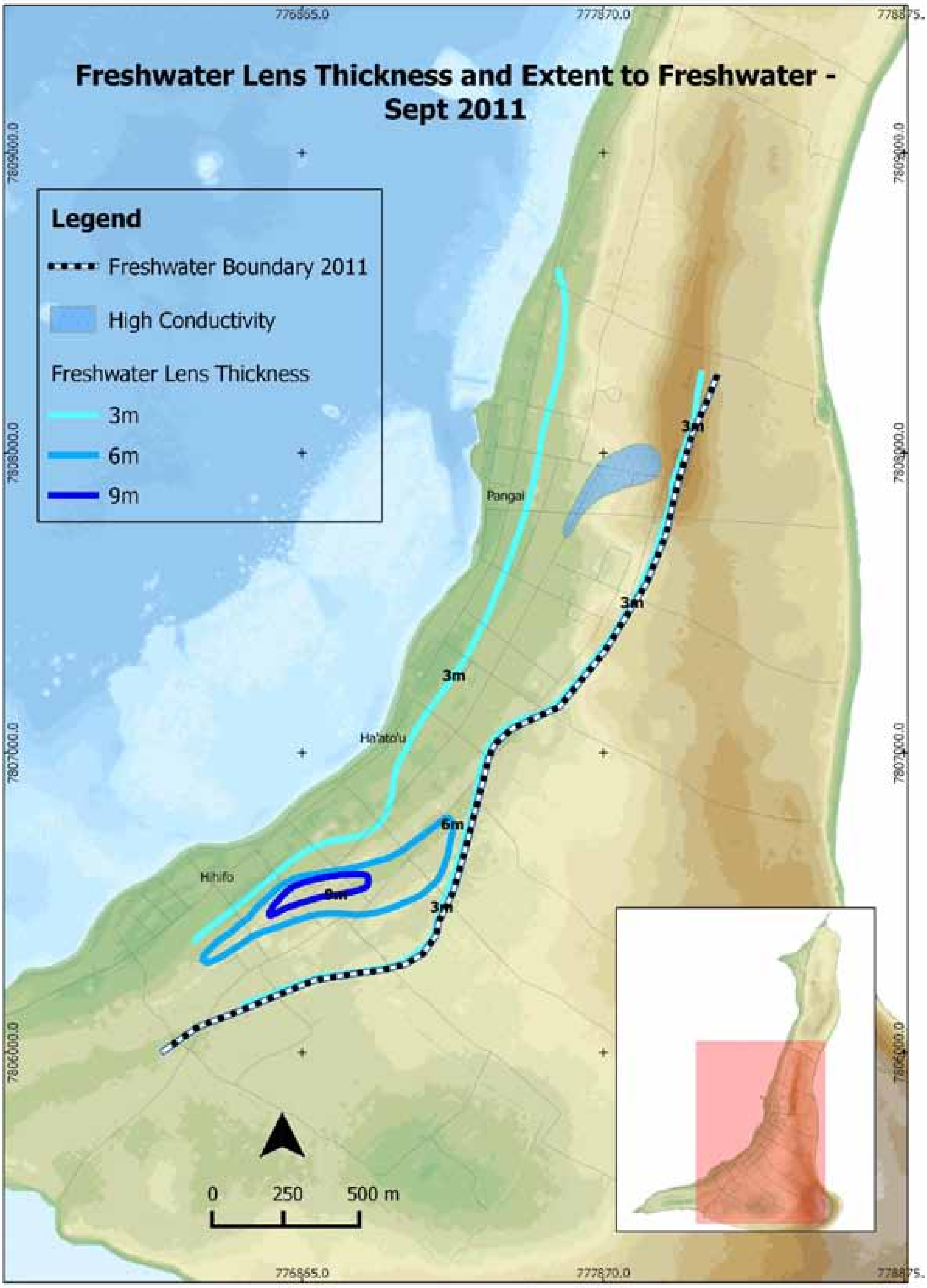


Figure 19. Estimated freshwater lens thickness from EM34 survey, Lifuka, Ha'apai September 2011. Contours represent the thickness of the freshwater lens to 2,500 µS/cm.

2.6 Electrical resistivity profiling investigations

Electrical resistivity profiling involves the measurement of the apparent resistivity of soil and rock as a function of depth over a section to provide a profile of apparent resistivity which allows interpretation of the geology and hydrogeology of the subsurface. The resistivity of soils is a function of porosity, permeability, ionic content of the pore fluids, and clay mineralisation. Resistivity is a geophysical technique that can be used to determine groundwater targets and is useful in determining freshwater lens thickness and saline intrusions.

Resistivity profiling using a SuperSting R1/IP with 56 electrodes from Advanced Geophysics Inc. allows a profile to be constructed using a number of different user-selected arrays and spacings. In Lifuka, a dipole–dipole array with 56 electrodes was predominantly used. A description of resistivity is provided as Annex 4.

This section presents the results of the resistivity surveys undertaken to investigate the groundwater thickness on Lifuka. Resistivity surveys depict the resistivity variation through the survey profile. Furness (1993) carried out electrical resistivity studies on Lifuka within the coral limestone area. His results indicated no development of a freshwater lens of any measurable thickness within the limestone.

Scott undertook some resistivity investigations on Lifuka in 1999, using both an offset Wenner array and a Schlumberger array. His results indicated the difficulty in clearly identifying an intermediate layer of fresh water when its thickness is less than the thickness of the overlying unsaturated zone.

2.6.1 Methodology

Resistivity profiling using the SuperSting was undertaken in September 2011.

The locations of electrical resistivity surveys on Lifuka are shown in Figure 15. Of the five surveys undertaken, four were done in Hihifo and one in Pangai. In most cases, the surveys were conducted along the road, near TWB production wells and salinity monitoring bores. The resistivity surveys were used to provide additional information on the shape of the freshwater lens and the potential impact abstraction may be having on the lens.

The spacing between electrodes for the five surveys was 1.5–2.0 m (Figure 20). Dipole–dipole arrays were used and results were calibrated against available monitoring bores where possible.

Figure 20: Resistivity surveys on Pangai rugby field (left) and Hihifo oval (right)

2.6.2 Results

The results from the resistivity surveys helped confirm the thickness and shape of the freshwater lens. It can be seen from the following resistivity profiles (Figures 21–25) that at the time of the survey the lens was very thin.

The top of the water table is indicated as the base of the high resistivity response, which appears to be at, or just above 0 m elevation. Below this, it is clear that the lower resistivity of the fresh water can be seen as a sloping wedge from the seaward western side towards the east in profiles HIHIFO RES 1, HIHIFO RES 2, and PANGAI RES 1, underlaid by very low resistivity values, indicating seawater. These profiles represent the sandy, silty sediments containing a thin, freshwater lens overlying brackish water that thickens as you go to the west before reaching the limestone. The lens thickness is estimated from the resistivity profiles produced and indicated in Table 6.

Table 6: Estimated freshwater lens thickness from resistivity profiles.

Resistivity profile name	Freshwater lens thickness estimate (m) (approx. 20 m from westward end of profile)	Freshwater lens thickness estimate (m) (approx. 20 m from eastward end of profile)	Resistivity range Ohm m for fresh water
HIHIFO RES 1 – silty sands (1.5 m spacing)	1.5	1.8	33–235
HIHIFO RES 2 – silty sands (1.5 m spacing)	1.0	2.9	28–387
HIHIFO RES 3 – silty sands (1.5 m spacing)	2.9	4.4	34–315
HIHIFO RES 4 – silty sands – limestone (1.5 m spacing)	3.0	2.8	32–280
PANGAI RES 1 – silty sands (2.0 m spacing)	1.9	2.9	56–622

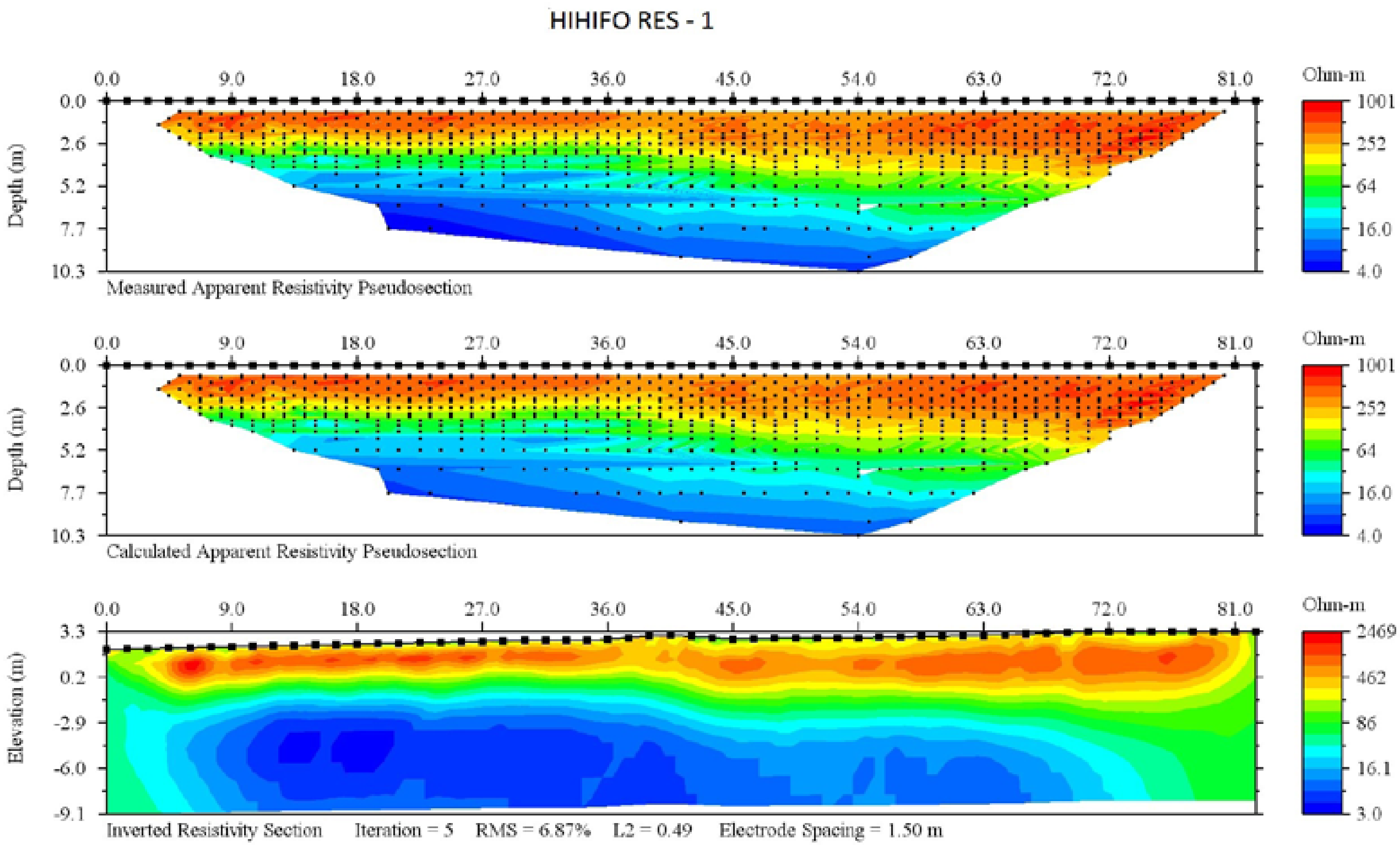


Figure 21: Resistivity profile Hihifo Res 1. Note the wedge shape of the freshwater lens thickening westward, and the apparent 'kink' in the profile at around 39–42 m. This is possibly in response to a change in geological formation, although this is not observed/recorded in the drilling logs.

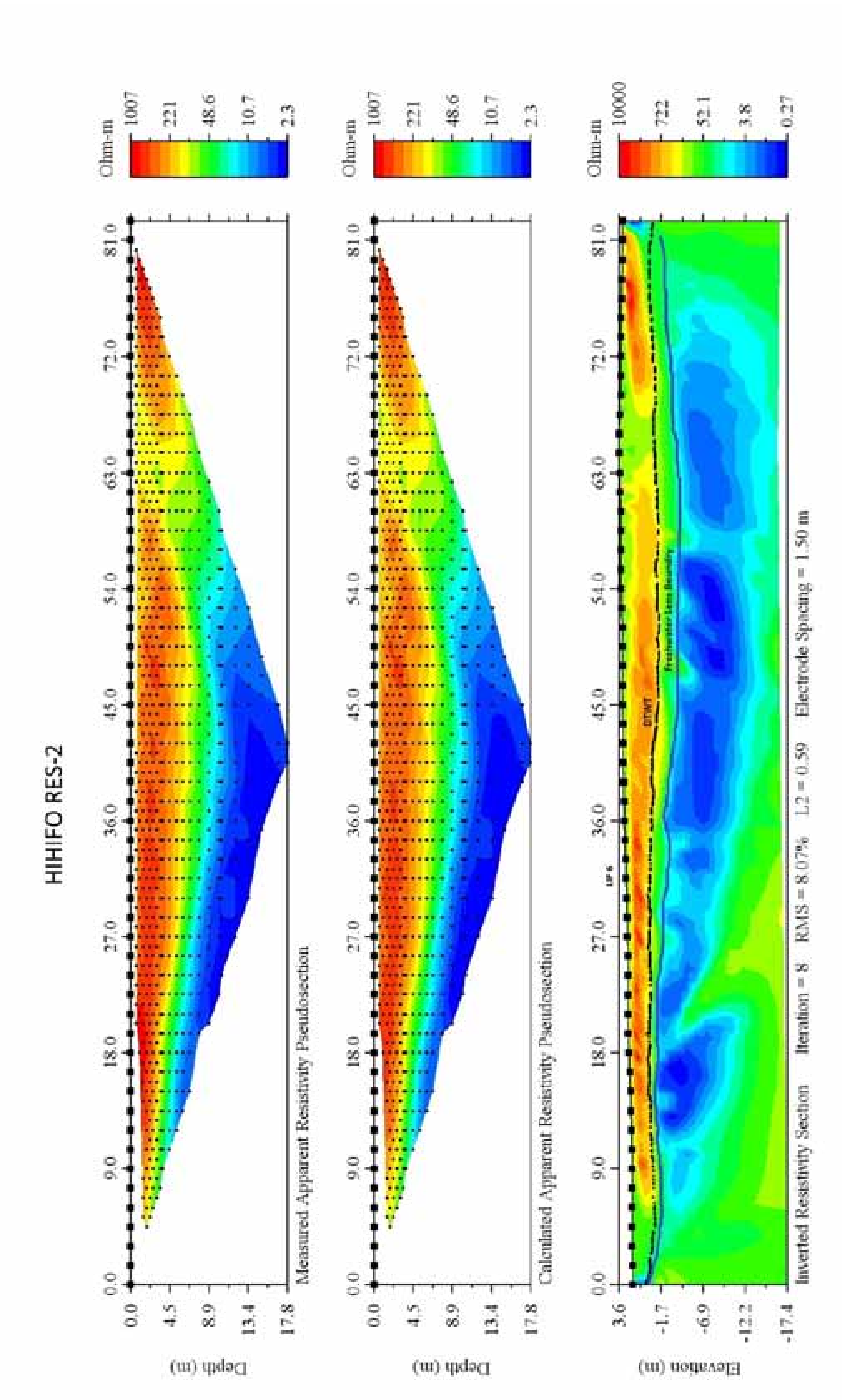


Figure 22: Resistivity profile Hihifo Res 2. The freshwater lens is wedge-shaped, thickening westward.

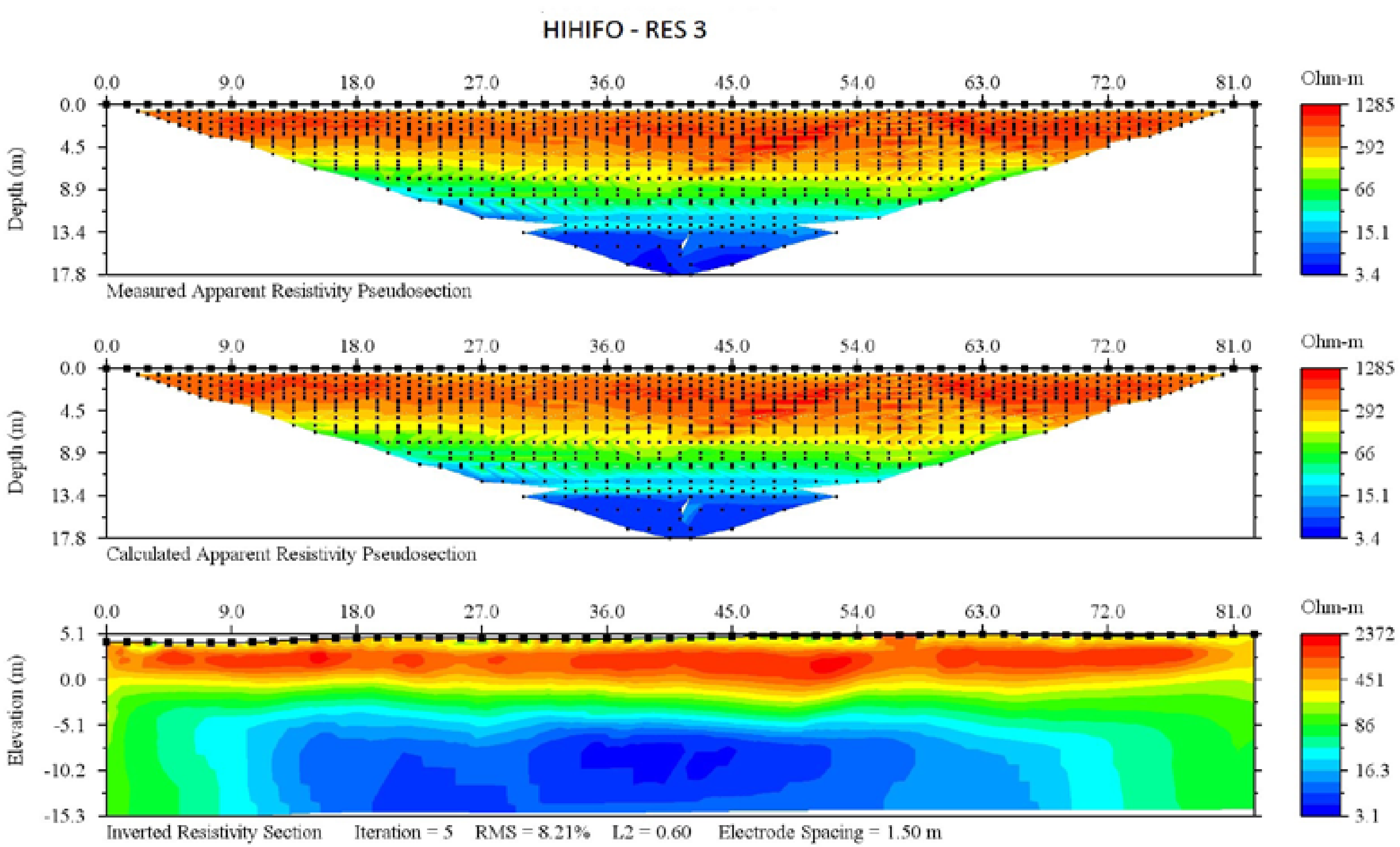


Figure 23: Resistivity profile Hihifo Res 3. The freshwater lens is 3–4.5 m thick. There is an apparent increase in the unsaturated zone at 45–52 m. Note that the Hihifo Gallery East is located at about 45 m on the profile. This apparent increase in unsaturated zone thickness could be a response to abstraction from the gallery with some induced drawdown, or a response to disturbed ground during installation.

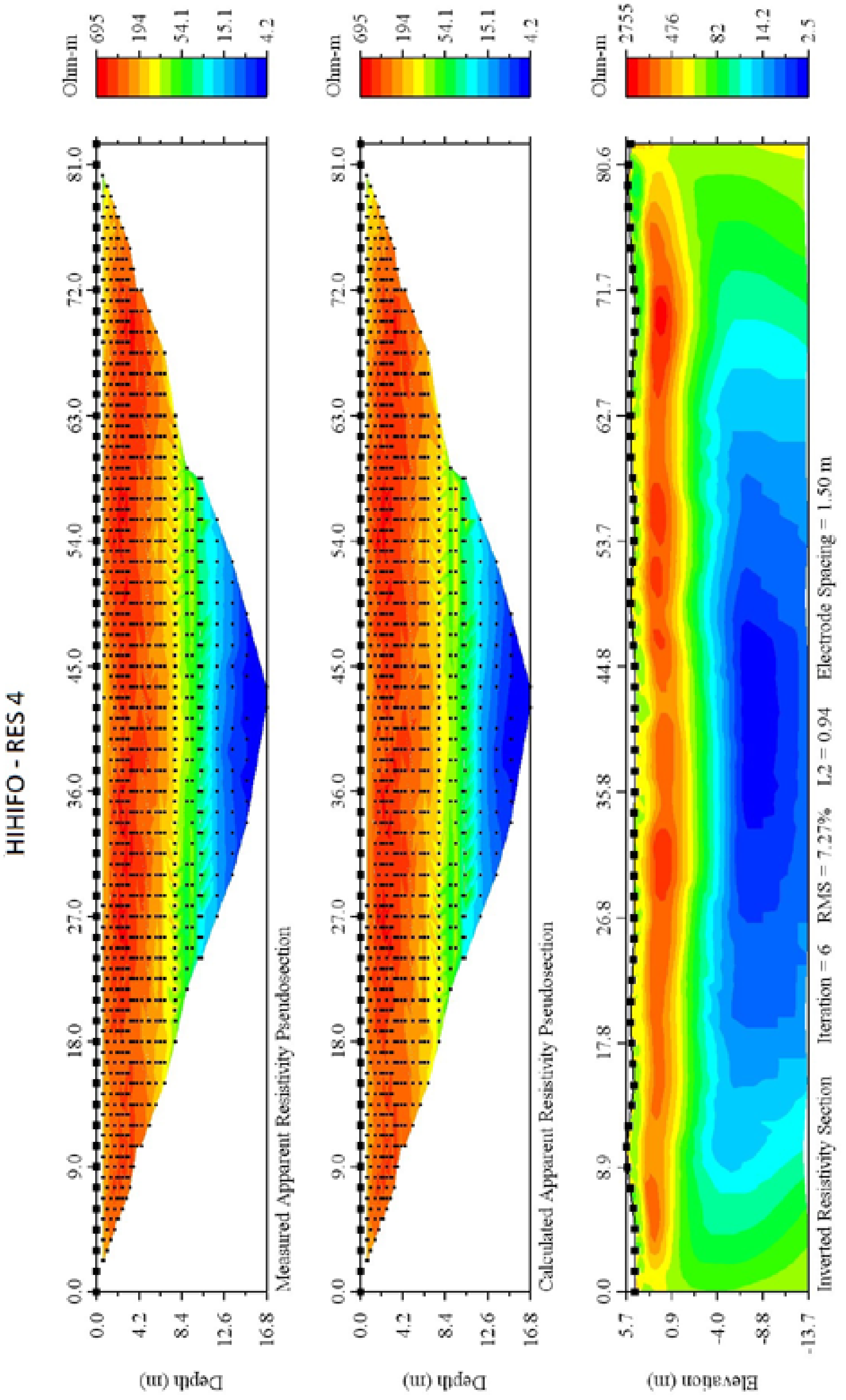


Figure 24: Resistivity profile Hihifo Res 4. This profile transect shows the silty sands and the limestone. The freshwater lens is approximately 3 m thick.

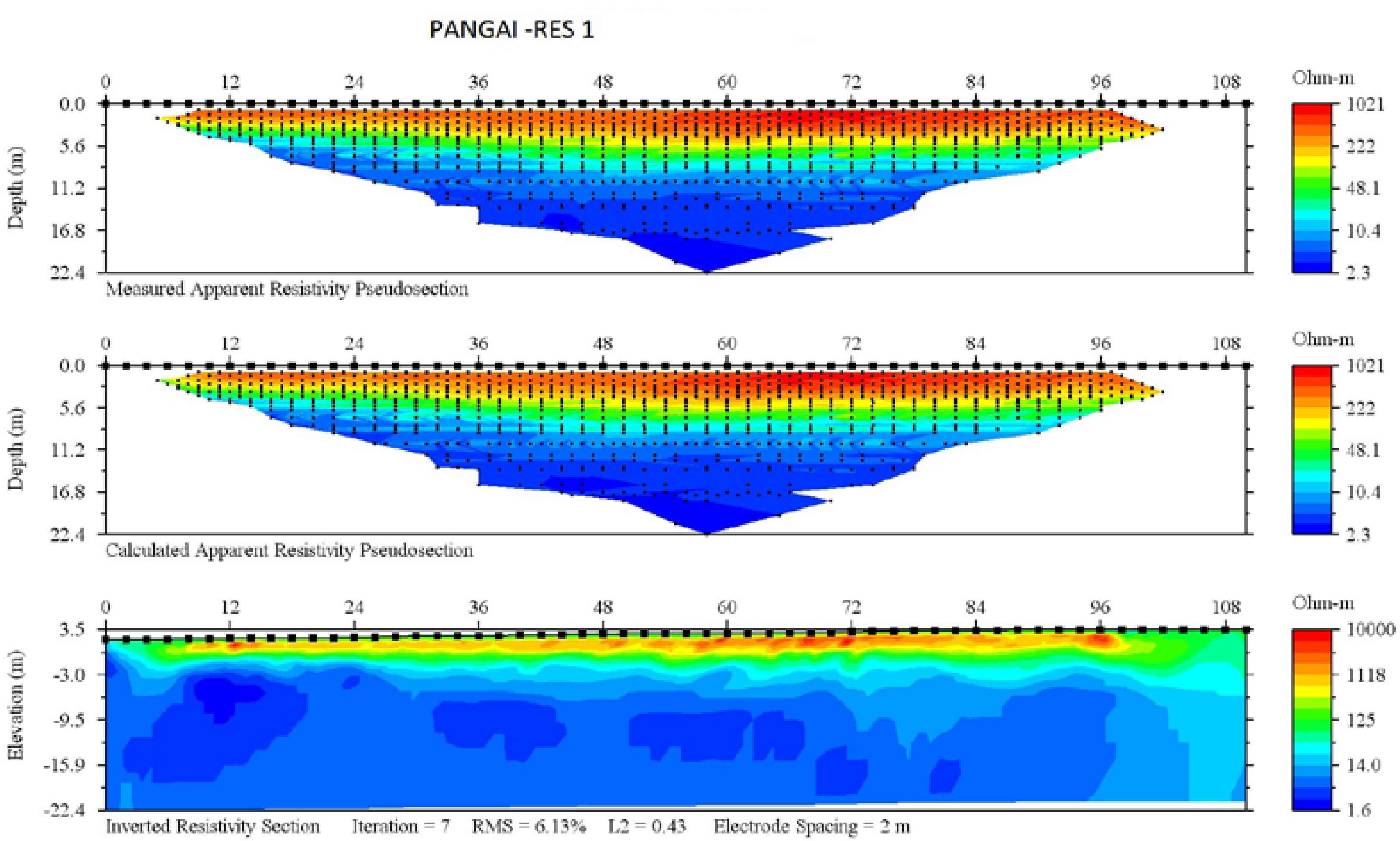


Figure 25: Resistivity profile Pangai Res 1. This profile shows a thin freshwater lens, 1.9 m, on its westward side, closest to the ocean. The lens thickens eastward, to 2.9 m thick near the gallery eastern end, with an increase in the unsaturated zone as you move eastward.

2.7 Borehole monitoring salinity and water level measurements

Salinity monitoring boreholes were installed in 1997 (Turner 1998). The nine boreholes installed were constructed with multi-level sampling tubes, which allow sampling of the groundwater at selected depths.

Previously collected data for the monitoring bores are available for the period between January 1998 and August 2001. Since 2001 two of these monitoring bores (LIF 1 and LIF 5) have been destroyed, during construction of a school and house respectively, and one bore cannot be located (LIF 3). A metal detector may be useful to help locate this bore. Some of the remaining monitoring bores have their sampling tubes blocked and cannot be sampled.

A programme was established during the project under which MLSNRECC staff monitor the available boreholes on a quarterly basis. Data from the monitoring bores were used to help assess the impact on the lens of the subsidence in 2006 and the potential impact of abstraction by TWB bores, and to help calibrate the geophysics data.

This section presents the results of the monitoring of these salinity bores. The multi-level salinity monitoring bores are important infrastructure for the longer-term management of the resource, as they allow the salinity of the groundwater to be determined directly with depth, providing confidence in the measurement of the freshwater lens thickness and the sustainable management and development of the resource.

2.7.1 Methodology

Salinity monitoring bores allow the behaviour of the freshwater lens to be measured over time. Six of the monitoring bores constructed in 1997 (Turner 1998), were sampled on a quarterly basis over the period of the investigation – September 2011 to October 2012 – providing information on both the variability of the freshwater lens and the potential impact of the 2006 subsidence on the lens.

The sampled monitoring bores are located near TWB production wells (Figure 26 and Table 7).

Table 7: Location of sampled salinity monitoring bores (SMBs) on Lifuka

		GPS coordinates	
SMB came	**Location**	**South**	**West**
LIF 2	Hihifo rugby field	19°48. 809′	174°21. 266′
LIF 4	West side Pangai RF	19°48. 503′	174°21.077′
LIF 6	North side Moa Rd	19°48. 979′	174°21. 393′
LIF 7	Airport	19°46. 600′	174°20. 579′
LIF 8	Hihifo rugby field	19°48. 798′	174°21. 236′
LIF 9	Hihifo rugby field	19°48. 841′	174°21.285′

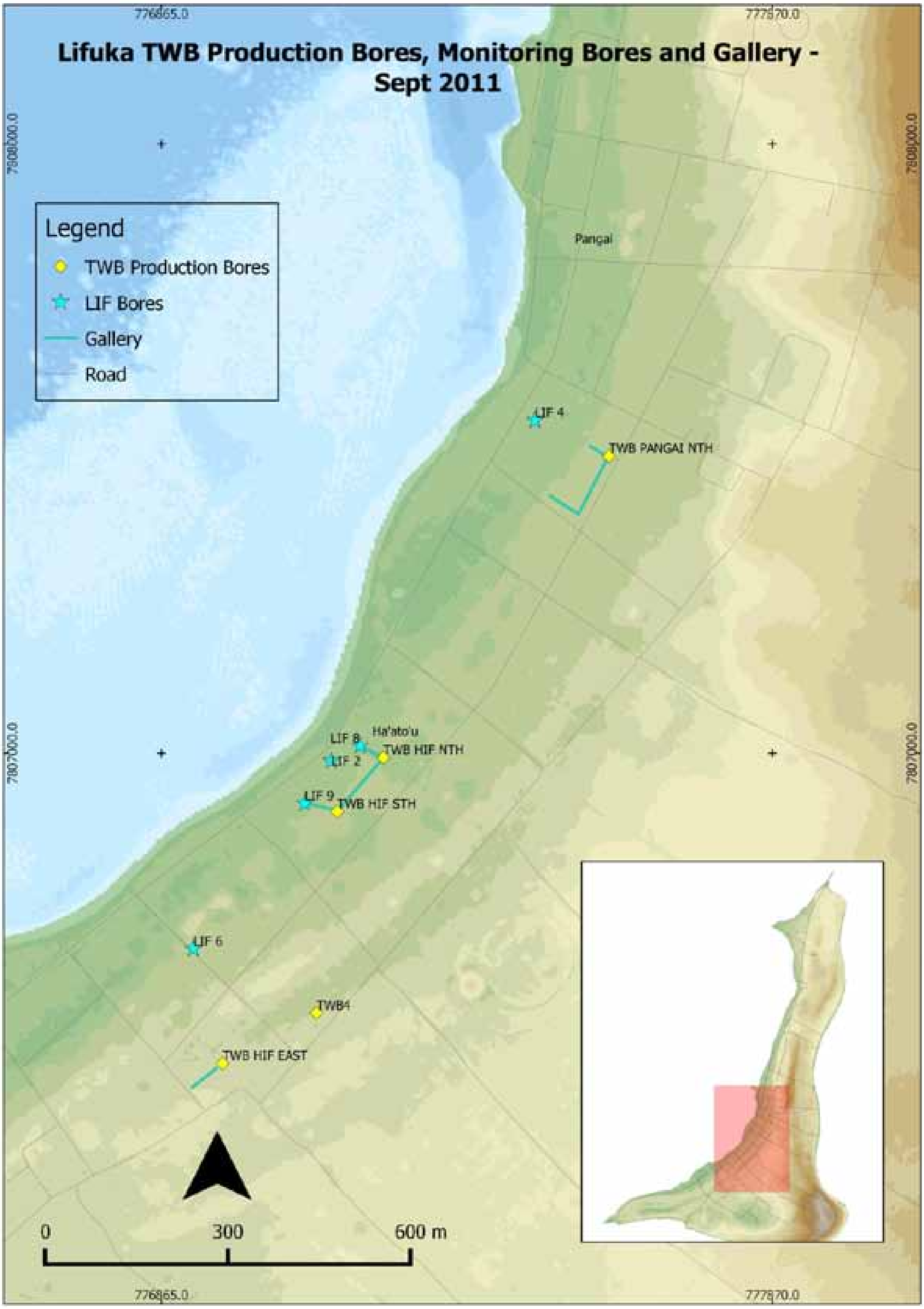


Figure 26: Location of TWB production bores and galleries and LIF salinity monitoring bores

Monitoring bore types

Three different types of monitoring bores were constructed:

1. Type A – LIF1, LIF2, LIF3, LIF4, LIF6 and LIF8 consist of a series of 5/16” nylon tubes set at various predetermined depths. At the base of each tube a glass filter is attached. Between four and seven 5/16” nylon tubes, with fittings, are installed in each borehole. Sampling is possible using a diaphragm-style pump. A slotted PVC pipe (piezometer) was originally installed to allow water-level measurements. Only LIF 4 had a serviceable PVC piezometer from the Type A bores to obtain a water-level measurement. Originally, the monitoring bores had gatic covers to protect the pipes. A number of these gatic covers were replaced during the course of the project.

2. Type B – LIF5 and LIF7 consist of a set of 32 mm PVC pipes (‘monitoring tubes’) terminating at predetermined depths. These tubes are slotted near the base and sealed with insulation tape. This type of monitoring system was used when the ground water was more than 3 m below the ground surface.

3. Type C – LIF9 consists of a combination of types A and B as described above: two nylon tubes and three PVC pipes were installed in the borehole.

Gravel was used as backfill in all bores and bentonite seals were placed at intermediate depths between the monitoring pipes/tubes.

The design of the Type A multi-level borehole system is shown in Figure 27 (Falkland et al. 2003).

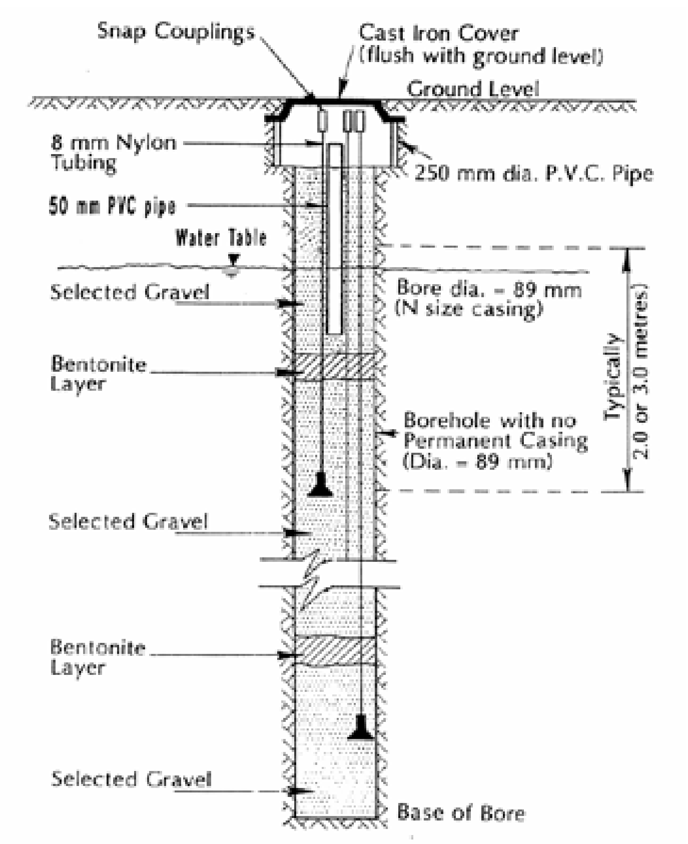


Figure 27. Multi-level borehole system for monitoring salinity and water level (Falkland et al. 2003)

Construction details for monitoring bores are found in Annex 2 (Turner 1998).

Measurement procedure

Bores with the 5/16” sampling tubes were pumped using a ‘Shurflo’ diaphragm-type pump powered by a 12 V car battery. The suction side of the pump was attached to John Guest couplings at the top of each nylon monitoring tube and each tube was purged for about five minutes, abstracting more than 5 litres prior to collection to ensure sampling of formation water. Measurements of conductivity and temperature were made with a portable WP 84 TPS meter (calibrated each morning prior to fieldwork), and stable electrical conductivity (EC) readings were recorded in the data sheet. All sampling equipment, including the pump, battery and chargers and salinity meter, were provided by the project and are retained by TWB on Lifuka to allow future monitoring.

Bores with 32 mm pizometers allowed for measurements to be undertaken using a calibrated Solinst TLC (temperature/level/conductivity) meter. Table 8 summarises the details about the available monitoring bores and sampling tubes.

During the initial monitoring, the bores were cleaned and purged and any seized brass snap couplings fitted at top of each tube were replaced with the John Guest couplings. Gatic covers that had been damaged or lost were replaced for a number of monitoring bores.

Figures 28 and 29 show the sampling tubes and couplings and sampling setup using the diaphragm pump.

Figure 28: Brass snap couplings (left) were replaced with John Guest fittings (right)

Figure 29: Sampling at the monitoring bores

Field data sheets were provided to the MLSNRECC and TWB for recording the measurements from the monitoring bores.

Table 8: Monitoring boreholes and tubes available for monitoring

Monitoring bore	Location	GPS coordinates		Monitoring bores construction depths	
Name		South	West	Pipe and nylon tubes	Measured total depth (mbgl)
LIF 2	West side of Hihifo rugby field	19°48. 809′	174°21. 266′	PVC	3
				Tube 1	3.5
				Tube 2	5.47
				Tube 3	7.35
				Tube 4	11.98
				Tube 5	15.57
LIF 4	West side Pangai rugby field	19°48. 503′	174°21.077′	PVC	1.9
				Tube 1	3.46
				Tube 2	6.68
				Tube 3	5.47
				Tube 4	4.55
				Tube 5	8.11
LIF 6	North side Moa Rd	19°48. 979′	174°21. 393′	PVC	2.25 (Dry)
				Tube 1	4.17
				Tube 2	5.62
				Tube 3	6.72
				Tube 4	8.32
				Tube 5	10.7
				Tube 6	13.15
LIF 7	Kuolo near airport	19°46. 600′	174°20. 579′	PVC 1	5.59
				PVC 2	5.95
				PVC 3	7.05
				PVC 4	9.23
LIF 8	Hihifo rugby field	19°48. 798′	174°21. 236′	PVC	2.9
				Tube 1	4.0
				Tube 2	5.0
				Tube 3	6.0
				Tube 4	8.3
LIF 9	Hihifo rugby field	19°48. 841′	174°21.285′	PVC 1	2.8
				PVC 2	5.0
				PVC 3	6.0
				Tube 4	7.0
				Tube 5	8.0

2.7.2 Rainfall residual mass curve

A rainfall residual mass curve is a cumulative plot of the difference between the actual rainfall for the month and the average rainfall for the month. A positive slope on the graph indicates a period of above average rainfall, while a negative residual mass slope indicates a period of lower than average rainfall. This method enables correlation of rainfall with water level or water-quality fluctuation within groundwater bores, and is similar to the curve created by the 12-month moving average of the monthly rainfall data.

For monthx = (Actual rainfall for monthx – average rainfall for monthx) + (the cumulative sum of actual rainfall for month – average rainfall for month for all previous months).

The residual rainfall mass curve has been plotted for monthly rainfalls for Lifuka (Figure 30). It shows that 1947 to 1977 has been, on average, a wetter period with above average rainfall, albeit with a significant dry period of below average rainfall from March 1951 to November 1954. This was followed by a significant dry period spanning nearly two decades, from January 1977 to November 1998, where, in general, rainfall recorded was below average. Since 1999, there has been a pattern of increasing rainfall overall.

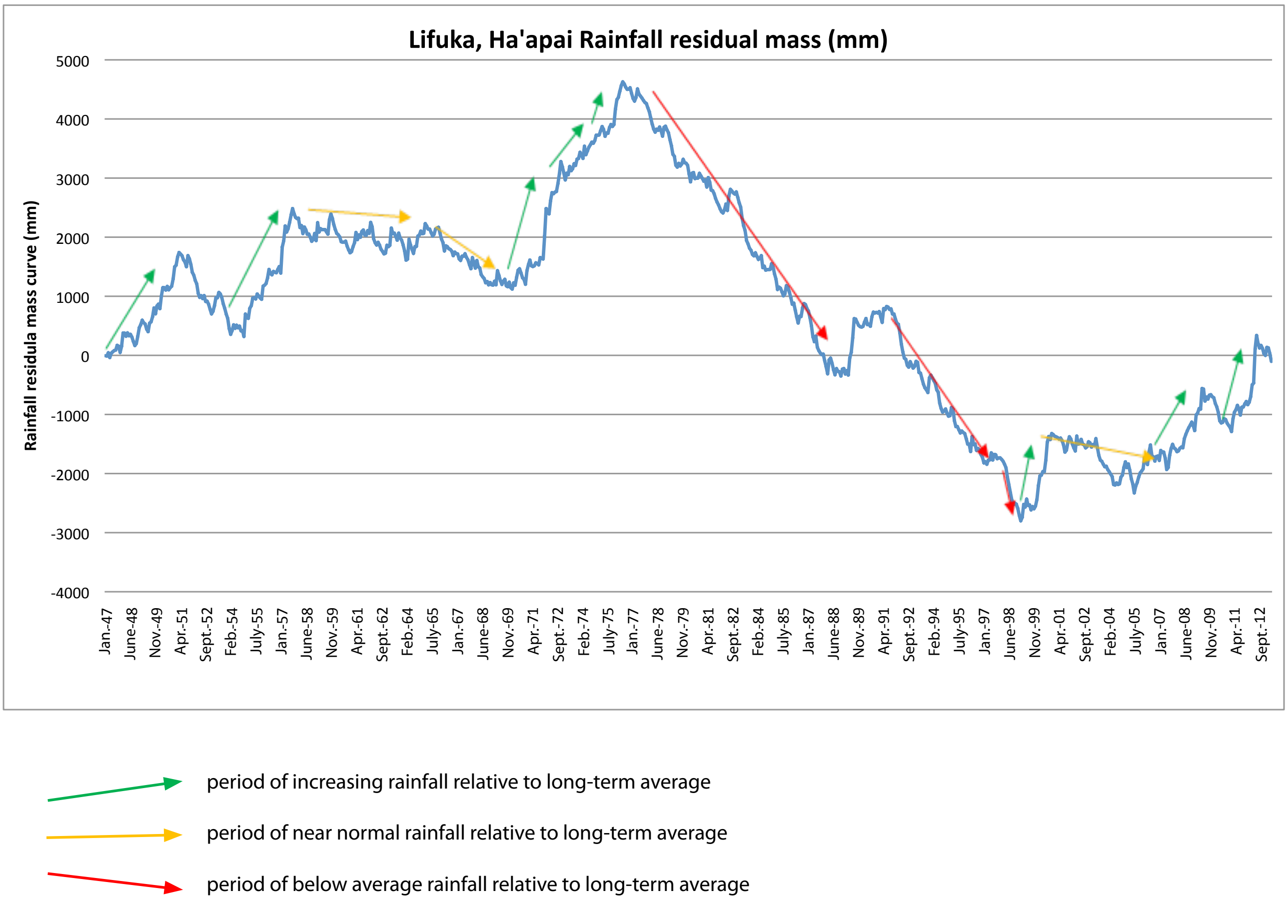


Figure 30: Rainfall residual mass curve for Lifuka, Ha’apai

It is useful to track residual rainfall in more detail over the project period to understand in what part of the rainfall cycle the investigations took place, and to assess this impact on the freshwater lens and the investigations.

Figure 31 is used to demonstrate the monitoring periods relative to the rainfall residual over the period of monitoring. Monitoring of groundwater started at the end of an extended dry period in December 1998 and was followed by a short but intense wet period lasting until the end of 2000. Monitoring that occurred between September 2011 and February 2012 was dominated by above-average rainfall, with rainfall then declining and becoming average to below average from February 2012 until October 2012.

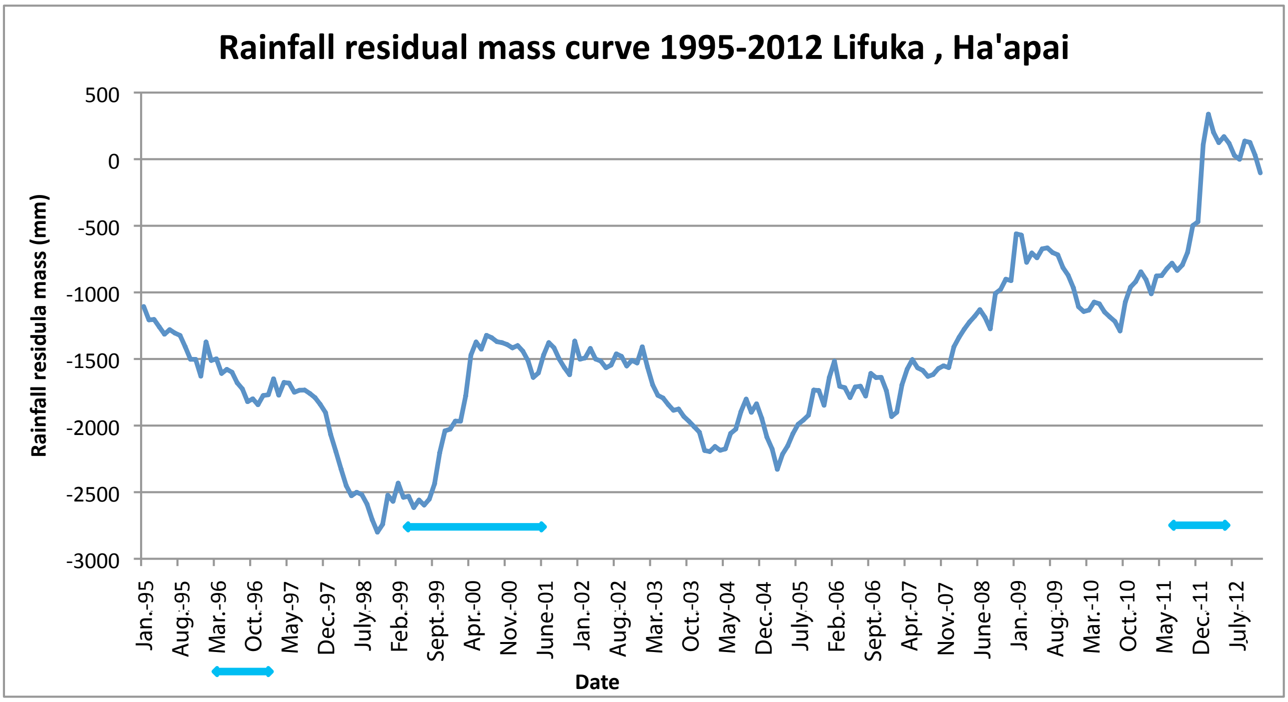


Figure 31: Rainfall residual mass curve for Lifuka 1995–2012 with groundwater monitoring periods identified

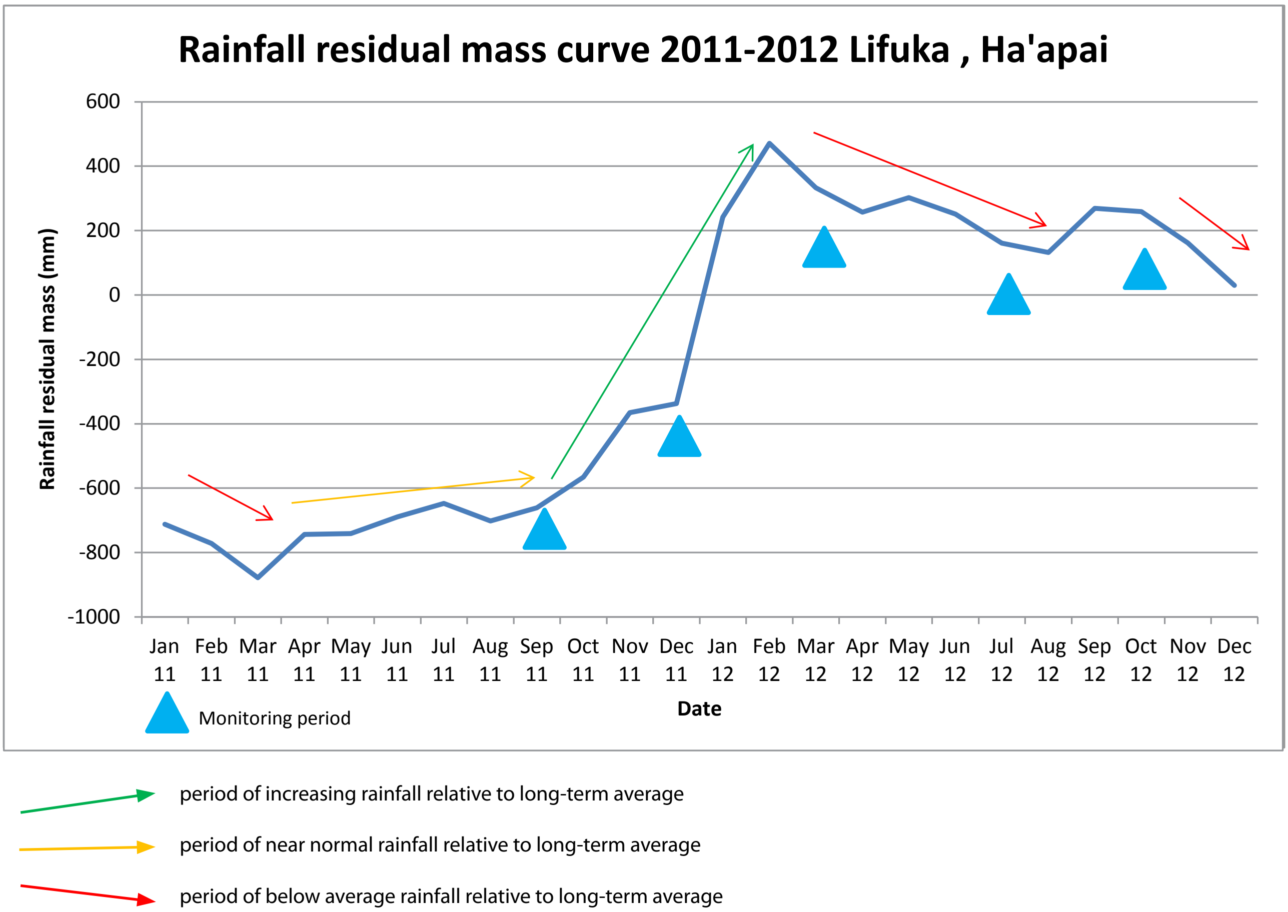


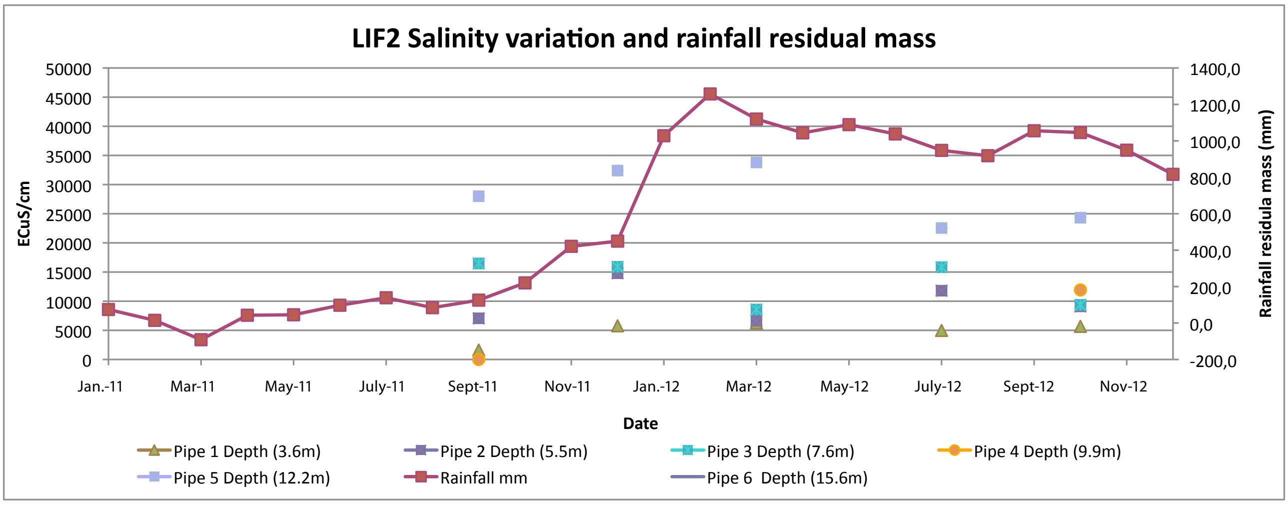
Figure 32: Rainfall residual mass curve for Lifuka 2011–2012 with specific groundwater monitoring periods identified.

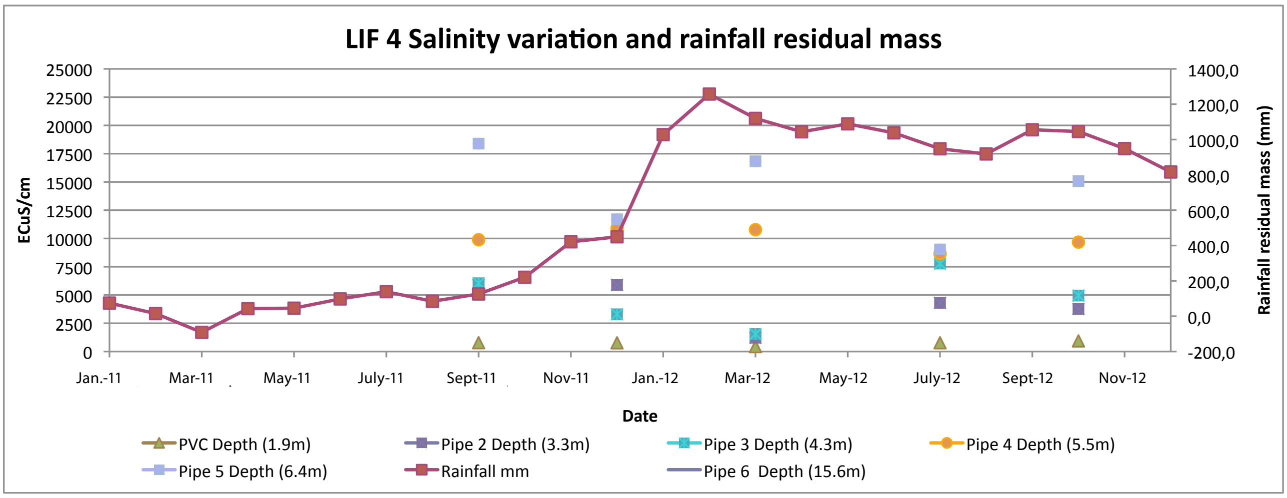
2.7.3 Results

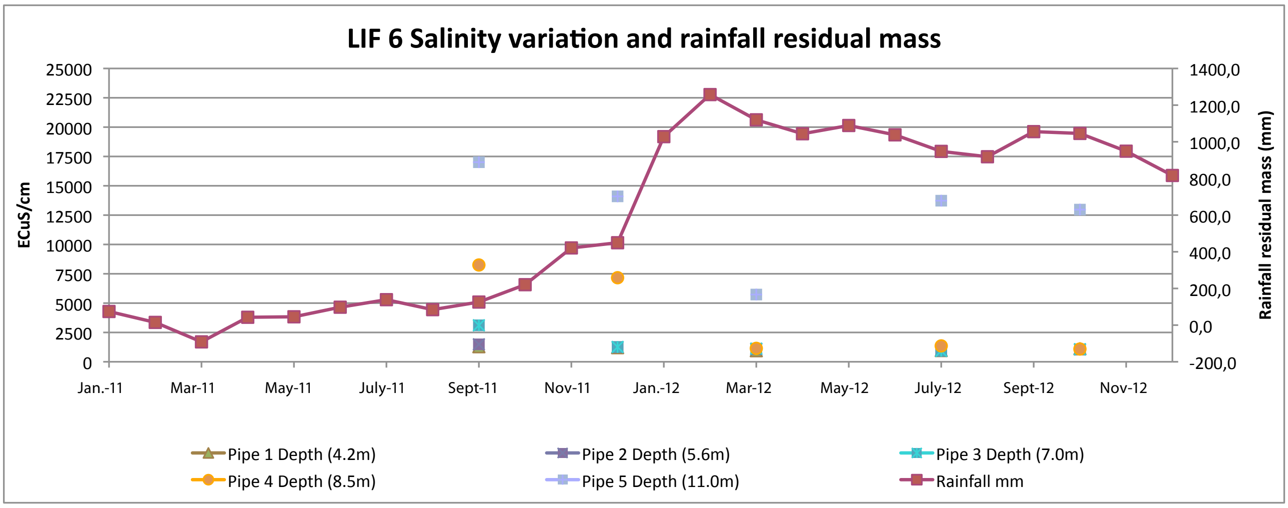
The results for salinity monitoring are shown graphically for each site in Figure 33, plotted against the rainfall residual mass curve for Lifuka. The results of the salinity monitoring undertaken over 12 months demonstrate the considerable variability in salinity due to rainfall.

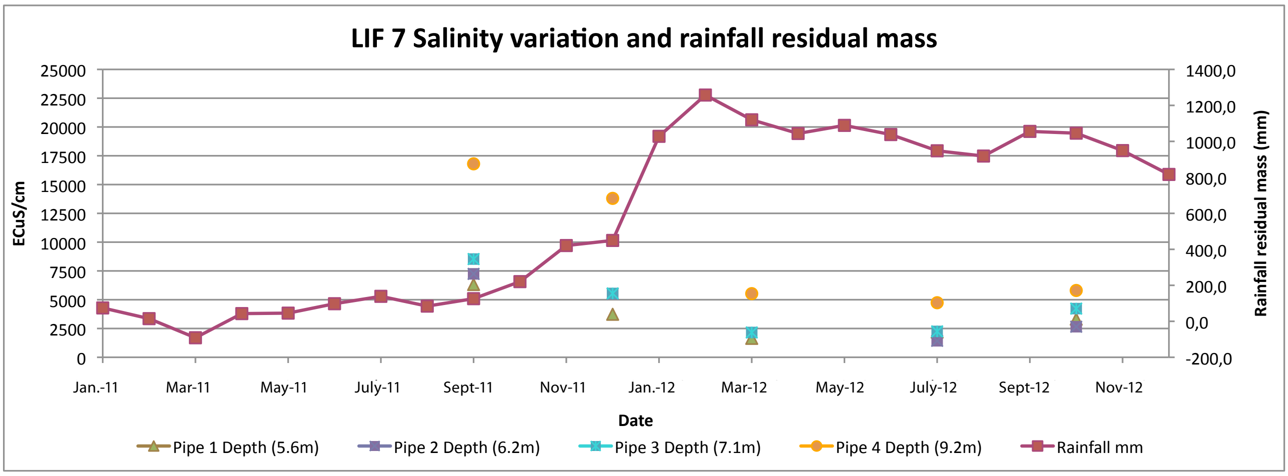
Figure 33 shows a general pattern or trend between the different depths and between monitoring bores in relation to salinity and rainfall. That is, after a period of increased rainfall there is a corresponding decrease in salinity. Similarly, a period of decreasing rainfall results in an increase in salinity.

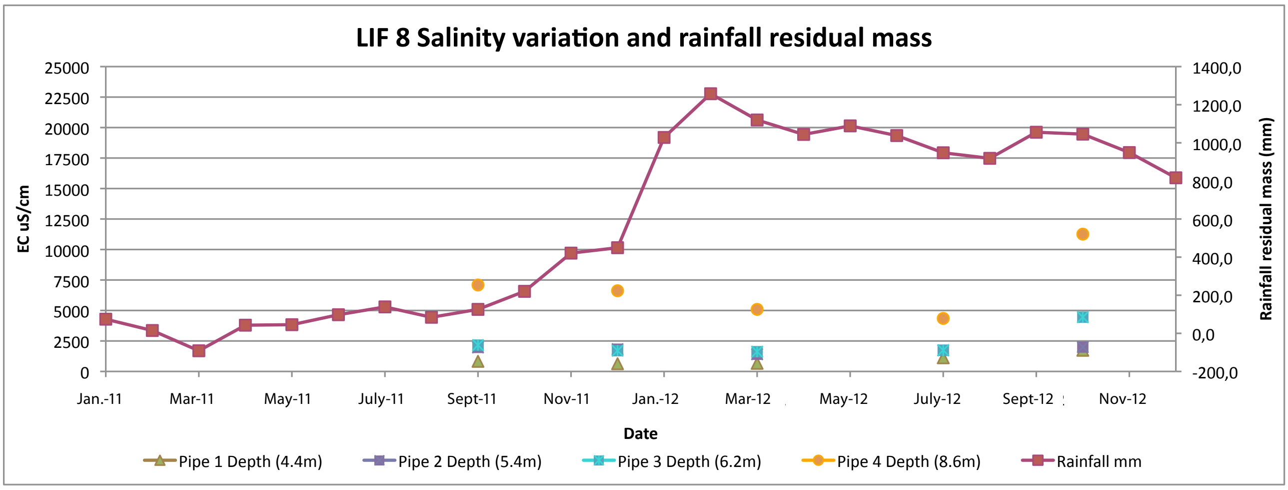
It is possible from these results to get an appreciation of the lag time between the rainfall event and impact on salinity to give an approximation of the responsiveness of the freshwater lens. The data suggest that, for the deeper part of the lens within the transition zone, the time lag between the event and the response in salinity is approximately five months (LIF 2 Pipe 5, LIF 7 Pipe 4). A quicker response, as to be expected, is indicated for the shallower and fresher parts of the freshwater lens, with freshening of the lens in this area within a month of a rainfall event (LIF 8 Pipe 1 and LIF 9 Pipe 1).

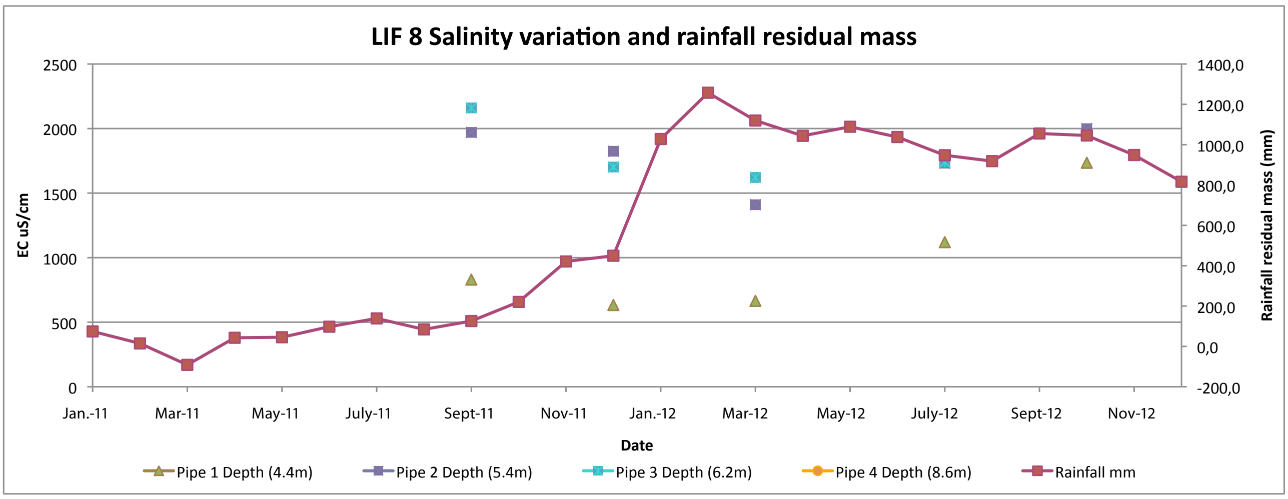

LIF2 Salinity variation and rainfall residual mass
ECuS/cm
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residula mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Date
Pipe 1 Depth (3.6m)
Pipe 2 Depth (5.5m)
Pipe 3 Depth (7.6m)
Pipe 4 Depth (9.9m)
Pipe 5 Depth (12.2m)
Rainfall mm
Pipe 6 Depth (15.6m)

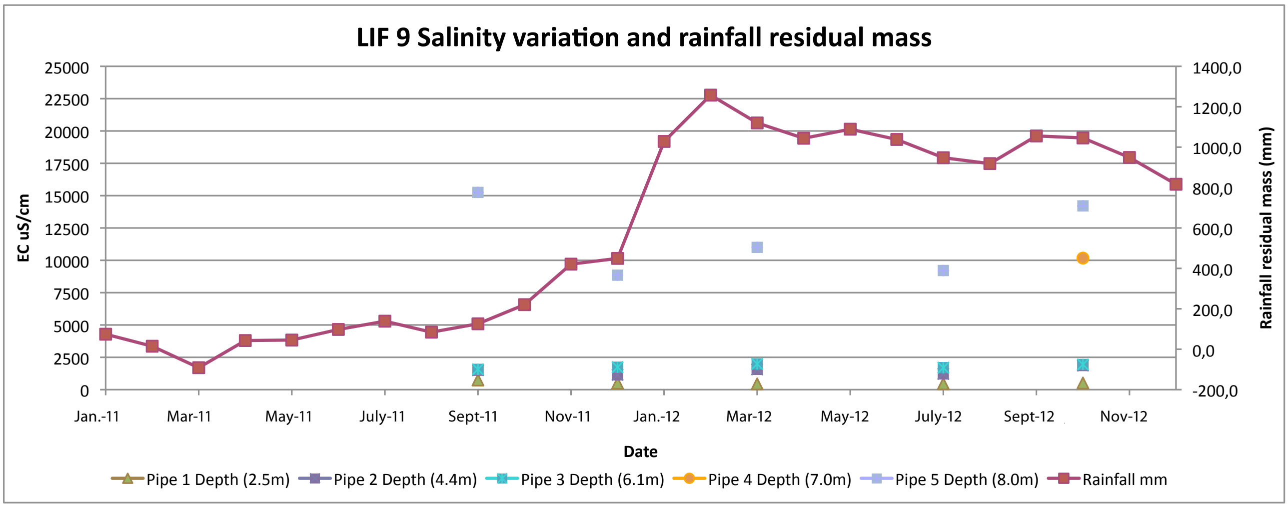

LIF 4 Salinity variation and rainfall residual mass
ECuS/cm
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residual mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Date
PVC Depth (1.9m)
Pipe 2 Depth (3.3m)
Pipe 3 Depth (4.3m)
Pipe 4 Depth (5.5m)
Pipe 5 Depth (6.4m)
Rainfall mm
Pipe 6 Depth (15.6m)


LIF 6 Salinity variation and rainfall residual mass
ECuS/cm
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residual mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Pipe 1 Depth (4.2m)
Pipe 2 Depth (5.6m)
Pipe 3 Depth (7.0m)
Pipe 4 Depth (8.5m)
Pipe 5 Depth (11.0m)
Rainfall mm


LIF 7 Salinity variation and rainfall residual mass
ECuS/cm
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residual mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Date
Pipe 1 Depth (5.6m)
Pipe 2 Depth (6.2m)
Pipe 3 Depth (7.1m)
Pipe 4 Depth (9.2m)
Rainfall mm


LIF 8 Salinity variation and rainfall residual mass
EC uS/cm
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residual mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Date
Pipe 1 Depth (4.4m)
Pipe 2 Depth (5.4m)
Pipe 3 Depth (6.2m)
Pipe 4 Depth (8.6m)
Rainfall mm


LIF 8 Salinity variation and rainfall residual mass
EC uS/cm
2500
2000
1500
1000
500
0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
-200,0
Rainfall residual mass (mm)
Jan.-11
Mar-11
May-11
July-11
Sept-11
Nov-11
Jan.-12
Mar-12
May-12
July-12
Sept-12
Nov-12
Date
Pipe 1 Depth (4.4m)
Pipe 2 Depth (5.4m)
Pipe 3 Depth (6.2m)
Pipe 4 Depth (8.6m)
Rainfall mm



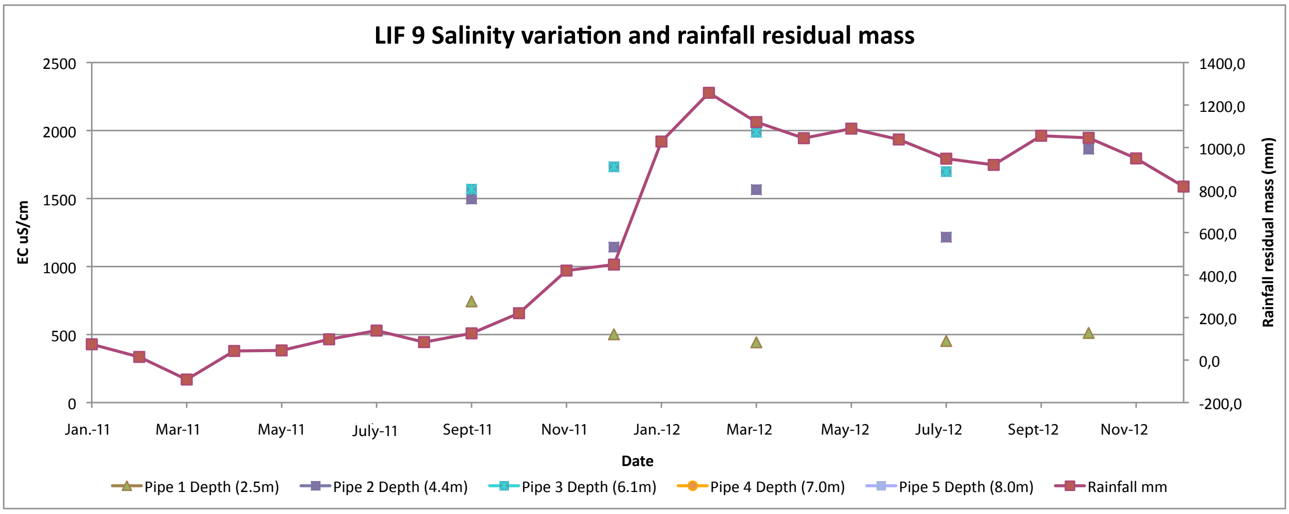


Figure 33: Salinity variation and monthly rainfall comparison

Borehole salinity profiles are often used to give an indication of the thickness of the fresh water in the various monitoring boreholes for a specific period. As indicated in the previous graphs, salinity and freshwater thickness will vary in response to rainfall over time, and also in response to abstraction.

A comparison of monitoring bores around Pangai and Hihifo pumping galleries over selected periods of time can provide an indication of the thickness of the lens and available fresh water over time periods that correlate with the wetter and drier periods indicated by the rainfall residual mass curves. This analysis provides an indication of the resilience of the lens in relation to the location of pumping galleries, and variance over time.

A summary of the available monitoring periods matched against the trend in the rainfall residual mass curve during each period is provided in Table 9 and can be used to help interpret the results for the salinity monitoring bores.

Table 9: Selected periods of monitoring and their relationship to period rainfall residual mass curve for that period

Period of monitoring	Position on rainfall residual mass curve
October 1998	End of 8-year dry period
April 1999	Approx. 5 months of above-average rainfall
July 1999	Approx. 8 months of above-average rainfall
September 2011	Approx. 12 months of above-average rainfall
March 2012	End of 18-month period of above-average rainfall
July 2012	End of a 5-month period of below-average rainfall
October 2012	Period of approx. 3 months of average rainfall

2.7.4 Discussion on salinity monitoring

The variability of salinity between bores and the subsequent formation of the lens is predominantly a function of the geology, with coarser sediments and limestone having greater hydraulic conductivity and a correspondingly reduced ability to 'store' the water to allow the development of a usable freshwater lens over time. The finer sand and silt sediments with lower hydraulic conductivity are more likely to develop a thicker freshwater lens, as found in Hihifo and Pangai.

LIF 7 – Koulo

Koulo monitoring bore LIF 7 demonstrates a rise in the water table from prior to 2006, pre-earthquake, to post-2006. Figure 34 shows the change in measured water levels for PVC 1 from pre-2006 to post-2006. The water table height is a function of both recent recharge and tidal impacts, as shown by the range of the data; however, there is a clear difference in heights between pre-2006 and post-2006 water tables, which is interpreted as an apparent rise in sea level at this bore due to subsidence. There is a relative average height difference of 0.45 m between the averaged readings for pre-2006 and post-2006 water-level data.

Specific yield is used to indicate the volume of water that can freely drain from a material with a unit decline in hydraulic head and is a function of porosity of the material. It is calculated as follows:

$$Sy = \frac{Vwd}{Vt}$$

where

Vwd is the volume of water drained, and
Vt is the total rock or material volume

A uniform total volume increase of 0.45 m^3 for a volume of water of 0.23 m^3 would indicate a specific yield for the sediments in LIF 7 of 51%.

This calculated value for specific yield is higher than the literature would suggest for the type of sediments in question (Johnson 1967), suggesting that either the actual subsidence may have been less than measured or that the change in water level is influenced by either a rainfall and or tidal response, resulting in underestimation of the total volume increase and overestimation for the calculated specific yield.

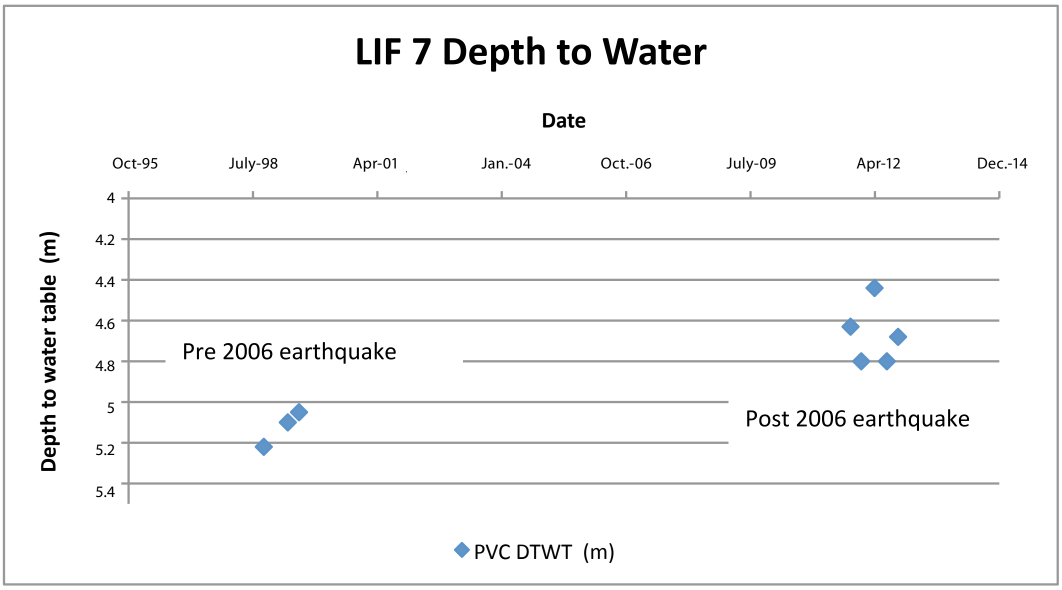


Figure 34: Depth to water table values for LIF 7 PVC 1, indicating a general increase of 0.45 m in the depth to the water table in response to the 23 cm subsidence

LIF 7 (Figure 35) also indicates significant variability in salinity with a very thin freshwater lens. The freshwater lens is generally less than 2 m thick and not present at all during drier periods. It would appear that the salinity in the lens for this part of the island is dominated by the available recent rainfall, as well as the associated geology (a mix of limestone and sand deposits from 3.2 to 5.0 m and limestone below 5 m). It is suggested that the more permeable geology is less able to constrain the freshwater, with corresponding greater 'tidal mixing'.

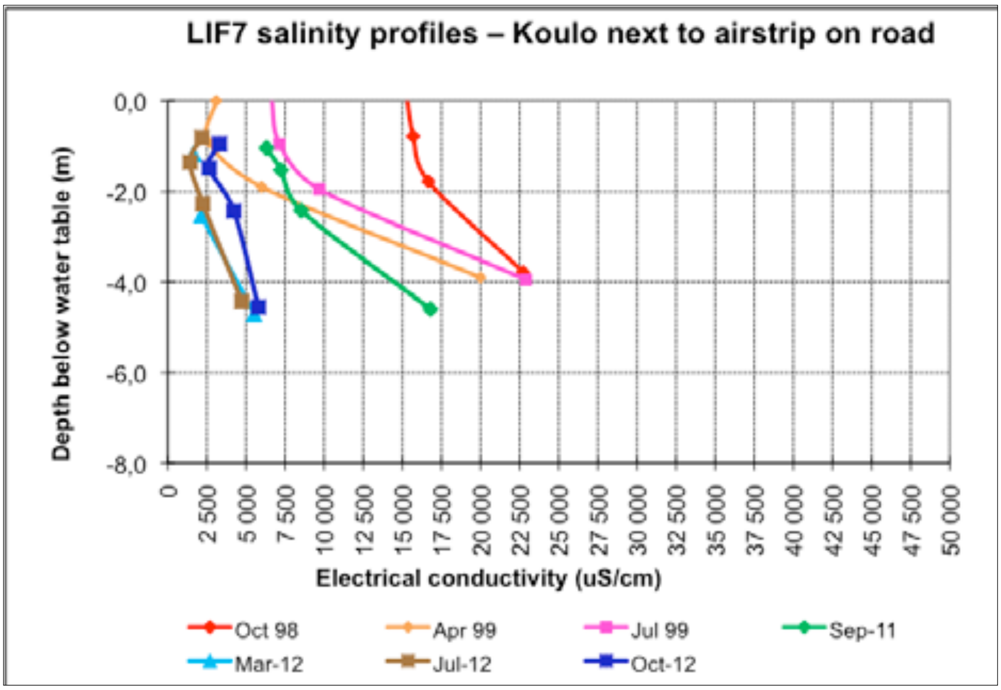


Figure 35: Freshwater thickness values for LIF 7 below the water table over selected monitoring periods. Note the predominantly fresher water lens in recent times.

It is interesting to note that the freshwater component of the lens and the transition zone is slightly thicker in the 2011–2012 monitoring compared with the 1998–1999 monitoring period. Whilst rainfall is expected to be a dominant factor in determining the thickness of the lens, it is noted that the drilling logs indicate the presence of sandy silt sediments in the zone in which the water table is now located. The 23 cm land subsidence and the subsequent lifting of the freshwater lens into geology that is more favourable for the development of a freshwater lens may partially account for the increased storage and thickness of the freshwater lens at this site.

LIF 4 – Pangai rugby field

Monitoring bore LIF 4 in the Pangai rugby field is located on the western periphery of the freshwater lens. During wetter periods the freshwater lens may be up to 2 m thick and during dry periods it may not be present at all. The shape of the salinity trend lines indicate that, during the drier periods, salinity generally increases, the freshwater lens thins, and the transition zone thickness increases. That is, in times of low rainfall, there appears to be increased mixing of the available fresh water with the more saline waters, creating a thicker transition zone. During wetter periods, the salinity decreases, the freshwater lens increases in thickness, and the transition zone thins, with a rapid change from relatively low-salinity water to high-salinity water. It is suggested that this is an indication of the increased recharge/discharge, causing a sharper boundary to the fresh and saltwater interface and a correspondingly thinner transition or mixing zone.

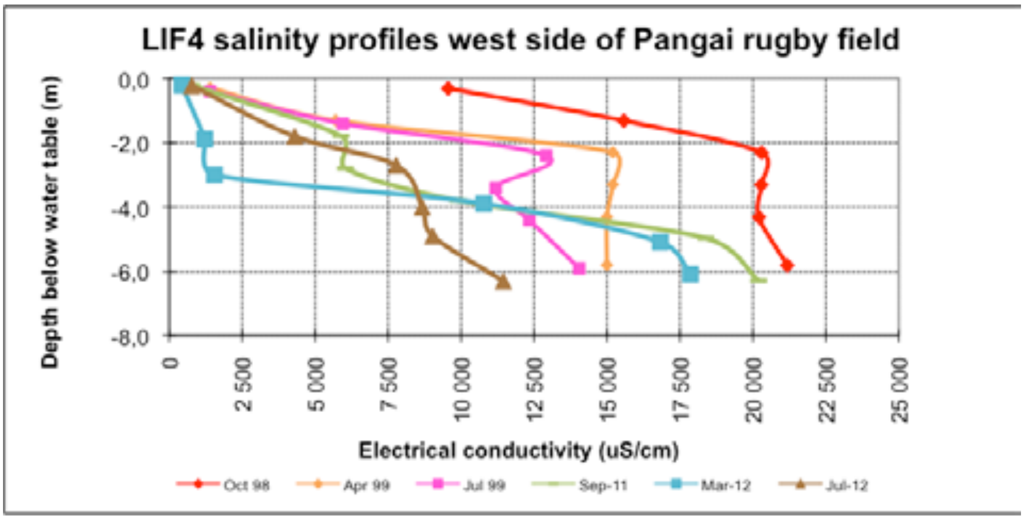


Figure 36: Freshwater thickness values for LIF 4 below the water table over selected monitoring periods. Note the greater thickness of brackish water, indicating a less defined boundary between the fresh and brackish water at times of low recharge and greater mixing.

LIF 2 – Hihifo rugby field, western side

Hihifo rugby field is the site of one of the existing TWB galleries. LIF 2 is located on the western periphery of the freshwater lens. At this location the lens is less than 1.5 m thick and during dry periods becomes increasingly saline with depth.

During periods of lower rainfall, it appears there is increased mixing of the available freshwater with the more saline waters, represented by a thicker transition zone. It is clear that the peripheral monitoring bores are the first to show salinity changes in response to rainfall, and are useful sentinel bores for indicating the first sign of impact on the lens.

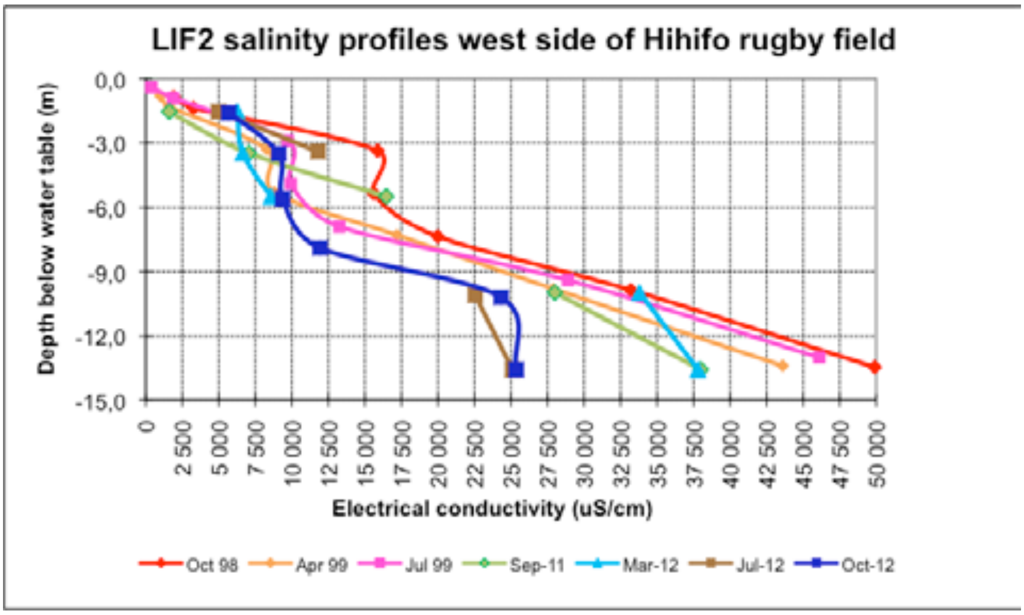


Figure 37: Freshwater thickness values for LIF 2 below the water table over selected monitoring periods. Note the greater thickness of brackish water at times of low recharge and reduced discharge, allowing greater mixing.

LIF 8 – Hihifo rugby field, northern side

Monitoring of LIF 8 at the northern side of Hihifo rugby field indicates recent thinning of the freshwater lens. This freshwater lens thickness is in contrast with the observations from the 1998–1999 monitoring, where even after an extended period of dryness the freshwater lens was identified as being deeper. This anomaly is interpreted as an expression of the impact of the apparent rise in sea level in response to the subsidence post-2006. Another plausible consideration is that the abstraction from the TWB gallery has caused a thinning of the lens. However, LIF 9, which is located in the same area but further from the TWB gallery, also indicates an increase in the salinity at depth, and is considered to be too far from the abstraction well to show an observable impact from pumping.

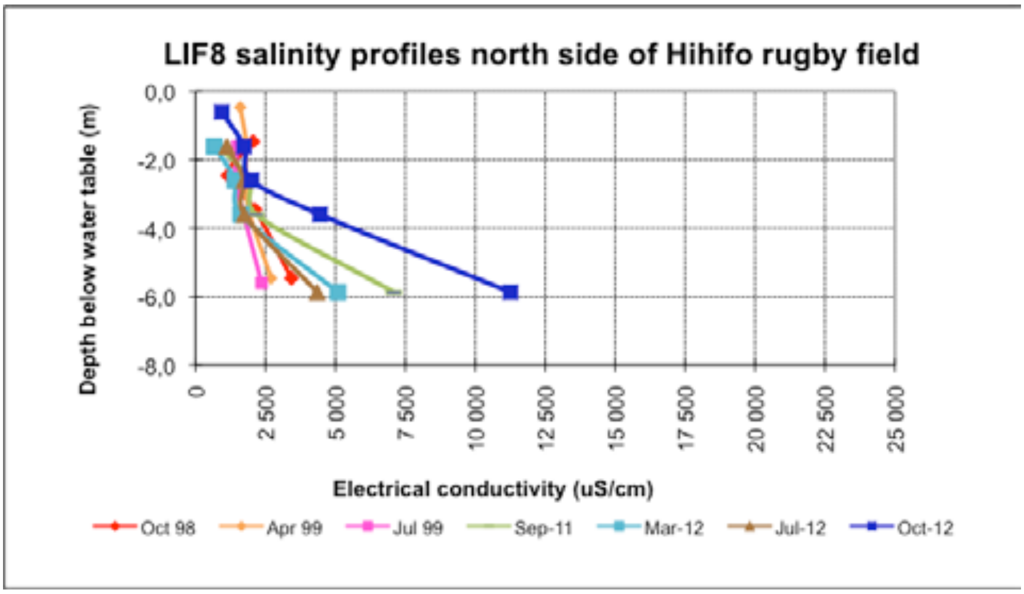


Figure 38: Freshwater thickness values for LIF 8 below the water table over selected monitoring periods. Note the apparent increase in salinity in the wells during recent times, suggesting that the lens is thinning, possibly in response to a rise in sea level.

LIF 9 – Hihifo rugby field, southern side

LIF 9, located on the southern side of Hihifo rugby field, and just south of the TWB groundwater abstraction gallery equipped with the non-operational solar pump, indicates a relatively consistent freshwater lens thickness of up to about 4.2 m, dependent on rainfall. This is slightly thicker than the observed freshwater lens thickness from the pre-2006 readings of 3.7 m, indicating that there has been a 0.5 m increase in thickness of the freshwater lens at this point.

The 23 cm sea-level rise in response to the earthquake was observed in two monitoring bores in which water levels could be measured (LIF 7 and LIF9) and corresponds to a rise in water levels of 45 cm and 55 cm respectively. It is interesting to observe that these two bores also indicate an overall increase in the freshwater lens thickness of about 0.5 m. This suggests that the rise in the freshwater lens, whilst causing the water table to become shallower, also allowed the lens to become thicker. It is suggested that the 0.5 m increase in freshwater thickness is a combination of both the lifting of the freshwater lens into an area of geology more favourable for the development of a thicker freshwater lens and an increased period of rainfall.

In comparison to LIF 8, LIF 9 does not appear to demonstrate any impacts from abstraction and has a relatively thin and sharp transition zone, becoming brackish to moderately saline at 1.5 m. There is a some indication that in the deeper pipe 5 (8.0 m) the salinity levels have increased post-2006, possibly an indication of the rise in sea level following the subsidence. That is, the transition zone has become shallower, with more brackish water now observed at the depth of the tube.

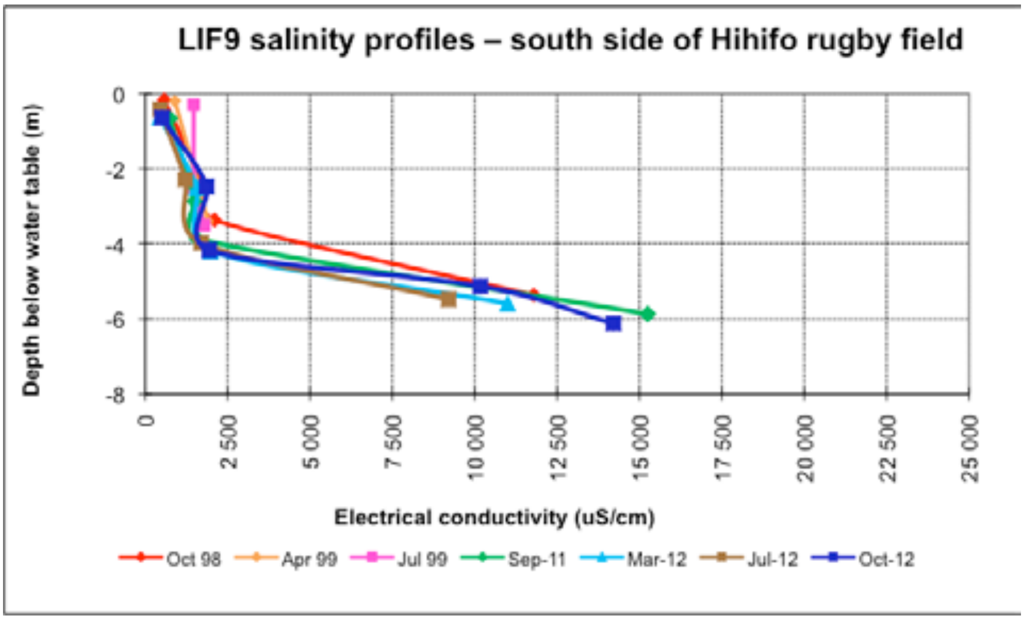


Figure 39: Freshwater thickness values for LIF 9 below the water table over selected monitoring periods. Note that the salinity in the sampling tubes at depth are generally indicating an increase in salinity at depth, suggesting a rise in the salinity of the deeper sampling tube in response to the rise in the sea level as a result of subsidence.

A comparison of the depth to the water table for the PVC pre-2006 and post-2006 subsidence indicates a change in water level, which supports the observed increase in salinity at depth indicated above. Figure 40 shows the change in measured water levels for PVC pre-2006 and post-2006.

Whilst the water table height is a function of both recent recharge and tidal impacts, as shown by the spread of data, there is a clear difference in heights between pre-2006 and post-2006 water tables, interpreted as a rise in sea level due to subsidence. Taking the difference between the averaged readings for pre-2006 and post-2006 water-level data, we are able to get a relative height difference of 0.55 m. Assuming a measured subsidence of 23 cm at this point, we are able to estimate specific yield.

Assuming a uniform total volume increase of 0.55 m^3 for a volume of water drained of 0.23 m^3 it is possible to estimate the specific yield for the sediments in LIF 9 to be 42%.

As was the case for LIF 7, the calculated specific yield value for LIF 9 appears to be higher than the literature would suggest for these sediments (Johnson 1967), indicating that perhaps actual subsidence at this point may have been less than the measured subsidence, or that water-level measurements have been affected by rainfall.

The difference in relative 'rises' in the water table between LIF 7 (0.45 m) and LIF 9 (0.55 m) is a function of the porosity of the sediments. LIF 7 indicates greater porosity than LIF 9, suggesting that LIF 9 has lower hydraulic conductivity than LIF 7.

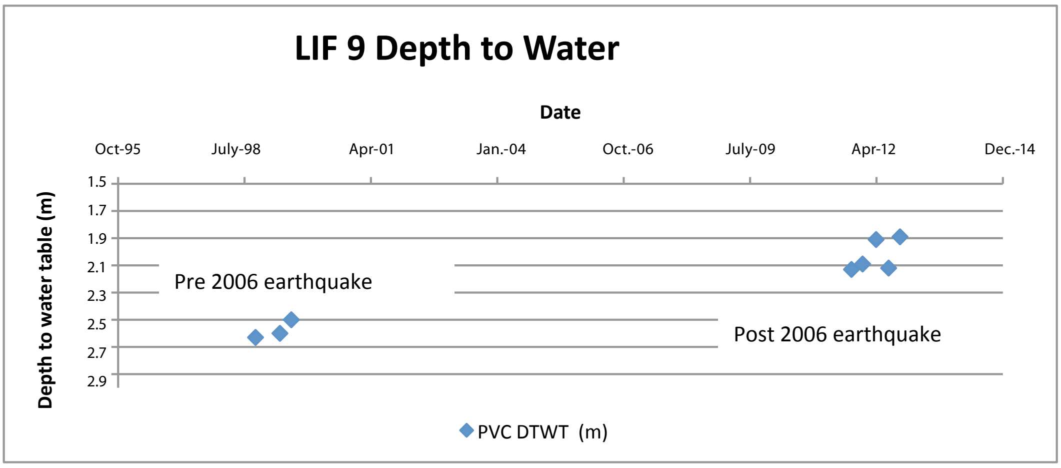


Figure 40: Depth to water table values for LIF 9 over selected monitoring periods. Note the decrease in the depth to the water table post-2006 compared to pre-2006 measurements, indicating a 'lifting' of 0.55 m in the water table in response to the rise in the sea level from subsidence.

LIF 6 – Moa Road, Hihifo

LIF 6 on Moa Road in Hihifo indicates that the freshwater lens can be quite variable in response to rainfall. During dry periods it was measured at about 1.5 m thick, but in wetter periods it measured about 6 m, and represents one of the thickest parts of the lens, based on recent monitoring. The salinity profiles suggest, however, that during very dry periods such as in October 1998 at the end of a long period of below-average rainfall, the lens was not only very thin but appeared to take some months to recover.

Of note is that the salinity measurements in the monitoring bores taken before the 2006 earthquake and subsidence, and salinity measurements taken after, do not demonstrate any significant impact from this event. That is, the variation in salinity found within the lens at various depths over time is dominated by the rainfall recharge that occurs, rather than any strong geological factor.

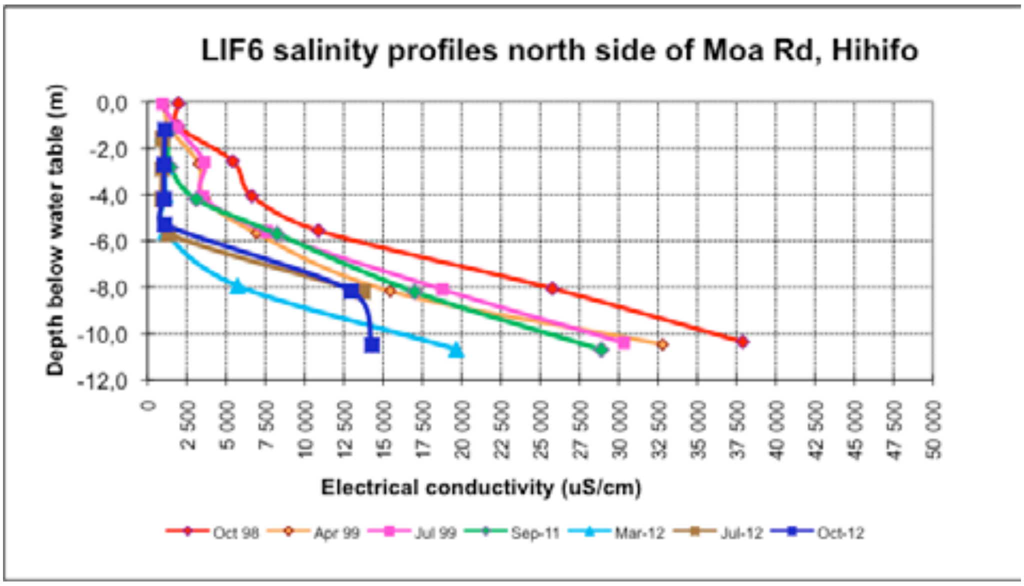


Figure 41: Freshwater thickness values for LIF 6 below the water table over selected monitoring periods. Note the considerable variability of freshwater lens thickness over time in response to rainfall. At the end of the extended dry period in 1998, the lens thickness was measured at less than 2.0 m, whilst during periods of higher rainfall, the freshwater lens was greater than 6.0 m thick.

2.8 Water level and salinity loggers

Diver CTD (conductivity/temperature/depth) loggers with barometric loggers were installed in three of the pumping galleries to establish water-level and salinity trends. At the time of reporting, the period of logging was from March 2013 to July 2013. The loggers were installed in Hihifo Gallery East (diesel), Hihifo Gallery North (electric), and Pangai Gallery North (solar). All sites at which loggers were installed are active pumping sites.

It is clear from the graphs (Figure 42) that the water levels in Hihifo Gallery East and Pangai Gallery North are influenced by the tides. The tidal lag is the time difference between the high tide in the ocean at Lifuka and the high-tide response in the aquifer. Tidal efficiency is the ratio of well-water fluctuation to that of the ocean. Tidal lag and efficiency are an indication of the communication between the ocean and groundwater. Permeability of the soils, proximity to tidal influence, and tidal range will impact on the tidal response in the aquifer. In general, the greater the tidal lag, the lower the tidal efficiency. Table 10 shows the tidal lag and efficiency response for Hihifo Gallery East and Pangai Gallery North.

Note that there is no clear tidal influence observable at Hihifo Gallery North. This is surprising, given its proximity to the ocean. This is possibly a function of the lower permeability of the sediments, which would generally dampen the tidal response, or of a low permeability layer below Hihifo Gallery North that is reducing the tidal impact. Drilling logs (Turner 1998) from LIF 8 indicate silty sands from the water table to about 6.0 m with a coarse gravel layer at 5.5 m.

Table 10: Tidal efficiency and tidal lag estimates for Hihifo Gallery East and Pangai Gallery North. Note that there was no discernible tidal influence observed at Hihifo Gallery North.

	Tidal range and for high tide time on 9/4/2012	Tidal efficiency	Tidal lag (hours)
Lifuka predicted tides	1.536 m; 09:10		
Hihifo Gallery East	0.043 m; 14:00	3%	4–4.5 hours
Pangai Gallery North	0.143 m; 11:45	9%	2–2.5 hours

All loggers show a response to the rain events recorded during the period of measurement, from April to July 2012. A large rainfall event occurred, with more than 90 mm of rain, which resulted in a significant rise in the water levels of all wells within a couple of days of the event, indicating rapid recharge under these types of conditions. Recharge following smaller events is often not as pronounced and also may take longer to be realised in the groundwater. The type of rain event will influence the recharge response observed at the water table such as water level height, as well as the duration of the water-level change. It is proposed that a rainfall event involving slower, more steady rain will generate a broader response in the water level, as opposed to a shorter-duration, high intensity rain event, resulting in a pronounced spike in the water table, as indicated in 'diver' profiles of the water table recorded after 9 May 2012, Figure 42.

Also of note is the gradual decline in the water level in HIF North and Pangai North Solar. These two bores, which are closer to the ocean and with a thinner freshwater lens, demonstrate a gradual decline in the water level over a three-month period of 20 cm. This was most pronounced during June 2012, where the water level pattern recorded is indicative of excessive drawdown in the well, resulting in the pump switching off, followed by a rise in the water level after some hours and the pump switching back on for a number of hours.

In light of the observations from the monitoring bore LIF 8, which is near Hihifo Gallery North, indicating an increase in the salinity and reduction in the freshwater lens thickness over time, it would appear that the abstraction from Hihifo Gallery North is stressing the aquifer. This is likely to have been compounded by the apparent 'lift' in the freshwater lens of 0.55 m relative to the existing galleries and pumping wells after the 2006 earthquake.

It is suggested that some care is required to ensure that a sustainable pumping rate is applied during dry periods and that the water abstracted is of sufficient quality to be of use to the community. During dry periods the abstraction rate should be reduced to avoid drawing in more saline waters.

As the freshwater lens is thinner in the areas where Hihifo North and Pangai North pumping wells are located, the abstraction potential is more limited. During dry times, as expected, these bores experience both a decline in water level and an increase in salinity.

Hihifo East, where the lens is thicker, can be expected to be more resilient and its water levels less impacted. However, it should be noted that salinity readings of 1600–1700 µS/cm from Hihifo East Gallery are quite high, indicating that the current abstraction rate at Hihifo Gallery East, 1.5L/s, is likely to be too high. Abstraction from this bore should be managed, based on the maximum agreed salinity that will be tolerated by the community. Whilst this tolerance will vary from person to person, the community should be given the opportunity to determine what is acceptable for piped water. Personal communication with different members of the community, and the results of the household survey (Sinclair et al. 2013), indicate that TWB piped water is considered to be too high in salinity.

The salinity values identified in Table 11 are a useful starting point for consideration of acceptable salinity range in TWB piped water, and guidance for management purposes.

Table 11: Guide on the salinity threshold values for consideration by the community of Lifuka and to provide guidance for management purposes.

Salinity range µS/cm	Comments
<200	Rainwater
200–1,100	Suitable range for drinking purposes, slight taste of salinity perceptible to many people at the upper end of range.
1,100–1,500	Upper desirable range for drinking water, where salinity in water will be perceptible to most people, but tolerated.
1,500–2,500	Salinity taste in the water will be perceptible to all and unacceptable to many. (Water from production bores with salinity above 1,500 µS/cm would not be used except in emergency situations.)
> 2,500	Upper limit of freshwater. Salinity taste in water will be unacceptable to most people for drinking water.

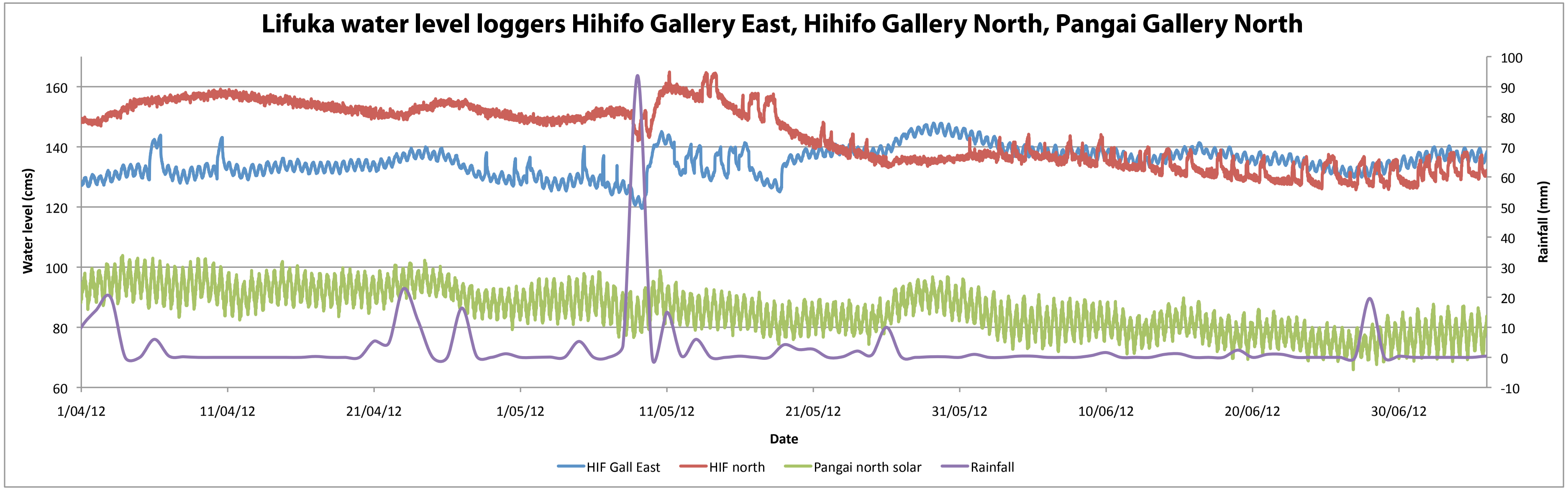


Figure 42: Water level profiles for Hihifo Gallery East, Hihifo Gallery North, and Pangai Gallery North (solar). Hihifo Gallery East and Pangai Gallery North demonstrate tidal influence on the water table. This is less discernible at Hihifo Gallery North. All water-level profiles indicate a response to rainfall recharge and periods without rain. During June 2012, a period of low rainfall, Hihifo Gallery North shows evidence of drawdowns, during which the water level dipped below the level of automatic cut-off for the pump, causing it to switch off. Once the water level recovered sufficiently, the pump resumed pumping until it again drew the water table below the automatic cut-off level, resulting in a step-type signature on the logged water level.

2.9 Freshwater lens thickness summary

The geophysical survey using the EM34 during the September 2011 period was used as a first-approach to delineate the extents of the usable portion of the freshwater lens and calculate volumes of freshwater available. As the survey was undertaken at the end of a dry period, the volumes of fresh water (<2,500 µS/cm) calculated in Table 5 are likely to be conservative and refer to the contoured thicknesses identified in Figure 19.

Table 12: Estimated available freshwater lens volumes, to 2,500 µS/cm, delineated from EM34 survey, Lifuka, Ha'apai September 2011

Freshwater contour	Freshwater area (m^2)	Freshwater volume (m^3)	Available freshwater volume (m^3)
3 m	874,740	2,624,220	787,266
6 m	111,580	669,480	200,844
9 m	18,980	170,820	51,246
Total	**1,005,300**	**3,464,520**	**1,039,356**

Note: the specific yield used to calculate the freshwater volume available was 0.30. This figure was based on a comparison of established literature for sediment type (Johnson 1967) and the specific yield calculated based on the observed impact on the water table for monitoring bores resulting from the rise in sea level.

As indicated in section 2.5.2, the EM34 survey identified an area of high conductivity, suggesting a potential thinning of the freshwater lens in this area. The explanation for the anomaly is not clear but it could be caused by an anomalous geological feature or potential issues with the calibration of the EM34 equipment itself. The estimates of freshwater lens areas and volumes in Table 5 do not include the area of high conductivity (36,700 m^2) in the calculations and are thereby conservative in their estimation of available freshwater volume.

2.9.1 Groundwater recharge and sustainable yield

Groundwater recharge

Fry and Falkland (2011), provide a detailed analysis of recharge calculations, using both a simple analysis of recharge for Vava'u, the island group to the north of Ha'apai, based on the relationship between annual rainfall and recharge (UNESCO 1991; Falkland 1992) (Figure 42), and using WATBAL, an analytical recharge calculation model.

A simple analysis of recharge can be calculated from rainfall based on empirical experience, (UNESCO 1991). Using an average annual rainfall of 1700 mm and the relationship for recharge from average annual rainfall (Figure 43), recharge is estimated to be about 480 mm, or 28% of rainfall. Given the relatively low tree cover within the lens area, the estimate for recharge could be increased by 5–10% (Fry and Falkland 2011), leading to an estimate recharge of 31% of average annual rainfall.

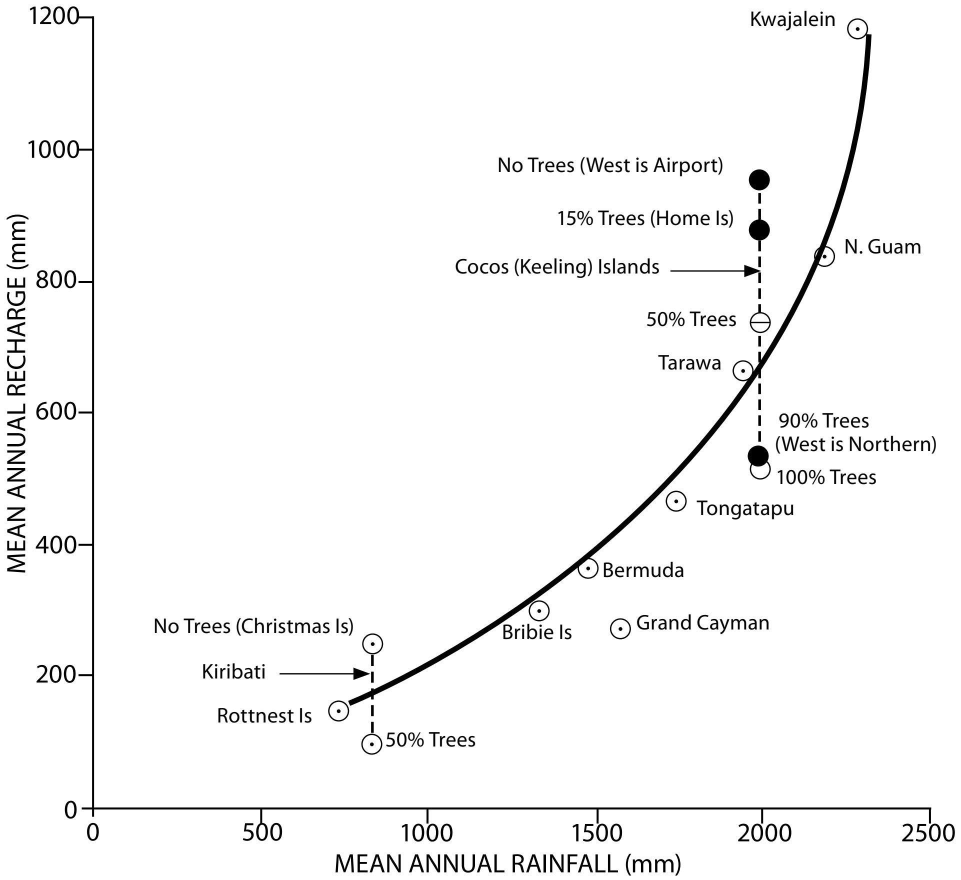


Figure 43: Annual rainfall recharge analysis and relationship for a number of islands (UNESCO 1991)

WATBAL, (Falkland 1992), calculates the water budget using either monthly or daily rainfall and evaporation rates. Monthly time steps with monthly evaporation and rainfall data were used to estimate recharge, which is 5%–10% more conservative in recharge calculations than using daily rainfall and evaporation data and time steps.

The estimated Penman potential evapotranspiration is 1,548 mm per year (Thompson 1986). Falkland (1992) estimated the recharge on Lifuka based on a water-balance simulation to be 478 mm per year or 28% of the mean annual rainfall. This accords well with annual rainfall recharge relationship calculated.

It is suggested that, based on the previous work of Falkland (1992) and Fry and Falkland (2011) and the low tree coverage within the recharge area, a recharge estimate of 30% could be used as a first estimate.

Sustainable yield estimates

The sustainable yield determined or assigned to any particular groundwater aquifer is ultimately a negotiation between the technical considerations on the amount of water that can be abstracted for a defined period without adverse affects on the aquifer, water quality, or the environment, and the level of impact on the water resource the community is prepared to accept.

In an atoll environment, the dominant impact for potable and domestic water supplies is water quality, and the level of 'saltiness' that the community is prepared to accept. As indicated in Table 11, there is a range of salinity that communities are prepared to tolerate under different conditions and situations. This potential range of salinity levels acceptable for the community will have an impact on the estimated sustainable yield. If the community is tolerant of higher-salinity water for domestic and potable purposes, their sustainable yield from the groundwater will increase, compared to a community that is tolerant only of low-salinity water. This can, and will, vary over time and, as such, sustainable yield will be a range.

Historically, in atoll situations, water-resource assessments have identified an electrical conductivity level of 2,500 uS/cm as a useful cut-off for usable freshwater resources, although in some places this threshold is much lower. WHO (2011) assigns a value of 250 mg/L chloride as the desirable limit for drinking water (~ 500 µS/cm), although this is based on aesthetic values of taste, as there is no health-related reason to assign this value.

Based on the area of available fresh groundwater, using the 2,500 µS/cm cut-off value, at the time of the survey, the volume of fresh groundwater in Pangai and Hihifo is estimated to be 1,039,356 m^3. Using the recharge value of 30% of the average annual rainfall, (512 mm/year), the recharge volume for the freshwater lens is calculated at 533,296 m^3/year.

Traditionally, the sustainable yield for an atoll is considered a function of the available recharge, the available storage and the discharge or outflow of groundwater. The type of abstraction and the pumping rate can also affect the sustainable yield with regard to management of salinity at the abstraction point.

UNESCO (1991) indicates a sustainable yield range for small islands ranging from 20% of annual average rainfall to up to 80% for higher-rainfall islands. Fry and Falkland (2011) indicate that preliminary sustainable yield estimates in Vava'u of 20% and 25% of recharge are now considered too conservative; a value between 30% and 40% of recharge is considered more appropriate, given the moderately high rainfall experienced there.

As a preliminary assessment, based on experiences in similar environments in the Pacific, a sustainable yield range of 30%–40% of recharge would be considered more applicable. Using the range of 30%–40% of recharge, the sustainable yield for the fresh groundwater area is estimated to be 159,989 m^3/year to 213,318 m^3/year.

The more conservative value for sustainable yield of 159,989 m^3/year or 30% of recharge is applied, given the thin nature of the lens at the time of the survey. Under current estimated abstraction from the lens of 98,185 m^3/year, with the sustainable yield conservatively calculated at 30% of recharge, current abstraction is equivalent to 61% of the estimated sustainable yield.

Using the sustainable yield range of 30%–40% of recharge, or 159,989 m^3/year to 213,318 m^3/year, the average sustainable yield per unit area is in the range of 4,206 L/day/Ha to 5,609 L/day/Ha, given a groundwater recharge area of 1,042,000 m^2. This is equivalent to a sustainable pumping rate per square kilometre (km^2) of about 0.4 ML/day to 0.56 ML/day or about 4.8–6.5 L/s per square kilometre. Groundwater abstraction is not uniformly distributed across the area with Hihifo Gallery East 118 pumping 49% of the total volume abstracted at an estimated 1.5 L/s, which is greater than the estimated sustainable pumping rate. An abstraction rate of 1.0 L/s is recommended to reduce the impacts on the freshwater lens and reduce the salinity of the water from this well.

2.10 Seawater inundation impacts

Seawater inundation impacts were predicted using numerical modelling undertaken as part of this study; refer to C.1.0 Coastal Hazards (Kruger et al. 2013). The inundation modelling identified the impact of predicted sea-level rise plus the impacts of a direct hit from a Category 5 cyclone with the associated storm surge.

The 1:100 year inundation event indicates inundation of up to 5 m above the current mean sea level. The impact of an event this size would affect 79% of existing infrastructure (Kruger et al. 2013), including the TWB water treatment plant. Whilst this rare event would clearly be catastrophic for the community of Lifuka, there is potential for inundation events of smaller magnitude to affect land and infrastructure, including water supply wells, with increased frequency.

The impacts of a 1:100 year inundation event with regard to the freshwater lens were modelled (Figure 44), with the potential areas and volumes affected identified in Tables 12 and 13. It is calculated that under such an event, 73% of the freshwater lens would be affected. In other words, just 27% of the freshwater lens area would not be subjected to inundation under such an event.

Table 12: Estimated available freshwater lens volumes to 2,500 µS/cm affected by 1:100 year inundation.

Freshwater contour	Freshwater area (m^2) impacted by 1:100 year inundation	Freshwater volume impacted by 1:100 year inundation (m^3)	Available freshwater impacted volume by 1:100 year inundation (m^3)
3 m	567,144	1,701,431	510,429
6 m	109,456	656,739	197,022
9 m	18,980	170,820	51,246
Total	695,580	2,528,989	758,697

Note: The specific yield used to calculate the freshwater volume available is 0.30 based on published specific yield values for similar sediments (Johnson 1967) and the calculated specific yield from monitoring bores.

Table 13: Estimated available freshwater lens volumes to 2,500 µS/cm, NOT affected by 1:100 year inundation.

Freshwater contour	Freshwater area (m^2) NOT impacted by 1:100 year inundation	Freshwater volume NOT impacted by 1:100 year inundation (m^3)	Available freshwater volume NOT impacted by 1:100 year inundation (m^3)
3 m	307,596	922,789	276,837
6 m	2,124	12,741	3,822
9 m			
Total	309,720	935,531	280,659

Note: The specific yield used to calculate the freshwater volume available is 0.30 based on published specific yield values for similar sediments (Johnson 1967) and the calculated specific yield from monitoring bores.

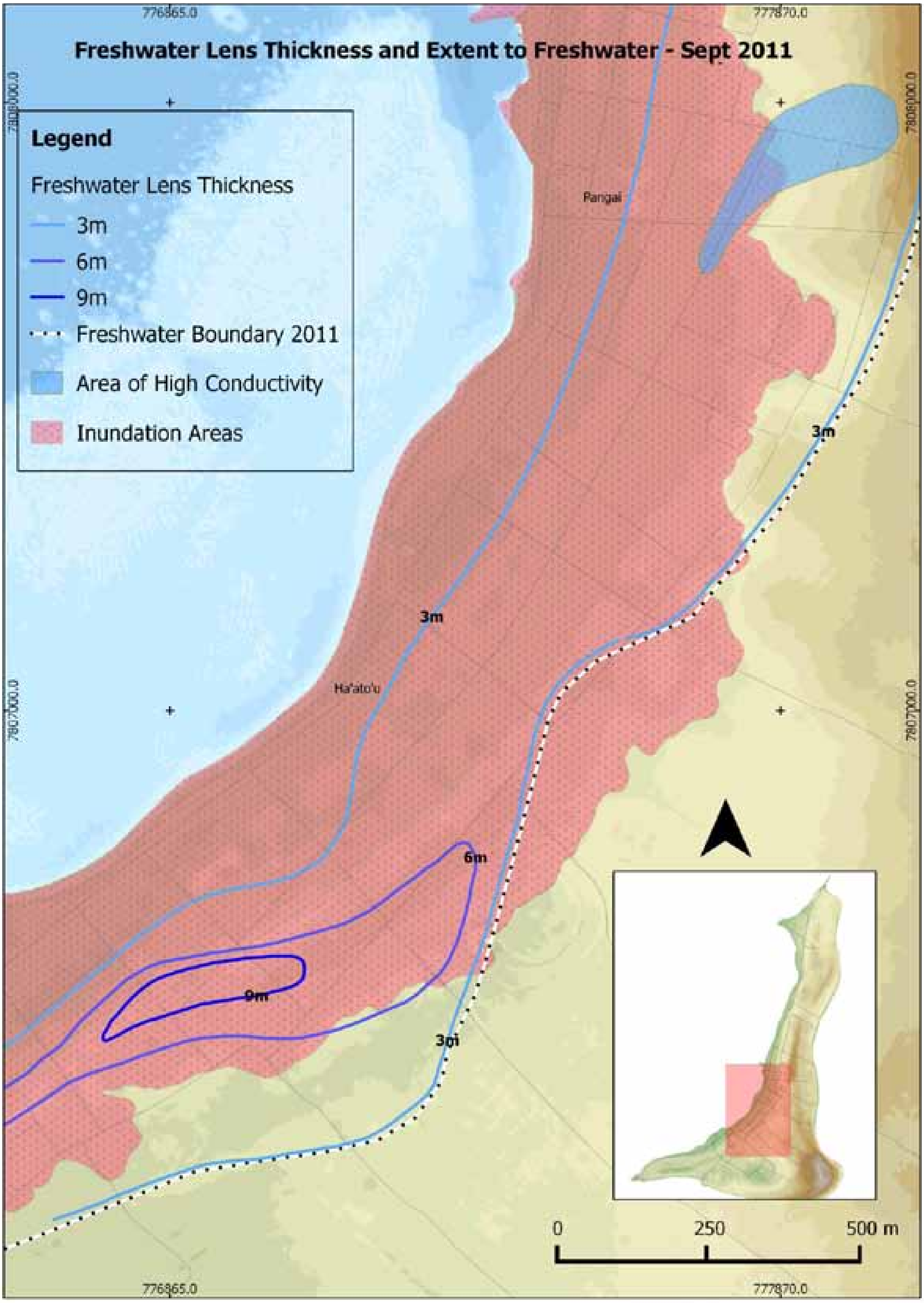


Figure 44: Extent of inundation from 1:100 year inundation event on the area of freshwater lens

Whilst the general extent of the impact has been determined, the impact of inundation on the water lens with regard to salinisation and expected recovery has not been quantified. It can be expected that a large inundation event of 1 m or more in height that lasts for a number of hours would have a significant effect both on the salinity of the lens and on the infrastructure used to abstract groundwater.

Consideration should be given to constructing bunds around well-head infrastructure. The bunds would provide some protection against smaller-magnitude inundation events whilst also reducing the potential for surface run-off to reach the well or gallery.

3. Groundwater quality and protection

3.1 Threats and risks to groundwater quality

The sandy nature of the soils of Lifuka, coupled with the shallow depth to the water table of 2.5 m (Sinclair et al. 2013) makes the risk of contamination from land-use activities high.

This risk has been identified by previous investigations (Furness 1993; Crennan 2001). Sampling of domestic and TWB production wells during the current investigation confirmed this risk, with 95% of the wells tested returning positive results for *E. coli*, suggesting contamination from poor domestic wastewater management (Sinclair et al. 2013).

The main threats to water quality include the high number of bottomless or poorly constructed septic tanks that are leaking effluent directly into the groundwater, and the large number of animals (pigs and dogs) that can be found roaming across and into abstraction and well-head areas. Their waste can readily be transmitted into wells and the areas surrounding water sources.

As Lifuka's villages are located above the main fresh groundwater resource, the likelihood of contamination is high. Crennan (2001) investigated the contamination of groundwater on Lifuka and concluded that it was not possible to determine a safe distance between septics and wells, given the high density of septic tanks and pit toilets within Lifuka, which contributed to the groundwater contamination. Crennan (2001) found that wells located further away from septics and contamination sources had, as expected, a reduced *E. coli* count compared to wells closer to contamination sources.

It can be concluded from Crennan (2001) that as long as households continue to occupy the land located above the water resource and use pit latrines and poorly-constructed septic tanks, and as long as pigs and dogs continue to be allowed to roam on and around well areas, contamination of the groundwater will continue. Conversely, if the distance between the contamination sources and the groundwater catchment and abstraction points is increased, the risk of contamination can be expected to decrease.

Increasing salinity in the groundwater resource resulting from over-abstraction as well as natural effects such as reduced rainfall during extended dry periods poses a real threat to groundwater quality and the community of Lifuka.

3.2 Management and mitigation options

In the absence of any safe setback distances to separate wells from contamination sources, a pragmatic approach to reducing the risk of contamination to well heads and groundwater catchment zones could be applied. Whilst such an approach would not remove the risk of contamination, it would reduce the risk.

Pragmatic steps that could be taken to reduce the threat of contamination are listed below.

- Setback protection zones for land-use around the wells and galleries (100 m recommended). Setback zones would restrict land-use activities, including housing of pigs, use of wastewater disposal systems that adversely impact the groundwater, and the storage and use of chemicals and fuels.

- Fencing around all TWB well heads – a nominal 10 m setback would be fenced off to restrict access to well heads, in particular to keep animals out.

- Systematic improvement to wastewater disposal for Lifuka households, replacing the bottomless septic tanks and pit latrines with alternative wastewater disposal practices such as composting toilets or improved septic tank designs. Households in close proximity to the TWB well heads and galleries, within the setback zone, should be targeted first, with consideration given to providing financial support.

- Installation of fencing around the perimeter of the TWB Well 4 depression area with bunding around the perimeter to direct surface drainage away from the well head.

- Ongoing maintenance of fencing and the area within the enclosure (grass cutting).

- Enforcement of existing regulations restricting dogs and pigs from roaming freely (especially in groundwater capture zones for well heads).

Figure 45 indicates the likely extent of 100 m setback protection zones around the abstraction areas. It should be noted that Crennan (2001) indicates that there is no safe distance between septics and wells in Lifuka due to the density of wells. The nominal setback protection zone (recommended 100 m) is provided as a pragmatic approach to reduce the impact of contamination. Land-use restrictions should be enforced, by means such as fines for households with pigs found within the area, and financial assistance provided to introduce appropriate waste-water disposal practises to those households within the setback zone.

Salinity impacts from over-pumping can be reduced through the management of abstraction at individual wells. It is recommended that the Tonga Water Board take a pragmatic approach to achieve greater consistency in water quality supplied by restricting its abstraction to wells that have salinity below predetermined levels.

Individual wells could be monitored on a weekly basis with abstraction restricted to those wells with readings below a maximum salinity threshold. The overall salinity of the water supplied to households could then be restricted to a predetermined range, to ensure that a sufficient volume of water can be provided to the community during dry periods.

It is recommended that the Tonga Water Board monitor the salinity and the volumes abstracted from the individual wells on a weekly basis, with daily monitoring of the salinity and the volume of water leaving the treatment plant. This usage and salinity information will allow the board to improve its management of the groundwater resource and overall water supply to the community of Lifuka.

Additional pragmatic approaches to improved water management are described below.

- A reduction in the 51% of water that is produced but unaccounted for through targeted leakage programmes and identification of causes at the household level, such as illegal connections.

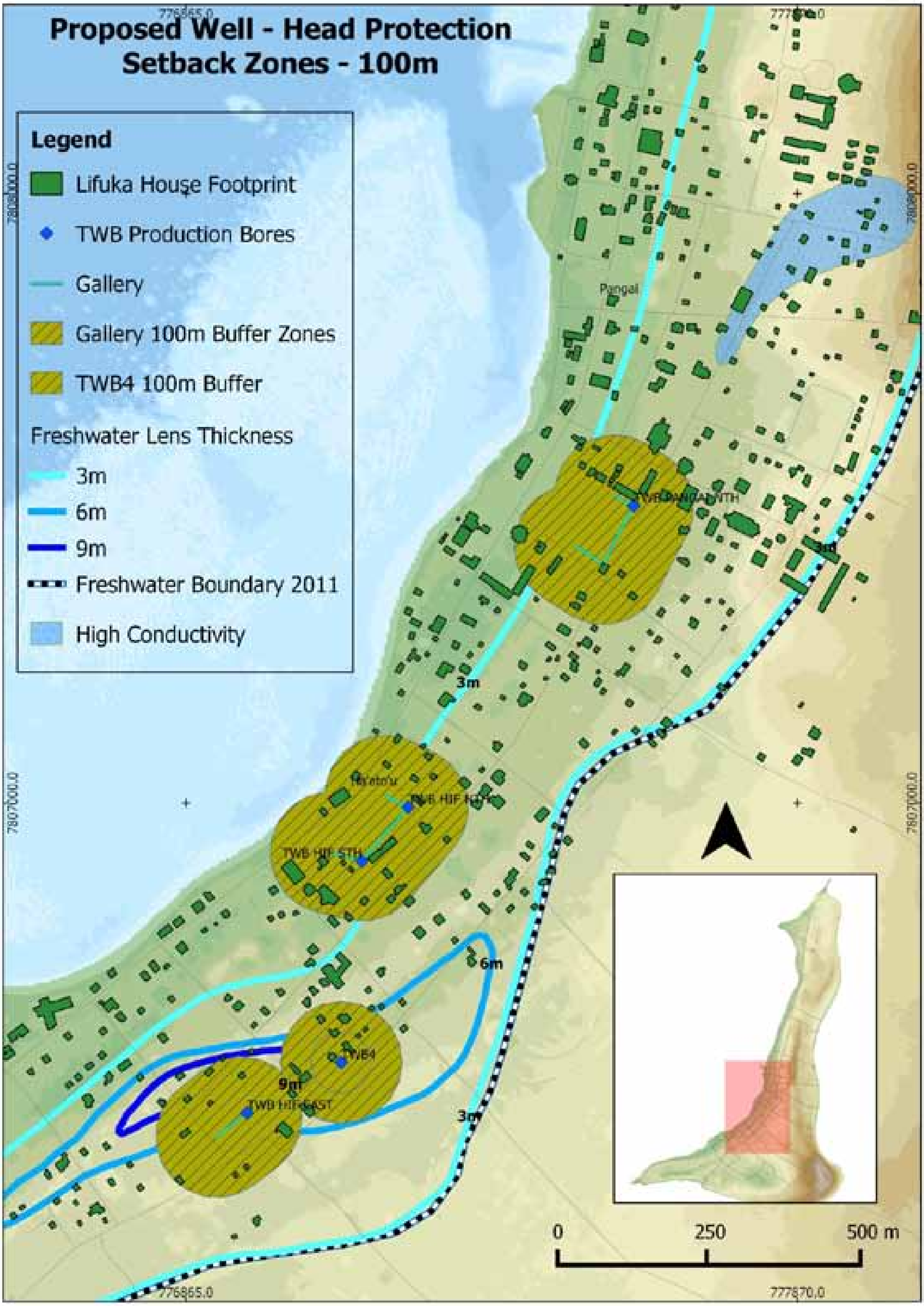


Figure 45: Extent of 100-m well-head protection zones around galleries and well heads; 100-m setback zones would provide greater protection. It is proposed that land-use activities be restricted and onsite wastewater disposal systems upgraded within the well-head protection setback zones.

- Investigation and construction of additional groundwater abstraction galleries to increase the overall availability and supply of fresh groundwater. Future groundwater investigation should focus on areas outside the areas at risk of inundation in the first instance.

During extended dry periods with reduced rainfall and recharge as indicated from the monitoring, the freshwater lens will shrink and the salinity of the abstracted groundwater will increase naturally in response to reduced recharge. It is during these extended dry periods, when there is a reduction in stored harvested rainwater, that groundwater will be more heavily relied on. To better manage the available fresh groundwater resources during this period a drought management response action plan could be developed with TWB, other Government of Tonga departments and the community to detail appropriate actions to ensure the best use of the available fresh groundwater and improve water conservation measures. An example of such a plan is detailed in the Government of Kiribati Drought Response Plan for South Tarawa, 2011. A similar approach for drought management was recommended in Hyland (2013) for Vava'u and could be applied on Lifuka.

A drought management response action plan outlines the:

- structures and responsibilities of government, community and other organisations to contribute to the development of an appropriate response;
- processes and techniques used to identify the onset of drought;
- information needed to determine the severity of the situation, and a simplified drought classification system used to inform the community;
- different range of actions available that will help to maximise water conservation and reduce stress on the resource; and
- communication options to help inform the community and encourage water conservation.

4. Adaptation options for improved water security

4.1 Rainwater harvesting improvements

The 2013 household survey report for Lifuka (Sinclair 2013) indicates that there is a preference and reliance on rainwater for drinking, cooking and washing clothes. Rainwater harvesting provides additional water security through diversification of water sources. Future climate scenarios (Australian Bureau of Meteorology and CSIRO 2011) predict rainfall patterns that in time will result in wetter wet seasons and decreased rain during dry seasons. Improvements could be initiated by households with local government support to help maximise the collection and storage of rainwater, and improve the quality of the water harvested and stored. The application and enforcement of appropriate building codes to maximise rainwater harvesting potential for new and renovated households and buildings will provide greater resilience against expected rainfall scenarios into the future.

Guttering improvements

- 94% of all households are capturing 75% or less of the roof area.
- 75% of houses require guttering improvements, with improperly fitted gutters resulting in water loss.
- A programme for improving guttering and ensuring ongoing maintenance is required to increase the effective collection of rainwater. The programme should focus on enlisting householder participation. For example, a rainwater harvesting maintenance workshop whereby householders are encouraged to participate with sharing of tools, knowledge and manpower. A village-based rainwater harvesting inspection on a regular basis (annually, for example) with an incentive or reward system that recognises both efficient and improved rain water harvesting systems would be useful.

Rainwater quality improvements

- 46% of connected household tanks do not have any screens to filter debris, and only 5% of all households regularly boil their drinking water.
- The installation of first flush devices and the use of screens at tank openings will improve water quality, reducing sediment and organic matter debris from tanks.

Storage improvements

- It is estimated that 12% of households have 5,000 L of storage or less, with the average amount of storage 14,663 L per household. It is possible to identify households with limited storage for consideration for targeted support to increase storage in the future.
- Note that whilst the use of concrete tanks is the norm on Lifuka (75% of all tanks are concrete), plastic tanks are gaining favour and have the advantage that they can be relocated if necessary, and are of standard sizes and therefore easier to link for increased and connected storage in the future.

4.2 Reduce leakage in TWB piped system

- Total unaccounted for water in TWB system is 51% of overall water production.
- Leakage is estimated to cause the loss of 33% of total production, with water that is unaccounted for between the treatment plant and the household estimated at 18% of total production.
- It is recommended that support be provided to assist TWB to identify and reduce these losses, with a target of reducing loss to no more than 20% of total production.
- Identifying leakage losses between the production bores and the treatment plant is expected to lead to a reduction in loss of 13% of the total water production.
- Reducing the number of illegal connections and unaccounted for water at the household could lead to a reduction in loss of 18% of the total water production.

4.3 Management of abstraction by salinity

- As indicated in Table 1, most wells are abstracting at a rate of 0.5 L/s over 24 hours (the solar pump for Pangai is estimated to be abstracting close to 1 L/sec for 12 hours operation).
- Hihifo gallery East 118 is pumping at 1.5 L/s over 24 hours and is responsible for 49% of total abstraction.
- The salinity in Hihifo Gallery East 118 is indicated to be more than 1,700 µS/cm when pumping during dry periods. It is concluded that the pumping rate at this bore is too high and is affecting the freshwater lens, and that therefore it should be reduced.
- Greater surveillance of the relationship between pumping rate and salinity will allow TWB to determine appropriate abstraction rates for each well and assist in improving both water quality to the consumer and protection of the well over time.
- It is recommended that weekly salinity monitoring on the production wells be undertaken and results examined along with abstraction rates to establish relationships between pumping rates and salinity, with consideration to rainfall for improved operation and management as indicated above.
- A drought management response action plan should be developed to identify the responsibilities and actions by government and community alike to improve water management and water conservation during extended dry periods and droughts.

4.4 Improved monitoring

- Water quality testing for *E. coli* and FAC (free available chlorine) is undertaken by TWB in Tongatapu and the results are reported back to TWB Lifuka if they are above acceptable limits. Efficiencies could be achieved if this testing could be undertaken by hospital staff in Lifuka. Modest support for equipment and consumables would be required; however, improved and more responsive operation and integration between departments could be achieved if this testing was carried out locally.
- Quarterly monitoring should be undertaken through the salinity monitoring bores. Modest support could be provided to TWB to undertake this work on behalf of MLSNRECC on a quarterly basis. The contractual obligations to MLSNRECC would also require data to be reported back to MLSNRECC with operational budget support provided to MLSNRECC to undertake annual site auditing.

5. Summary of the findings and recommendations

5.1 Findings

The key findings from this work with regard to groundwater resource investigations are given below.

- The freshwater lens on Lifuka is naturally very dynamic and fragile. It is very responsive to rainfall events and begins to thin within a few months of little or no rainfall.
- Inundation modelling shows that all existing TWB piped infrastructure, including the production bores and galleries and the treatment plant, are at risk of some level of inundation from a 1:100 year inundation event.
- The subsidence and the associated rise in sea level on Lifuka has had an impact on the fresh groundwater lens, causing it to be 'lifted' by an observed 0.45–0.55 m in monitoring bores. In some cases, this appears to have increased the thickness of the freshwater lens and hence the amount of water stored.
- The freshwater lens is mapped as being thickest in the area around Hihifo Gallery East. Geophysics indicates a lens thickness of up to 9 m, but of limited extent.
- The sustainable yield for the fresh groundwater area is conservatively estimated to be 159,989 m^3/year.
- Abstraction rates for some bores are too high, causing localised increased salinity during dry periods.
- The potential for increased development of the freshwater lens is limited. The area of the existing Pangai High School offers greatest potential for development of a horizontal infiltration gallery. Additional investigation is recommended to confirm the optimal location in this area.
- Rainwater harvesting should be promoted to increase water security. However, the projected climate scenarios of longer dry periods and wetter wet seasons suggest that Lifuka's community will have a greater reliance on groundwater in future.

5.2 Recommendations

- Introduce groundwater protection setback zones for TWB infrastructure. A nominal setback of 100 m from groundwater capture zones and well heads would reduce the risk of groundwater contamination. Consideration should be given to providing support to households within the setback zone to replace or improve their onsite waste water disposal to reduce groundwater contamination risk.
- Add bunding around water supply infrastructure as protection against inundation and surface water ingress. This would include all TWB pump installations and the treatment plant.

- Fence off well heads to provide a minimum 10 m setback distance from the well head with restricted access.
- Work to improve rainwater harvesting, in particular gutter collection and transmission, and introduce incentives and a rainwater harvesting maintenance programme, developed in collaboration with the community and local government.
- Establish a leakage reduction programme for TWB piped water supply to help improve water quality and reduce costs.
- Ensure weekly monitoring of salinity and abstraction rates at all TWB production wells to establish pumping rates based on salinity.
- Undertake additional investigation and consider constructing an additional horizontal gallery in the northern area of Pangai, near the current high school, which is outside of the area of modelled inundation, to provide additional security and to increase the quantity of water supplied to Lifuka.
- Develop a drought management response action plan for Lifuka.

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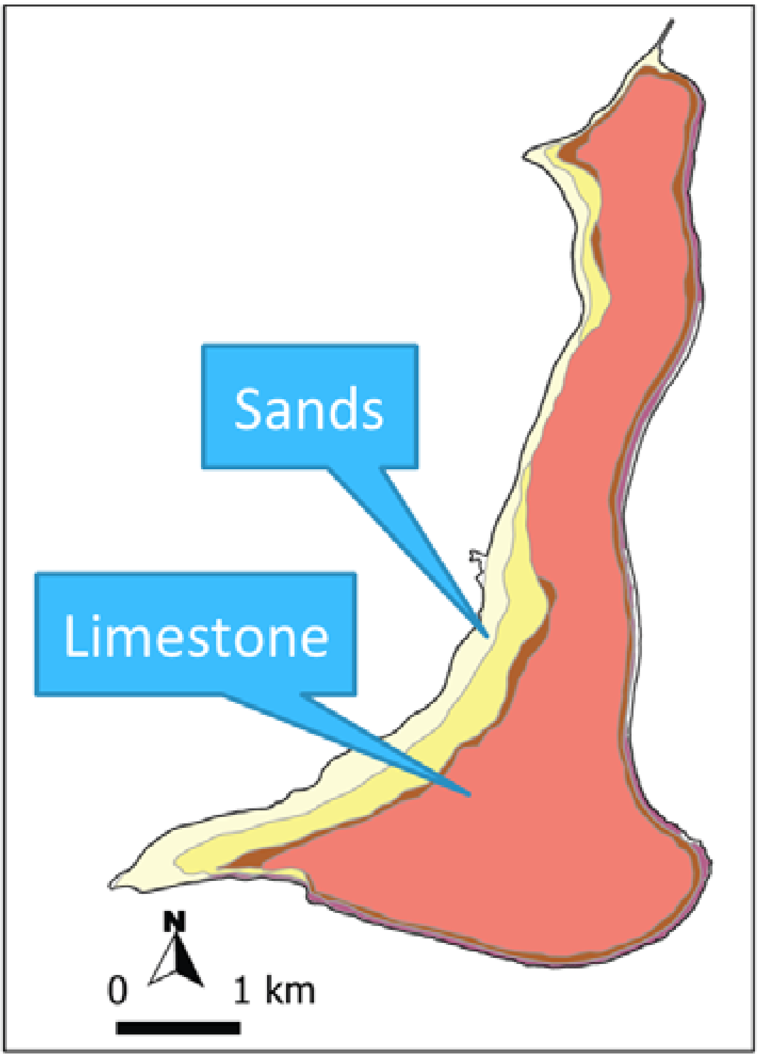
Annex 1: Soil map of Lifuka



This is a simplified soil map of Lifuka. Note that the low-lying coastal plains of the western shoreline comprise unconsolidated sands.

Annex 2

Drilling logs for Lifuka salinity monitoring boreholes
from Turner 1998, Report on Water Monitoring Borehole Installation Lifuka, Ha'apai

Summary of borehole locations

Borehole	Location
LIF 1	East side of Hihifo rugby field.
LIF 2	West side of Hihifo rugby field.
LIF 3	East side of Pangai rugby field.
LIF 4	West side of Pangai rugby field.
LIF 5	North side of Moa Road, between Lotokolo and Tu'akolo roads.
LIF 6	North side of Moa Road, between Holopeka and Lotokolo roads.
LIF 7	Koulo, West side of main road, south side of Airport gates.
LIF 8	North side of Hihifo rugby field.
LIF 9	South side of Hihifo rugby field.

Legend for borelogs

bgl	below ground level
M	nylon monitoring tube
m/c	moisture content
PVC	PVC monitoring tube
SWL	static water level below ground level

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	28/11/1997
Site:	East side of Hihifo rugby field	**Date finish:**	29/11/1997
Borehole No:	**LIF 1**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 2.1 m: SANDY SILTY CLAY (CH/CL):** Stiff to very stiff, brown dark brown, m/c greater than plastic limit, with trace ash and plant material.		
1.5 m	**1.5 m – 12.2 m: SILTY GRAVELLY SAND:** Fine to coarse grained, loose to medium dense, pale brown to cream, moist,		
	becoming wet below 3.0 metres with moderate to high fluid loss below 4.0 metres	SWL 3.0 m 29/11/97	**M1: 4.5 m**
			M2: 6.5 m
12.0 m	**12.2 m – 13.0 m: SILTY GRAVELLY SAND:** Fine to coarse grained, loose to medium dense, grey and cream with some ash and pumice.		**M3: 8.5 m**
13.0 m	**13.0 m – 14.0 m: GRAVELLY SILTY SAND:** Fine to coarse grained, medium dense, cream, wet. With some limestone cobbles		**M4: 10.5 m**
15.0 m			**M5: 12.5 m**
	14.0 m – 19.0 m: As above: With some limestone cobbles between 18.0 m – 19.0 m.		
	19.0 m – 21.5 m**: LIMESTONE:** Slightly to moderately weathered, highly fractured, cream, high strength, high mud loss.		**M6: 14.7 m**
			M7: 18.0 m
	END OF BOREHOLE LIF 1 AT 21.5 m		
	Slotted PVC standpipe placed at 4.1 m below ground level		
	Note: Borehole caved to 18.0 m below ground level on withdrawal of drill string.		

Drilling log

Location:	Lifuka, Kingdom of TONGA.	**Date start:**	29/11/1997
Site:	West side of Hihifo rugby field	**Date finish:**	1/12/1997
Borehole No:	**LIF 2**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m			
	0.0 m – 1.9 m: CLAYEY SILTY SAND: Fine to medium grained, loose to medium dense, grey and brown moist.		
		SWL	
	1.9 m – 15.0 m: SILTY GRAVELLY SAND: Fine to medium		
2.0 m	grained, medium dense, grey and cream moist to wet	1.5 m	
	Medium fluid loss.	1/12/1997	
			M1: 3.5 m
4.0 m			
			M2: 5.5 m
6.0 m	With increase in silt content below 6.0 m		
	Low fluid loss below 6.5 m		
8.0 m			**M3: 7.5 m**
10.0 m	With trace volcanic ash and becoming grey 10.5 m – 11.1 m		**M4: 9.5 m**
12.0 m	With trace volcanic ash 12.6 m – 12.8 m		**M5: 12.0 m**
	With some limestone (coral) cobbles below 13.2 m		
14.0 m			
15.0 m	**15.0 m – 16.5 m: LIMESTONE:** Highly to moderately weathered, highly fractured, cream, low to medium strength, medium fluid loss.		
			M6: 15.6 m
18.0 m			
	END OF BOREHOLE LIF 2 AT 16.5 m.		
	Slotted PVC standpipe placed at 3.0 m below ground level.		

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	2/12/1997
Site:	East side of Pangai rugby field	**Date finish:**	3/12/1997
Borehole No:	**LIF 3**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 0.6 m: SILTY SAND:** Fine to medium dense, fine to medium grained, grey and cream, moist with trace silty clay and volcanic ash		
	0.6 m – 6.4 m: SILTY GRAVELLY SAND: Fine to coarse grained, loose to medium dense, cream. (Coral sands and gravels with some fines)		
2.0 m			
	Medium fluid loss	SWL	
4.0 m		3.0 m	**M1: 4.5 m**
		2/12/97	
6.0 m	**6.4 m – 8.5 m: GRAVELLY SILTY SAND:** Fine to coarse grained ,medium dense, cream with some limestone cobbles up to 600 mm in diameter.		**M2: 6.5 m**
8.0 m	Medium fluid loss		
	Becoming cream and brow below 8.3 m.		
			M3: 8.5 m
10.0 m	**8.5 m – 14.5 m: LIMESTONE:** Highly weathered, highly fractured, cream, low strength.		**M4: 10.5 m**
12.0 m			**M5: 12.2 m**
14.0 m	Becoming highly to moderately weathered below 12.7 metres		
			M6: 14.2 m
	END OF BOREHOLE LIF 3 AT 14.5 m.		
	Slotted PVC standpipe placed at 4.0 m below ground level		

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	3/12/1997
Site:	West side of Pangai rugby field	**Date finish:**	4/12/1997
Borehole No:	**LIF 4**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 0.6 m: CLAYEY SILTY SAND:** Fine to medium grained, loose to medium dense, brown and grey moist, with trace ash and plant material.		
	0.6 m – 8.5 m: SILTY GRAVELLY SAND: Fine to medium grained, loose to medium dense, cream, moist to wet.		
	Medium to high fluid loss 0.6 m – 4.0 m.		
2.0 m		SWL 2.05 m 5/12/97	
			M1: 3.5 m
4.0 m	Increase in gravel content below 4.0 m.		**M2: 4.5 m**
			M3: 5.5 m
	Increase in silt content below 5.0 m. Medium to low fluid loss.		
6.0 m			
			M4: 6.5 m
	With trace volcanic ash and becoming grey 6.5 m to 7.3 m.		
8.0 m			**M5: 8.0 m**
10.0 m	**END OF BOREHOLE LIF 4 AT 8.5 m.**		
	Slotted PVC standpipe placed at 2.5 m below ground level.		

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	5/12/1997
Site:	Nth side Moa Road between Lotokolo and Tu'akolo roads, Hihifo	**Date finish:**	6/12/1997
Borehole No:	**LIF 5**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 1.5 m: SILTY CLAYEY SAND / SILTY SANDY CLAY:** Stiff to very stiff, brown and grey, m/c greater than plastic limit, with trace ash and plant material.		
	Increase in sand content below 1.0 m		
	1.5 m – 6.3 m: SILTY GRAVELLY SAND: Fine to medium grained, loose cream, moist to wet.		
	High fluid loss.		
2.0 m			
	With some limestone (coral) gravel below 4.6 m	SWL	**PVC1: 4.5 m**
		3.4 m	
4.0 m		5/12/97	
6.0 m	**6.3 m – 7.5 m: LIMESTONE:** Highly weathered, moderately fractured, cream, low strength.		**PVC2: 6.0 m**
	Moderate fluid loss.		
	7.5 m – 10.8 m: SILTY GRAVELLY SAND: Fine to coarse grained, loose to medium dense, cream.		**PVC3: 7.5 m**
8.0 m	Moderate to high fluid loss.		
			PVC4: 9.0 m
10.0 m			
12.0 m	**10.8 m – 14.5 m: LIMESTONE:** Highly weathered, moderately to highly fractured, cream, low to medium strength, with minor sand lenses, moderate fluid loss.		
14.0 m	END OF BOREHOLE LIF 5 AT 14.5 m		

Drilling log

Location:	Lifuka, Kingdom of TONGA.	**Date start:**	8/12/1997
Site:	Nth side Moa Rd, between Holopeka and Lotokolo Roads, Hihifo.	**Date finish:**	8/12/1997
Borehole No:	**LIF 6**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 0.5 m: SILTY CLAY (CH):** Stiff to very stiff, brown dark brown, m/c greater than plastic limit, with trace to some sand.		
	0.5 m – 1.5 m: SANDY CLAY/ CLAYEY SAND: fine to medium grained, loose to medium dense, cream and grey, moist.		
2.0 m	**1.5 m – 10.2 m: SILTY GRAVELLY SAND:** Fine to medium grained, medium dense, cream, moist.	SWL	
	Becoming wet below 2.5 m.	2.6 m	**M1: 4.0 m**
4.0 m		8/12/97	
6.0 m			**M2: 5.5 m**
8.0 m	With trace volcanic ash and becoming grey and cream below 9.0 m		**M3: 7.0 m**
	10.2 m – 12.0 m: CLAYEY GRAVELLY SAND: fine to medium grained, medium dense, light grey to dark grey. (Ash layers interbedded with sand layers.)		**M4: 8.5 m**
10.0 m			
			M5: 11.0 m
	12.0 m – 13.0 m: SILTY CLAY: Stiff, highly plastic brown to dark brown, M/C > Plastic limit.		
12.0 m			
	13.0 m – 15.5 m: SILTY CLAYEY SAND: Fine to medium		**M6: 13.3 m**
14.0 m	grained, medium dense, grey, wet, with trace volcanic ash.		
16.0 m	**END OF BOREHOLE LIF 6 AT 15.5 m.**		
	Slotted PVC standpipe placed at 3.0 m below ground level.		

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	9/12/1997
Site:	Koulo, WST side Main Rd STH side airport gates	**Date finish:**	9/12/1997
Borehole No:	**LIF 7**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 2.8 m: SILTY CLAY (CH):** Stiff to very stiff, brown dark brown, m/c greater than plastic limit, with trace ash and plant material.		
2.0 m	**2.8 m – 3.2 m: SILTY GRAVELLY SAND:** Fine to coarse grained, loose to medium dense, cream, moist to wet. High fluid loss.		
	3.2 m – 9.5 m: LIMESTONE: Highly to moderately weathered, moderately fractured, cream, low to medium strength. (With some sand lenses.)		
4.0 m	**3.7 m – 3.9 m: SILTY SAND (lens):** Fine to medium grained, loose to medium dense, cream, wet.		
	4.3 m – 4.6 m: SILTY SAND (lens): Fine to medium grained, loose to medium dense, cream, wet.	SWL 4.6 m 8/05/97	**PVC1: 5.0 m**
6.0 m			
	4.9 m – 5.0 m: SILTY SAND (lens): Fine to medium grained, loose to medium dense, cream, wet.		**PVC2: 6.0 m**
8.0 m			**PVC3: 7.0 m**
10.0 m	**END OF BOREHOLE LIF 7 AT 9.5 m.**		**PVC4: 9.0 m**

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	10/12/1997
Site:	North side Hihifo rugby field	**Date finish:**	10/12/1997
Borehole No:	**LIF 8**	**Drilling rig:**	Walkerwell ASW286
Driller:	Taniela Heimuli	**Drill method:**	Wash boring
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 0.5 m: CLAYEY SILTY SAND:** Fine to medium grained, loose, grey to dark grey, moist.		
	0.5 m – 6.0 m: SILTY SAND: Fine to medium grained, loose to medium dense, grey and cream, moist.		
2.0 m	Becoming wet below 2.3 m.	SWL	
	(Very OPEN fluid return difficult to maintain 2.2 m to 2.6 m.)	2.5 m	**M1: 4.0 m**
4.0 m		10/12/97	
	With some coarse grained coral gravel below 5.5 m.		**M2: 5.0 m**
6.0 m	**6.0 m – 9.0 m: SILTY SAND:** Fine to medium grained, medium dense, grey and cream, wet with trace volcanic ash.		**M3: 6.0 m**
8.0 m			**M4: 8.0 m**
10.0 m	**END OF BOREHOLE LIF 8 AT 9.0 m.**		
	Slotted PVC standpipe placed at 3.0 m below ground level.		

Drilling log

Location:	Lifuka, Kingdom of TONGA	**Date start:**	
Site:	South side of Hihifo rugby field	**Date finish:**	
Borehole No:	**LIF 9**	**Drilling rig:** Walkerwell ASW286	
Driller:	Taniela Heimuli	**Drill method:** Wash boring	
Assistants:	Sione Saipa'ia, Himuiti Fuimaous and Sione Lemeki		

Depth (m)	Material (lithology)	Other tests	Monitors (m bgl)
0.0 m	**0.0 m – 0.6 m: CLAYEY SILTY SAND:** Fine to medium grained, loose, grey and dark grey, moist. High fluid loss.		
	0.6 m – 4.2 m: SILTY GRAVELLY SAND: Fine to medium grained, loose to medium dense, cream, moist to wet.		
2.0 m			
	Medium to high fluid loss.	SWL	
4.0 m	**4.2 m – 6.2 m: GRAVELLY SILTY SAND:** Fine to coarse grained, medium dense, highly to moderately weathered, slightly fractured, cream, low to medium strength.	2.3 m 11/12/97	**PVC1: 2.8 m**
	Medium fluid loss.		
			PVC2: 5.0 m
6.0 m	**6.2 m – 9.0 m: SILTY GRAVELLY SAND:** Fine to medium grained, medium dense, cream and grey. Wet. With trace volcanic ash between 6.3 m to 8.3 m.		**PVC3: 6.0 m**
			M4: 7.0 m
8.0 m			**M5: 8.5 m**
10.0 m	**END OF BOREHOLE LIF 9 AT 9.0 m.**		

Annex 3

EM34 principles

The basic principle of operation of electro-magnetic conductivity surveys is illustrated in Figure 1. The EM34 uses two coils – a transmitter and a receiver – to get a measure of ground conductivity. The ground conductivity values obtained are then used to interpret possible geological and hydrogeological models to obtain the survey results.

The transmitter coil radiates an alternating electromagnetic field which induces electrical currents (termed eddy currents, *Je*) in the earth below the coil. These eddy currents in turn generate a secondary magnetic field (*Bs*). The receiver coil detects both the primary and the secondary magnetic field. The secondary magnetic field is influenced by factors such as coil spacing, operating frequency and ground conductivity. The receiver coil detects and measures both the secondary and primary magnetic fields and calculates the apparent conductivity based on the ratio between the two fields.

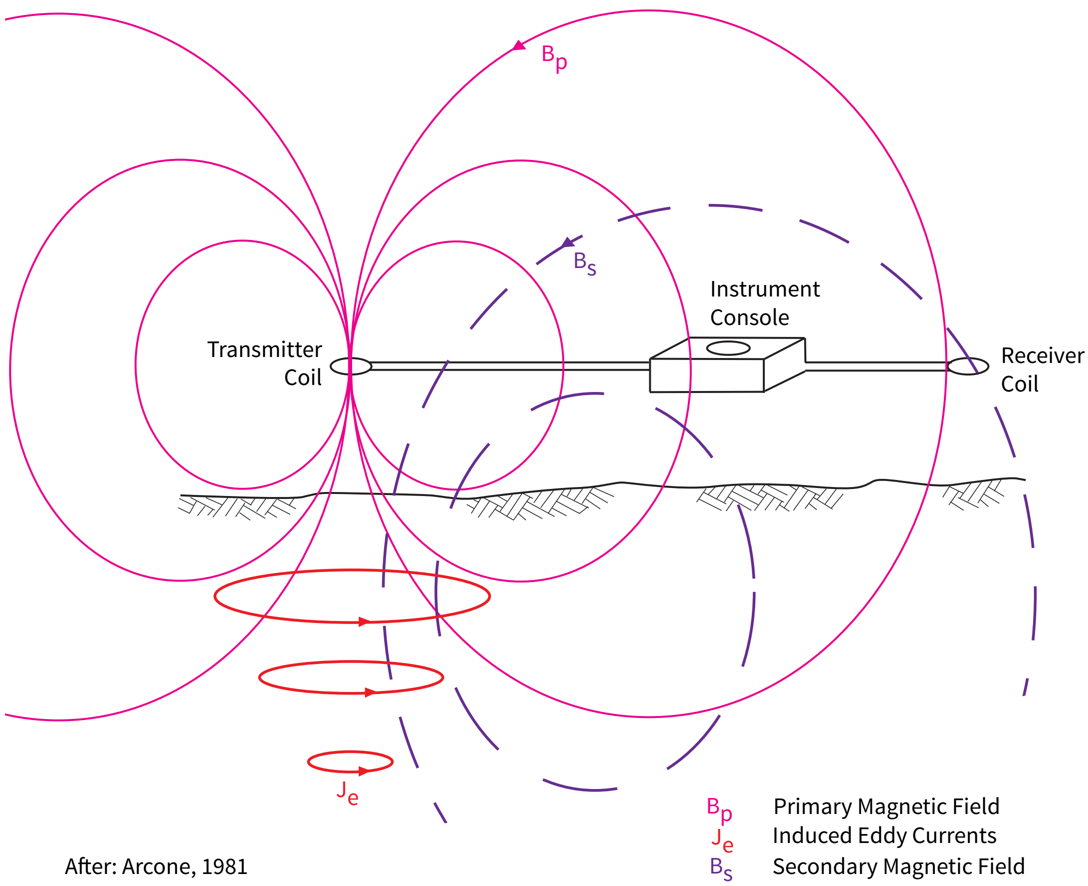


Figure 1: EM survey principle of operation (NGA 2000, p 1)

The two coils are held by operators and are connected by a cable of one of three defined lengths, 10 m, 20 m or 40 m. The coils are placed in the vertical or horizontal dipole position, depending on the investigation design of the survey, the ground conditions and the targets.

The depth of exploration depends on the separation between the transmitter coil and the receiver coil, as well as on the coil orientation (coil axis/dipole horizontal or vertical). McNeill (1980) explains that geological factors such as moisture content, dissolved electrolyte content, temperature, phase state of pore water, and composition of colloids in the ground will influence the conductivity and the success of the survey.
This technique does not produce a unique result or solution. Measured values can be interpreted in a number of different ways, and the interpretation relies upon an understanding of the local ground conditions. A calibration technique used in atoll environments for groundwater exploration is the comparison of the measured apparent conductivity values against actual salinities measured in monitoring boreholes to develop a logarithmic profile of the freshwater lens thickness.

Annex 4

Resistivity principles

The electrical resistivity method involves the measurement of the apparent resistivity of soil and rock as a function of depth. The resistivity of soils is a function of porosity, permeability, ionic content of the pore fluids and clay mineralisation. The most common electrical methods used in hydro-geological and environmental investigations are vertical electrical soundings (resistivity soundings) and resistivity profiling. The basic principle of operation in electrical resistivity methods is the injection of DC current into the ground using a pair of electrodes. This current causes a potential difference (voltage) in the ground, which is measured by a separate pair of electrodes. The voltage measured can then, using the parameters of the survey, be converted into an apparent resistivity value. This value can provide a range of information regarding the survey site. Different types of soil compositions have different resistivity. The depth of investigation is a function of the electrode spacing, the greater the spacing, the deeper the investigation. Common arrays include the dipole–dipole array, the pole–pole array, the Schlumberger array, and the Wenner array. The surveys on Lifuka were done using the dipole–dipole array and the Schlumberger array.

The basic dipole–dipole configuration includes a set of current input electrodes (A) and (B) and a set of voltage measurement electrodes (M) and (N). This configuration places the (A) and (B) electrodes to one side with a spacing between them denoted as 'a'. The (M) and (N) electrode pair with equal 'a' spacing is placed collinearly a distance 'na' away from (A) and (B).

The Schlumberger array consists of a pair of current electrodes (A) and (B) Current is passed between (A) and (B) and monitored by potential electrodes (M) and (N). As the distance between (A) and (B) is increased, deeper horizons have more effect on the potential between (M) and (N).

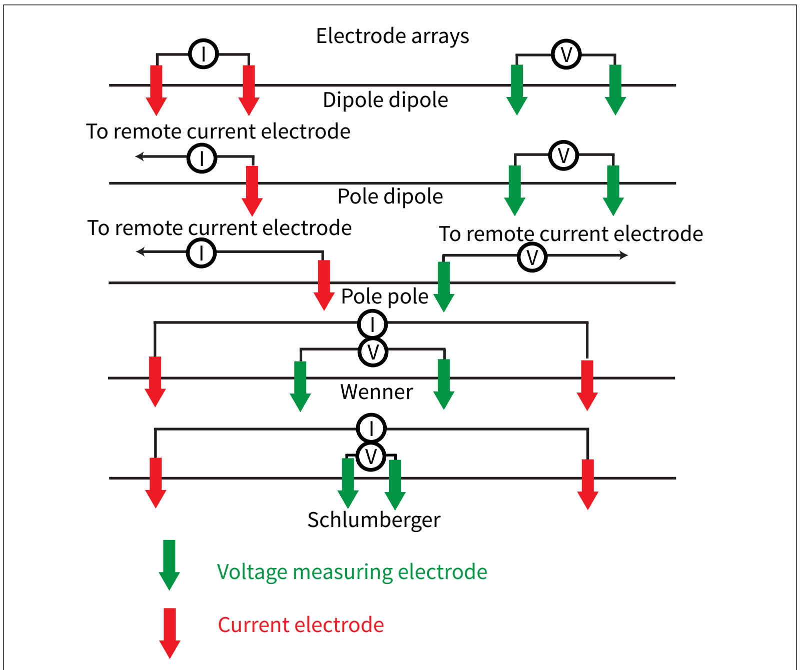


Figure 1. Electrode arrays used to measure resistivity (http://www.cflhd.gov/resources/agm/engApplications/RoadwaySubsidence/513ResistivityMethods.cfm)

Annex 5. EM34 survey results

Site: Hihifo Oval South Gallery West to East Transect								
Field personnel: Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	North	East	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.822	174°21.317	120°	Start at beach end
5	145.0		0.4					
10		210.0		0.6				
15	76.0		2.1					
20								
25	54.0		3.7					
30		144.0		2.0				
35	52.0		3.9					
40								
45	46.0		4.6					
50		120.0		3.0				
55	36.0		5.9					
60								
65	28.0		7.2					
70		99.0		4.4				
75	24.0		8.0					
80								LIF9 at 78 m
85	25.0		7.8					
90		85.0		5.6				
95	23.0		8.2					
100								
105	31.2		6.6					
110		74.0		6.8				
115	27.5		7.3					
120								
125	25.2		7.7					
130		59.0		8.9				
135	21.1		8.6					
140								
145	21.1		8.6					
150		54.0		9.7				
155	21.5		8.5		19°48.8677	174°21.237		END

Site Location: Hihifo Oval Central West to East Transect								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	**EM conductivity (mS/m)**		**Estimated maximum freshwater thickness (m)[1]**		**GPS**		**Bearing of coil orientation**	**Comments**
(m)	**10 m**	**20 m**	**10 m**	**20 m**	**North**	**East**	**Degrees**	**e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.**
0					19°48.810	174°21.272		
5	54.9		3.6					
10		120		3.0				
15	49.2		4.2					LIF 2
20								
25	49.8		4.1					
30		99.8		4.3				
35	34.2		6.2					
40								
45	31.1		6.7					
50		84.5		5.7				
55	30.9		6.7					
60								
65	30.6		6.7					
70		78.2		6.3				
75	30.6		6.7		19°48.824	174°21.228		
80								

Site location: Hihifo Oval North Gallery West to East Transect

Field personnel: K. Hyland, A. Moala and Amit

Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	North	East	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.789	174°21.525	105°	From E side of the road
5	54		3.7					
10		104		4.0				LIF 2
15	45		4.7					
20								
25	37.3		5.7					
30		80		6.1				
35	32.6		6.4					
40								42 m North Gallery well LIF 8
45	30.9		6.7					
50		71		7.2				
55	31.5		6.6					
60								
65	29.8		6.9					
70		64		8.1				73 m Pumping Shed-ON
75	26.2		7.5		19°48.813	174°21.2215		
80								
85	24.1							

Site location: Pangai Oval-Harkness Rd WE

Date: 14/09/2011

Field personnel: K. Hyland, A. Moala and Amit

Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.451	174°21.093		Start at beach at vegetation
5	85.31		1.7					
10		196		0.8				
15	71.8		2.4					
20								
25	60.9		3.1					
30		140		2.1				
35	44		4.8					
40								
45								
50		128		2.6				
55								
60								
65								
70								
75								
80								
85								
90								
95								
100								
105								
110								
115								
120								
125	63.5		2.9					
130		105		3.9				

135	28		7.2					
140								
145	40.9		5.2					
150		75		6.7				
155	38.5		5.5					
160								
165	36.5		5.8					
170		75		6.7				
175	30.9		6.7					
180								
185	29		7.0					
190		41		12.2				
195	19.4		9.0					
200								
205	38.8		5.5					
210		38		12.8				
215	34.5		6.1					
220								
225	33.6		6.2					
230		62		8.4				
235	33.3		6.3					
240								
245								
250		67		7.7	19°48.535	174°21.893		END
255								
260								

Site location: Pangai Oval Central WE LIF4								
Date: 14/09/11								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	**EM conductivity (mS/m)**		**Estimated maximum freshwater thickness (m)[1]**		**GPS**		**Bearing of coil orientation**	**Comments**
(m)	**10 m**	**20 m**	**10 m**	**20 m**	**N degrees**	**E degrees**	**Degrees**	**e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.**
0					19°48.496	174°21.089		Start east side of road
5	64.3		2.9					
10		127		2.7				
15	59.4		3.2					
20								
25	61		3.1					
30		120		3.0				
35	63.8		2.9					
40								LIF 4
45	62.8		3.0					
50		116		3.3				
55	65.8		2.8					
60								
65	63.5		2.9					
70		96		4.6				
75	54.2		3.7					
80								
85	45.6		4.6					
90		80		6.1				
95	39.9		5.3					
100								
105	36		5.9					
110		66		7.8				
115	34.2		6.2					
120								
125	32.8		6.4					
130		61		8.6				

135	31.6		6.6					
140								
145	28.5		7.1					
150		56		9.3				
155	25.7		7.6					
160								
165	23.3		8.1					
170		54		9.7				
175	22.5		8.3					
180								
185	21.6		8.5					
190		53		9.9				
195	22.3		8.3					
200								
205	21.2		8.6					
210		55		9.5	19°48.553	174°21.979		END

Site location:	Moe Rd FIL5 West to East Transect							
Date:	14/09/2011							
Field personne:	K. Hyland, A. Moala and Amit							
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.931	174°21.453	122°	Start at beach\h at vegetation
5	127.2		0.6					
10		203		0.7				
15	89.6		1.5					
20								
25	80.1		1.9					
30		158		1.6				
35	74.81		2.2					
40								
45	75.41		2.2					
50		148		1.9				
55	71.2		2.4					
60								
65	68.7		2.6					
70		133		2.4				
75	70.3		2.5					
80								
85	57.7		3.4					
90		110		3.6				
95	44.4		4.7					
100								Slight Ridge
105	45.4		4.6					
110		84		5.7				
115	40.4		5.3					
120								
125	40.4		5.3					

130		79		6.2				
135	42.4		5.0					
140								LIF 6=10,000mS
145	39.5		5.4					
150		73		6.9				
155	35.8		5.9					
160								
165	34.1		6.2					
170		64		8.1				
175	34.7		6.1					
180								
185	33.6		6.2					
190		56		9.3				
195	32		6.5					
200								
205	30.8		6.7					
210		51		10.2				
215	29.2		7.0					
220								
225	26.7		7.4					
230		44		11.5				
235	24.1		7.9					
240								
245	18.4		9.2					
250		35		13.5				
255	15.1		10.0					
260								
265	13.6		10.4					
270		33		14.0				
275	13.9		10.3					
280								
285	14.8		10.1					
290		35		13.5				
295	15.1		10.0					

300								
305	16.9		9.5					
310		36		13.3				
315	16.4		9.7					
320								
325	15.5		9.9					
330		26		15.9				
335	17.5		9.4					
340								
345	17.9		9.3					
350		19		17.9				
355	16.8		9.6					
360								
365	14.7		10.1					
370		37		13.1				
375	10.7		11.2					
380								
385	11.4		11.0					
390		33		14.0				
395					19°49.078	174°21.291		END

Site location: Sifa Road West to East								
Date: 15/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	**EM conductivity (mS/m)**		**Estimated maximum freshwater thickness (m)[1]**		**GPS**		**Bearing of coil orientation**	**Comments**
(m)	**10 m**	**20 m**	**10 m**	**20 m**	**N degrees**	**E degrees**	**Degrees**	**e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.**
0					19°48.992	174°21.628	120°	Start at beach at vegetation
5	146.1		0.4					
10		232		0.4				
15	133.6		0.5					
20								
25	120.5		0.7					
30		206		0.7				
35	134.4		0.5					
40								
45	128.7		0.6					
50		280		0.2				
55	148.8		0.3					
60								
65	138.4		0.4					
70		211		0.6				
75	143.8		0.4					
80								
85	140.3		0.4					
90		226		0.5				
95	126.5		0.6					
100								
105	128.8		0.6					
110		169		1.3				
115	95.5		1.3					
120								
125	84.8		1.7					
130		156		1.6				

135	84		1.7					
140								
145	79.4		2.0					
150		146		1.9				
155	77.3		2.1					
160								
165	74.5		2.2					
170		132		2.5				
175	70.7		2.4					
180								
185	64.4		2.9					
190		114		3.4				
195	61.6		3.1					
200					19°49.075	174°21.576	128°	Change Direction
205	55.2		3.6					
210		93		4.9				
215	49.2		4.2					
220								
225	42.8		4.9					
230		83		5.8				
235	43.3		4.9					
240								
245	49.5		4.2					
250		108		3.7				
255	47.3		4.4					
260								
265	37.1		5.7					
270		93		4.9				
275	30.5		6.8					
280								
285	28.5		7.1					
290		82		5.9				
295	27.6		7.3					
300								

305	25.6		7.7					
310		71		7.2				
315	21.1		8.6					
320								
325	18.6		9.1					
330		47		11.0				
335	18.4		9.2					
340								
345	20.5		8.7					
350		55		9.5				
355	22.2		8.3					
360								
365	24.4		7.9					
370		66		7.8				
375	26.7		7.4					
380								
385	28.2		7.2					
390		55		9.5				
395	35.9		5.9					
400								
405	29.9		6.9					
410		61		8.6				
415	26.9		7.4					
420					19°49.179	174°20.484		END

Site location: Satek/Vuna Road WE

Date: 15/09/2011

Field personnel: K. Hyland, A. Moala and Amit

Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.9747	174°21.486	122°	Start east side of road
5	82.9		1.8					
10		188		0.9				
15	94.4		1.3					
20								
25	92.3		1.4					
30		182		1.0				
35	88.8		1.5					
40								
45	85.9		1.7					
50		157		1.6				
55	77.8		2.0					
60								
65	64.3		2.9					
70		120		3.0				
75	52.4		3.9					
80								
85	49.3		4.2					
90		96		4.6				
95	42.4		5.0					
100								
105	38.8		5.5					
110		76		6.6				
115	33.2		6.3					
120								
125	27.8		7.2					

130		70		7.3				
135	25.9		7.6					
140								
145	23.3		8.1					
150		53		9.9				
155	22.6		8.3					
160								
165	18.5		9.2					
170		43		11.8				
175	16.8		9.6					
180								
185	14		10.3					
190		30		14.8				
195	13.5		10.4					
200								
205	13.1		10.5					
210		34		13.8				
215	13.9		10.3					
220								
225	14.9		10.0					
230		34		13.8				
235	14.5		10.1					
240								
245	15.7		9.8					
250		38		12.8				
255	15.8		9.8					
260								
265	16.96		9.5					
270		40		12.4				
275	17.4		9.4					
280								
285	19.4		9.0					
290		40		12.4				
295	24.5		7.9					

300								
305	25.6		7.7					
310		52		10.0				
315	27.1		7.4					
320								
325	28.1		7.2					
330		52		10.0				
335	25.9		7.6					
340			19°49.121	174°21.370				END

Site location: Satek/Vuna Road WE Continued								
Date: 15/09/2011								
Field personnel: K. Hyland, A. Moala and								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0							115°	
5	16		9.8					
10		49.2		10.5				
15	16.9		9.5					
20								
25	16.6		9.6					
30		47.6		10.8				
35	15.2		10.0					
40								
45	13.4		10.4					
50		44.5		11.4				
55	13.5		10.4					
60								
65	14.8		10.1					
70		46.5		11.0				
75	15.7		9.8					
80								
85	16.9		9.5					
90		48.8		10.6				
95	16.3		9.7					
100								
105	16.4		9.7					
110		46.5		11.0	19°49.148	174°21.292	105°	
115	16.2		9.7					
120								
125	17.1		9.5					
130		45.7		11.2				

135	16.9		9.5					
140								
145	16.1		9.7					
150		45.9		11.2				
155	14.5		10.1					
160								
165	15.1		10.0					
170		45.1		11.3				
175	15.1		10.0					
180								
185	19.1		9.0					
190		49.5		10.5				
195	24.9		7.8					
200								
205	32.9		6.4					
210		49.2		10.5				
215	36.8		5.8					
220								
225	38.5		5.5					
230		53.6		9.8				
235	44.7		4.7					
240								
245	50.3		4.1					
250		57.3		9.1				
255	56.5		3.5					
260								
265	60.4		3.2					
270		66.1		7.8	19°49.205	174°21.233	120°	
275	61.1		3.1					
280								
285	62.9		3.0					
290		76.9	14.7	6.5				
295	54.1		3.7					
300								

305	59.3		3.3					
310		76.8		6.5				
315	56.1		3.5					
320								
325	64		2.9					
330		79.7		6.2				
335	64.3		2.9					
340								
345	63.2		2.9					
350		72		7.1				
355	62.8		3.0					
360					19°49.249	174°21.195		END

Site location: Hihifo South Church Road WE								
Date: 15/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	**EM conductivity (mS/m)**		**Estimated maximum freshwater thickness (m)[1]**		**GPS**		**Bearing of coil orientation**	**Comments**
(m)	**10 m**	**20 m**	**10 m**	**20 m**	**N degrees**	**E degrees**	**Degrees**	**e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.**
0					19°48.885	174°21.346	120°	
5	55.6		3.6					
10		126		2.7				
15	58.1		3.4					
20								
25	55.1		3.6					
30		138		2.2				
35	56.1		3.5					
40								
45	52.3		3.9					
50		164		1.4				
55	48.1		4.3					
60								
65	52.3		3.9					
70		165		1.4				
75	46.7		4.5					
80								
85	43.1		4.9					
90		169		1.3				
95	45.6		4.6					
100					19°48.898	174°21.302	125°	Change Direction
105	48.2		4.3					
110		155		1.6				
115	44.3		4.8					
120								
125	39.4		5.4					
130		160		1.5				

135	35.5		6.0					
140								
145	34.3		6.1					
150		147		1.9				
155	37.2		5.7					
160								
165	34.2		6.2					
170		145		2.0				
175	30.5		6.8					
180								
185	23.4		8.1					
190		106		3.9				
195	35.5		6.0					
200								
205	36.6		5.8					
210		125		2.8				
215	35.6		5.9					
220								
225	28.5		7.1					
230		133		2.4				
235	26.5		7.5					
240								
245	25.4		7.7					
250		105		3.9				
255	26.8		7.4					
260								
265	26.8		7.4					
270		115		3.3	19°49.205	174°21.233	120°	
275	23.6		8.1					
280								
285	22.6		8.3					
290		95		4.7				
295	22.5		8.3					
300								

305	25.7		7.6					
310		100		4.3				
315	26.8		7.4					
320								
325	26.5		7.5					
330		75		6.7				
335	21.4		8.5					
340								
345	21.6		8.5					
350		52		10.0				
355	22.1		8.4					
360								
365	18.3		9.2					
370		45		11.3				
375	16.9		9.5					
380								
385	13.5		10.4					
390		32		14.3				
395	14		10.3					
400					19°49.022	174°21.184	120°	Change Direction
405	13.3		10.5					
410		32		14.3				
415	12.7		10.6					
420								
425	12.5		10.7					
430		35		13.5				
435	11.3		11.0					
440								
445	11.5		10.9					
450		30		14.8				
455	11.8		10.9					
460								
465	14.3		10.2					
470		32		14.3				

475	17		9.5					
480								
485	18		9.3					
490		35		13.5				
495	19.7		8.9					
500								
505	21.2		8.6					
510		39		12.6				
515	24.2		7.9					
520								
525	35.7		5.9					
530		46		11.1				
535	47.8		4.4					
540								
545	53.6		3.8					
550		57		9.2				
555	53.3		3.8					
560								
565	51.8		3.9					
570		58		9.0				
575	50		4.1					
580								
585	45		4.7					
590		52		10.0				
595	49.7		4.2		19°49.100	174°21.108		END

Date: 16/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	
0					19°48.283	174°20.870	180°	
5	80.6		1.9					
10		165		1.4				
15	70.1		2.5					
20								
25	68.2		2.6					
30		115		3.3				
35	67.3		2.7					
40								
45	64.4		2.9					
50		126		2.7				
55	66.7		2.7					
60								
65	60.2		3.2					
70		127		2.7				
75	74.3		2.2					
80								
85	78.4		2.0					
90		132		2.5				
95	86.7		1.6					
100								
105	82.9		1.8					
110		142		2.1				
115	79.5		1.9					
120								
125	86.2		1.6					
130		121		3.0				
135	86.2		1.6					
140								
145	77.9		2.0					
150		142		2.1				
155	58.8		3.3					
160								
165	53		3.8					
170		100		4.3				

Site location: Fau Rd W-E								
Date: 16/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	
0					19°48.260	174°21.486	82°	Start east side of road
5	16		9.8					
10		49.2		10.5				
15	16.9		9.5					
20								
25	16.6		9.6					
30		47.6		10.8				
35	15.2		10.0					
40								
45	13.4		10.4					
50		44.5		11.4				
55	13.5		10.4					
60			14.7					
65	14.8		10.1					
70		46.5		11.0				
75	15.7		9.8					
80								
85	16.9		9.5					
90		48.8		10.6				
95	16.3		9.7					
100								
105	16.4		9.7					
110		46.5		11.0				
115	16.2		9.7					
120								
125	17.1		9.5					
130		45.7		11.2				
135	16.9		9.5					
140								
145	16.1		9.7					
150		45.9		11.2				
155	14.5		10.1					
160								
165	15.1		10.0					
170		45.1		11.3				End

Site Location: Ha'apai High School W								
Date: 16/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0							115°	Start
5	60.2		3.2					
10		86.1		5.5				
15	59.7		3.2					
20								
25	66.9		2.7					
30		83		5.8				
35	71.1		2.4					
40								
45	69.6		2.5					
50		97.3		4.5				
55	71.1		2.4					
60								
65	68.1		2.6					
70		86.1		5.5				
75	69.1		2.5					
80								
85	72.1		2.4					
90		89.6		5.2				
95	72.8		2.3					
100								
105	72		2.4					
110		84.4		5.7				
115	65.3		2.8					
120								
125	62.1		3.0					
130		76.4		6.5				

135	57.2		3.4					
140								
145	52.5		3.9					
150		57.4		9.1				
155	45.8		4.6					
160								
165	41.4		5.1					
170		49.2		10.5				End

Site location: Ha'apai High School N-S								
Date: 16/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.157	174°21.684	180°	Start
5	39.4		5.4					
10		50.8		10.2				
15	38.4		5.5					
20								
25	38.1		5.6					
30		49.5		10.5				
35	36.4		5.8					
40								
45	34.6		6.1					
50		45.7		11.2				
55	36.3		5.8					
60								
65	33.2		6.3					
70		43.1		11.7				
75	32.5		6.4					
80								
85	36.9		5.7					
90		44.9		11.4				
95	38.3		5.5					
100								
105	38.8		5.5					
110		47.3		10.9				
115	42.1		5.0					
120								
125	42.2		5.0					
130		49		10.6				

135	43.2		4.9					
140								
145	43.8		4.8					
150		47.2		10.9				
155	49.7		4.2					
160								
165	49.7		4.2					
170		55.7		9.4	19°48.250	174°20.705	180°	END

Site location: Hihifo South potential Gallery S-N								
Date: 17/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.114	174°21.537	210°	Start
5	18.5		9.2					
10		48		10.8				
15	22.6		8.3					
20								
25	22.3		8.3					
30		54		9.7				
35	24		8.0					
40								
45	23.3		8.1					
50		50		10.4				
55	17.7		9.4					
60								
65	19.7		8.9					
70		14		19.6				
75								
80								
85								
90		5		22.9				
95	16		9.8					
100								
105	20.3		8.8					
110		50		10.4				
115	20.7		8.7					
120								
125	20.8		8.6					

130		48		10.8				
135	20.6		8.7					
140								
145	20.6		8.7					
150		50		10.4				
155	21.3		8.5					
160								
165	21.7		8.4					
170		51		10.2				
175	21.4		8.5		19°49.151	174°21.599		

Site location: Pangai East Rugby Field Potential Gallery

Date: 17/09/2011

Field personnel: K. Hyland, A. Moala and Amit

Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.488	174°20.816	007°	Start
5	57.2		3.4					
10								
15	58.4		3.3					
20								
25	59.8		3.2					
30								
35	62.1		3.0					
40								
45	60.8		3.1					
50								
55	58.8		3.3					
60								
65	61.4		3.1					
70								
75	66.1		2.7					
80								
85	71.1		2.4					
90								
95	74.1		2.2					
100								
105	75.6		0.4					
110					19°48.448	174°20.804		END

Site location: Houmatofua Far South Trans WE								
Date: 17/09/2011								
Field personnel: K. Hyland, A. Moala and Amit								
Distance from previous point	EM conductivity (mS/m)		Estimated maximum fresh-water thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°49.156	174°21.758	180	
5								
10		181		1.0				
15								
20		162		1.4				
25								
30		144		2.0				
35								
40		132		2.5				
45								
50		125		2.8				
55								
60		118		3.1				
65								
70		113		3.4				
75								
80		110		3.6				
85								
90		109		3.7				
95								
100		98		4.5				
105								
110		93		4.9				
115								
120		91		5.0				
125								
130		88		5.3				

135								
140		85		5.6				
145								
150		75		6.7				
155								
160		75		6.7				
165								
170		72		7.1				
175								
180		65		8.0				
185								
190		61		8.6				
195								
200		54		9.7				
205								
210		55		9.5				
215								
220		50		10.4				
225								
230		56		9.3				
235								
240		66.1		7.8				
245								
250		58		9.0				
255								
260		59		8.9				
265								
270		60		8.7				
275								
280		63		8.3				
285								
290		63		8.3				
295								
300		69		7.4				

305								
310		66		7.8				
315								
320		69		7.4				
325								
330		69		7.4				
335								
340		74		6.8				
345								
350		83		5.8				
355								
360		90		5.1				
365								
370		90		5.1				
375								
380		103		4.1				
385								
390		103		4.1				
395								
400		104		4.0				
405								
410		109		3.7				
415								
420		104		4.0				
425								
430		97		4.5				

Site location: Tua Rd NS Large

Date: 17/09/2011

Field personnel: K. Hyland, A. Moala and Amit

Distance from previous point	EM conductivity (mS/m)		Estimated maximum freshwater thickness (m)[1]		GPS		Bearing of coil orientation	Comments
(m)	10 m	20 m	10 m	20 m	N degrees	E degrees	Degrees	e.g. nearby wells, babai pits, if ground is flat or not, if raining or wet ground, tree type etc.
0					19°48.676	174°20.939	200°	Start
5	16.2		9.7					
10		75		6.7				
15	14.8		10.1					
20								
25	19.9		8.8					
30		82		5.9				
35	12.2		10.8					
40								
45	17.2		9.5					
50		84		5.7				
55	27.8		7.2					
60								
65	28.4		7.1					
70		87		5.4				
75	40.3		5.3					
80								
85								
90		74		6.8				
95	17.6		9.4					
100								
105	21.8		8.4					
110								
115	22.4		8.3					
120								
125	16.9		9.5					
130		98		4.5				
135	19.5		8.9					
140								
145	19.5		8.9					

150		84		5.7				
155	18.8		9.1					
160								
165	20.5		8.7					
170		89		5.2				
175	19.1		9.0					
180								
185	18.4		9.2					
190								
195	20.1		8.8					
200								
205	22.2		8.3					
210								
215	24.1		7.9					
220								
225	25.6		7.7					
230								
235	24.8		7.8					
240								
245	21.7		8.4					
250								
255	22.7		8.2					
260								
265	22.6		8.3					
270								
275	24.4		7.9					
280								
285	23.5		8.1					
290								
295	21.6		8.5					
300								
305	21.6		8.5					
310								
315	23.2		8.1					
320								
325	27.4		7.3					
330								
335	26.6		7.5					

340								
345	34.1		6.2					
350		53		9.9				
355	52.1		3.9					
360								
365	64.1		2.9					
370		58		9.0				
375	39.1		5.4					
380								
385	39.5		5.4					
390		68		7.6				
395	31.7		6.6					
400								
405	28.3		7.1					
410		53		9.9				
415	27.3		7.3					
420								
425	20.4		8.7					
430		51		10.2				
435	24.6		7.8					
440								
445	31.8		6.5					
450		50		10.4				
455	27.7		7.3					
460								
465	20.9		8.6					
470		45		11.3				
475	23.4		8.1					
480								
485	25.8		7.6					
490		49		10.6				
495	27.1		7.4					
500								
505	27.4		7.3					
510		58		9.0				
515	24.1		7.9					
520								
525	25.3		7.7					

530		53		9.9				
535	26.2		7.5					
540								
545	27.6		7.3					
550		64		8.1				
555	24.1		7.9					
560								
565	25.3		7.7					
570		57		9.2				
575	26.2		7.5					
580								
585	27.6		7.3					
590		62		8.4				
595	29.2		7.0					
600								
605	26.9		7.4					
610		65		8.0				
615	26.6		7.5					
620								
625	20.8		8.6					
630		68		7.6				
635	29.6		6.9					
640								
645	34.5		6.1					
650		72		7.1				
655	28.9		7.0					
660								
665	27.6		7.3					
670		81		6.0				
675	23.7		8.0					
680								
685	29.1		7.0					
690		83		5.8				
695	25.4		7.7					
700								
705	31.1		6.7					
710		68		7.6				
715	29.8		6.9					

720								
725	25.4		7.7					
730		55		9.5				
735	31.1		6.7					
740								
745	29.8		6.9					
750		46		11.1				
755	27.7		7.3					
760								
765	27.1		7.4					
770		45		11.3				
775	28.5		7.1					
780								
785	30.8		6.7					
790		47		11.0				
795	29.1		7.0					
800								
805	28.1		7.2					
810		52		10.0				
815	22.8		8.2					
820								
825	20.9		8.6					
830		56		9.3				
835	21.1		8.6					
840								
845	21.8		8.4					
850		60		8.7				
855	22.1		8.4					
860								
865	21.5		8.5					
870		56		9.3				
875	20.9		8.6					
880								
885	20.9		8.6					
890		63		8.3				
895	21.6		8.5					
900								
905	23.4		8.1					

910		60		8.7				
915	24.2		7.9					
920								
925	26.4		7.5					
930		59		8.9				
935	26.3		7.5					
940								
945	24.4		7.9					
950		62		8.4				
955	25.3		7.7					
960								
965	23.7		8.0					
970		46		11.1				
975	23.8		8.0					
980								
985	22.9		8.2					
990		40		12.4				
995	20.8		8.6					
1000								
1005	19.4		9.0					
1010		45		11.3				
1015	20.2		8.8					
1020								
1025	20		8.8					
1030		51		10.2				
1035	18.8		9.1					
1040								
1045	18.5		9.2					
1050		49		10.6				
1055	17.7		9.4		19°49.116	174°21.324		

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