Tongan Government **SPC-SOPAC Division** **European Union**

MINISTRY OF LANDS, ENVIRONMENT, CLIMATE CHANGE AND NATURAL RESOURCES

EXPANSION OF THE SALINITY MONITORING NETWORK ACROSS TONGATAPU

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EXECUTIVE SUMMARY

Funded by the European Union (UN) Disaster Risk Reduction Project in Eight Pacific ACP States (B-Envelope) and implemented by the Applied Geosciences and Technology (SOPAC) Division of the Secretariat of the Pacific Community (SPC), this project is worked closely with Tonga’s Ministry of Lands, Environment, Climate Change and Natural Resources (MLECCNR) to of 6 new investigative and Salinity Monitoring Bores (SMB's) across Tongatapu which is outlined in this report. These new investigative monitoring bores all assess the resource potential to be further defined and ongoing monitoring to be undertaken to allow development of this resource in the future.

Summary of Work

The following work was undertaken by Naryba Engineering Enterprises & Development Services (NEEDS) under the supervision of the MLECCNR staff as part of the expansion of the salinity monitoring network across Tongatapu:

- Drilling of two salinity monitoring boreholes and installation of multi-level water salinity monitoring systems in the freshwater lens in the Mataki’eua/Tongamai wellfield. The monitoring systems at Mataki'eua and Tongamai are designed to enable salinity profiles of the lens to be more efficiently managed, and assess the impact of abstraction on the freshwater lens.
- Drilling of four salinity monitoring boreholes and installation of multi-level water salinity monitoring systems in the freshwater lens at Houma and Fua’amotu/Pelehake, to investigate alternate groundwater sources for Nuku’alofa’s water supply and to increase the distribution of water monitoring across Tongatapu .
- Upgrade 7 original SMB's to protect them from damage and ensure their longevity.

Results

Houma Region

The thickness of the fresh water lens at SMB08 recorded at the time of drilling was 19 m. Depth to water at SMB08 was 10.10 m below ground level (bgl). The salinity of the groundwater at the water table was 660 µS/cm.

Fua'amotu Region

The thickness of the fresh water lens recorded at the time of drilling at the Fua'amotu (SMB10) and Toloa (SMB09) was 16 m and 21 m at Pelehake (SMB11). The depth to water at SMB09, SMB10 and SMB11 was 26.18 m bgl, 40.00 m bgl and 24.5 m bgl respectively. The salinity of the groundwater at the water table was 400 µS/cm to 550 µS/cm.

Mataki’eua/Tongamai Wellfield

The total thickness of the freshwater lens Tongamai (SMB13) at the time of drilling, was 16 m and at Mataki'eua (SMB12) the thickness was 11 m. The depth to water at SMB12 and SMB13 was 19.02 m bgl and 12.27 m bgl respectively. The salinity of the groundwater at the water table was 380 µS/cm to 420 µS/cm.

Conclusions

- While the cost of pipelines from the Fua'amotu area will be significant, the groundwater in the region of the International Airport has several advantages as a future water source for Nuku’alofa as it is government owned land and there is a thick freshwater lens over a significant area of land.
- The groundwater in the region of Houma could also provide a future water source for Nuku’alofa as it is closer to the current wellfield but outside the approximate zone are of influence from the pumping.

Recommendations

- A more detailed investigation of both the Houma and Fua’amotu regions is recommended involving a series of geopysical EM34 and resistivity to determine the extents of the water resource and potential water reserve area. An estimate of sustainable yield should be determined before these areas are developed.
- SMB12 and SMB13 within the Matakieua/Tongamai TWB borefield should be added to the monthly monitoring currently being conducted by the Natural Resources Division of the MLECCNR (refer to Appendix C and D). All results recorded, graphed and to be made available for the TWB use.
- SMB08 to SMB11 located within the Fua'amotu and Houma regions should be monitored on a quarterly basis as per the procedure in Appendix C, and results provided to TWB on a regular basis, at least annually.
- As recommended by White et al (2009) a contingency plan to address the impacts of droughts on water supply involving voluntary and compulsory water restrictions and other instruments should be developed for Tongatapu.
- Also recommended by White et al (2009) groundwater recharge should be estimated at the end of each month by collection of the monthly rainfall. The frequency of groundwater monitoring should be increased and a warning should be given to the government and the TWB when there are more than 8 consecutive months all with zero estimated recharge. When there are more than 12 consecutive months of zero recharge consideration should be given to implementing the drought contingency plan (White et al, 2009).

Acknowledgements

I personally would like to acknowledge the following people for their generous support, time and help in the successful completion of this project:

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- The TWB staff, including Saimone Helu, Kutusi Fielea, Pita Moala, for providing access to the TWB sites, valuable information and discussions.

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List of Abbreviations and Acronyms

°C	degrees Celsius
ADB	Asian Development Bank
AusAID	Australian Agency for International Development
EC	electrical conductivity (a measure of water salinity)
B Envelope	Disaster RiskReduction in Eight Pacific ACP States project(B Envelope)
EOC	Emergency Operating Centers
EU	European Union
km	kilometre
L	litres
L/s	litres per second
m	metres
ML	megalitres (1 ML = 1,000,000 litres)
ML/day	megalitres per day
MLECCNR	Ministry of Land, Environment, Climate Change and Natural Resources
NEEDS	Naryba Engineering Enterprises & Development Services
SMB	salinity monitoring bore
SPC-SOPAC	Applied Geoscience & Technology Division, Secretariat of the Pacific Community
TCDT	Tonga Community Development Trust
TWB	Tonga Water Board
WHO	World Health Organization
µS/cm	microsiemens per centimetre (unit of electrical conductivity, EC)

1. INTRODUCTION

1.1. Overview

Funded by the European Union (UN) Disaster Risk Reduction Project in Eight Pacific ACP States (B-Envelope) and implemented by the Applied Geoscience and Technology (SOPAC) Division of the Secretariat of the Pacific Community (SPC), this project is worked closely with Tonga's Ministry of Lands, Environment, Climate Change and Natural Resources (MLECCNR) to bore holes that will be used to monitor water quality on Tongatapu. The B-Envelope – European Union (EU) Disaster Risk Reduction Project overall objective of the project is *poverty alleviation and sustainable development through disaster risk reduction*.

The project purpose is to build resilience in selected communities to reduce the risk to Pacific Island communities to disasters targeting two specific areas:

- *Access to Safe Drinking Water* – The Regional Action Plan on Sustainable Water Management identifies the vulnerability of water resources and water supply systems to climatic hazards and proposes approaches to mitigate against these risks. Low lying islands are vulnerable to climatic variability due to the lack of natural ground water storage. On islands that have sufficient supply, maintaining the quality of drinking water is important for rural communities. Measures for water sustainability, land use, sanitation, wastewater and solid waste disposal are important factors in determining appropriate solutions.
- *Emergency Communications and Emergency Operation Centres* – The Regional Framework for Action 2005 – 2015 Building the Resilience of Nations and Communities to Disasters, calls for planning for effective preparedness, response and recovery with key actions to establish functional emergency communications systems and emergency operations centres (EOC). The Framework calls for establishment of an effective, integrated and people-focused early warning system. In many of the participating countries, early warning systems lack basic equipment, skills and resources. The weakest element is the dissemination of warnings and the preparedness of the communities to respond.*(SPC-SOPAC, 2011)*

Activities for Tonga under the EU-B Envelope funding included the following:

- Electrification and upgrade of the Matakei'eua and Tongamai wellfield.
- Provision of water quality monitoring equipment.
- Assessment and refurbishment of village water supplies in Tongatapu.
- Together with Tonga Community Development Trust (TCDT) helped raise awareness and management of rainwater catchment supplies systems in the outer islands.
- Funding a 4WD vehicle dedicated to specialised water quality and water resources monitoring.

- Drilling and constructing of 6 new investigative and Salinity Monitoring Bores (SMB's) across Tongatapu which is outlined in this report. These new investigative monitoring bores all assess the resource potential to be further defined and ongoing monitoring to be undertaken to allow development of this resource in the future.

1.2. Goal

Improved water supply to the people of Tonga through sustainable development of Tongatapu’s groundwater resources.

1.3. Objective

Develop a network of spatially relevant and properly constructed monitoring bores which can provide early information on the status of the groundwater resource, helping to maximize the potential for providing sufficient quantity and quality suitable for drinking and domestic water needs of Tongatapu into the future.

1.4. Purpose

The purpose of the drilling program is to:

- Drill two salinity monitoring boreholes and install multi-level water salinity monitoring systems in the freshwater lens in the Mataki’eua/Tongamai wellfield. The monitoring systems at Mataki'eua and Tongamai are designed to enable salinity profiles of the lens to be more efficiently managed, and assess the impact of abstraction on the freshwater lens.
- Drill four salinity monitoring boreholes and install multi-level water salinity monitoring systems in the freshwater lens at Houma and Fua’amotu/Pelehake, to investigate alternate groundwater sources for Nuku’alofa’s water supply and to increase the distribution of water monitoring across Tongatapu .
- Provide professional training opportunities to MLECCNR in hydrogeological logging and drill rig supervision.

1.5. Background

Groundwater salinity profiles are vital to assist in managing the groundwater resources in Tongatapu and to assess the sustainability of groundwater longer term. Currently there are seven SMB's on Tongatapu which are clustered around the Mataki’eua/Tongamai wellfield. The Mataki’eua/Tongamai wellfield is used to provide all of the water needs for the capital of Tonga, Nukualofa. Until 2002, these bores were monitored by the Tongan Water Board (TWB) and in 2010 the MLECCNR recommenced monthly monitoring after an 8 year gap in data collection.

The thickness of freshwater available in the remainder of Tongatapu is poorly known with only limited data being available from the three salinity monitoring boreholes located in Kolonga, Fua’amotu and Niumate. White et al. (2009) recommended an additional 10 SMBs be installed in Tongatapu and monitored quarterly.

The EU-B Envelope together with the MLECCNR, extended the SMB network across Tongatapu to identify future water resource potential in the Fua’amotu and Houma regions and extend the coverage of monitoring bores for improved management in Mataki’eua/ Tongamai. This project completed the installation of two additional SMBs at Mataki’eua/Tongamai and four SMB's in the Fua'amotu and Houma regions.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

2.1. Geological Setting

Tonga's archipelago is situated on the Tonga-Kermadec Ridge, an active fore-arc to the east of the Lau Basin and to the west of the Tonga Trench, the second deepest sea trench, reaching 10,882 m below sea level. The Tonga Trench separates two tectonic plates, the into-Australian Plate and the Pacific Plate. The ridge is formed by the subduction of the western edge of the Pacific Plate under the eastern edge of the Indo-Australian Plate (Falkland, 1992).

A smaller scale depression called the Tofua Trough is located within the island group and is approximately parallel with and to the west of the Tonga trench (1,800m below sea level). The islands to the west of the trough are of volcanic origin and some are still active with more than 35 recorded eruptions in the last 200 years (Falkland, 1992). The islands to the east of the trough are generally low-lying coral limestone islands built from reef deposits deposited at times when sea level was on Tertiary to recent volcanic sediments. These eastern islands include Tongatapu and the Ha'apai and Vava'u groups of islands (Fry, 2011).

2.2. Hydrogeological Setting

The freshwater resources of the Kingdom of Tonga are restricted mainly to groundwater in the form of freshwater lenses and some rainwater harvesting. Freshwater lenses form on top of seawater in many of the islands due to a combination of favourable geology, and the the difference in density of seawater and fresh water. The interface, between the two fluids is reffered to as a tranisition zone, representing a zone of variable salinity, increasing with depth. Within the transition zone, the water salinity increases from being fresh to being seawater over a number of meters (Fry, 2011).

The upper surface of a freshwater lens is the water table. The thickness of the freshwater and transition zones are dependent on the many factors but the most important are:

- Rainfall amount and distribution.
- Permeability and porosity of the geological formations, and the presence of cave systems and solution cavities within limestone formations
- Amount and nature of surface vegetation and the nature and distribution of soils (influencing evapotranspiration).
- Size of the island, particularly the width from sea to lagoon.
- Tidal range.

- Methods of abstraction and quantity of water extracted by pumping .

Within Tongatapu, the freshwater is stored in the limestone which is karstic in nature with many large openings including caves at sea level. From previous drilling information, solution cavities are known to exist at different levels above sea level. Discharge from the freshwater lens is increased by the presence of solution cavities and caves.

The salinity of the water table can be obtained by measurements from exposed water surfaces such as existing wells or drilled boreholes. The lower surface of the freshwater zone can only be reliably determined by establishing dedicated and specifically designed and constructed monitoring bores which allow the measurement of water quality at specific depths. The salinity limit adopted for freshwater suitable for drinking water is taken as an electrical conductivity of 2,500 µS/cm at 25°C (Fry, 2011).

According to previous logs and studies, the thickness of the freshwater lens at Mataki'eua, Tongatapu is about 12 m thick. The thickness of the freshwater lens is less understood across the remainder of Tongatapu as only limited data was available. Three salinity profiles from deep monitoring bore taken November of 1978 at Liahona, Fua'amotu and Kolonga, indicate a freshwater thickness of 11 m, 12 m and 13 m, respectively (Falkland, 1992).

The MLECCNR well monitoring database for Tongatapu dating back to 1959 indicates a large variation in the depth to water table across Tongatapu ranging from approximately 1.43 to 60.9 meters, consistent with the southeast-northwest tilt of the island. The variation in EC is smaller but has an almost four-fold difference between the minimum and maximum values in the southeast, 314 µS/cm and northwest, 6,990 µS/cm respectively(Falkland, 1992 and MLECCNR database).

2.3. Soil

Tongatapu has an extensive fertile and volcanic rich soil layer overlying coral limestone. The soils are derived mainly from andesitic tephra (volcanic ash) (Falkland, 1992). Other soils found include coral sand, lagoonal sands and clayey-muds.

The tephra was deposited by a series of volcanic eruptions from emergent volcanoes such as Tofua and Kao and from submarine volcanoes to the west (Falkland, 1992). Two types of tephra are found, corresponding to two main phases of ash accumulation, one occurring earlier than 20,000 years ago and the other occurring between 5,000 and 10,000 years ago (Falkland, 1992). Generally, soils on the west side of the islands are thicker and have larger particle sizes whilst those on the east side are thinner and made of finer ashes (Falkland, 1992).

From a water resource viewpoint, the factors which are important with soils are the rate of infiltration, the thickness and moisture content at both field capacity and wilting point (Falkland, 1992).

3. GROUNDWATER SUPPLY

3.1. Nuku'alofa urban water supply

Groundwater is abstracted from the Mataki'eua/Tongamai wellfield and water reserve located at the rear of the late Kings residential residence. There are 36 wells which operate up to 24 hours per day, 23 of which have electric pumps with the remaining wells operated by diesel pumps (TWB data 2011-2012). The majority of the wells which were upgraded to electric pumps under the UN-B Envelope project in 2009-2011, have functioning meters while the meters are either not been installed or are not functioning on the remaining wells. The water from all wells is directed to 6 reservoir tanks located at the site office where daily chlorination treatment occurs. There is an average abstraction rate of approximately 4.2 L/s for the electric pumps and 2.3 L/s for the diesel pumps (TWB data 2011-2012).

The TWB salinity monitoring database for the wellfield at Mataki'eua/Tongami dating back to 1990 indicates a large variation in EC between the 349 and 3,050 µS/cm with average conductivity of 1,025 µS/cm.

A critical issue in the management of the Mataki’eua/Tongamai wellfield is the influence of pumping on the salinity of the pumped groundwater. The supply of piped groundwater to Nuku’alofa commenced in 1966 from five hand-dug wells at Mataki’eua. By 1971, eight wells were operating (Furness and Helu, 1993) and by 1991, 31 dug and drilled wells had been installed at Mataki’eua and Tongamai. It has been estimated that in March 1991, 22 wells were operating with a combined production rate of 5.3 ML/day (White et al 2009). From April to November 1995, the average combined production rate was 5.8 ML/day (Falkland, 1995). In August 2007, the estimated groundwater pumping rate was 8 ML/day, and in August of 2011 the estimated pumping rate was 10.4 ML/day (extrapolated from the TWB production data 2011). There has, therefore, been a 50% increase in groundwater pumping since 1991. The estimated groundwater pumping rates are listed in Table 1 together with the log mean EC for groundwater at Mataki’eua/Tongamai for the years with pumping data.

Year	No. Pumps Operating	Pumping Rate (L/sec)	Pumping Rate (ML/day)	Estimated Log Mean EC (µS/cm)
1966	5	15	1.30	646
1968	6	18	1.56	670
1971	8	24	2.07	825
1991	20	60	5.30	917
1995	22	66	5.80	1,259
1998	26	78	6.80	1,175
2007	31	93	8.04	1,231
2011	34	120	10.41	996

Table 1 Estimated pumping rates and mean ECs at Mataki’eua/Tongamai wellfield

The overall trend in Figure 1 appears as a linear increase in pumping rate with time at Mataki'eua/Tongamai for the years with pumping data.

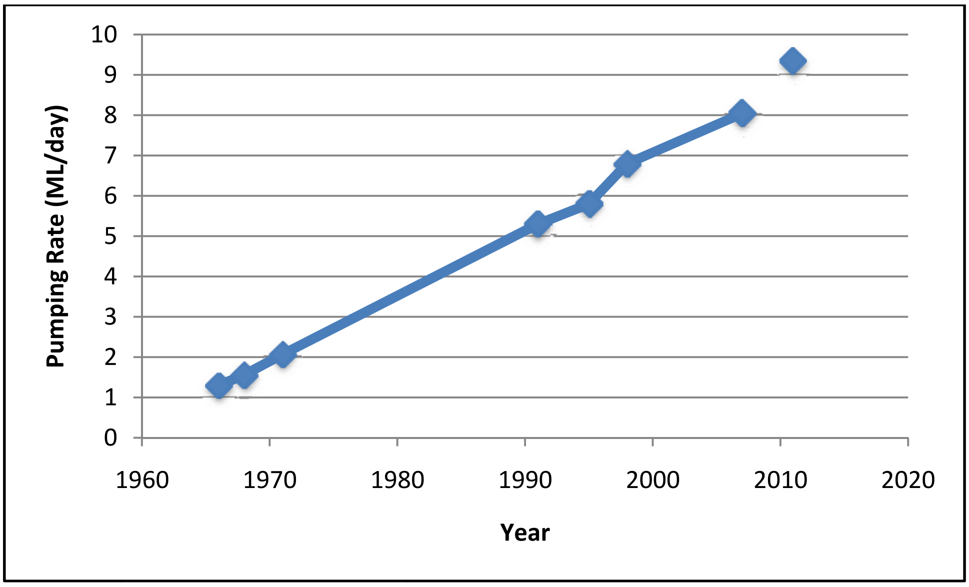


Figure 1 Estimated increase in pumping rate from the Mataki'eua/Tongamai wellfield

The sustainable yield of a groundwater aquifer can be defined as the maximum amount of water that can be extracted on a continuous basis, including during drought periods, without causing long-term depletion of the aquifer or adverse effects on the extracted water and on the environment. White et al (2009) estimates the sustainable yield for the whole of Tongatapu is 60 ML/day. The following approximate sustainable yield estimates per region were made by White et al (2009).

Liahona region	21.5 – 29 ML/day
Fua'amotu region	21.5 - 29 ML/day
Kolonga region	11 – 14.5 ML/day.

The total estimated production from the Mataki'eua/Tongamai wellfield represents nearly 40% of the lower bound estimate of sustainable yield from the much larger Liahona, region which is a significant proportion.

3.2. Village Water Supply

Village water supply varies between villages and there is no standard design or requirements for the system. For the most part, the wells are located at the edges of the village, generally on higher ground. The bores are either hand dug or are drilled bores which usually penetrate a meter or so into the water table. Most of the wells are operated by diesel helical pumps and some are now upgraded to solar submersible pumps from various aid development funds (Fry, 2011).

Current pumping from village and other wells is more difficult to estimate as there are no flow meters installed on the pumps on these well. Based on available information at the time, White et al (2009) estimated that the total rural groundwater extraction was about 5.4 ML/day. The lack of data on volumes extracted shows the necessity of installing flow meters on all village and other water supply systems. Without proper measurement and assessment of pump flow, it is very difficult to manage the groundwater resources.

As mentioned in Falkland (1992), a high proportion of the rural groundwater extraction takes place in the western Liahona region of the island. If it is assumed that 50% of the rural groundwater extraction takes place in this region, then 2.7 ML/day would be currently pumped from there

For the areas of Tongatapu other than the western region, total current extraction is approximately 2.7 ML/day. This is about 8% of the lower bound sustainable yield for the rest of Tongatapu (32.5 ML/day)

3.3. Future Water Supply

The total estimated production from the Liahona region is about 12.9 ML/day by combining the extraction from the western Liahona region with the production from the Mataki'eua/Tongamai wellfield. This represents about 60% of the lower bound sustainable yield estimate for this region. The Asian Development Bank (ADB) funded Tonga Water Supply Improvement Subproject proposes an additional 12 production wells increasing the maximum capacity of the Mataki'eua/Tongamai wellfield to 17 ML/day (Planning and Urban Management Agency, MLSNR, 2011). If all of the proposed 12 additional wells are eventually in production, the maximum extraction rate could be over up to 92% of the lower bound estimate of the sustainable yield for the Liahona region.

White et al (2009) states that an increased extraction rate will have significant impacts on the salinity of extracted water and on the thickness of the freshwater lens in this region. This is why it is worthwhile considering other groundwater sources, such as the area around Fua’amotu International Airport and Liahona, as alternative water supply sources for Nuku’alofa.

4. METHODS

4.1. Selection of groundwater investigation sites

The locations of the two SMB's at Mataki’eua/ Tongamai wellfield (Figure 2) have been chosen to better capture the fresh water response to the pumping across southern region of the Mataki'eua Wellfield and of the proposed expansion in the Tongamai area. Currently there are no SMB's in south east area of the Mataki’eua/ Tongamai wellfield where the conductivity of the water is greater than 1,000 µS/cm (MLSNR data, 2012).

Recommendations have been made by *SOPAC* to increase the distribution of the monitoring bores across the Mataki’eua/ Tongamai borefield to assist in better management of the resource with regard to the potential risks of over abstraction and contamination. A monitoring bore has also been recommended at Tongamai to monitor increased abstraction impacts due to additional production bores planned for this area of the wellfield.

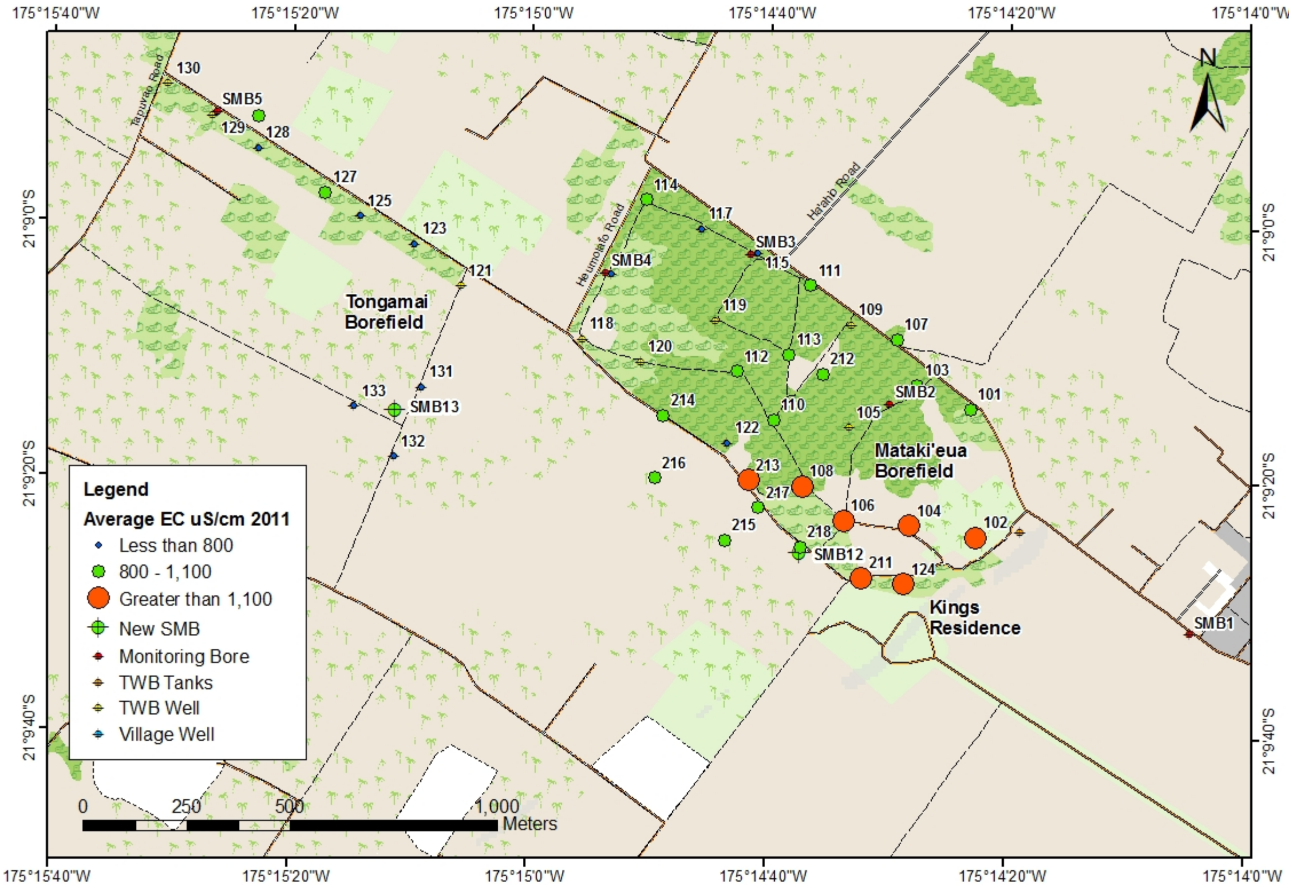


Figure 2 Mataki'eua/Tongamai Wellfield Proposed SMB Locations

In addition, it has been recommended by White et al (2009) to assess the potential for sourcing water for Tongatapu and Nuku'alofa's water supply from other locations such as the International Airport at Fua'amotu or at Houma (Figure 3 and Figure **4**). Placing three SMB's at Fua'amotu and one at Houma provides valuable specific information on the suitability of these locations as a future water reserve and water supply wellfield.

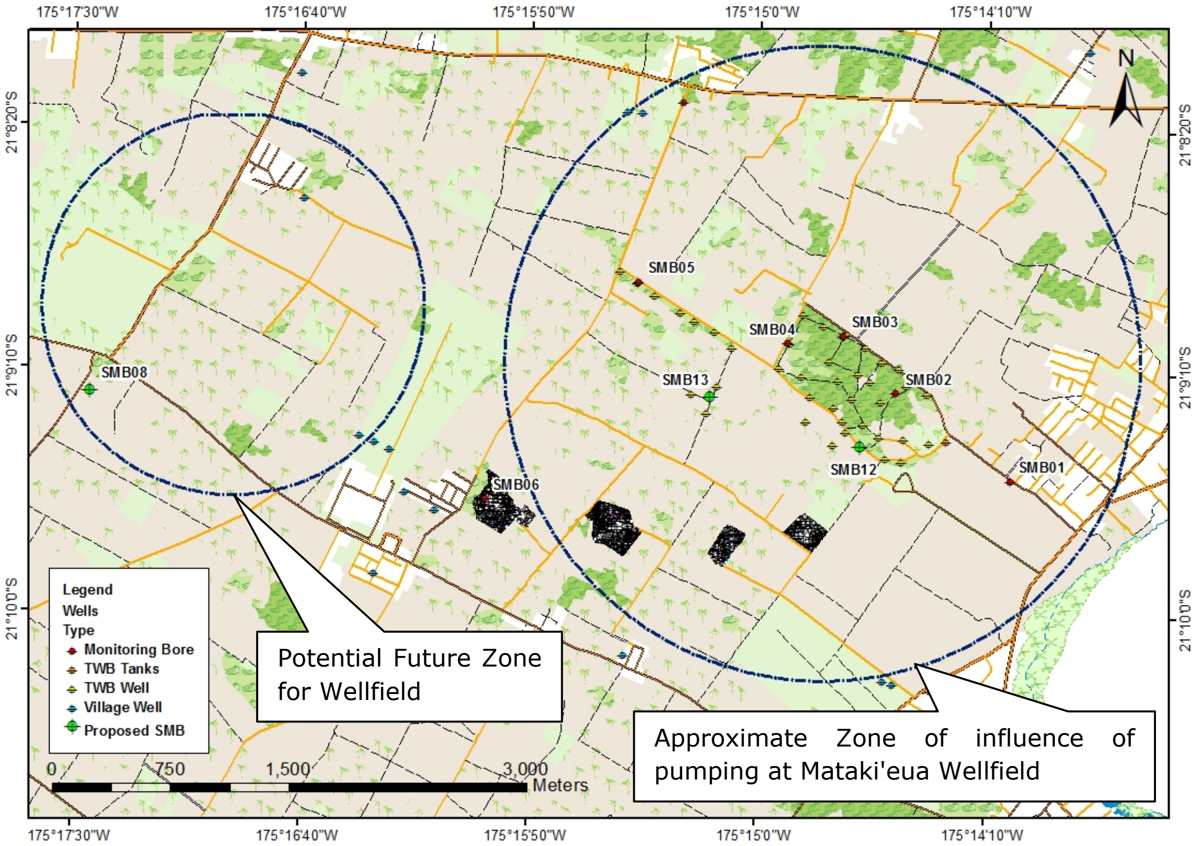


Figure 3 Mataki'eua/Tongamai wellfield and Niumate Proposed SMB Locations

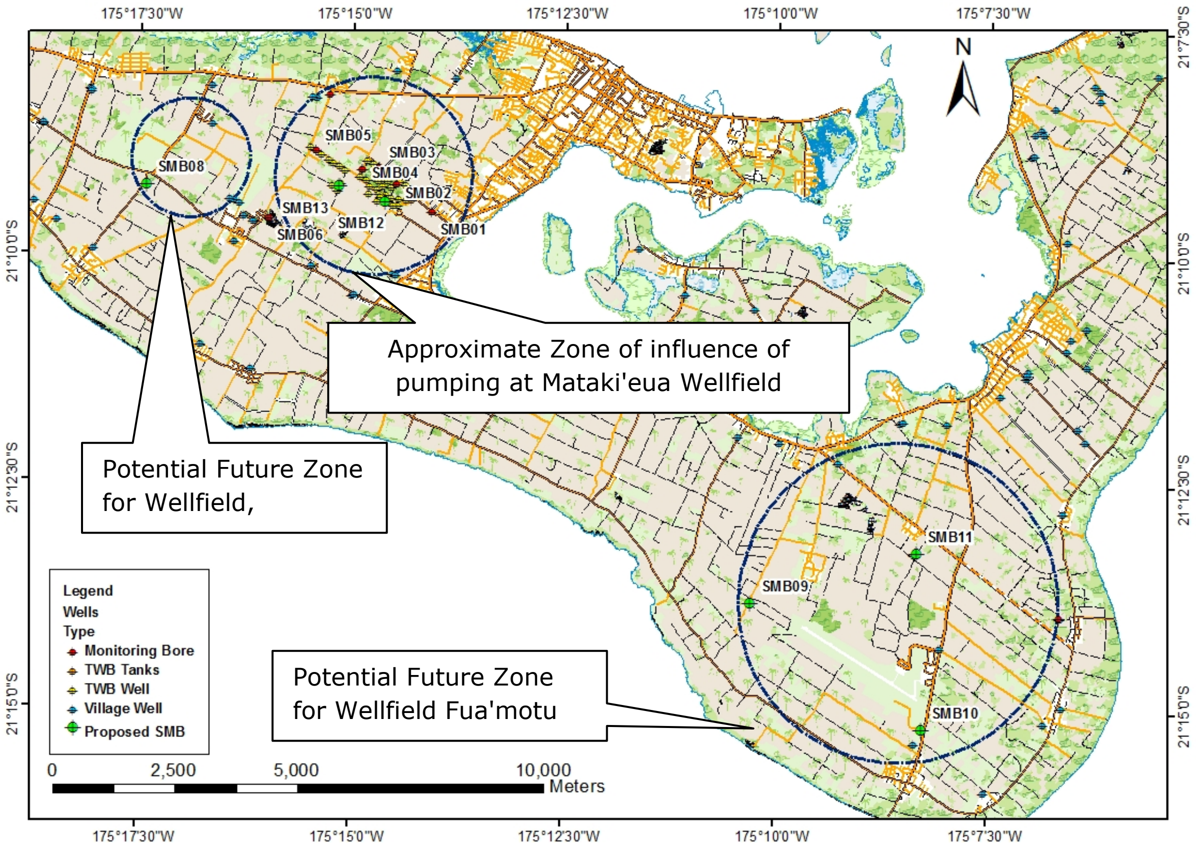


Figure 4 Mataki'eua/Tongamai wellfield, Niumate and Fua'amotu Proposed SMB Locations

4.2. Land Rights

Access rights were gained to all sites through negotiations with the current land owners. Malo 'aupito to those who generously gave permission for the drilling and installation of monitoring bores. The following sites were approved as follows:

- Houma (SMB08), Hon. Baron Vaea, Minister for Internal Affairs Ministry of Internal Affairs.
- Toloa and Fua'motu (SMB9 and SMB10), Viliami Ma'ake, The Deputy CEO & Director of Operation Tongan Airports Limited Fua'amotu International Airport.
- Pelehake (SMB11), Suliasi Kulikefu Moala, Mataki'eua (SMB12) Sam Piliu and Asinate Piliu, California, USA and Saimone Helu, General Manager Tonga Water Board.
- Tongamai (SMB13) Rev. Siotame Havea, Principle of Sia'atoutai Theological Collage Free Wesleyan Church.

To minimise environmental disturbances and provide future access, where possible drilling targets were sited on previously disturbed areas or adjacent to existing roads and tracks.

4.3. Drilling Introduction

Naryba Engineering Enterprises & Development Services (NEEDS) were engaged to undergo the work required to complete the drilling of six monitoring boreholes on Tongatapu, Tonga, for MECCNR. Drilling was to be completed at a depth specified and supervised by MLECCNR staff. Interim payments to the contractor varied depending on depth of boreholes. Drilling was to be undertaken by NEEDS using the cable tool rig.

Payments were made in Tongan Pa'anga (TOP) for the maximum amount of TOP$118,236.00. The payment structure was completed as follows:

Stages	Location	Payment (TOP)	Payment Structure
	Advance	$23,647.20	20%
Borehole 1	SMB8 –Pelehake	$17,735.40	15%
Borehole 2	SMB9 - End of airport runway	$17,735.40	15%
Borehole 3	SMB10-Fua'amotu	$17,735.40	15%
Borehole 4	SMB11-Mataki'eua	$17,735.40	15%
Borehole 5	SMB12-Mataki'eua		
Borehole 6	SMB13-Mataki'eu	$23,647.20	20%
	Total	$118,236.00	

Table 2 Breakdown of the NEEDS contract payments

An advance comprising twenty per cent of the total cost was paid upon signature of the contract totalling TOP$23,647.00. Interim payments were be made progressively upon the completion of drilling for each borehole.

Due to a number delays, the drilling program took a total of 7 months and hence 3 addendums were made to extend the contracts duration.

Due to actual drilling depths exceeding the original contract by 12.5 m a final addendum was made to contract for an additional payment of TOP $5,185.80. The work was also extended to include the upgrade of the original 7 SMB's to ensure their protection and longevity.

4.4. Drilling Equipment

Cable tool drilling, otherwise known as percussion drilling, is probably the oldest drilling method. It involves the lifting and dropping of a string of solid steel drilling tools suspended from a wire rope, which hit the bottom of the hole. This process drives the cutting bit, fracturing or pulverizing the formation. The crushed material forms a slurry on mixing with water that is either added or naturally present in the hole. The blow rate varies from 40 to 60 strokes per minute and due to the characteristic lay of the wire rope cable, the bit turns and strikes across a different section of the bottom of the hole at each blow.

When the bit can no longer fall freely through the water-cuttings mix, the drill tools are withdrawn from the hole. A tubular bailer which is run on a separate smaller wire rope, is then used to pick up the slurry and cuttings and remove them from the hole before drilling is resumed. In cable tool or percussion drilling, there are basically three major operations:

- The drilling of the hole by chiseling or crushing the rock, clay or other material by the impact of the drill bit.
- Removing the cuttings with a bailer as cuttings accumulate in the hole.
- Driving or forcing the bore casing down into hole as the drilling proceeds.

Because of the relatively low initial cost and simplicity of the equipment used, cost per unit drilled is relatively low. However, the technique is slow and when the increased cost of labour is taken into account, there is usually little net advantage over faster rotary drilling methods in the drilling of new bores. The benefits of using cable tool rigs in a limestone stratified aquifer as found in Tongatapu for the logging and investigative hydrogeolgy include:

- There is no use of drilling fluids and so the water samples are uncontaminated and water quality can be determined at any depth.
- The drilling is able to continue through cavities or highly fractured sections when other rotary drilling methods may lose circulation and are unable to continue.
- Rock and soil sample are able to be taken at specific depths for logging purposes and are not lost out into fractures and cavities during drilling.

Figure 5 Cable Tool Rig Used for the SMB

4.5. Field supervision and data collection

The rig supervision required the onsite supervisor to liaise between the NEEDS, MLECCNR staff and SOPAC to record and communicate the daily events occurring at the drill rig. The following items were recorded in a daily log of drilling activities

- Delays or mechanical issues, time spent drilling, tripping in and out of the borehole, and bit changes, due to changes in ground conditions.
- Well construction details were recorded

The MLSNRE staff Geology Unit staff and hydrogeologist supervised the drilling, testing (where undertaken) and completion of all wells. Information recorded during drilling included:

- Lithology, based on drill cuttings collected at 2 m intervals. The cuttings were collected every 2 m and placed in a plastic container labelled with the depth and site. Photos of the final samples were taken.
- Groundwater temperature, electrical conductivity (EC, mS/cm) and pH, were measured using the TPS electronic conductivity meter after bailing at 2 m intervals and at new water cuts.

- Groundwater temperature and electrical conductivity (EC, mS/cm) were measured using a Solinist Temperature, Level, Conductivity meter, when access to the hole was available during drilling.
- Depth to groundwater, when possible during and after drilling.
- After completion of the borehole and the temporary casing was removed, groundwater temperature and electrical conductivity (EC, mS/cm) were measured every 1-2 m using a Solonist TLC.
- During well development, field measurements of temperature, pH and EC were continuously recorded and a water sample collected once consecutive readings stabilised to within 10% of previous recording, using the TPS conductivity meter.
- Airlift water yield estimated, measured using a bucket.

Detailed logs of each SMB are presented in Appendix A including all the information logged during the drilling and photographs of the collected samples.

The lithological descriptions were conducted according to the Geotechnical standard for soil and rock descriptions and adapted for Tonga purposes (Appendix B).

Figure 6 Identification of the Rock Samples

4.6. Well construction

All wells were drilled and constructed to the standards specified in the Minimum Construction Requirements for Water Bores in Australia (Land and Water Biodiversity

Commission, 2003) and adapted for raised coral island situations and applications in Tonga.

Composite well specifications and detailed designs and drawings of all aspects of monitoring bore construction were provided and agreed to by MLSNR Geology staff and supervising hydrogeologist during the design and planning phase and prior to construction and mobilisation:

- Holes extended well into the freshwater/saltwater transition zone when a electrical conductivity of 40,000 µS/cm was reached.
- Multi nested piezometers (32 mm IDClass 12 PVC) with screens 1 m in length and a 1m sump with end cap. (Figure 7).
- The depth of each piezometer was dependent upon the thickness of the freshwater lens, spacing between midpoints of screen were constructed to capture salinity variations within the transition zone, (approximately 3-8 m) with final determination based on field conditions. The depths of the pizometers were designed to capture the mid point of the freshwater zone, the base of the freshwater zone (2,500 µS/cm), the midpoint of the transition zone (20,000 µS/cm) and the base of the transition zone (40,000 µS/cm).
- Each hole was backfilled with coarse sand/gravel. Bentonite layers were installed between piezometers of thickness 0.5 m to ensure hydraulic separation between piezometers. Concrete bentonite seals of a minimum of 0.5 m thick from the surface were installed.
- Bore headwork protection was built to minimise potential vandalism. A 152 mm machine cut steel casing was installed to a depth of 1 m below ground and above ground. The piezometers are contained within the steel protector casing. The headwork protection is fitted with a lockable cap fitted with a lock with the same key for four boreholes.
- Surrounding each of the is a 1 x 1 m concrete pad with 4 steel pillars to provide visability and protection and restrict vegation encroaching upon the stand pipe and casing.

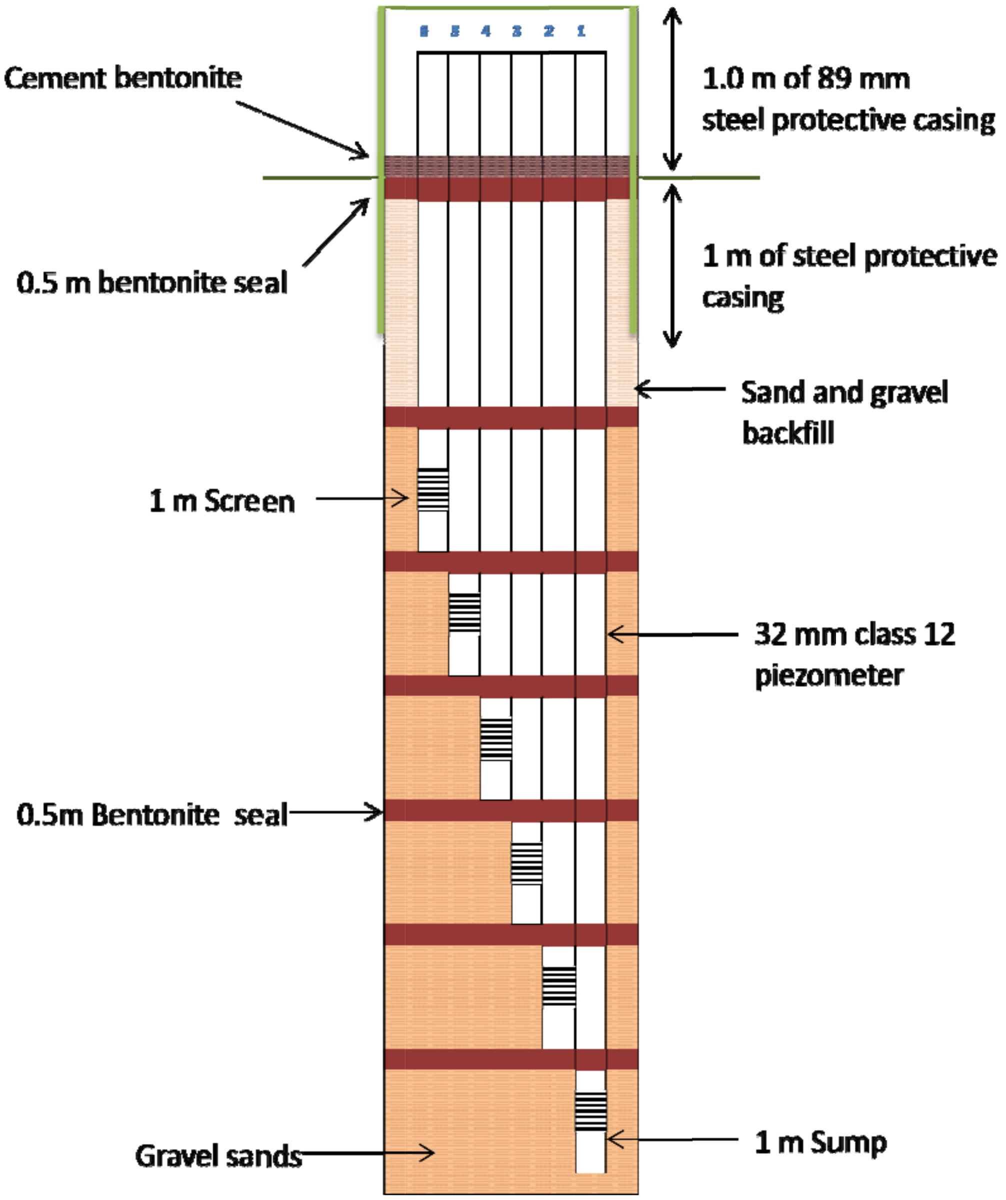


Figure 7 Schematic of multi-nested piezometer design (NOT TO SCALE),

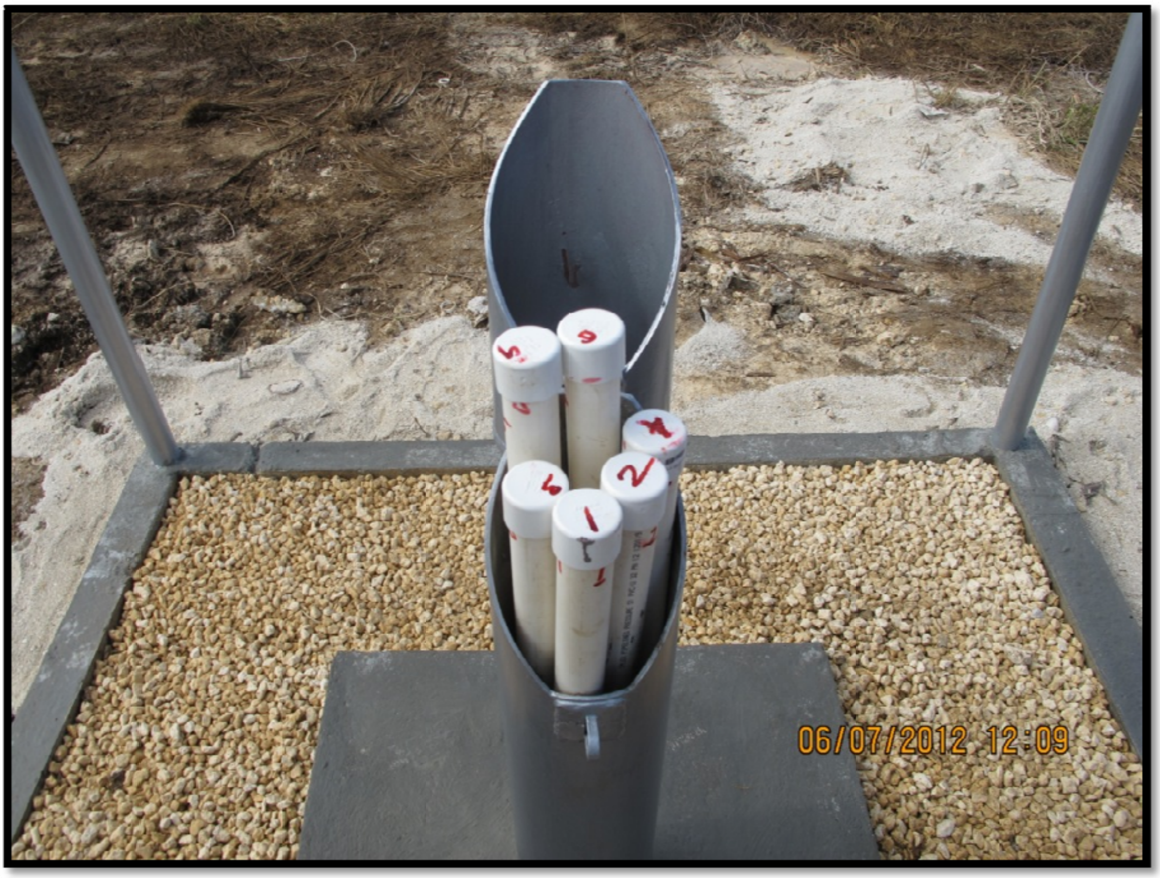


Figure 8 Borehole completion photos

4.7. Borehole Development

Each well was developed via airlifting, using a portable compressor. Airlift development of the wells was achieved using a 1″ hose submerged approximately 1 m from the total depth of the piezometer. Each piezometer was developed for at least 10 minutes or until measured parameters (EC, pH, temperature) of the returned groundwater stabilised. This was done in order to remove all drill cuttings and to induce a hydraulic connection between the bore and the aquifer.

4.8. Monitoring Water Quality

After the boreholes were developed and left for a week, a water quality monitoring was undertaken. The monitoring recorded the parameters for each pizometer contained within the new SMB sites:

- Total depth.
- Electrical conductivity at the midpoint of the screen screen and at the water table.
- Temperature at the midpoint of the screen and at the water table.
- Depth to water.
- Weather conditions.

- Status of the surrounding pumping stations where relevant.

Figure 9 Monitoring of the completed SMB's

5. RESULTS

5.1. Stratigraphy

Two major strata were encountered during drilling operations. The first stratum is a silty clay layer comprised of a highly plastic SILTY CLAY, brown to dark brown in colour. These clays are considered to be stiff to very stiff in consistency and have a moisture content greater than the plastic limit. The depth of this stratum varied from 0.80 m to 3.00 m in boreholes .

The underlying second stratum is an older limestone in various degrees of weathering and fracturing. As well as being highly permeable there are voidal zones and areas of loose and semi-consolidated materials which, when drilled, are unstable (caving).

5.2. Drilling Groundwater Salinity and Water Levels

Overview

The vertical distribution of groundwater salinity during drilling is presented for each SMB site in the borehole logs in Appendix A.

Salinity is further summarised in Figure 12, Figure 11 and Figure 12. Overall, increases in groundwater salinity were measured with depth and marked changes often coinciding with changes in lithology.

The first water cut for all wells occurred from 10 to 20.7 m. In many cases this was associated with a fracture or karst.

The salinity of the freshwater lens is variable across the island. Measured EC at the water table ranges from 420 to 670 µS/cm.

Houma Region

The thickness of the fresh water lens at SMB08 recorded at the time of drilling was 19 m. Depth to water at SMB08 was 10.10 m below ground level (bgl). The salinity of the groundwater at the water table was 660 µS/cm.

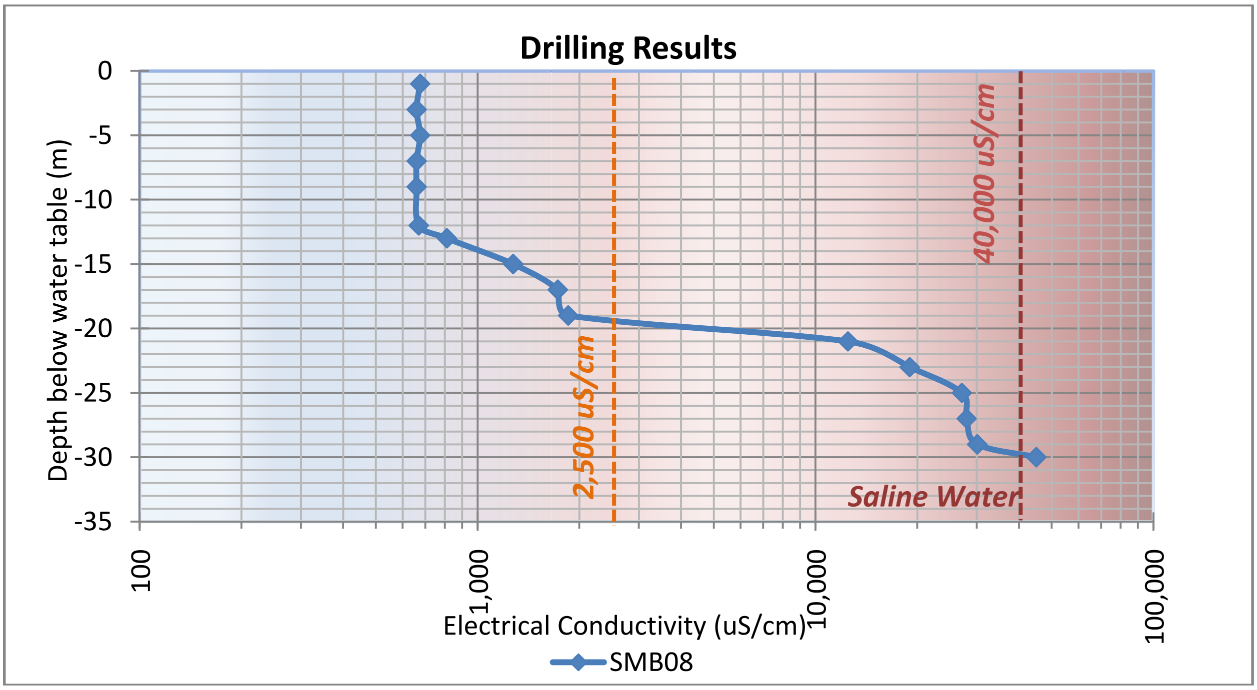


Figure 10 Electrical conductivity results while drilling at Houma

Fua'amotu Region

The thickness of the fresh water lens recorded at the time of drilling at the Fua'amotu (SMB10) and Toloa (SMB09) was 16 m and 21 m at Pelehake (SMB11). The depth to water at SMB09, SMB10 and SMB11 was 26.18 m bgl, 40.00 m bgl and 24.5 m bgl respectively. The salinity of the groundwater at the water table was 400 µS/cm to 550 µS/cm.

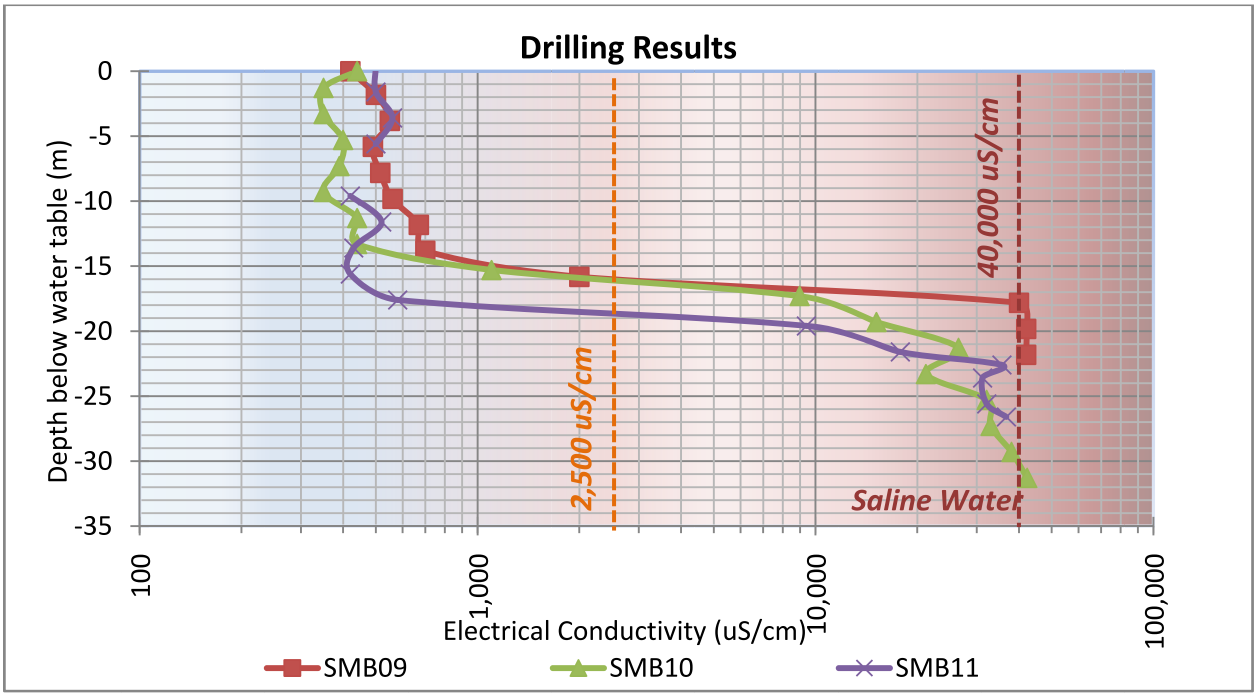


Figure 11 Electrical conductivity results while drilling at Fua'amotu, Toloa and Pelehake.

Mataki'eua/Tongamai

The total thickness of the freshwater lens Tongamai (SMB13) at the time of drilling, was 16 m and at Mataki'eua (SMB12) the thickness was 11 m. The depth to water at SMB12 and SMB13 was 19.02 m bgl and 12.27 m bgl respectively. The salinity of the groundwater at the water table was 380 µS/cm to 420 µS/cm.

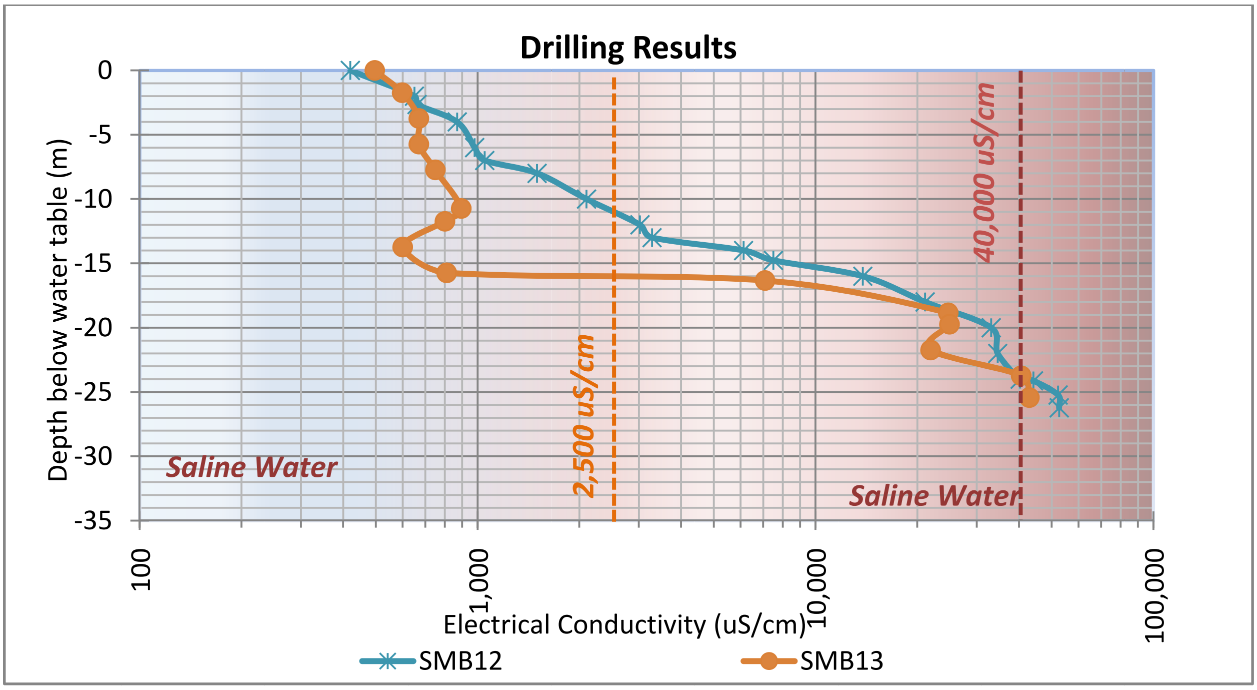


Figure 12 Electrical conductivity results while drilling at Mataki'eua/Tongamai

5.3. Final Construction

Table 3 summarises the final construction of the 6 SMB's.

Well ID	**SMB08**	**SMB09**	**SMB10**	**SMB11**	**SMB12**	**SMB13**
Location	**Houma**	**Toloa**	**Fua'amotu**	**Pelehake**	**Mataki'eua**	**Tongamai**
Total Depth (m)	41.5	48	72	51.5	46.5	38
Tube 1 (m)	41.5	48	70	52	46	38
Tube 2 (m)	35	45	62	46	42	35
Tube 3 (m)	32	41.5	59	43	37	32
Tube 4 (m)	28	39	56	40	33	28
Tube 5 (m)	20	36	53	38	28	22
Tube 6 (m)	16	31	48	29	25	17

Table 3 Final construction of the SMB's

5.4. Final Monitoring Groundwater Salinity and Water Levels

A monitoring round was completed on the 23rd of October and the final results are presented in Figure 13. The thickness of the freshwater lens is approximately 16 m at all SMB sites except for SMB12 located next to production well 218 which has a fresh water thickness of 11 m.

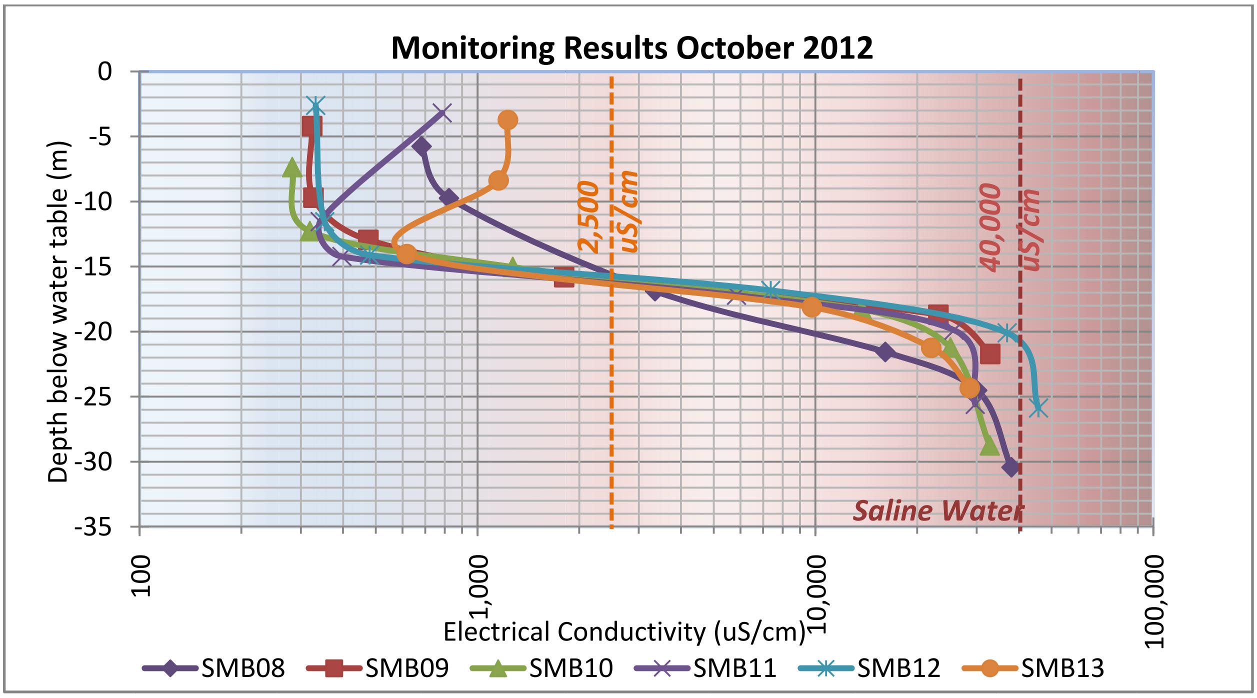


Figure 13 SMB electrical conductivity results October 2012 monitoring round

Well ID	**SMB08**	**SMB09**	**SMB10**	**SMB11**	**SMB12**	**SMB13**
Location	**Houma**	**Toloa**	**Fua'amotu**	**Pelehake**	**Mataki'eua**	**Tongamai**
Depth to Water (m)	11.00	26.18	40.00	26.18	20	12.27
Distance to the Sea (m)	2,820	1,750	1,900	2,650	1,375	2,520
Thickness of the Freshwater Lens (m)						
Drilling	19	16	16	21	11	16
Final (Oct-Nov, 2012)	16	16	16	16	11	16

Table 4 Summary of all the results

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

While the cost of pipelines from the Fua'amotu area will be significant, the groundwater in the region of the International Airport has several advantages as a future water source for Nuku’alofa and for the Vaini and Tatakamotonga districts. These advantages include:

- The region is within government owned land.
- There is a thick freshwater lens over a significant area of land (16 m).
- The salinity of the freshwater lens is very low (400-550 µS/cm).
- Land use impacts would be minimal due to the location of the airport and minimal development.

The groundwater in the region of Houma could also provide a future water source for Nuku’alofa. The advantages of sourcing groundwater from Houma include:

- The Houma region is close to the current Matakieua wellfield but outside the approximate zone of area of influence from the pumping.
- The cost of pipelines would be significantly less than at the Fua'amotu region.

6.2. Recommendations

- A more detailed investigation of both the Houma and Fua’amotu regions is recommended involving a series of geopysical EM34 and resistivity to determine the extents of the water resource and potential water reserve area. An estimate of sustainable yield should be determined before these areas are developed.
- SMB12 and SMB13 within the Matakieua/Tongamai TWB borefield should be added to the monthly monitoring currently being conducted by the Natural

Resources Division of the MLECCNR (refer to Appendix C and D). All results recorded, graphed and to be made available for the TWB use.

- SMB08 to SMB11 located within the Fua'amotu and Houma regions should be monitored on a quarterly basis as per the procedure in Appendix C, and results provided to TWB on a regular basis, at least annually.
- As recommended by White et al (2009) a contingency plan to address the impacts of droughts on water supply involving voluntary and compulsory water restrictions and other instruments should be developed for Tongatapu.
- Also recommended by White et al (2009) groundwater recharge should be estimated at the end of each month by calculating 30% of the monthly rainfall. The frequency of groundwater monitoring should be increased and a warning should be given to the government and the TWB when there are more than 8 consecutive months all with zero estimated recharge. When there are more than 12 consecutive months of zero recharge consideration should be given to implementing the drought contingency plan.

6. REFERENCE

Crennan L. and Mafi K. (2007). National Integrated Water Resource Management, Diagnostic Report: *Tonga, Sustainable integrated water resources and wastewater management project in Pacific Island countries, SOPAC* Miscellaneous Report 646, 85p.

Falkland A. (1992).*Tonga Water Supply Master Plan Project Water Resources Report. PPK Consultants Pty Ltd and Australian International Development Assistance Bureau, Figure 5.2.*

Falkland A. (1995). Technical component progress report. Tonga Water Board Institutional Development Project, ACTEW Corporation, Canberra, December 2005.

Fry, N. (2011), *National Water, Sanitation and Climate Outlook An evaluation of Water and Sanitation in The Kingdom of Tonga,* National Water Resources Committee with the assistance of SOPAC, p 38.

Furness L. and Helu S.P. (1993). The *Hydrogeology and Water Supply of the Kingdom of Tonga.* Ministry of Lands, Survey and Natural Resources, Nuku'alofa, February 1993, p 143.

Land and Water Biodiversity Committee, (2003). *Minimum Construction Requirements for Water Bore in Australia, Addition 2.*

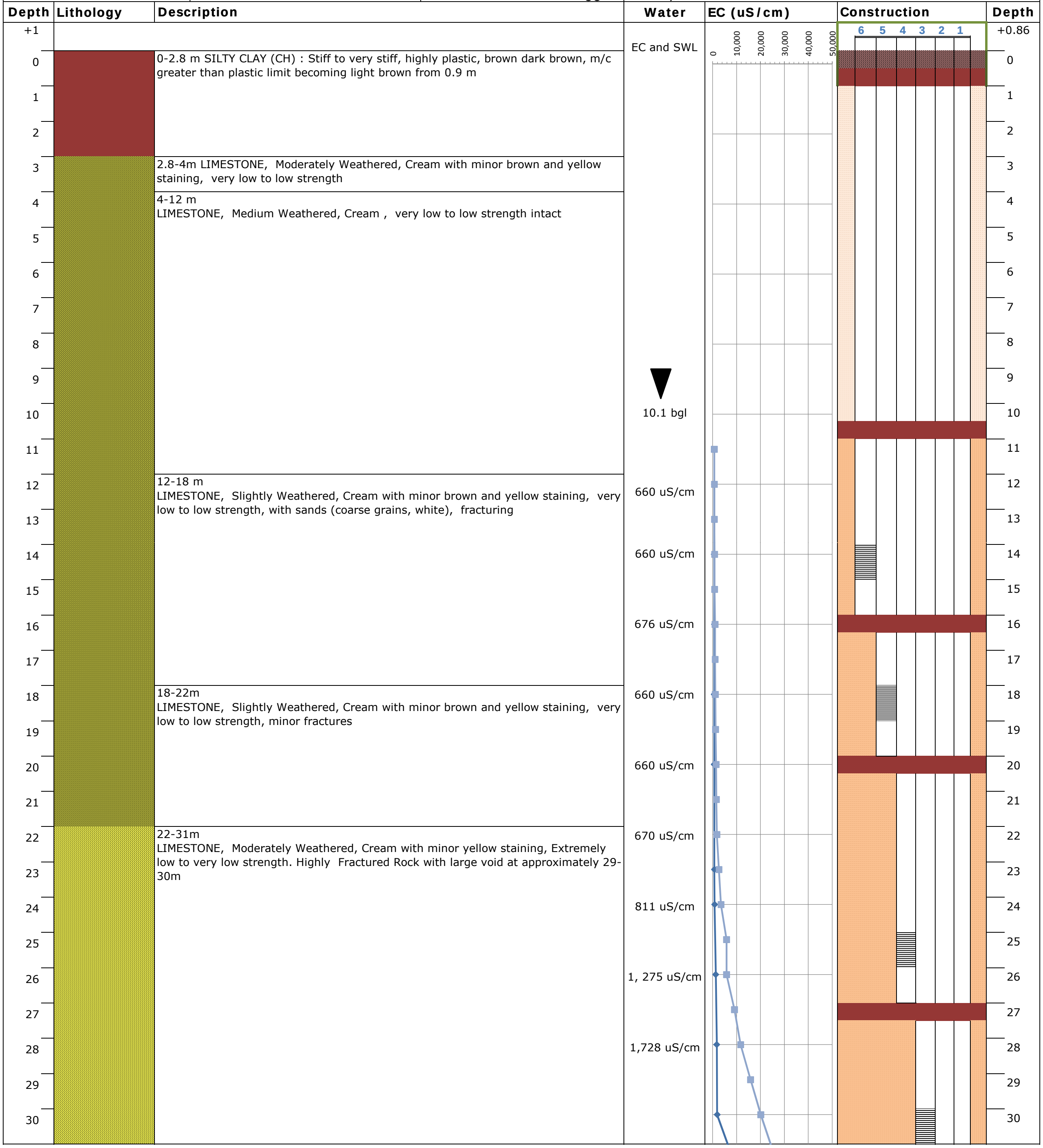
Planning and Urban Management Agency, MLSNR (2011). *Tong: Nuku'alofa Urban Development Sector Project Water Supply Improvement Subproject, Water Supply Production, Storage and Distribution*, prepared For the Asian Development Bank (ADB), p 37.

SPC-SOPAC, (2011). *Reducing Vulnerability <http://www.sopac.org/index.php/reducing-vulnerability-eu-b>*

White, I, Falkland, T, and Fatai, T. (2009). *Vulnerability of groundwater in Tongatapu, Kingdom of Tonga, Groundwater evaluation and monitoring assessment*, SOPAC/EU EDF 8 Reducing the Vulnerability of Pacific APC States, Australian National University, p 31 and 169

Appendix A Borehole logs

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Houma	**Start Date:**	9/10/2012
Borehole No:	SMB08	**Finish Date:**	9/21/2012
Driller:	N.E.E.D.S, Moe	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	Kate Hyland and Sione and Ma'ake



Description

0-2.8 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m

2.8-4m LIMESTONE, Moderately Weathered, Cream with minor brown and yellow staining, very low to low strength

4-12 m
LIMESTONE, Medium Weathered, Cream , very low to low strength intact

12-18 m
LIMESTONE, Slightly Weathered, Cream with minor brown and yellow staining, very low to low strength, with sands (coarse grains, white), fracturing

18-22m
LIMESTONE, Slightly Weathered, Cream with minor brown and yellow staining, very low to low strength, minor fractures

22-31m
LIMESTONE, Moderately Weathered, Cream with minor yellow staining, Extremely low to very low strength. Highly Fractured Rock with large void at approximately 29-30m

Water

EC and SWL

10.1 bgl

660 uS/cm

660 uS/cm

676 uS/cm

660 uS/cm

660 uS/cm

670 uS/cm

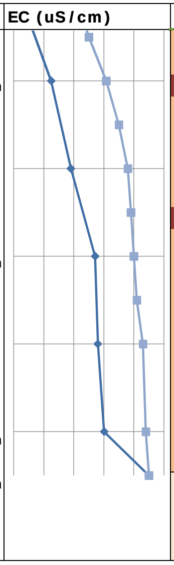
811 uS/cm

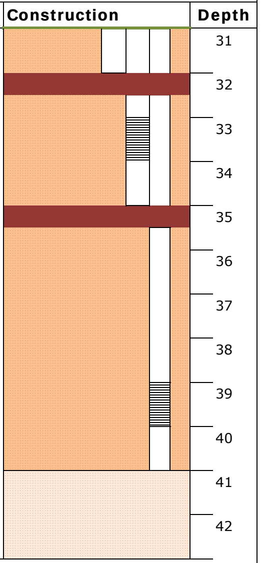
1, 275 uS/cm

1,728 uS/cm

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Houma	**Start Date:**	9/10/2012
Borehole No:	SMB08	**Finish Date:**	9/21/2012
Driller:	N.E.E.D.S, Moe	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	Kate Hyland and Sione and Ma'ake

Depth	Lithology	Description	Water
31	▨	31-36 m LIMESTONE, Fresh Rock to Slightly Weathered, Cream, medium t hard strength.	
32			12,470 uS/cm
33			
34		NB: Very slow drilling	
35			
36	▨	36-40m LIMESTONE, Slightly to Moderately weathered , Cream with minor yellow staining, very low to low strength. Fractured Rock	27,100 uS/cm
37			
38			
39			
40	▨	40-43m LIMESTONE, Slightly Weathered to fresh rock, Cream, medium strength. Intact	30,100 uS/cm
41			45,000 uS/cm
42			
43			

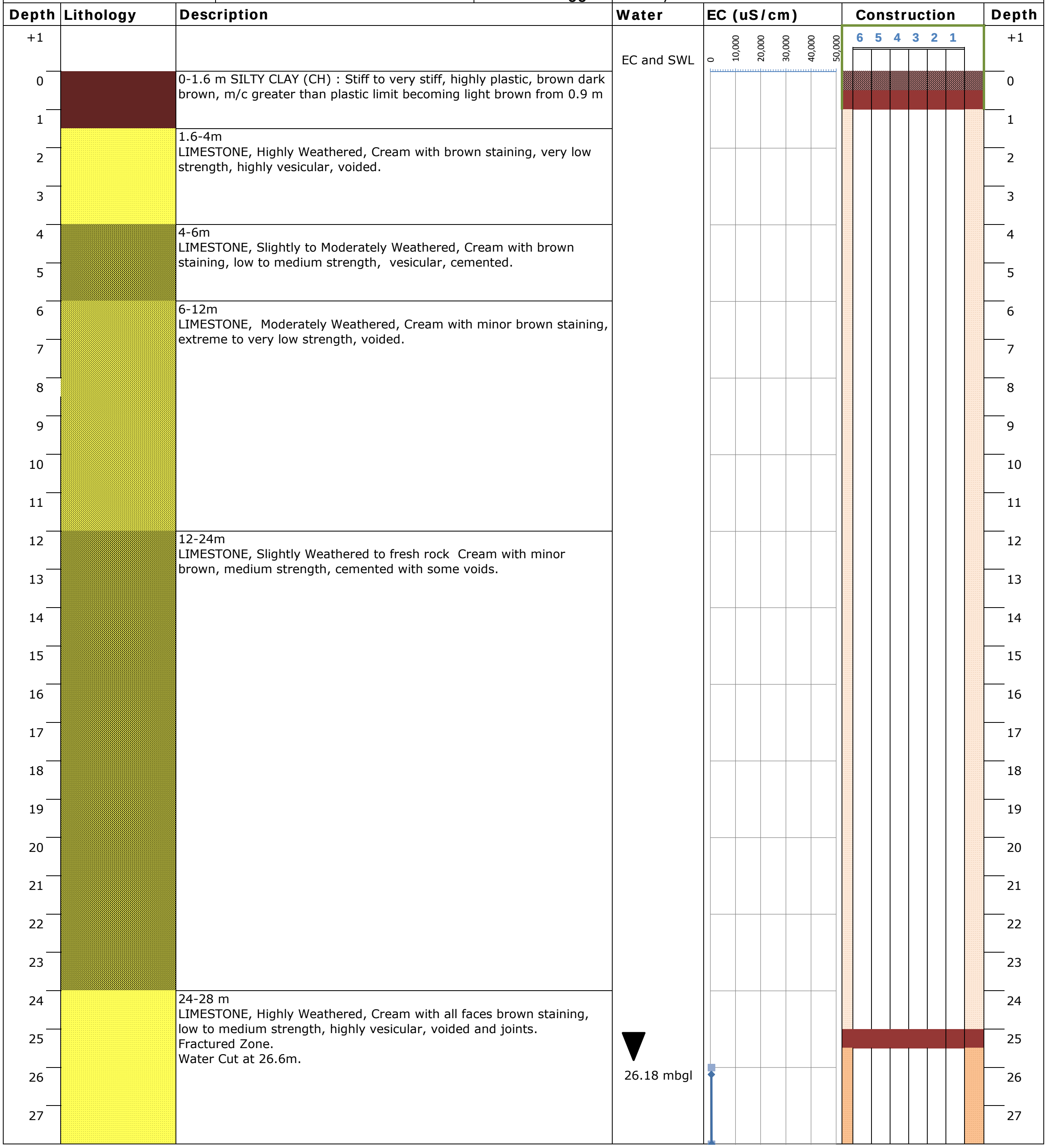




bgl Below ground level
m/c Moisture content
SWL ▼ Static water level below ground l

▨	SILTY CLAY (CH)	▤	Slotted Screen
▨	LIMESTONE, Highly weathered	▨	Bentonite Seal
▨	LIMESTONE, Moderately weathered	▨	Gravel Pack
▨	LIMESTONE, Slightly Weathered	▨	Backfill
▨	LIMESTONE with Clayey Sand lenses	▨	Bentonite Cement Seal
▤	GRAVELY SAND	☐	Steel Casing

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Toloa-End of Airport Runway	**Start Date:**	6/19/2012
Borehole No:	SMB09	**Finish Date:**	7/5/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: 21.22935	**Drilling Method:**	Percussion
	W: 175.17130	**Logger:**	Kate Hyland and Sione Nonu



0-1.6 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m

1.6-4m
LIMESTONE, Highly Weathered, Cream with brown staining, very low strength, highly vesicular, voided.

4-6m
LIMESTONE, Slightly to Moderately Weathered, Cream with brown staining, low to medium strength, vesicular, cemented.

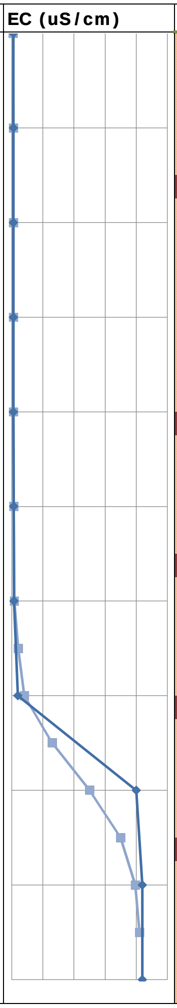
6-12m
LIMESTONE, Moderately Weathered, Cream with minor brown staining, extreme to very low strength, voided.

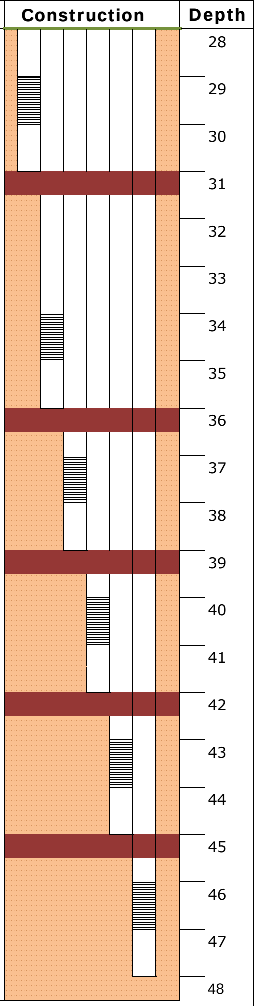
12-24m
LIMESTONE, Slightly Weathered to fresh rock Cream with minor brown, medium strength, cemented with some voids.

24-28 m
LIMESTONE, Highly Weathered, Cream with all faces brown staining, low to medium strength, highly vesicular, voided and joints.
Fractured Zone.
Water Cut at 26.6m.

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Toloa-End of Airport Runway	**Start Date:**	6/19/2012
Borehole No:	SMB09	**Finish Date:**	7/5/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: 21.22935	**Drilling Method:**	Percussion
	W: 175.17130	**Logger:**	Kate Hyland and Sione Nonu

Depth	**Lithology**	**Description**	**Water**
28–32	▨	28-32m LIMESTONE, Moderately Weathered, Cream and white with minor brown staining, low to medium strength, with Layers of Sand, white, coarse grained.	550 uS/cm
32–36	▨	32-36m LIMESTONE, Slightly Weathered, Cream with minor brown staining, high strength, cemented and some crystallised LIMESTONE, slightly vesicular	515 uS/cm
36–38	▨	36-38m LIMESTONE, Slightly Weathered, Cream with minor brown staining, high strength, cemented and some crystallised limestone, slightly vesicular. with Layers of Sand, white, coarse grained	670 uS/cm
38–44	▨	38-44m LIMESTONE, Moderately to Highly Weathered, Cream with brown staining, low to very low strength, slightly vesicular.	
41–42	▨	41-42 Highly fractured zone with abundant sand lenses; GRAVELY SANDs, white, medium to coarse grained.	2,000 uS/cm
44–46	▨	44-46 m LIMESTONE, Moderately Weathered, Cream with brown staining, very high strength, highly vesicular. Highly fractured zone.	40,000uS/cm
46–48	▨	46-48 m LIMESTONE, Moderately Weathered, Cream, medium strength, with Layers of Sand, white, coarse grained.	42,000 uS/cm





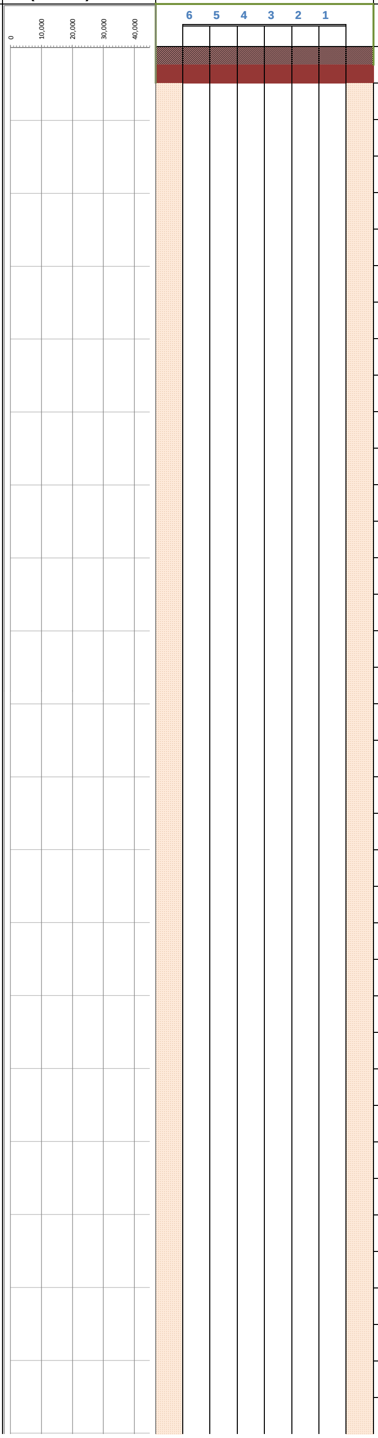
bgl	Below ground level
m/c	Moisture content
SWL	Static water level below ground level

▼

▨	SILTY CLAY (CH)	▤	Slotted Screen
▨	LIMESTONE, Highly weathered	▨	Bentonite Seal
▨	LIMESTONE, Moderately weathered	▨	Gravel Pack
▨	LIMESTONE, Slightly Weathered	▨	Backfill
▨	LIMESTONE with Clayey Sand lenses	▨	Bentonite Cement Seal
▤	GRAVELY SAND	☐	Steel Casing

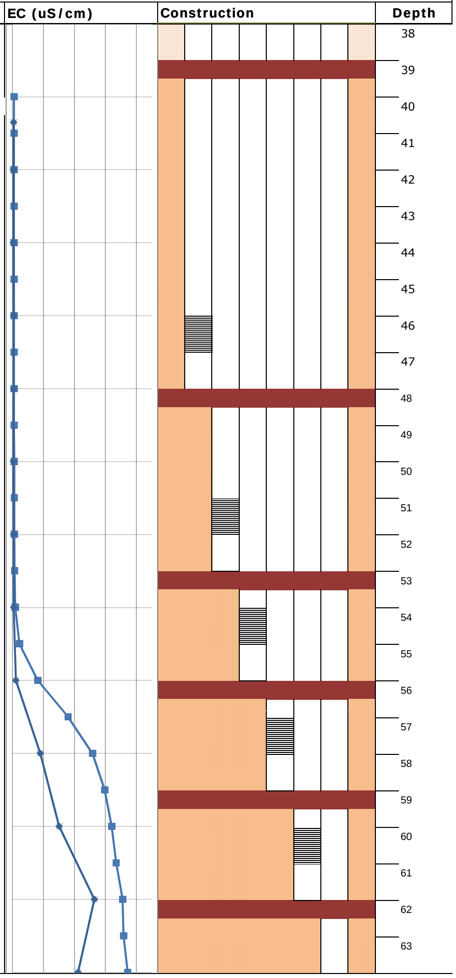
Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Fua'amotu	**Start Date:**	19/7/2012
Borehole No:	SMB10	**Finish Date:**	9/8/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	'Akapei Vailea & Sione Nonu

Depth	Litholo	Description	Water	EC (uS/cm)	Construction	Depth
+1						+1
0		0-3 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m	EC and SWL			0
1						1
2		3-4 m LIMESTONE, Highly Weathered, Cream, yellow and brown staining, Extremely to Very strength, highly voided				2
3						3
4		4-8m LIMESTONE, Slightly to Moderately Weathered, Cream with brown staining, medium strength, voided.				4
5						5
6						6
7						7
8		8 - 14m LIMESTONE, Slightly to Moderately weathered, cream and minor yellow, very low to low strength, fractured structure				8
9						9
10						10
11						11
12						12
13						13
14		14-22 m LIMESTONE, slightly to moderately weathered, cream with minor yellow and minor brown, medium to high strength, voids structure				14
15						15
16						16
17						17
18						18
19						19
20						20
21						21
22		22 - 30 m LIMESTONE - moderately to highly to moderately weathered, cream and minor brown, low to medium strength, Intact structure				22
23						23
24						24
25						25
26						26
27						27
28						28
29						29
30		30 - 38 m LIMESTONE - moderately to highly to moderately weathered, cream, yellow and minor brown, low to medium strength, fractured structure				30
31						31
32						32
33						33
34						34
35						35
36						36
37						37



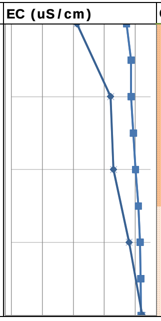
Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Fua'amotu	**Start Date:**	19/7/2012
Borehole No:	SMB10	**Finish Date:**	9/8/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	'Akapei Vailea & Sione Nonu

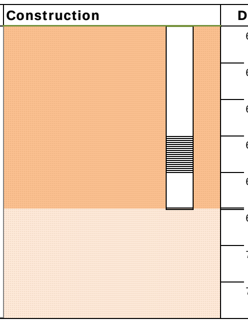
Depth	Litholo	Description	Water
38	▨	38 - 46 m LIMESTONE - slightly to moderately weathered, cream, yellow, low to medium to high strength, sand with coarse grain, Slightly to High vesicular, fractured structure	▼
39			40.70 m blg
40			440 uS/cm
41			
42			350 uS/cm
43			
44			350 uS/cm
45			
46	🟨	46 - 52 m LIMESTONE - highly to moderately weathered, cream, yellow, medium to high strength, slightly to highly vesicular, sand with very coarse grain, fractured structure	400 uS/cm
47			
48			390 uS/cm
49			
50			350 uS/cm
51			
52	▨	52 - 58 m LIMESTONE - slightly to moderately weathered, white, cream, yellow, Slightly to High vesicular, sand with coarse grain, voids structure.	440 uS/cm
53			
54			440 uS/cm
55			1,100 uS/cm
56			
57			
58	▨	58 - 64 m LIMESTONE - slightly to moderately weathered, white, cream and yellow, high to very high strength, voids structure, highly vesicular, sand with coarse grain.	
59			15,150 uS/cm
60			
61			
62			
63			21,200 uS/cm



Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Fua'amotu	**Start Date:**	19/7/2012
Borehole No:	SMB10	**Finish Date:**	9/8/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	'Akapei Vailea & Sione Nonu

Depth	Litholo	Description	Water	EC (uS/cm)	Construction	Depth
64	▨	64 - 68 m LIMESTONE - slightly to moderately weathered, white, cream and yellow, medium to high strength, voids structure, highly vesicular				64
65	▨					65
66	▨					66
67	▨		33,000 uS/cm			67
68	▨	68 - 72 m LIMESTONE - slightly to moderately weathered, white, cream, yellow, medium to high strength, voids structure, highly vesicular.				68
69	▨					69
70	▨					70
71	▨		42,300 uS/cm			71
72						





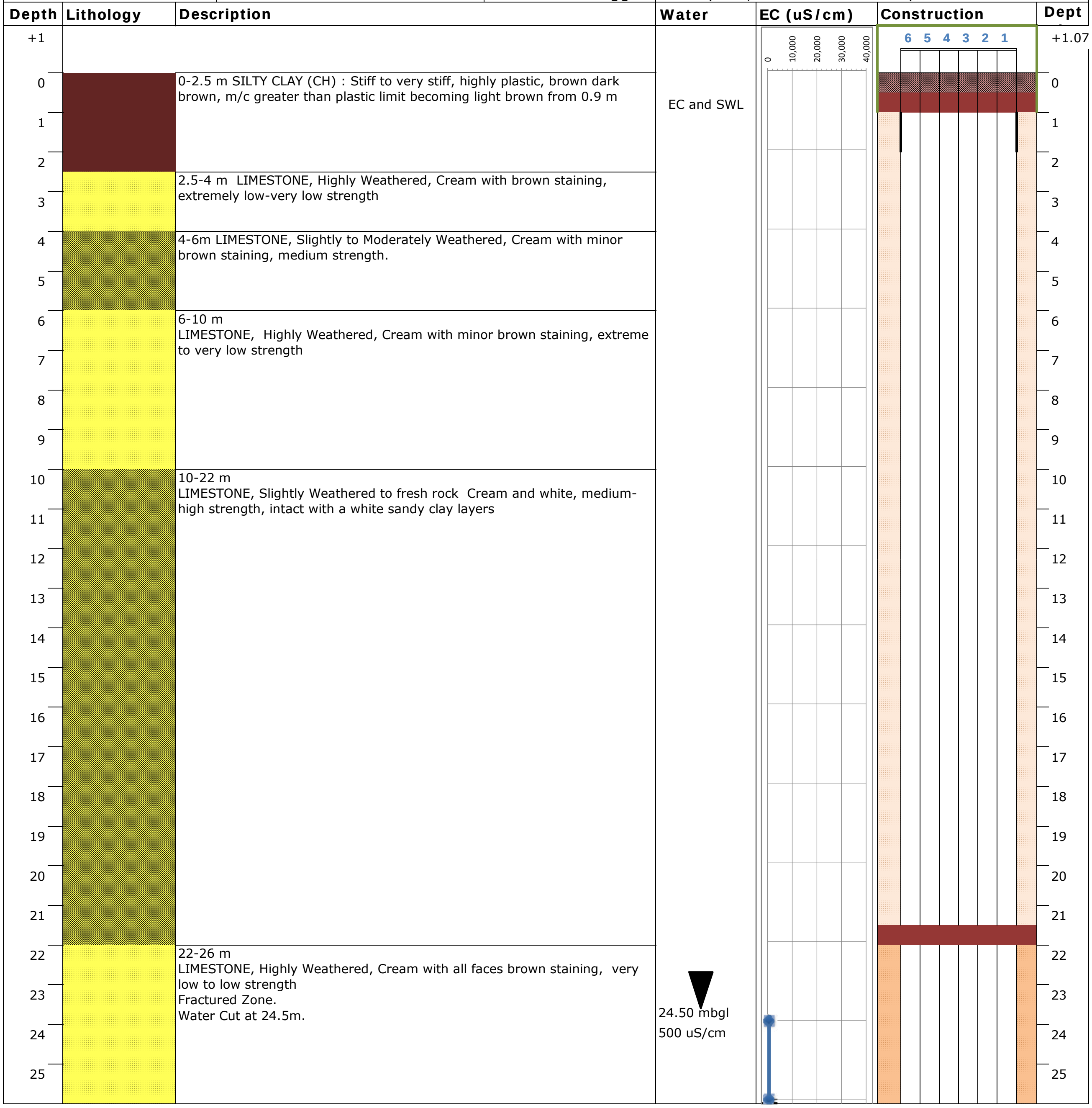
bgl	Below ground level
m/c	Moisture content
SWL	Static water level below ground leve

▼			
■	SILTY CLAY (CH)	▤	Slotted Screen
■	LIMESTONE, Highly weathered	■	Bentonite Seal
▨	LIMESTONE, Moderately weathered	■	Gravel Pack
▨	LIMESTONE, Slightly Weathered	■	Backfill
▨	LIMESTONE with Clayey Sand lenses	▨	Bentonite Cement Seal
▤	GRAVELY SAND	□	Steel Casing

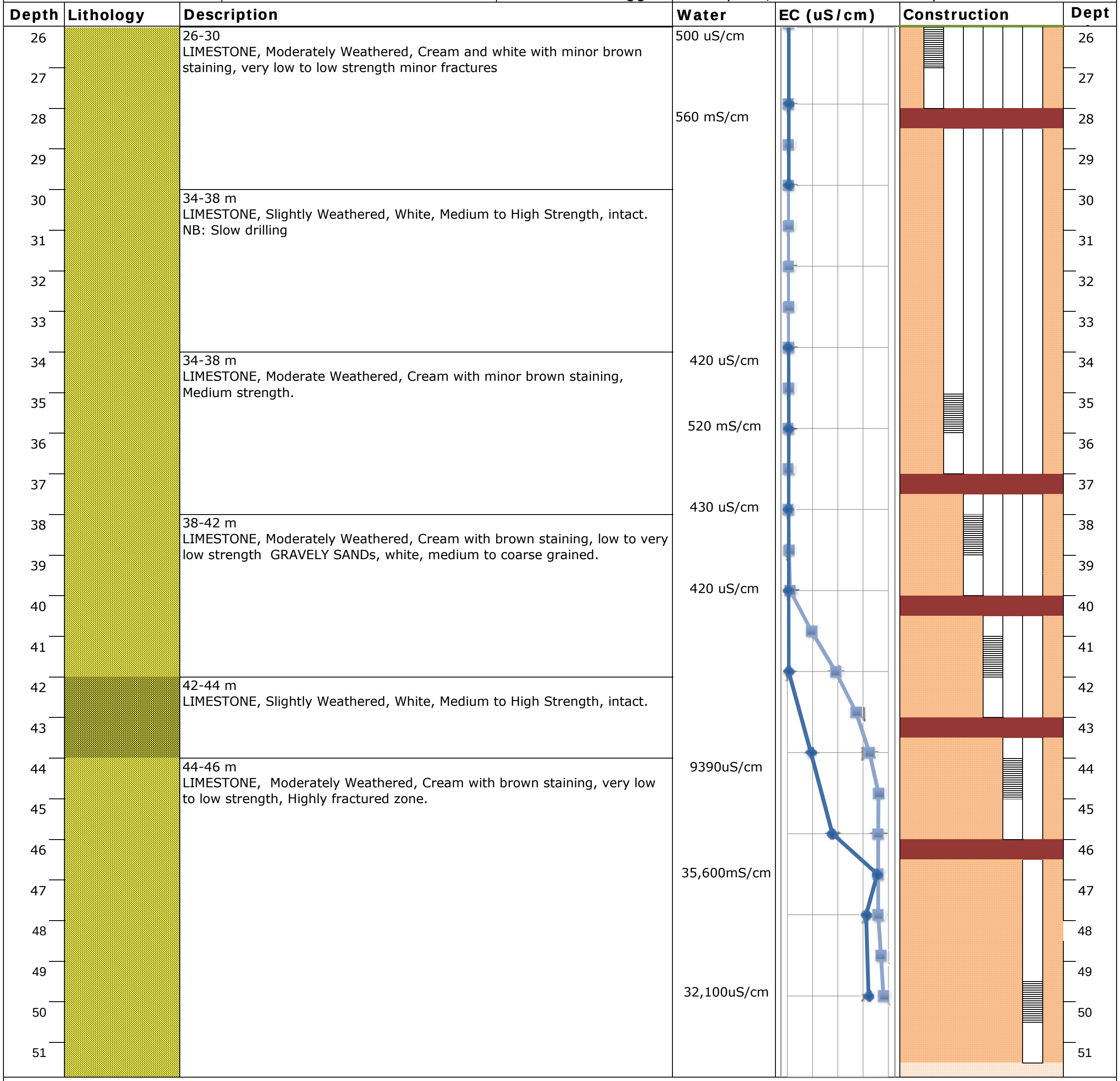
Location: Tongatapu, Tonga
Site: Pelehake-Next to Village Well
Borehole No: SMB11
Driller: N.E.E.D.S, Naisa
Co-ordinates S: - 21.22086
W: - 175.13928

Program SOPAC UN Envelope B
Start Date: 7/27/2012
Finish Date: 8/6/2012
Rig: Cable Tool
Drilling Method: Percussion
Logger: Kate Hyland, Sione Nonu and 'Akapei Vailea

Depth	Description
0	0-2.5 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m
2.5	2.5-4 m LIMESTONE, Highly Weathered, Cream with brown staining, extremely low-very low strength
4	4-6m LIMESTONE, Slightly to Moderately Weathered, Cream with minor brown staining, medium strength.
6	6-10 m LIMESTONE, Highly Weathered, Cream with minor brown staining, extreme to very low strength
10	10-22 m LIMESTONE, Slightly Weathered to fresh rock Cream and white, medium-high strength, intact with a white sandy clay layers
22	22-26 m LIMESTONE, Highly Weathered, Cream with all faces brown staining, very low to low strength Fractured Zone. Water Cut at 24.5m.



Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Pelehake-Next to Village Well	**Start Date:**	7/27/2012
Borehole No:	SMB11	**Finish Date:**	8/6/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.22086	**Drilling Method:**	Percussion
	W: - 175.13928	**Logger:**	Kate Hyland, Sione Nonu and 'Akapei Vailea



26-30
LIMESTONE, Moderately Weathered, Cream and white with minor brown staining, very low to low strength minor fractures

34-38 m
LIMESTONE, Slightly Weathered, White, Medium to High Strength, intact. NB: Slow drilling

34-38 m
LIMESTONE, Moderate Weathered, Cream with minor brown staining, Medium strength.

38-42 m
LIMESTONE, Moderately Weathered, Cream with brown staining, low to very low strength GRAVELY SANDs, white, medium to coarse grained.

42-44 m
LIMESTONE, Slightly Weathered, White, Medium to High Strength, intact.

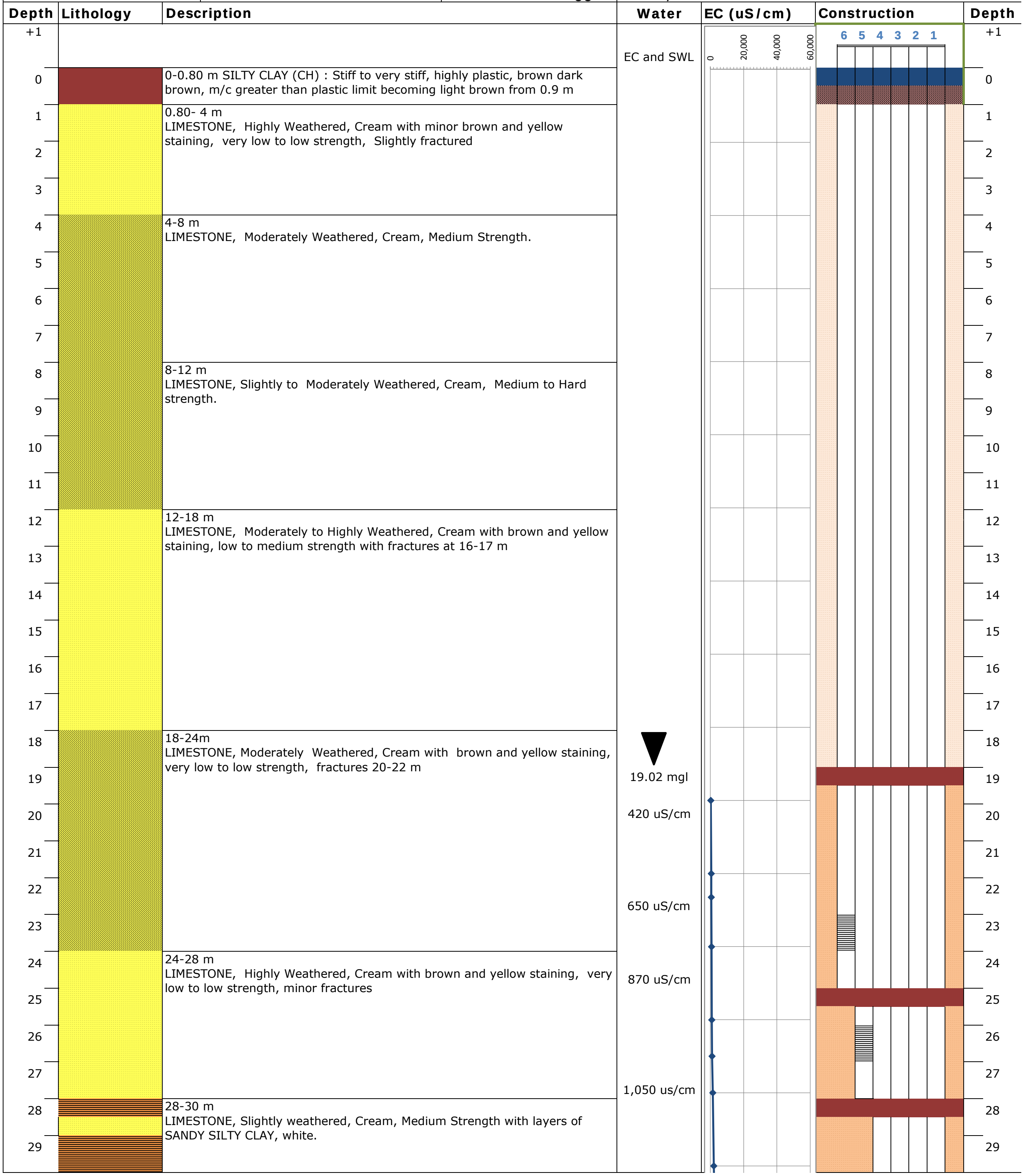
44-46 m
LIMESTONE, Moderately Weathered, Cream with brown staining, very low to low strength, Highly fractured zone.

500 uS/cm
560 mS/cm
420 uS/cm
520 mS/cm
430 uS/cm
420 uS/cm
9390uS/cm
35,600mS/cm
32,100uS/cm

bgl	Below ground level
m/c	Moisture content
SWL	Static water level below gr

▼ ▨	SILTY CLAY (CH)	▤	Slotted Screen
▨	LIMESTONE, Highly weathered	▨	Bentonite Seal
▨	LIMESTONE, Moderately weathered	▨	Gravel Pack
▨	LIMESTONE, Slightly Weathered	▨	Backfill
▨	LIMESTONE with Clayey Sand lenses	▨	Bentonite Cement Seal
▨	GRAVELY SAND	☐	Steel Casing

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Mataki'eua	**Start Date:**	9/22/2012
Borehole No:	SMB12	**Finish Date:**	10/5/2012
Driller:	N.E.E.D.S, Moe	**Rig:**	Cable Tool
Co-ordinates	S: -175.243853	**Drilling Method:**	Percussion
	W: -21.156921	**Logger:**	Kate Hyland and Sione and Ma'ake



0-0.80 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m

0.80- 4 m
LIMESTONE, Highly Weathered, Cream with minor brown and yellow staining, very low to low strength, Slightly fractured

4-8 m
LIMESTONE, Moderately Weathered, Cream, Medium Strength.

8-12 m
LIMESTONE, Slightly to Moderately Weathered, Cream, Medium to Hard strength.

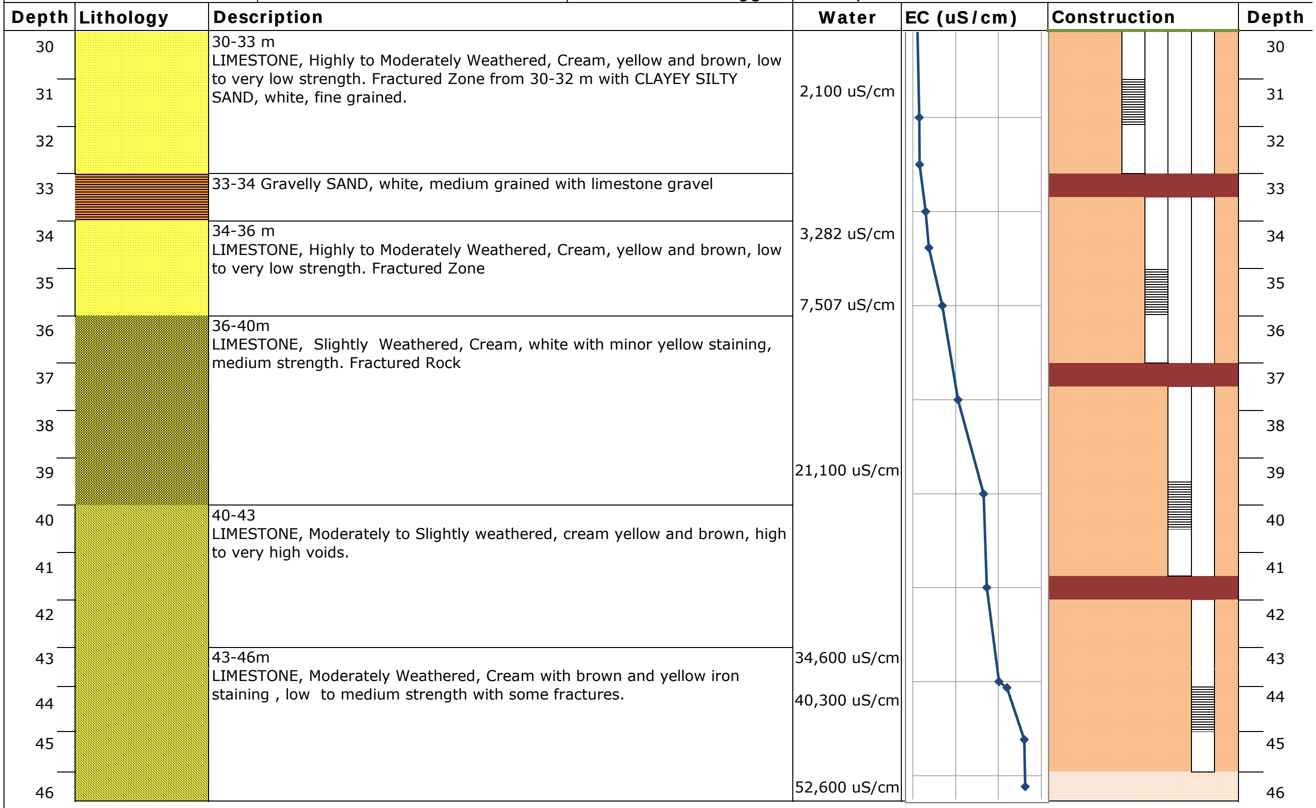
12-18 m
LIMESTONE, Moderately to Highly Weathered, Cream with brown and yellow staining, low to medium strength with fractures at 16-17 m

18-24m
LIMESTONE, Moderately Weathered, Cream with brown and yellow staining, very low to low strength, fractures 20-22 m

24-28 m
LIMESTONE, Highly Weathered, Cream with brown and yellow staining, very low to low strength, minor fractures

28-30 m
LIMESTONE, Slightly weathered, Cream, Medium Strength with layers of SANDY SILTY CLAY, white.

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Mataki'eua	**Start Date:**	9/22/2012
Borehole No:	SMB12	**Finish Date:**	10/5/2012
Driller:	N.E.E.D.S, Moe	**Rig:**	Cable Tool
Co-ordinates	S: -175.243853	**Drilling Method:**	Percussion
	W: -21.156921	**Logger:**	Kate Hyland and Sione and Ma'ake



Description	Water
30-33 m LIMESTONE, Highly to Moderately Weathered, Cream, yellow and brown, low to very low strength. Fractured Zone from 30-32 m with CLAYEY SILTY SAND, white, fine grained.	2,100 uS/cm
33-34 Gravelly SAND, white, medium grained with limestone gravel	
34-36 m LIMESTONE, Highly to Moderately Weathered, Cream, yellow and brown, low to very low strength. Fractured Zone	3,282 uS/cm 7,507 uS/cm
36-40m LIMESTONE, Slightly Weathered, Cream, white with minor yellow staining, medium strength. Fractured Rock	21,100 uS/cm
40-43 LIMESTONE, Moderately to Slightly weathered, cream yellow and brown, high to very high voids.	
43-46m LIMESTONE, Moderately Weathered, Cream with brown and yellow iron staining , low to medium strength with some fractures.	34,600 uS/cm 40,300 uS/cm 52,600 uS/cm

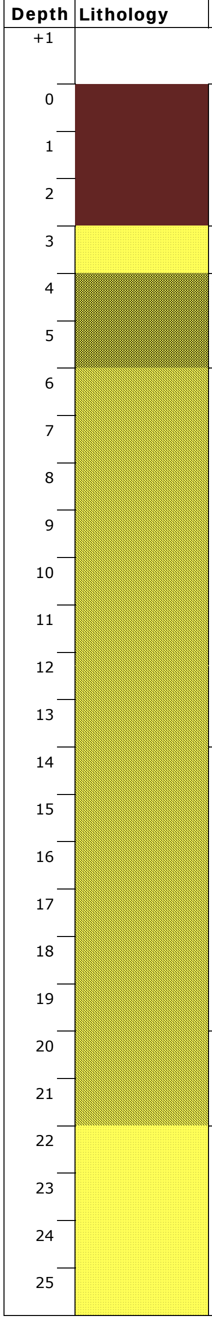
bgl	Below ground level
m/c	Moisture content
SWL	Static water level below ground level

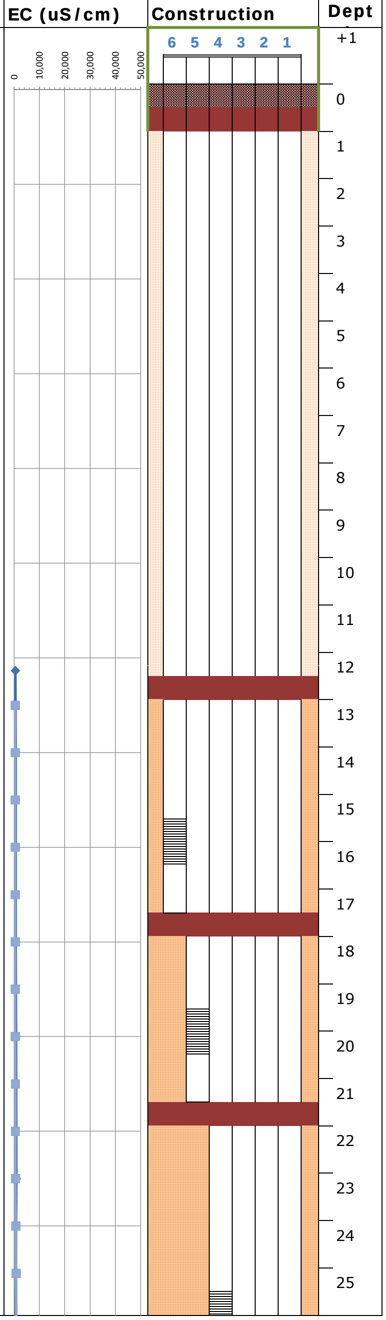
EC Final
EC drilling

▼ ■	SILTY CLAY (CH)	▤	Slotted Screen
■	LIMESTONE, Highly weathered	■	Bentonite Seal
▨	LIMESTONE, Moderately weathered	■	Gravel Pack
▨	LIMESTONE, Slightly Weathered	■	Backfill
▥	LIMESTONE with Clayey Sand lenes	▨	Bentonite Cement Seal
▤	GRAVELY SAND	□	Steel Casing

Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Tongamai	**Start Date:**	7/6/2012
Borehole No:	SMB13	**Finish Date:**	7/18/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	Kate Hyland and Sione and Akapei

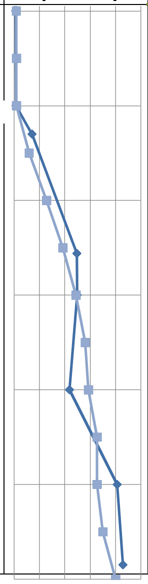
Depth	**Description**	**Water**
+1		EC and SWL
0	0-3 m SILTY CLAY (CH) : Stiff to very stiff, highly plastic, brown dark brown, m/c greater than plastic limit becoming light brown from 0.9 m	
3	3-4 m LIMESTONE, Highly Weathered, Cream, yellow and brown staining, Extremely to Very strength, highly voided	
4	4-6m LIMESTONE, Slightly to Moderately Weathered, Cream with brown staining, medium strength, voided.	
6	6-14m LIMESTONE, Slightly Weathered, Cream with minor brown and yellow staining, low strength.	
12		12.27 mbgl 496 mS/cm
14	14-20m LIMESTONE, Slightly Weathered, Cream with minor brown and yellow staining, medium strength, with sands, fracturing	598 mS/cm
16		670 uS/cm
18		670 uS/cm
20	20-22m LIMESTONE, Slightly Weathered, Cream with minor brown and yellow staining, low to medium strength, with sands	750 uS/cm
22	22-26m LIMESTONE, Highly Weathered, Cream with abundant brown and yellow staining, low to very low strength. voided and joints. Fractured Zone from 24-26 m	
23		894 uS/cm
24		800 uS/cm

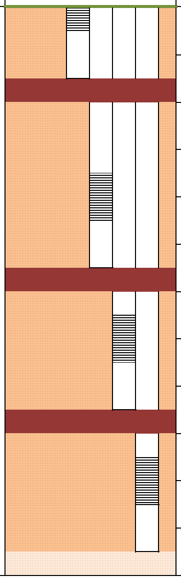




Location:	Tongatapu, Tonga	**Program**	SOPAC UN Envelope B
Site:	Tongamai	**Start Date:**	7/6/2012
Borehole No:	SMB13	**Finish Date:**	7/18/2012
Driller:	N.E.E.D.S, Naisa	**Rig:**	Cable Tool
Co-ordinates	S: - 21.15424	**Drilling Method:**	Percussion
	W: - 175.25308	**Logger:**	Kate Hyland and Sione and Akapei

Depth	**Lithology**	**Description**	**Water**	**EC (uS/cm)**	**Construction**	**Dept**
26	▨	26-30 m LIMESTONE, Moderately to highly Weathered, Cream with minor brown staining, low strength	600 uS/cm			26
27	▨					27
28	▨		7088 uS/cm			28
29	▨					29
30	▨	30-38 m LIMESTONE, Slightly to Moderately Weathered, Cream with minor brown staining, very low to high strength, Some SAND, white, medium to coarse grain from 34-38 m				30
31	▨		24,700 uS/cm			31
32	▨					32
33	▨					33
34	▨		21900 uS/cm			34
35	▨					35
36	▨		40600 uS/cm			36
37	▨		42,900 uS/cm			37





bgl	Below ground level
m/c	Moisture content
SWL	Static water level below ground level

▼

▨	SILTY CLAY (CH)	▤	Slotted Screen
▨	LIMESTONE, Highly weathered	▨	Bentonite Seal
▨	LIMESTONE, Moderately weathered	▨	Gravel Pack
▨	LIMESTONE, Slightly Weathered	▨	Backfill
▨	LIMESTONE with Clayey Sand lenses	▨	Bentonite Cement Seal
▤	GRAVELY SAND	☐	Steel Casing

Appendix B Logging Procedure and Templates

Rock Type (weathering)- Colour, Strength, Structure

Example: Limestone (moderately weathered)-Cream and pale brown, medium strength, highly fractured

Weathering

Degree of Weathering	Symbol	Weathering Description
Soil Residual	SR	Soil developed from weathering of rock inside, The mass structure and substructure fabric cannot be seen.
Extremely Weathered Rock	XW	Rock is weathered to such an extent that it has soil properties. With chemical weathering it disintegrates or can be remolded in water. It shows a rock fabric but is described as a soil. ma reduce hard rock to gravel.
Highly Weathered Rock	HW	Secondary minerals often weather to a clay. Staining and pitting of most grain boundaries. Often significant loss of strength. However cementing of joints can occasionally lead to strengthening.
Moderately Weathered Rock	MW	Staining and pitting of most secondary minerals and other grain boundaries. The loss of strength depends on the weathering and extent of secondary materials in rock matrix. The rock substance may be highly discolored by iron staining.
Slightly Weathered Rock	SW	Secondary minerals are stained but not pitted, slight staining of some grain boundaries. Slight loss in strength indicated by amount of colour change.
Fresh Rock	FR	Rock is uniform and shows no sign of decomposition or staining. Relatively strong.

Strength

Term	Extremely Low	Very Low	Low	Medium	High	Very High	Extremely High
Symbol	EL	VL	L	M	H	VH	EH
UCS	0.25-	1-5MPa	5-25 MPa	25-50	50-100	100-	>250

	1MPa			Mpa	Mpa	250mPa	Mpa
S	Indented by a thumb nail	Factures with sharp end of hammer	Shallow indentation made from the sharp end of hammer	Can fracture with single blow of hammer	Requires more than one blow of the hammer to fracture	Requires many blows of the hammer to fracture	Sample can only be chipped by a hammer

Structure

Term	**Description**
Intact	No Joints
Fractured	An extensive crack, break, or fracture in the rocks
Voids	Large open factures often filled with sand

Appendix C Reviewed Monitoring Plan for *Natural Resources Division (MLECCNR)*

The Natural Resources Division within the MLECCNR undertakes various monitoring of water in Tonga on a regular basis as presented on Table 1. All monitoring is recorded and analysed for any discrepancies and/or undesirable trends to the groundwater properties across Tongatapu. The monitoring locations are presented in Figures 1 to 7.

Monitoring	**Parameters**	**Frequency**
Urban water – TWB – Nuku'alofa and Village Monitoring		
Salinity Monitoring Bores Mataki'eua/Tongamai and Hihifo SMB01 SMB02 SMB03 SMB04 SMB05 SMB06 SMB07 SMB12 SMB13 SMB1 Hihifo SMB2 Hihifo SMB3 Hihifo	➢ Depth to Water ➢ Total Depth of Well ➢ Electrical Conductivity ➢ Temperature	Monthly
Salinity Monitoring Bores (Regional) SMB08 SMB09 SMB10 SMB11	➢ Depth to Water ➢ Total Depth of Well ➢ Electrical Conductivity ➢ Temperature	Quarterly
Rain gauge Mataki'eua	➢ Rainfall (mm)	Monthly
Mataki'eua Production Wells	➢ Depth to Water ➢ Total Depth of Well ➢ Electrical Conductivity ➢ Quantity ➢ Temperature ➢ General Maintenance	Bi-annually (January and July)
Mataki'eua Production Data Collection	➢ Usage ➢ Electrical Conductivity	Monthly
Village Water Supply Monitoring	➢ Depth to Water ➢ Total Depth ➢ pH ➢ Electrical Conductivity ➢ Temperature ➢ General Maintenance	Quarterly

Table 1 The water monitoring undertaken by the Natural Resources Division (MLECCNR)

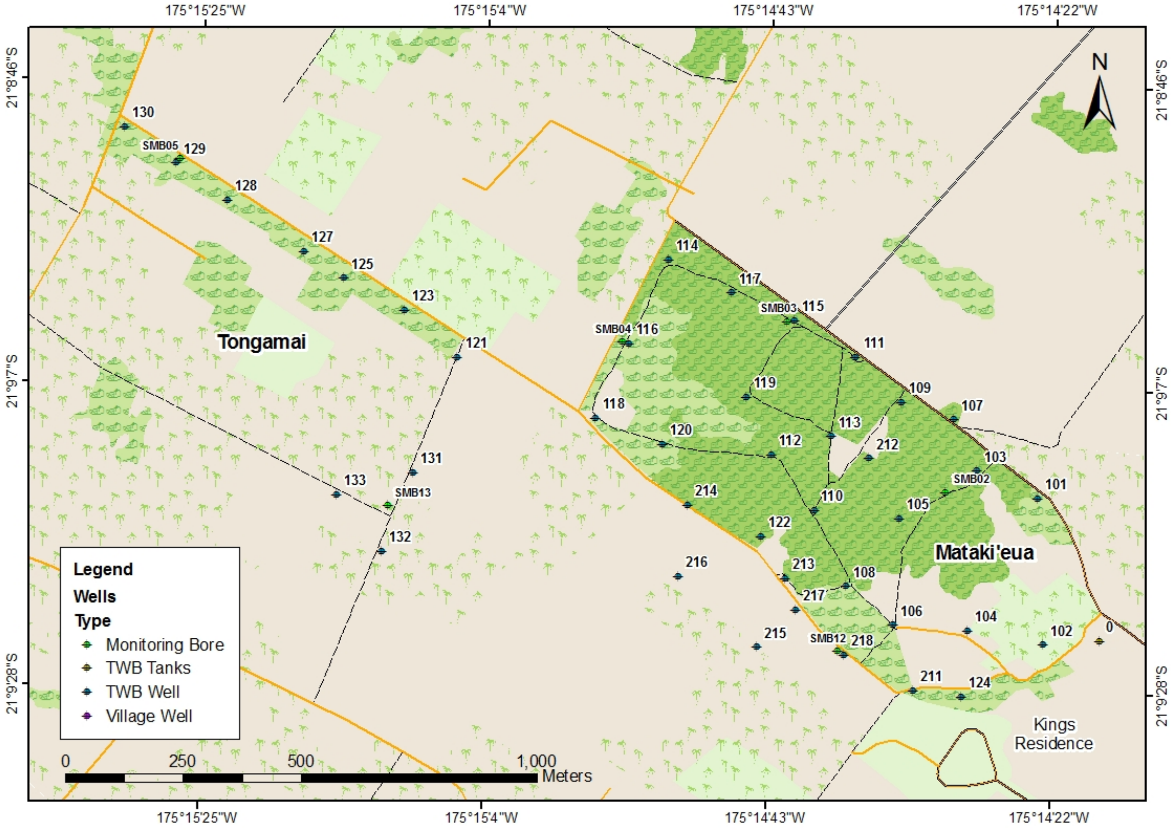


Figure 1 Salinity Monitoring Bores Mataki'eua/Tongamai

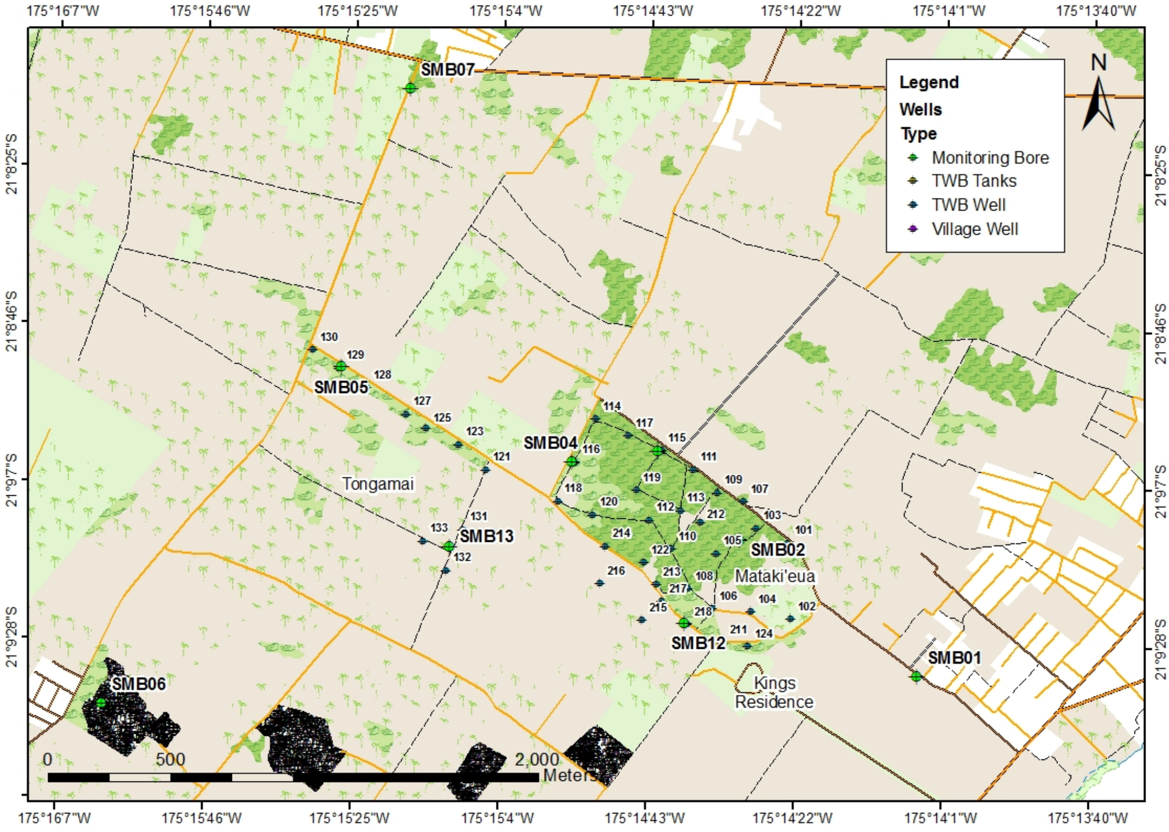


Figure 2 Mataki'eua/Tongamai Production Wells

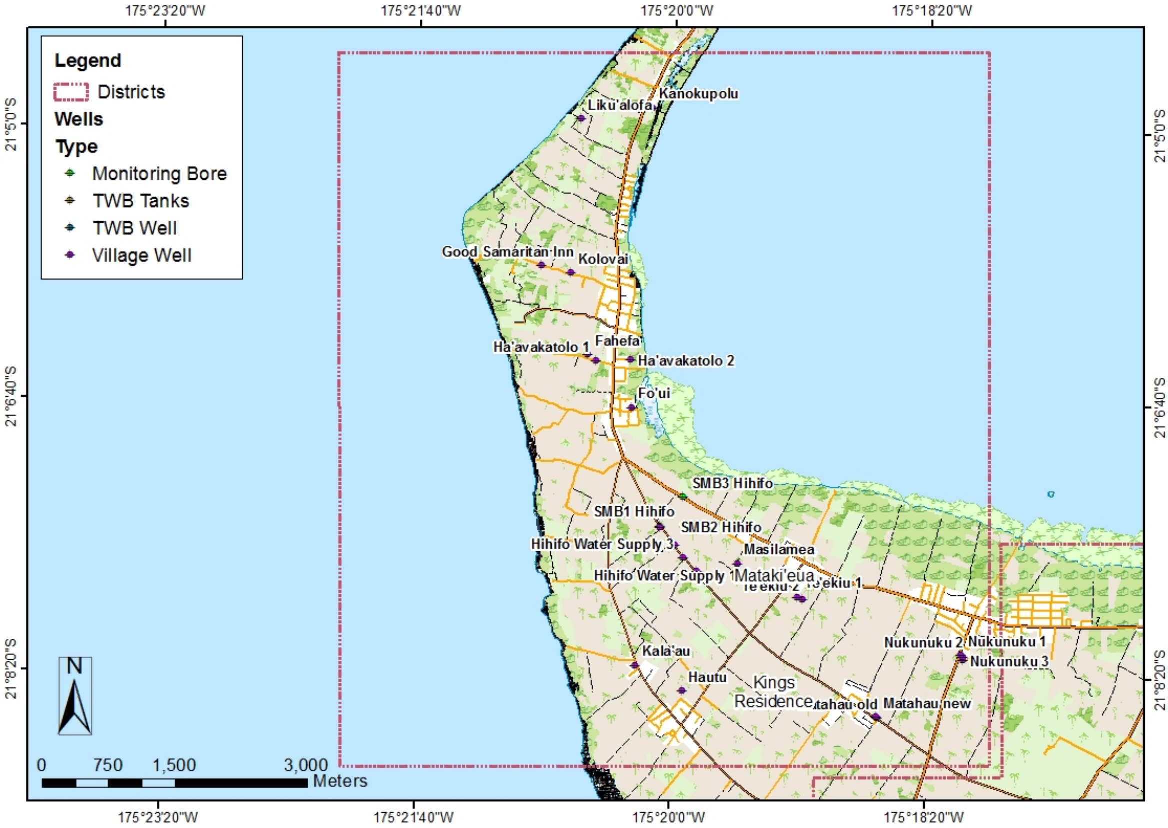


Figure 3 Village Monitoring Western D (hihifo)

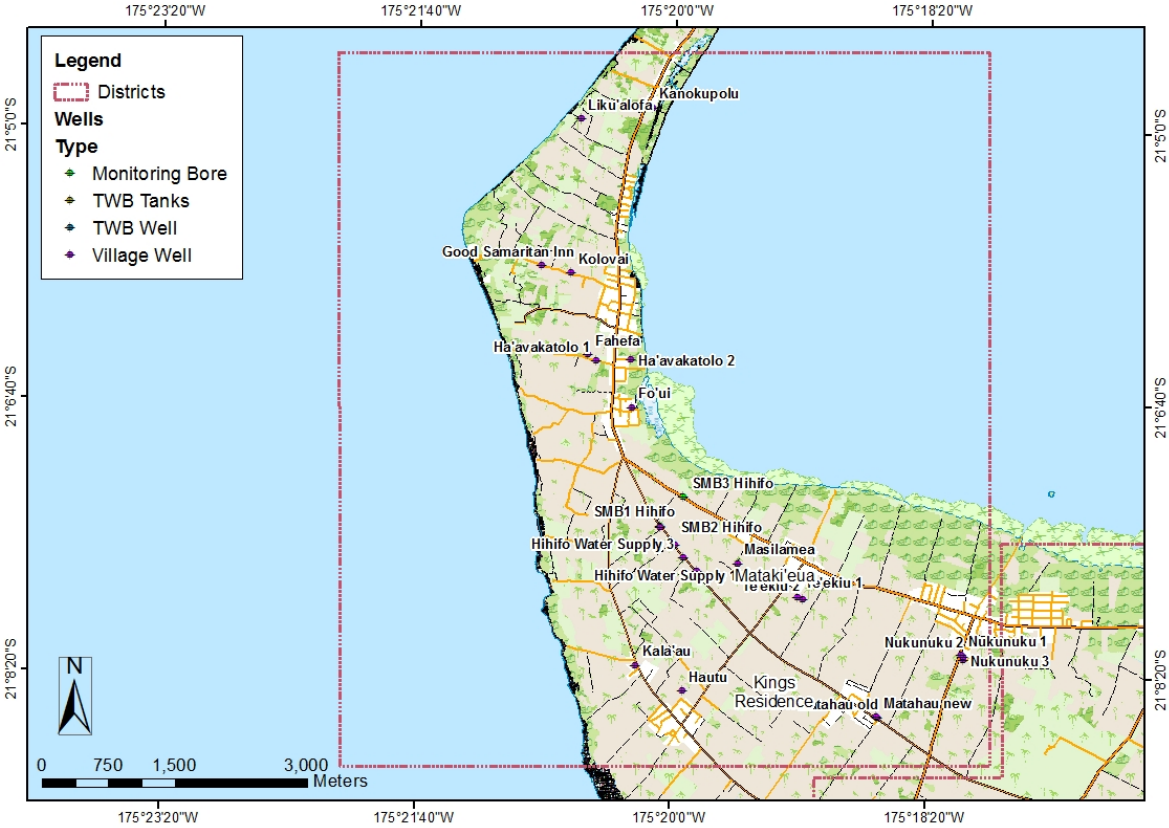


Figure 4 Village Monitoring Vaheloto District

Figure 5 Village Monitoring Vaini District

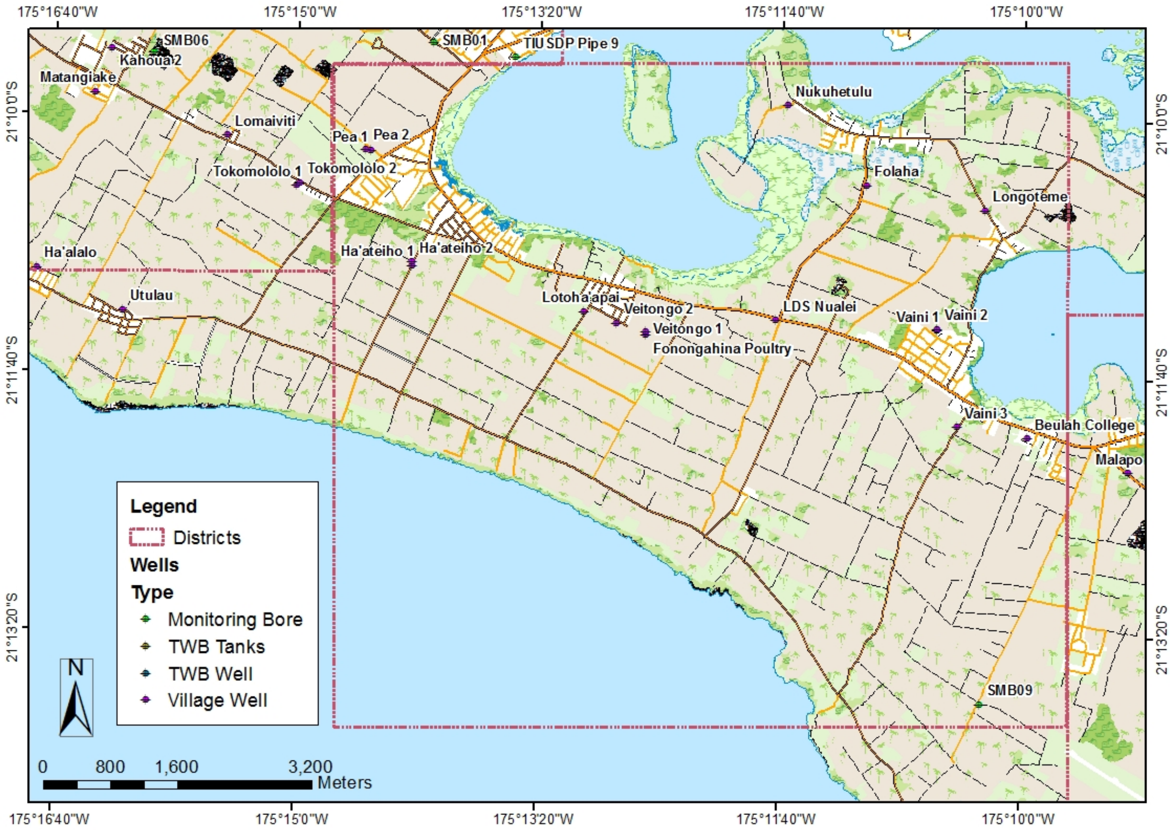


Figure 6 Village Monitoring Halaliku District

Figure 7 Village Monitoring Hahake (Eastern) District

Appendix D Reviewed Monitoring Procedure and Templates

Equipment list

- Water bottles (2L)
- Bucket
- Dip meter (solinst)
- Permanent marker pen
- Keys
- Tool bag (screwdrivers, spanners, duct tape, knife, plyers, tape)
- Sampling sheets and pen
- Calibration Solution
- Raincoats

Procedure

1. Remove well cover and clean the inside. Check the labels on each of the tubes and re-mark if fading.
2. Remove cap of tube and lower the solinist slowly down tube number until it beeps and record the depth to water and lower 50 cm and record the temperature and electrical conductivity at the water table.
3. Continue to slowly lower the solinist until you reach the bottom and record the total depth. Bring the solonist up 50 cm and record the electrical conductivity and temperature.
   NB: Check the total depth against the previous monitoring and if it does not match go to the unblocking step.
4. Repeat steps 2 and 3 for each PVC tubes present and ensure all the data is recorded including the time, date and weather into the template below.
5. Replace lid and lock the headwork protector and repeat for each borehole.

MONITORING DATA SHEET

Salinity Monitoring Bore (Tongatapu)

Geological Services Section - Natural Resource Division

Borehole No:……………………. Date:…………………

Observers………………………….. Time Arrived:…………………

Location....................................

Pipe No.	Water level (m)	EC at water level (unit)	T °C	Total Depth (m)	EC at midpoint of screen (unit)	T °C	Comments
7							
6							
5							
4							
3							
2							
1							

Note: Assume 1 metre screen from base of constructed hole. Midpoint of screen estimated to be total depth minus 0.5 metre.

<u>Comments:</u> (Maintenance of site, proximity to pumping, pumping or not)

………

………

………

………

Data entered……………………….. Date………………………. Officer…………………….

Data verified ……………………….. Date……………………….. Officer…………………….

File name and path of entered data…………………………………………