Climate and Abstraction Impacts in Atoll Environments (CAIA)

Groundwater Field Investigations Vaitupu, Tuvalu

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Amit Singh, Zulfikar Begg

EUROPEAN UNION

Pacific Community
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THE UNIVERSITY OF THE SOUTH PACIFIC

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- Public Works Department, Funafuti, Tuvalu
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- Department of Education
- Department of Health
- Vaitupu Fale Kaupule
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- Vaitupu Church

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Technical advisors involved with the implementation of the project included Flinders University, Adelaide, Australia, and Dr Vincent Post and Tony Falkland.

Abbreviations

ACP	African, Caribbean and Pacific Group of States
CAIA	Climate and Abstraction Impacts in Atoll environments
GSD	Geoscience Division
km	kilometres
m	metres
PWD	Public Works Department
RTK	Real Time Kinematics
SPC	Pacific Community
TMS	Tuvalu Meteorological Service
USP	University of the South Pacific

1. Introduction

1.1 Background

The Climate and Abstraction Impacts in Atoll environments (CAIA) project is a project in partnership with the African, Caribbean and Pacific Group of States (ACP) Secretariat as part of the ACP Caribbean and Pacific Research Programme for Sustainable Development attached to the 10th European Development Fund.

The CAIA project has the objective of improving water security in atoll environments from projected impacts of climate change and abstraction scenarios; supporting national, social and economic development, and environmental protection into the future.

The results include:

- improved understanding of atoll hydrology;
- application of the concept of sustainable yields in an atoll setting;
- quantified impacts to freshwater lens through modelling; and
- adopted technical and management options for improved and sustainable freshwater supply.

The project investigates two case studies: the Bonriki water reserve in South Tarawa in Kiribati, and the island of Vaitupu in Tuvalu.

The project was developed by the Geoscience Division (GSD) of the Pacific Community (SPC) in partnership with the University of the South Pacific (USP), the Government of Kiribati, the Government of Tuvalu, and Flinders University.

1.2 Purpose of this report

This report provides a summary of the groundwater field investigations conducted on Vaitupu, Tuvalu, undertaken as part of the CAIA project and documents key datasets and findings from these activities.

This report facilitates the discussion between stakeholders, technicians and the community on the results and understanding associated with the groundwater resources on Vaitupu, and the options for development and management of these fresh groundwater resources.

1.3 Structure and scope of this report

Improved understanding of the groundwater hydrology of Vaitupu, and consideration of sustainable development options and management with the community and government, requires information and datasets on the physical aspects of the groundwater system and its interaction with the environment and society. Detailed information is required on topography, rainfall, groundwater abstraction, extent, and groundwater characteristics. Additionally, being cognisant of the existing social context in which the groundwater system is used and relied on will help to promote the sustainable development of the resource.

This report provides details on activities, datasets and observations that were undertaken, developed and recorded during the course of this investigation and provides recommendations on options for the development and management of the resource in response to community articulated and perceived needs. The report is divided into two sections:

- a summary of the investigations and datasets collated and their analysis, and
- a summary of the social context in which the fresh groundwater resource on Vaitupu is used, and options for its development.

2 Background

Tuvalu comprises nine islands, classified as five coral atolls and four raised limestone islands. It is located between latitude 5°S and 11°S and longitude 176°E to 180° E, with a total land area of 26 km^2 (Figure 1). Tuvalu has an estimated population of 10,837 people (census 2012), across the nine islands with an average population density of 423 people/km^2, the second highest in the region. About 57% of Tuvalu's population resides in Funafuti, the capital (census 2012; Kinrade et al. 2014).

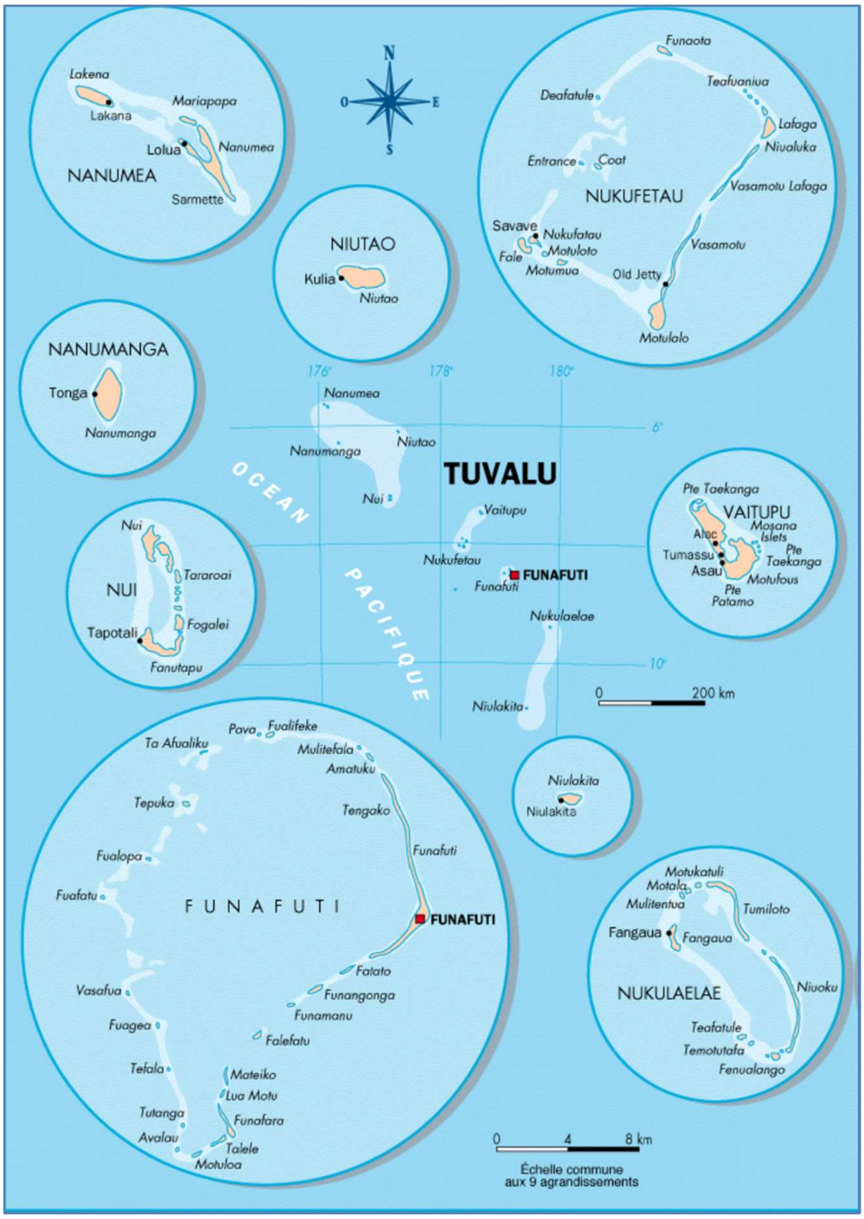

Figure 1: Tuvalu with inset maps of main islands and atolls.
Source: http://www.mappery.com/map-of/Tuvalu-Map

2.1 Government structure

The national government has an overall responsibility for governance although local island governance is via the Falekaupule Act of 1997, which awards significant authority to the *falekaupule* (council of elders) for remote island communities. The Falekaupule Act supports an island community governance system that is designed to promote decentralisation, by concentrating authority and development on local islands to support viable and sustainable outer island communities, and reduce the potential reasons for internal migration to Funafuti (Kinrade et al. 2014).

Community governance and island affairs are led by two bodies within each Tuvalu Island: the *falekaupule* and the *kaupule* (Figure 2). The *falekaupule* functions as an island council, acting as the primary decision-making group on each island. It comprises four people: the chief, the spokesperson, the assistant and the treasurer, each of whom is elected by the community. The *falekaupule* holds meetings once a month in which every person older than 18 years is able to participate; however, decisions are voted on only by those who are older than 40 years.

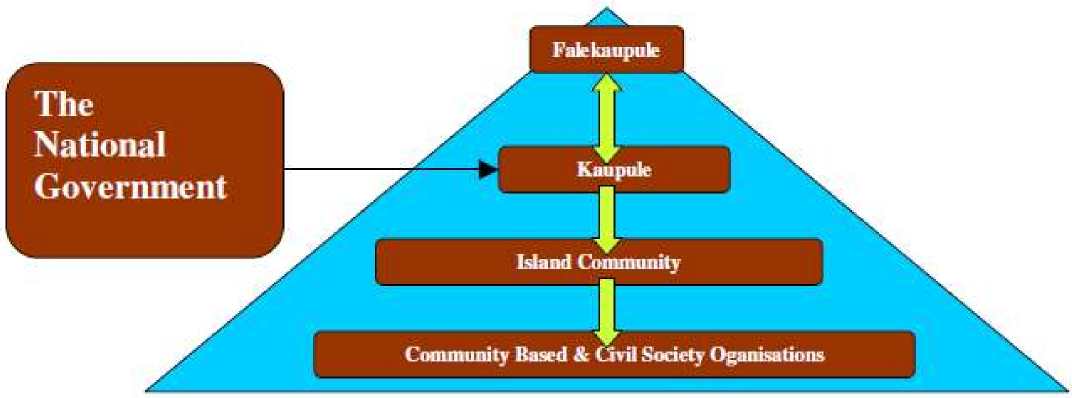

Figure 2: Community governance structure in Tuvalu.
Source: Tuvalu National Adaptation Programme of Action

The *kaupule* is the executive arm of the *falekaupule*, and is in charge of preparing and implementing development plans and other programmes such as transportation services, maintenance of public property and infrastructure, and management of land tenure. The *kaupule* are overseen at the national level by the Tuvalu Ministry of Home Affairs. The *kaupule* is headed by the *pule-kaupule*, the equivalent to the mayor of the island, supported by five helpers with specific roles, or ministries. The *kaupule* is also composed of the planner, secretary, finance, assistance, and the clerk (Figure 3).

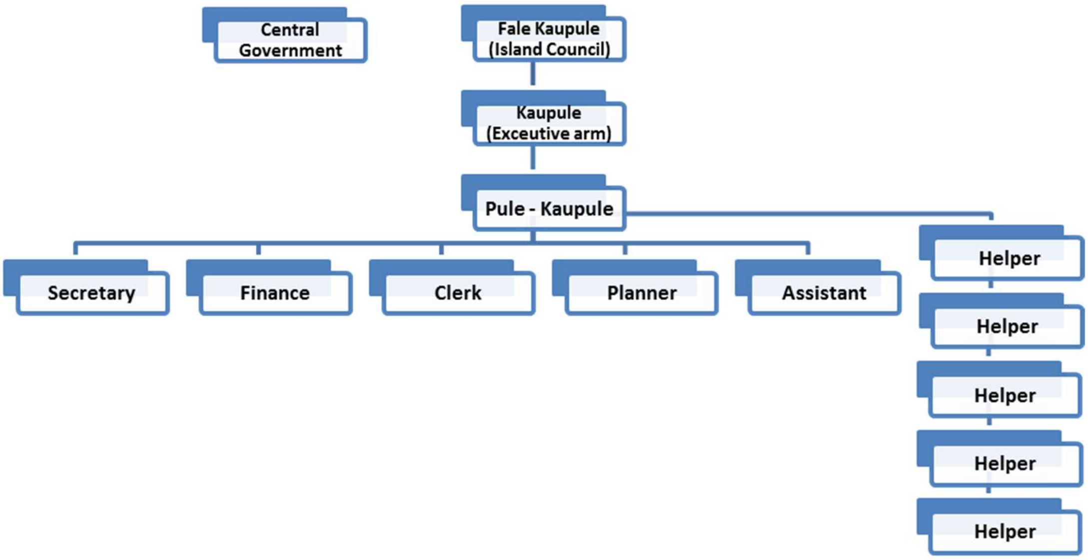

Figure 3: *Kaupule* structure in the outer islands.

2.2 Vaitupu Island

Vaitupu, which is a pear-shaped (elliptical) island with an area of 5.63 km^2, is the largest of the nine islands of Tuvalu (Figure *4*). It is the second-most populous island, with approximately 14.4% of the total population of the country (census 2012). Based on the 2012 census, 1 565 people live on 5.6 km^2 in 227 occupied households, including over 452 children at Motufoua School, the largest school in the country (census 2012; Sinclair et al. 2012). The main settlement corresponds to two joint villages: Asau and Temaseu.

Vaitupu is accessible by boat, with government-operated ships taking about eight hours to reach it from the main island of Funafuti. There is a small boat wharf on Vaitupu although larger ships must rely on ferrying passengers and supplies with a tender from the ship to shore. The island has an unpaved ring road with a number of smaller cross island tracks connecting to the main ring road. Vehicles are few on Vaitupu, and are mostly community owned, albeit with an increasing number of private motor scooters being purchased. The main guest house, Vivalia III, located near the main church is found in the main settlements of Asau and Temaseu.

An ancient settlement, Punatau, was located at the north end of Vaitupu before the villages of Asau and Temaseu were established (Manuella-Morris and Sioni 2012). The villages of Asau and Temaseu have been settled since the arrival of missionaries in 1865, in an area known as Te Fale, where the safest sea passage was located. People gradually moved from Punatau to Te Fale to have access to the facilities and services established and offered at Te Fale, such as the church, school and eventually the wharf. A map of the ancient settlement presented by Manuella-Morris and Sioni (2012) indicates the existence of seven wells, which were historically used by the community for their water needs.

Figure 4: Vaitupu Island in Tuvalu. Source: Google Earth 2015

2.2.1 Geographic characteristics

Geologically, Vaitupu may be considered to be a composite island, with a table reef and atoll island features (Kinrade et al. 2014). It is a complex reef, island atoll with two lagoon structures: a central lagoon that is connected to the ocean by a shallow passage, and a northern lagoon. A complex reef island structure is where continuous land is found over what is considered to be a number of patch reefs (Mclean and Hosking 1991). Vaitupu is located at 7.48^{0} S and 178.83^{0} W, within Tuvalu's central group of islands.

The dominant vegetation is coconut woodland, accounting for over 75% of the vegetation cover by land area (Mclean and Hosking 1991). Soils mapped by Mclean and Hosking (1991) are identified as being predominantly light sandy soils (46%) and darker sandy soils (30%).

Vaitupu has a tropical climate, with an average temperature of 27.1°C. The rainfall in Vaitupu is significant, with precipitation occurring year round and an average rainfall of 3,210 mm. Vaitupu relies heavily on rainwater harvesting as the main water supply, although water shortages affect the island during severe droughts, as observed during a severe drought in 2010–2011.

Vaitupu has viable supplies of fresh groundwater for non-potable uses, but its occurrence is distant from the main village and school, limiting its access and use. Increasing accessibility to the groundwater could promote the use of groundwater as an alternative to rainwater for non-potable needs such as washing, bathing and toilet flushing, although any development should ensure that groundwater quality is not compromised and that development and abstraction recognises the limitations of the available resource.

2.2.2 Previous groundwater studies

Since 1988, different studies have been conducted on Vaitupu to assess the groundwater potential as a water supply (Van Putten 1988; Salzmann-Wade and Hallett 1992; Kinrade et al. 2014). Assessments have also been conducted on the salinity of *pulaka* pits (swamp taro) (Webb 2007) and groundwater wells during the 2012 drought (Sinclair et al. 2012).

3 Field investigations

3.1 Field investigation structure

The field investigations included community engagement through meetings with the *kaupule* and the *falekauple* of Vaitupu, and field surveys to assess the rainwater harvesting infrastructure at the village and Motufoua school, the conditions of groundwater wells and use of groundwater, and geophysics to estimate the thicknesss and extents of the freshwater lens beneath the island.

The survey team for Vaitupu investigations included Peter Sinclair, Sandra Galvis-Rodriguez, Zulfikar Begg and Amit Singh from the Geoscience Division of the Pacific Community (SPC); Sakalalo Vaealiki and Gunter Koepke from the Public Works Department (PWD) of the Ministry of Public Works; Galivaka Tefaka from the Rural Development Office; and Vakafa Lupe and Ielemia Maheu from the Office of Land and Survey. In addition, five casual day labourers, selected by the *kaupule*, assisted with survey activities.

3.1.1 Community engagement

Community meetings with the *kaupule* and the *falekaupule* were held prior to conducting field investigations (Figure *5*) in order to explain the objectives of the study and field techniques to be used, as well as to capture the traditional knowledge of the occurrence of groundwater on Vaitupu. The consultations allowed the team to understand the traditional use of groundwater, management of the systems during droughts, and identify areas where fresh groundwater is normally found. The last point was important to help determine the specific locations where field work activities would be conducted.

Figure 5: Community consultation meetings on Vaitupu prior to field activities.

A follow up community meeting was held immediately after field work activities were finished, in which the preliminary results were presented to the *kaupule* and a discussion on water resource and sanitation issues and potential strategies to improve water resources management was held.

3.1.2 Field surveys

The assessment methods employed included geophysics, electrical resistivity surveys, well assessment, rapid rainwater harvesting assessment, tide gauge installation, Real Time Kinematic (RTK) survey levelling and automatic Tipping Bucket 3 (TB3) rain gauge installation.

A rapid assessment of the existing rainwater harvesting infrastructure was conducted in the village and at the school, including an assessment of roof and down-pipes conditions; storage dimensions; and condition of community tanks and cisterns. The survey of wells included an assessment of the construction features and materials, abstraction types, and measurement of electrical conductivity of groundwater in the wells. Water quality sampling and microbiological analysis were conducted from selected wells and rainwater tanks.

Transects using geophysics, including electromagnetics and EM34, were undertaken to determine the lateral variability in bulk ground conductivity, providing guidance on the likely fresh groundwater potential. The EM34 results identified areas of groundwater interest, which were subsequently investigated with Supersting R1 resistivity equipment, to further identify groundwater potential at selected sites.

3.2 Rainfall analysis

Monthly rainfall data are currently collected from Tuvalu Meteorological Service (TMS) stations located in Funafuti, Nanumea, Niulakita and Niu, providing an indication of the variability of rainfall from island to island. The location of the rainfall stations is presented in Figure *6*. Rainfall records for each of the islands where rainfall is collected by TMS are indicated in Table 1.

Rainfall records for Vaitupu are available as discontinuous records between 1941 and 2011, with only 27 years being complete over the 61-year history. Analysis of rainfall for complete records over the period in which full records are available suggests that the mean annual rainfall observed on Vaitupu is 3,210 mm/year. Existing rainfall records for Vaitupu are presented in Annex 1.

The rainfall in Tuvalu is characterised by two distinct seasons: increased rainfall from November to April, and a drier season from May to October (Figure *6*). There is a general trend, with mean annual rainfall decreasing closer to the equator, and an increase in rainfall moving southwards across the country (noting that Funafuti is the exception, receiving the highest mean rainfall for the recorded period) (Figure *7*). Similarly, the variability of rainfall decreases the farther south from the equator from the Tuvalu islands. This indicates that with lower annual mean rainfall and increased variability in rainfall in the northern islands, an increased severity of droughts can be expected for Tuvalu's northern islands (i.e. those closer to the equator).

Table 1: Rainfall stations currently maintained by the Tuvalu Meteorological Service.

Station	Latitude Longitude	Rainfall records Number of complete years	Coefficient of variation	Mean annual rainfall (mm)
Nanumea	Lat: -5.670 Long: 176.060	Jan 1941– present (74 yrs)	0.36	2,742
Nui	Lat: -7.200, Long: 177.040	Jan 1946– present (68 yrs)	0.28	3,019
Funafuti	Lat: -8.51, Long: 179.03	Jan 1933– present (83 yrs)	0.22	3,525
Nuilakita	Lat:-10.750 Long: 179.400	Jan 1953– present (60 yrs)	0.18	3,231

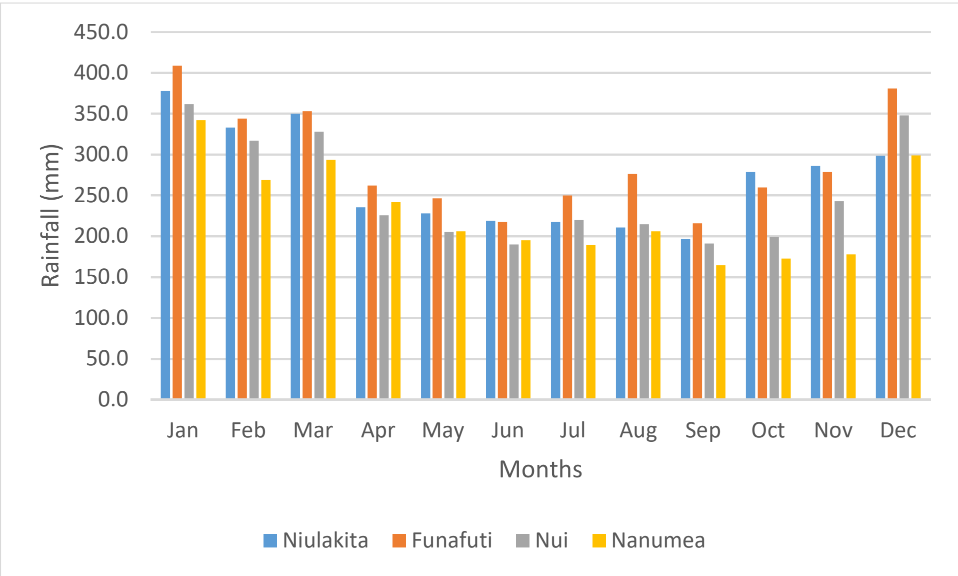

Figure 6: Monthly average rainfall in Tuvalu.

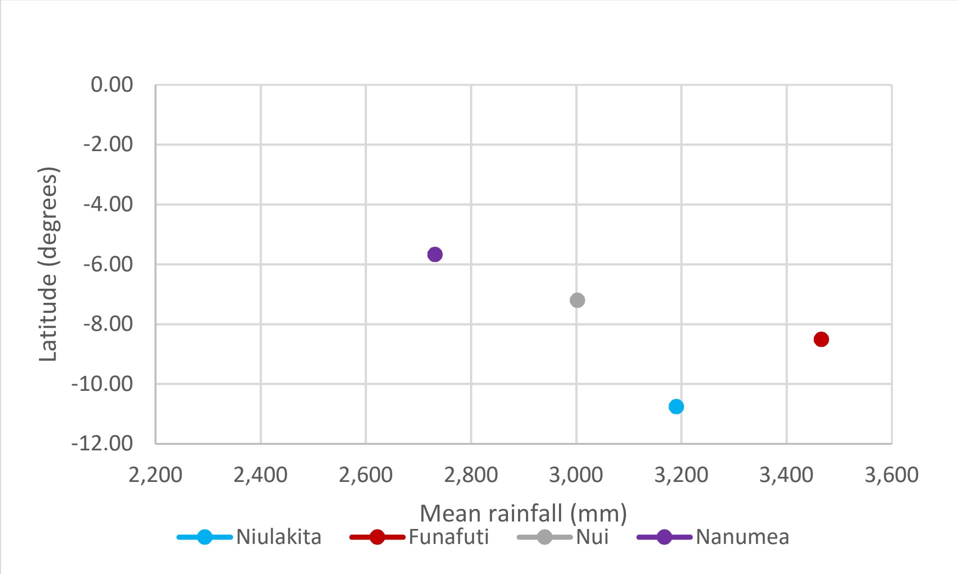

Figure 7: Average annual rainfall in Tuvalu varying with latitude.

El Niño-Southern Oscillation (ENSO) conditions strongly influence rainfall in the Pacific. An analysis of the number of droughts that have occurred over each of these islands for the period 1953–2016 using the three-month aggregate drought index and percentile methodology is presented in Table 2. Note that the analysis considers the definition of drought to be when the combined received rainfall for a three-month period is in the lowest 10% of all rainfalls received for that three-month period.

Table 2: Statistical analysis of the drought and ENSO condition for Nanumea, Nui, Funafuti and Nuilakita.

Station	Latitude	Total number of droughts 1953–2016	Number of droughts during El Niño 1953–2016	Number of droughts during La Niña 1953–2016	Number of droughts during neutral 1953–2016	Annual mean rainfall 1953–2016 (mm)
Nanumea	5.670S	13	1 (8%)	9 (69%)	3 (23%)	2733
Nui	7.20^{0}S	17	2 (12%)	9 (53%)	6 (35%)	3013
Funafuti	8.51^{0}S	28	4 (14%)	12 (43%)	12 (43%)	3496
Nuilakita	10.75^{0}S	28	6 (21%)	12 (43%)	10 (36%)	3231

Interestingly, rainfall data for the four stations between the period 1953 and 2016 suggest that rainfall totals that fall within the 10th percentile for the three-month index are less frequent the farther north and closer to the equator you are in Tuvalu. That is, for the same 63-year period, the islands of Funafuti and Niulikta have had more meteorological droughts[1], 28 in total, compared with 17 and 13 for Nui and Nanumea, respectively (where Nui and Nanumea are located farther to the north and closer to the equator). That is not to say that relative severity of drought is lessened for islands in the north or closer to the equator, rather the contrary; as the mean annual rainfall for these islands is less, meteorological droughts will, therefore, have greater impact. In general, drought across Tuvalu is associated with La Niña ENSO conditions, with a general trend of increasing correlation between La Niña events and the northern islands closer to the equator. Islands below about 8^0S of the equator in Tuvalu are statistically likely to experience drought conditions during both La Niña and neutral ENSO conditions.

An analysis of monthly rainfall records received for the four climate stations — Funafuti, Nanumea, Nui and Nuilakita — and the available rainfall for Vaitupu, indicated a large variance in monthly rainfall between islands. No apparent relationship on the total amount of rainfall for any given month between islands could be discerned. Caution is, therefore, required in transferring rainfall data from one rainfall station on one island to another island situation.

3.2.1 Rain gauge installation

Rainfall provides the recharge for the rainwater tanks and groundwater resources. Knowledge on the amount of rainfall and, therefore, recharge to these water sources is critical for the long-term management and development of these water sources as future water supplies. The observed variability between existing rainfall stations is indicated by the analysis in Section 3.2. It is recommended that daily rainfall records for each habitable island should be maintained to assist with the development and management of water sources in order to meet water needs in these islands.

In consultation with TMS, an automatic, tipping bucket rainfall station, TB3 with logger ML1, was installed on Vaitupu, at the location of the previous rainfall gauge in front of the Vaitupu *kaupule* (Figure *8*). The recording of rainfall with this new station will assist with the determination of potential recharge into the groundwater lenses and the design of a rainwater harvesting system, as well as other uses.

[1] A meteorological drought is defined when rainfall is below the 10th percentile (i.e. within the driest 10% of all previous such three months of rainfall totals).

Figure 8: TB3 rain gauge installed near *kaupule* office on Vaitupu.

3.3 Geodetic survey

A geodetic survey was included as part of the hydrogeological investigation for the CAIA project on Vaitupu. The geodetic survey included the installation of a temporary tide gauge, establishment of bench marks, levelling runs and a topographical survey. The detailed methodology of the survey and its findings are presented in the supporting technical report Begg et al. (2016 in draft). The following section presents a summary of the major findings for the topographical survey.

3.3.1 Establishment of bench marks

A reconnaissance survey was conducted in conjunction with the Lands Department on Vaitupu to investigate the status of bench and/or survey marks located on Vaitupu, and their suitability for global navigational satellite system (GNSS) surveys. A number of old benchmarks were identified and were incorporated into this survey.

Seven new benchmarks were established using Trimble R10, Trimble R8 and NetR9 GNSS system for point occupation via the static mode operation (Fig. 9). Eastings and northings of the benchmarks were derived from AUSPOS[2], while the elevation was adjusted from TUVA[3] (continuous GPS). The coordinate system used is based on UTM (universal transverse Mercator) zone 60 South ITRF 2005 (*Table 3*).

Table 3: List of benchmarks established during the survey. Datum for elevation is Australian Chart Datum.

Point ID	Easting	Northing	Elevation	Feature code
TUVA	741795.553	9056942.642	4.493	BM
VTM2	686919.952	9171674.215	4.458	BM
VTP01	684181.553	9174862.02	4.626	BM
VTP02	685235.968	9171747.846	6.211	BM
TEC11	686079.079	9171851.255	3.369	BM
VTP03	685128.216	9171713.404	4.203	BM
VTP04	684763.913	9172687.111	5.647	BM
VTP05	684173.861	9173745.52	5.146	BM

2 AUSPOS is a free online global positioning system data processing facility provided by Geoscience Australia
3 TUVA is a reference benchmark located on Funafuti in Tuvalu.

Figure 9: Location of benchmarks established as part of the survey. Benchmark elevation corrected from the continuous GPS (CGPS), TUVA based in Funafuti. Source: Google Earth 2015

3.3.2 Topographical survey

An RTK positioning system was used for the al survey on Vaitupu. RTK relies on two GPS receivers — a reference (base) receiver set up on a known point, and one roving receiver set up on a pickup truck (Figure *10*). The reference receiver takes measurements from the satellites in view, with a minimum of ten satellites, and transmits measurements with the position of the reference receiver via two Trimble radios to the roving receivers in real-time.

The roving receiver(s) also take measurements from the satellites in view, and processes them in real-time with the measurement data and location from the reference receiver. The result is measurement vectors in the WGS84 datum from the reference receiver to the rover receiver. Using these measurement vectors, coordinates for the points occupied by the rover can be computed.

The rover was programmed to record points every five seconds. The height of the rover was measured to ground level; therefore, all points collected were automatically adjusted to the reference level.

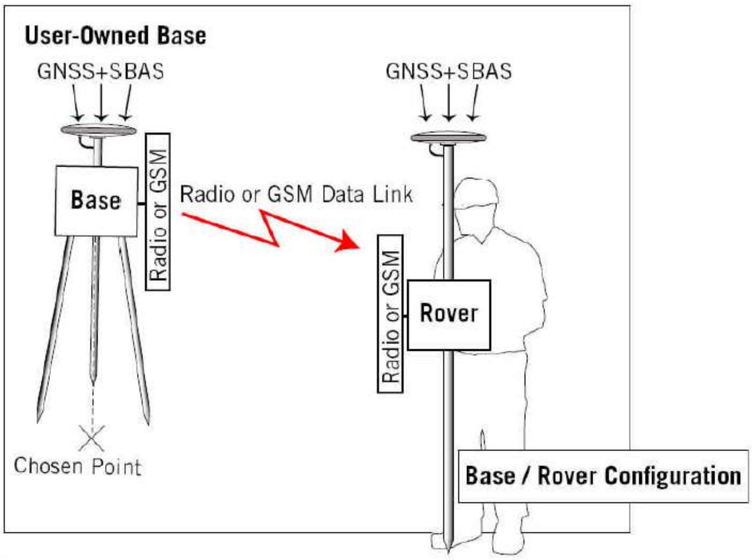

Figure 10: Real-time kinematic GPS survey principle.

The local coordinate system was established for the survey as follows:

- Map projection: UTM zone 60 South
- Horizontal datum: WGS84
- Vertical datum: Australian Chart Datum.

The RTK survey was completed on foot and on a bike trailer (Figure *11*). In total, 1,200 points were collected as part of the survey. The RTK survey was limited in certain areas due to dense vegetation, unfavourable weather conditions, and inaccessible sites (Figure *12*).

Figure 11: Continuous mode of RTK survey with the rover mounted on a trailer pulled by a motorbike.

With the available RTK dataset, a cross section (presented in Annex 3) was derived across northern Vaitupu to understand the atoll's geomorphology.

Figure 12: Satellite image of Vaitupu showing the area cover during the RTK survey (red points) and the transect (yellow) from which the cross section was derived. Source: Google Earth 2015.

3.4 Water resources reliance and infrastructure

3.4.1 Rainwater

The primary source of drinking water on Vaitupu is rainwater, which is harvested and stored in tanks or cisterns. The island has a storage capacity of approximately 7,080 m^3 between private and communal storage facilities (Kinrade et al. 2014; Sinclair at al. 2012) (Table *4*). During dry spells, rainwater is rationed, and during prolonged droughts groundwater becomes the only option available to meet water requirements for communities without supplementary desalination. In 2011, Tuvalu experienced one of its driest spells, with very little rainfall over a six-month period, resulting in the declaration of a national state of emergency by the Tuvalu government in September 2011. During the 2011 drought, water from community supplies on Vaitupu was rationed to provide an average of 25 L/household/day, which is, on average, 5.5 L/person/day (Kinrade et al. 2014).

Table 4. Estimated rainwater storage on Vaitupu, Tuvalu.

Storage type	Capacity (m^3)
Household rainwater tanks	4,458
Community and government cisterns	1,006
Motufoua School	1,616
Total	7,080

Source: Kinrade et al. 2014

3.4.2 Groundwater

Groundwater is generally used for non-potable purposes such as washing, bathing and toilet flushing, as well as livestock (pigs), due to its brackish conditions. The field investigations included an inventory of wells, in which construction features and salinity measurements were assessed. The assessment included:

- GPS location of wells,
- well construction details (e.g. parapet height, well cover, well lining, diameter, construction materials),
- total depth,
- depth to water table, and
- salinity at the top and base of the wells.

Sixteen wells were assessed. The summary of the current conditions of the groundwater wells is presented in Annex 4, and the location of the wells is shown in Figure *13*.

The villages of Asau and Temaseu have two wells, Vaimaua and Talai, which are used only during droughts for non-potable uses (washing and flushing toilets). The majority of wells on Vaitupu (seven in total) are found towards the northwest end of the island, close to the small lagoon and more than 3 km away from the villages (Figure *13*). These wells are used by the community during drought periods for different purposes, including drinking, cooking, washing and bathing. During the community consultation it was observed that there is general awareness of the occurrence of fresh groundwater at the northwest end of Vaitupu; however, access is difficult given the distance between the village and the wells. The main community well is Togalaa, which is administered by the *kaupule*, and is normally operated with a solar pump. During field investigations the pump was not functioning, requiring repair, and the *kaupule* had given instructions to avoid using the well until the pump was repaired. Teatuka and Seuga wells are also used as drought reserves by the community, especially when the Togalaa well is unavailable for use.

Motufoua School has three wells, which are used as a drought reserve. The main well, Motufoua desalination well, feeds water for a desalination plant. The desalinated water produced from this well is used for drinking and cooking during droughts exclusively.

It was observed that during the survey there were inappropriate covers for most of the surveyed wells on Vaitupu. Only one of the main community wells (Togalaa) and the school wells have appropriate structures to prevent direct contamination from sources on the ground.

Figure 13. Location of surveyed wells on Vaitupu. Source: Google Earth 2015

Groundwater salinity

The accepted upper EC (electrical conductivity) limit of 'freshwater resources' in many parts of the Pacific is 2,500 µS/cm (Falkland and Custodio 1991). Salinity is not considered to be a parameter based on health considerations but rather the aesthetic consideration of taste whereby the upper limit of salinity for drinking water is determined by the palate sensitivities of the individual. Some individuals and communities will accept slightly more brackish water than others, and at times a community may be willing to accept more brackish water during extended dry conditions to ensure sufficient water supply to meet their demands or needs. During community consultations it was revealed that communities believed brackish groundwater had medicinal properties to heal sun burn.

The determination of salinity thresholds is subjective, and any guidelines should take into consideration access to alternate supplies, and the capacity of the community to accept higher salinities during times of need. For example, salinity limits may be increased during extended dry periods based on pre-determined acceptance by the community as an emergency measure. EC measurements observed in wells are presented in Figure 14.

During field investigations, groundwater EC ranged from 330 µS/cm at one of the wells in the village to 8,150 µS/cm at Alaae well, located near the hospital. The wells located towards the northwest had low salinities, between 440 µS/cm and 540 µS/cm, despite being located next to the small lagoon. An area of lower salinity water was indicated by existing wells in the north. More saline waters are located in the west, as indicated by well John with 1,300 µS/cm, and towards the south by Tegao well, with 1,140 µS/cm. During the 2011 drought, salinities at Togalaa well, considered by the community as one of the freshest wells in the north, was reported to be 2,000–3,000 µS/cm. (Sinclair et al. 2012)

Farther south, in a northeast-southwest cross section across the centre of Vaitupu (along wells Siaki, Leti and Alaae), salinities were higher than observed in the north, ranging between 1,000 µS/cm and 8,150 µS/cm. The slightly high EC at wells Siaki and Leti indicates that fresh groundwater is limited within the central part of Vaitupu, even though the width of the island and the high rainfall observed on Vaitupu suggests good potential for a fresh groundwater lens to be developed. At Motufoua school, the groundwater EC ranged between 1,280 µS/cm and 1,390 µS/cm. During the 2011 drought, the Motufoua wells were reported to be brackish, with EC ranging between 4,500 µS/cm and 13,000 µS/cm.

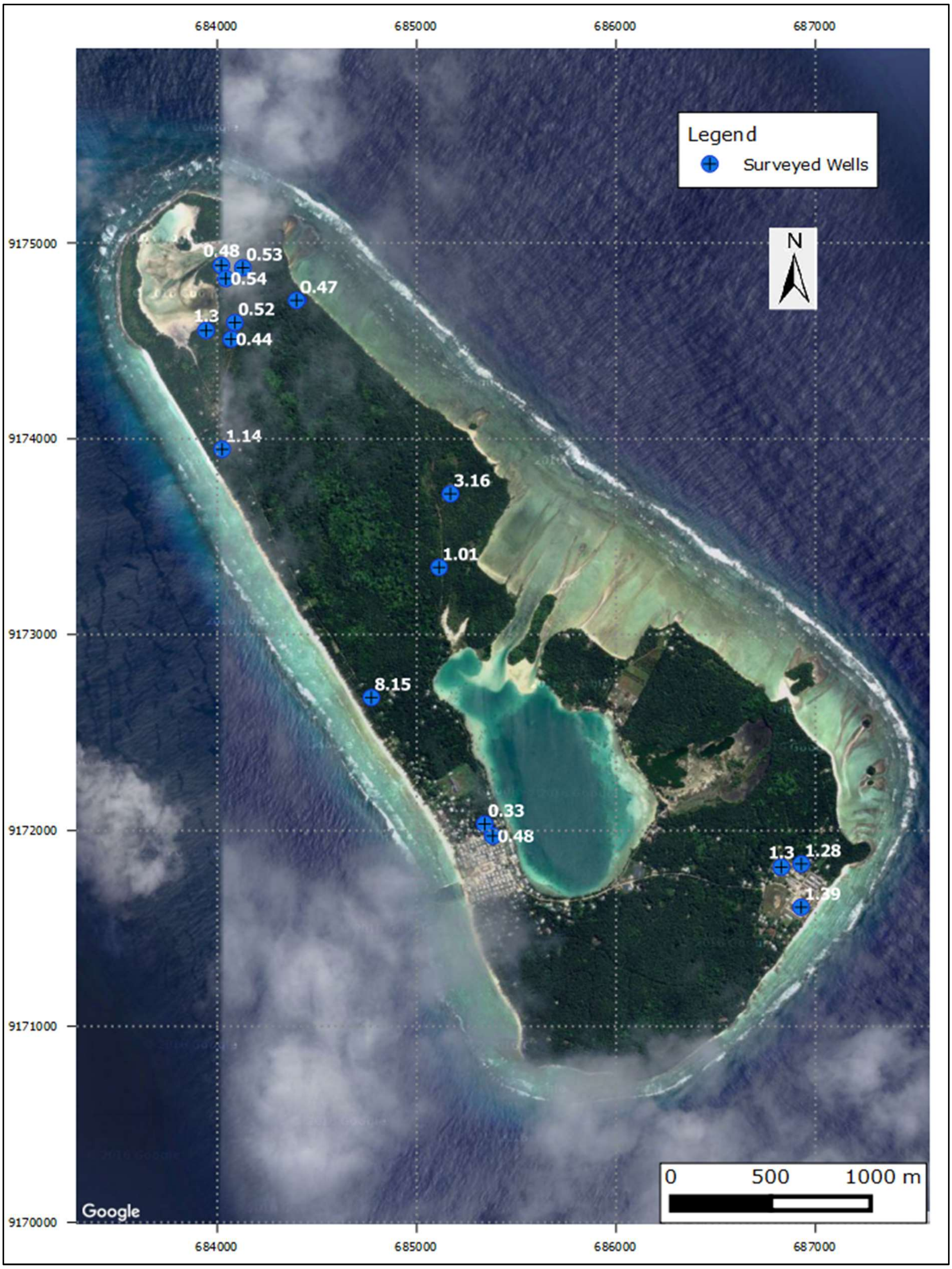

Figure 14. EC at the bottom of the surveyed wells (mS/cm). Source Google Earth 2015.
Note that 1 mS/cm = 1,000 µS/cm)

3.5 Downhole loggers

Schlumberger conductivity, temperature and depth (CTD) pressure transducer loggers were installed in the wells to record temperature, pressure and conductivity changes in the groundwater over a period of 10 days, from 23 June to 2 July 2015. The objective was to determine the hydraulic connection between the unconsolidated sediments and oceanic influences as a guide to determining the tidal influence on the aquifer because tidal fluctuations have a significant influence on groundwater levels, groundwater discharge to the sea, and the mixing between freshwater and seawater in the aquifer. Groundwater levels on atolls are highly variable due to their close relationship with water levels in the lagoon and ocean.

CTD loggers were installed in seven of the assessed wells, as shown in Figure *13*. The loggers were suspended on stainless steel wire at a depth that ensured they were submerged below the water table at all times. A barometric logger was installed in the village to compensate for barometric influences. The loggers were set up to record data every six minutes. Manual water level and EC readings were taken at the beginning and at the end of the 10-day monitoring period in order to validate the readings recorded by the loggers. The plots from each of the diver loggers are shown in Annex 5.

3.5.1 Tidal lag and efficiency

The compensated data were used to estimate tidal efficiencies and tidal lags at each well. These parameters determine the 'hydraulic connectivity' between the aquifer and the ocean or the lagoon. High efficiencies and short tidal lags indicate good connectivity between the ocean and the lens. Generally, connectivity decreases with distance from the shore (i.e. higher tidal lags and lower tidal efficiencies); however, in atoll islands, the propagation of tides also occurs through the highly conductive limestone from where it propagates vertically to the upper and lower sediments.

The highest efficiency, and corresponding shortest tidal lag, occurs at the southeast end of Vaitupu, at the desalination well in Motufoua School, where greater connectivity between the ocean and the aquifer occurs, as shown by the high efficiency of 73.2%.

Table *5* shows the estimated tidal lags and efficiencies of the wells. Tidal efficiencies vary considerable on Vaitupu, between 2.3% and 73.2% (Figure *15*), and tidal lags vary between 0.7 hours and 3.9 hours. In general, tidal efficiencies are higher towards the southeast end of Vaitupu and decrease towards the northwest.

The highest efficiency, and corresponding shortest tidal lag, occurs at the southeast end of Vaitupu, at the desalination well in Motufoua School, where greater connectivity between the ocean and the aquifer occurs, as shown by the high efficiency of 73.2%.

Table 5: Estimated tidal lags and efficiencies on Vaitupu, Tuvalu.

Well	Tidal lag (hr)	Efficiency (%)	Distance from the coast (m)
Seuga	2.9	5.5%	150
Togalaa	3.9	2.3%	120
Tegao	3.3	12.6%	65
Teatuka	3.3	7.5%	70
Leti	2.7	22.5%	330
Motufoua	0.7	73.2%	270

The lowest tidal efficiencies, and longest tidal lags, were identified in the wells located on the northwest end of Vaitupu, with efficiencies between 2.3% and 7.5%. The low connectivity with the ocean signal is correlated with fresher groundwater, whereby lower salinities are found at the wells located in this area of lower tidal efficiency. The area of low connectivity to the tidal ocean signal is restricted to the northwest end of Vaitupu. Tegao well, located farther south, has a slightly higher efficiency of 12.6% than those wells located in the northern end of Vaitupu (Figure *15*).

Towards the central part of Vaitupu, in the well Leti, the efficiency is intermediate, 22.5% and 2.7 hr of tidal lag, suggesting a higher connectivity with the ocean than the northwest end of Vaitupu. These results correspond with the higher salinities measured at Leti and Siaki wells. Unfortunately, the CTD logger located at the village at Vaimaua well, was removed from the well by unknown persons a few hours after its installation. The equipment was recovered by the community and returned to project staff at the end of the field campaign, however the returned logger was damaged and it was not possible to estimate the tidal efficiency and lag for this well.

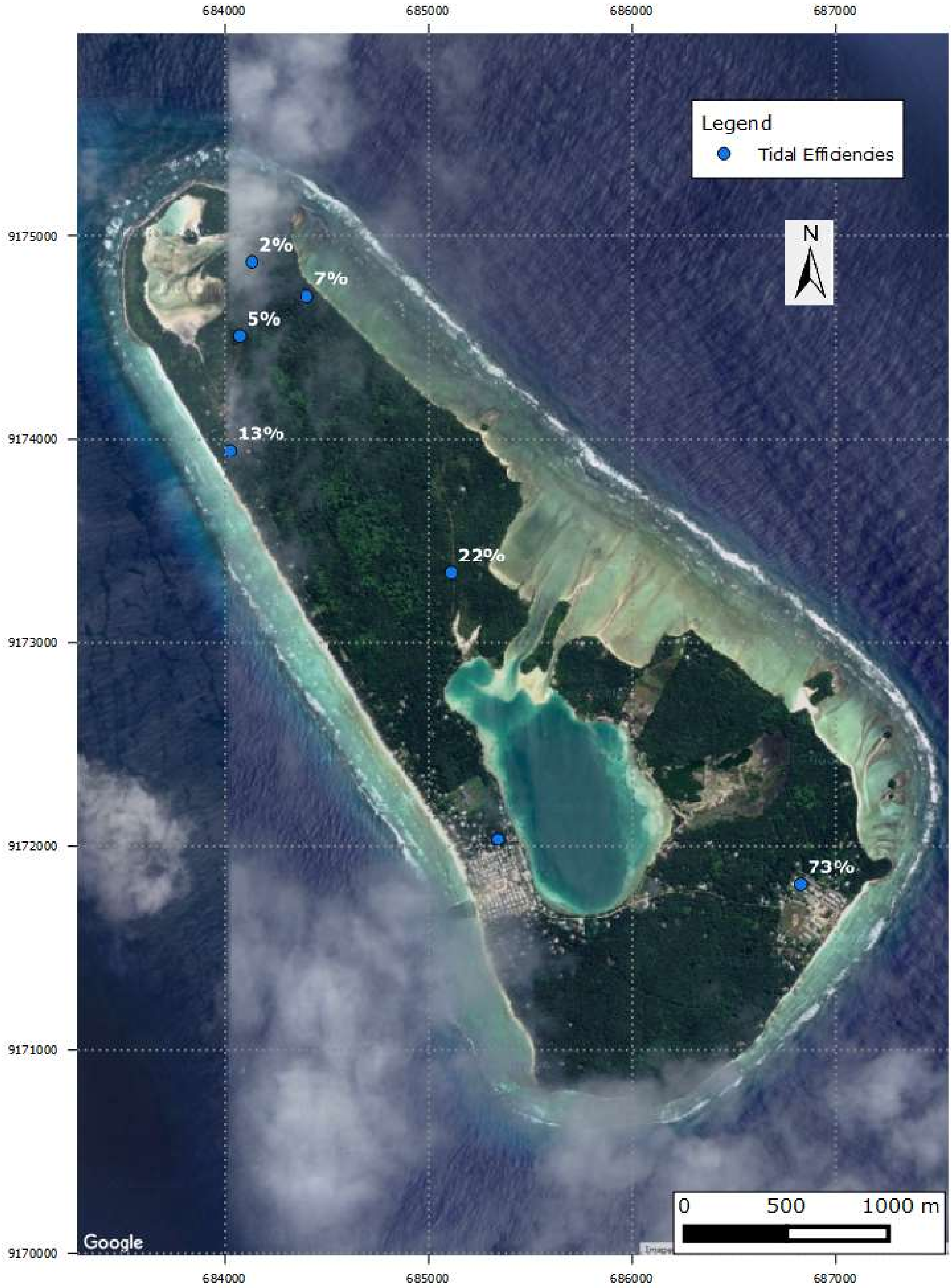

Figure 15. Estimated tidal efficiencies at Vaitupu. Source Google Earth 2015

3.5.2 Rainfall response

A high rainfall event occurred during the field investigation, with 100.5 mm of rainfall in a 24-hour period between 28 and 29 June. The data recorded by the loggers in four of the wells — Tegao, Togalaa, Seuga and Teatuka — were used to investigate the response of the recharge. The logger plots are presented in Annex 5.

In general, variations in the water table respond to two major drivers: the tidal signal and recharge events. Separation of these two components from the wells' hydrographs is not a simple and direct task. When observing the response to rainfall events from a hydrograph the following needs to be considered:

i) the infiltration process from the ground to the water table, which in atolls can be affected by the occurrence or absence of the reef rock (observed in Tegao, weathered in Seuga and absent in Togalaa and Teatuka, Annex 4); and
ii) the potential for the recharge event to dominate water table variations over the tidal signal, which is dependent on the intensity of the recharge and the hydraulic connectivity to the ocean.

If the reef rock is absent, infiltrating water moves unimpeded from the ground to the water table, with some water retained as soil moisture in the sediments above the water table. When reef rock is present, it behaves as a semi-permeable layer, impeding the movement of the water towards the water table, resulting in either a delay or reduction in the amount of water that reaches the freshwater lens (Ayers and Vacher 1986).

In the Togalaa, Seuga and Teatuka wells, the response to the rainfall event was observed as a steep rise by the water table elevation, which erased the tidal signal on the hydrograph. This response indicates that for those wells recharge became the dominant factor controlling the variations of the water table during the period in which the lens was responding to the rainfall event. In the Tegao well, however, the tidal signal was not erased, indicating that despite the large rainfall event, the recharge signal was not sufficiently strong enough to dominate the water table variations. This difference in the response of the wells could be related to the connectivity between the aquifer and the ocean (i.e. in those wells with lower connectivity, less recharge is required to imprint on the water table and dominate the water table response compared with wells that are better connected with the ocean).

In order to determine the effect of reef rock as a factor that delays or reduces recharge, the time between the start of the rainfall event (14:00 hours on 28 June) and the observed change in the water table from recharge, was estimated in Togalaa, Seuga and Teatuka. The results suggest that in the Togalaa and Teatuka wells, where reef rock is absent, the time period between the start of the rainfall event and the signal observed in the hydrographs is approximately 8 and 10 hours, respectively. In the Seuga well, where a weathered reef rock of approximately 30 cm occurs, the time was estimated to be 19 hours. These results suggest that the occurrence of reef rock is likely to produce a delay in recharge.

In Seuga, where the reef rock is cemented and is 40 cm thick (Annex 4), a slight rise in the hydrograph was observed approximately 34 hours after the start of the event. It is noted that determining the impact of recharge from a hydrograph with a continuous tidal signal is difficult and the results are approximate only. However, the rise in the hydrograph indicates that recharge did take place, albeit with a large delay, in response to the reef rock.

3.6 Bacteriological analysis

During drought periods, groundwater is used for both drinking and domestic water needs on Vaitupu. In general, boiling all well water prior to drinking is recommended. However, during discussions with households on Vaitupu, it was discovered that the treatment of water prior to consumption is not uniformly undertaken for household, village or communal wells.

In order to better understand the current groundwater quality and to identify bacteriological contamination, bacteriological sampling was of the wells and selected rainwater storage tanks and cisterns at the village and school was done. Standard sampling procedures were followed using sterile sample bottles, with samples kept cool in a field esky prior to analysis within 24 hours of sample collection.

Sample preparation relied on pre-prepared disposable petri dishes and used membrane filtration methodology to determine the most probable number of colonies for total coliforms and *Escherichia coli* (*E. coli*).

E. coli is found in the gut of warm-blooded animals, and is a useful indicator for potential contamination from pathogens. A practical guide on the suitability of water for potable purposes is provided by Wisner and Adams (2002). Sinclair et al. (2015b) presents the detailed methodology of the ‘EC compact dry’ analysis technique used. The sampling bacteriological results are presented in Annex 6.

3.6.1 Groundwater quality

In total, 16 groundwater samples were collected and analysed during field activities. Results from the sampling are provided in Annex 6, with a summary of the results presented in Table *6* and Figure 16. Freshwater lenses in atoll environments are susceptible to contamination due to the shallow depth of the water table. The commonly observed contamination sources include human graves, agriculture (*pulaka* pits), pig pens, poorly sited and constructed sanitation systems, and general household activities such as washing, gardening and waste disposal.

On Vaitupu, 15 of the 16 surveyed wells showed a moderate to high degree of bacteriological contamination; 10 wells with colony counts above 100 counts/100 mL, and 5 wells with colony counts between 10 and 100 counts/100 mL (Annex 6). All the wells located at the villages and at the school presented with more than 100 counts/100 mL, which can be associated with nearby anthropogenic activities such as settlements, waste disposal and land-use activities. Water quality of the wells located towards the northwest end of Vaitupu, where the fresher groundwater occurs, is poor, with only 1 well (Togalaa) within the tolerable range of *E. coli* counts.

Correspondingly, Togalaa well is the only well on Vaitupu, with the exception of the school wells, with appropriate covering and fencing structures, showing the importance of covering the wells to protect the water quality of the well. Covering and installing an adequate parapet is recommended in order to avoid direct contamination of the wells and potentially from the well to the groundwater.

Table 6: Summary of the results from groundwater bacteriological sampling on Vaitupu, Tuvalu.

E. coli/100 mL	Classification	Groundwater	
		Well samples	% of samples*
0	Guide compliant	0	0
1–10	Tolerable	1	6
10–100	Requires treatment	5	31
>100	Unsuitable without proper treatment	10	63

*Total samples: 16
Source: After Wisner and Adams 2002

Figure 16: Groundwater bacteriological sampling and *E. coli* positive test at Vaitupu, Tuvalu in June 2015.
Source: Google Earth 2015

3.6.2 Rainwater harvesting systems

In total, 12 samples were collected from cisterns and tanks, with the objective of assessing the water quality of the water storage in these structures. Results from the samplings are provided in Annex 6 with a summary of the results presented in Table 7 and Figure 17.

The sampled rainwater harvesting systems indicated good water quality, with most of the samples (7 out of 12) within the tolerable range. It was observed that tanks and cisterns are generally well maintained, with adequate covering and structures in place to avoid contamination from the surface and subsurface. Although the results of the sampling from the rainwater harvesting systems indicated good quality water, it is always recommended to boil water if it is going to be used for potable purposes.

Most of the community cisterns and tanks are well maintained, and only Asau cistern presented with more than 100 counts/100 mL. The *manneapa* (village meeting hall) roof, which feeds Asau cistern, had been recently replaced prior to field investigations, and it is possible that the cistern was exposed during construction activities. Maintenance of community cisterns and tanks is recommended to continue in order to guarantee adequate water quality of the storage infrastructure.

Two of the three private tanks that were sampled presented with more than 100 counts/100 mL, indicating contamination of the sampled water. It is recommended that maintenance also be conducted at the household level, and educational activities might be useful to inform the community about the benefits of maintaining good screens for storage tank inlets, and the good practice of boiling all water to be used for drinking purposes.

At Motufoua School, the girls' cistern and desalination tank sample results indicated *E. coli* contamination. Boiling water is necessary before it is used for potable purposes, and regular maintenance of the collection and storage structures is highly recommended in order to improve the water quality provided at the school's facilities.

Table 7: Summary of the results from rainwater storage systems bacteriological sampling on Vaitupu, Tuvalu.

E. coli/100 mL*	Classification	Rainwater	
		Samples	% of samples (12 total)
0	Guide compliant	0	0
1–10	Tolerable	7	58
10–100	Requires treatment	2	17
>100	Unsuitable without proper treatment	3	25

Source: After Wisner and Adams 2002

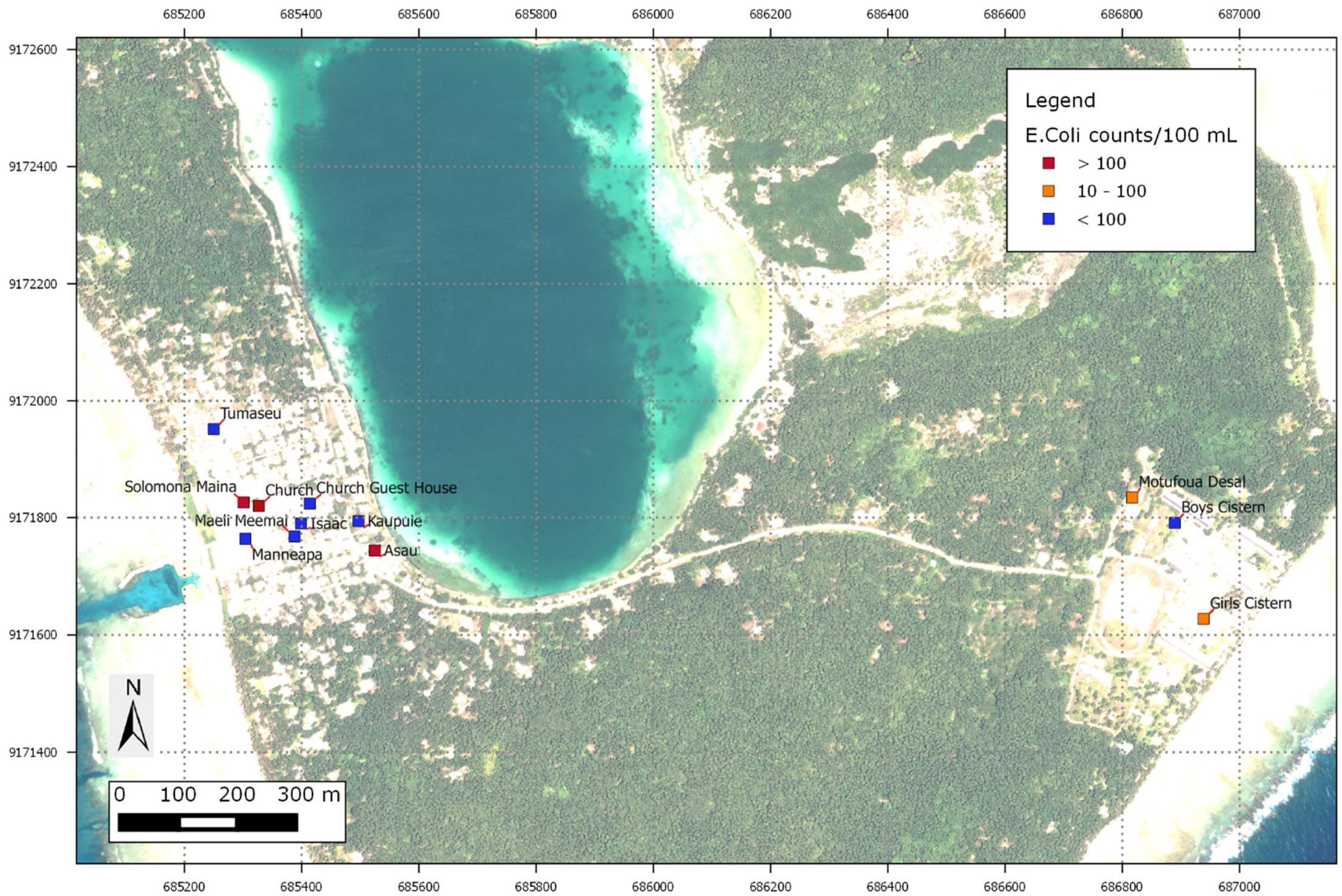

Figure 17: Rainwater harvesting bacteriological sampling and *E. coli* positive test on Vaitupu, Tuvalu, June 2015. Source: Google Earth 2015.

3.7 Geophysics

Geophysical survey techniques, including electromagnetics and resistivity, were undertaken during the CAIA project to delineate and locate the size and extent of the freshwater lens on Vaitupu. The information provided by the geophysics has been used to better understand the occurrence of groundwater on Vaitupu and to identify potential groundwater development sites that could be used by the community as a drought reserve.

3.7.1 Electromagnetics

Electromagnetics is a rapid geophysical survey technique that measures the ground conductivity of the subsurface and used to identify possible geological and hydrogeological models. A Geonics EM34 electromagnetic survey system was used during the Vaitupu 2015 field investigations.

The EM34 consists of two portable coils, a transmitter and receiver, to estimate ground conductivity. The transmitter coil radiates an alternating primary electromagnetic field that induces electrical currents in the earth below the coil, which in turn generate a secondary magnetic field, as a function of the conductivity of the earth materials it intercepts, inclusive of water and different geological formations such as sand and limestone. The receiver coil detects and measures both the primary and secondary magnetic fields, and estimates the apparent conductivity based on the ratio between the two fields.

The EM34-3 instrument requires only two people for field operation. The two coils are held by operators connected by a cable of one of three defined reference lengths: 10 m, 20 m or 40 m (Figure *18*). The coils are placed in the vertical or horizontal dipole position, depending on the investigation design of the survey, ground conditions and targets.

The portability of the equipment allows an experienced team to undertake rapid surveys, with 2 km or more of non-invasive surveys able to be achieved per day. The EM-34 is used mainly as a reconnaissance tool to identify areas of greater fresh groundwater potential, which can be further investigated with other investigation techniques such as resistivity to indicate the likely thickness and extent of the fresh groundwater.

Figure 18: EM34 survey on Vaitupu.

The depth of exploration depends on the separation between the transmitter coil and the receiver coil, and on the coil orientation (coil axis/dipole either horizontal or vertical). The effective depth of penetration increases with increasing coil separation, subject to ground conductivity characteristics. Geological factors such as moisture content, salinity of the pore water, temperature, and composition of colloids in the ground will influence the conductivity and success of the survey.

This technique does not identify a unique result and the measured values can be interpreted in a number of different ways. A correct interpretation relies on the 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. In the absence of monitoring wells on Vaitupu, the EM was calibrated with resistivity survey results along approximately five selected profiles. Sinclair et al. (2015b) presents further notes on EM principle, method and calibration.

Survey location

Nineteen EM34 survey lines covering a total distance of 11.67 km were completed across the island. The geophysical investigations were mostly prioritised for the northern section of Vaitupu, with survey lines included at Motufoua School and agricultural land (Figure *19*). Readings were taken with a coil separation of 20 m in the horizontal dipole position (coils vertical). Some survey lines had to be slightly diverted or cut short due to the presence of *pulaka* pits, dense vegetation and areas of flooding.

Figure 19: Location of EM34 transects on Vaitupu, Tuvalu. Source: Google Earth 2015

Results

The results from most of the survey lines indicated very high conductivities, suggesting a thin or very limited freshwater lens formation across the island.

Based on the measured apparent conductivities from the EM34 readings, using the 10 m and 20 m coil separation, areas of interest of expected greater freshwater lens thickness were identified and from which resistivity surveys were then carried out to better determine fresh groundwater potential.

The 10-m coil separation readings were relied on for interpretation because they suggested better estimates of the freshwater lens thickness than the 20 m coil separation distance.

3.7.2 Resistivity

Resistivity profiling using a SuperSting R1/IP with 56 electrodes from Advanced Geophysics Inc. was used for resistivity investigations on Vaitupu in June 2015 (Figure *20*).

Electrical resistivity profiling involves measuring the apparent resistivity of soil and rock as a function of depth, from which an interpretation of the geology and hydrogeology of the subsurface can be made. The resistivity of soils is a function of porosity, permeability, ionic content or salinity of pore fluids, and clay mineralisation. Resistivity is useful in determining freshwater lens thickness and shape.

Electrical current is injected into the ground through the use of stainless steel current electrodes, and then measured as a voltage in the potential electrode. Different spacing and sequencing of injection and measurement electrodes result in different arrays that are used for different investigations, depending on the depth and resolution of interest. On Vaitupu, dipole–dipole, Wenner, and trimmed Wenner arrays were trialled to determine which surveys would yield the best results for the available survey time.

Figure 20: The resistivity survey lines along established tracks on Vaitupu.

Survey methodology

The resistivity survey lines were focused on those areas delineated by low conductivity readings from the EM 34 survey lines, and followed existing tracks and, where possible, were orientated across the island from east to west, where it was anticipated that the freshwater lens thickness would be thickest towards the centre of the island (Figure *21*).

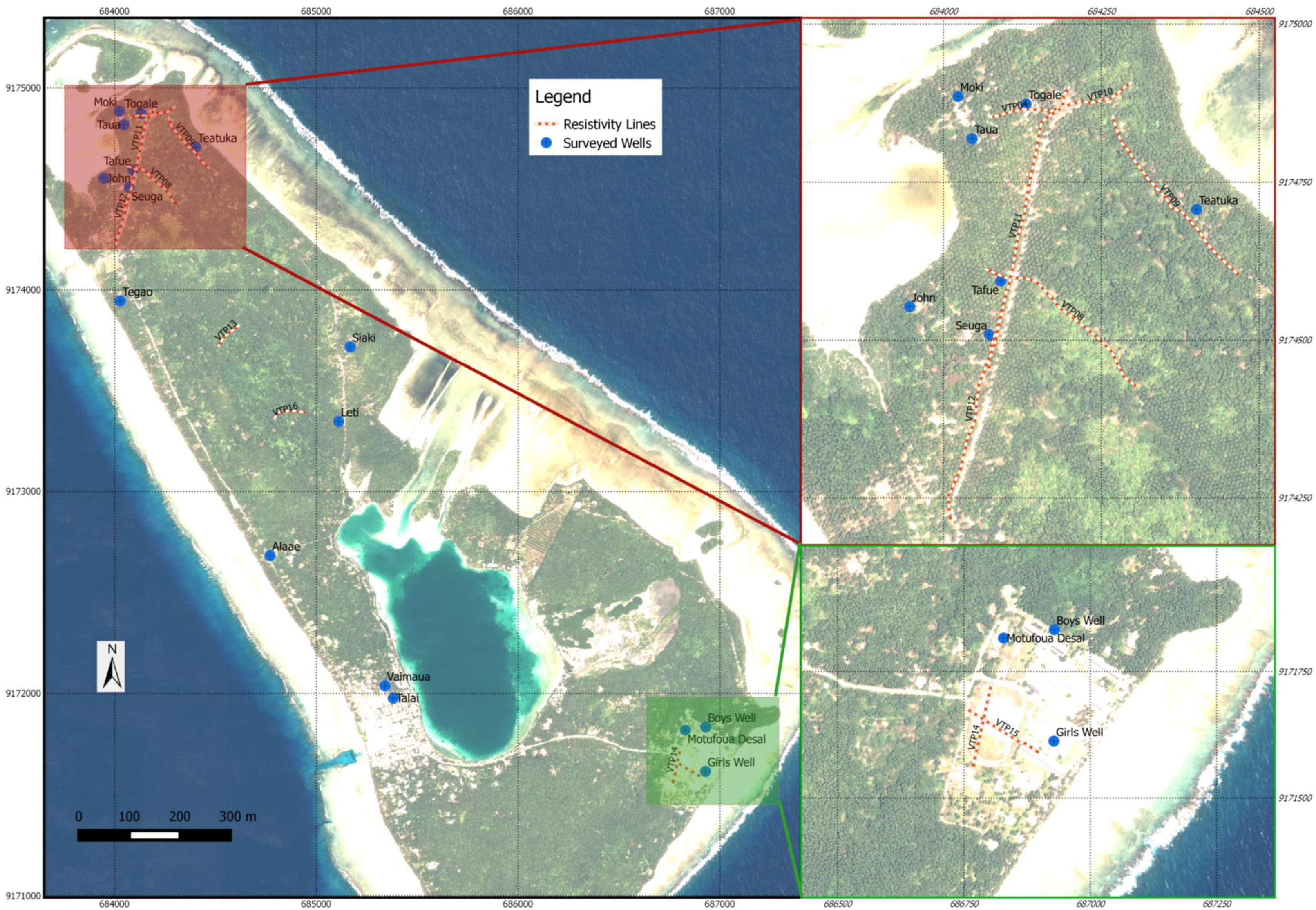

Figure 21: Location of resistivity lines on Vaitupu, detailing the location of lines at the northwest end and at Motufoua School. Source: Google Earth 2015

An electrode spacing of 3 m was used to provide sufficient ground coverage and resolution. The spacing of 3 m and the deployment of 56 electrodes in one full spread of electrodes allowed survey profiles of 165 m to be undertaken. Longer profiles using roll-along surveys, which involve leap frogging of the electrodes and cabling, were used to provide greater coverage of survey area and improved interpretation.

A trimmed Wenner array with a roll-along approach was found to be the most efficient survey technique, providing sufficient resolution given the shallow depth to the water table and thin fresh groundwater interface encountered. Using this array command and a roll-along approach, the team was able to reduce the survey time from about 1 hour and 20 minutes to about 1 hour for 56 electrodes. The trimmed Wenner array uses the standard Wenner array sequencing, excluding the deeper electrode combinations, resulting in a truncated profile at a specific depth, 15 m for Vaitupu profiles. The reduction in the data at depth did not affect the interpretation of the results, as the freshwater occurs at much shallower depths.

The survey provided good data collection with a capture of high quality data for the surveys and a limited number of anomalous values. The data were initially processed using the Earth Imager software from AGI and then reanalysed using the RES2DINV software, which resulted in improvements in data confidence and reduced error between measured apparent resistivities and calculated apparent resistivities. The resistivity profiles are presented in Annex 7. The analysis with the RES2DINV software provided greater confidence for the inverted apparent resistivities with the reduced mean residual error.

The information from existing wells, including depth to the water table and measured well water salinity, was used to help calibrate survey results and aid in the interpretation.

Results and interpretation

The inverted resistivity profiles for selected survey lines have been annotated with the location and features of existing wells, where available, and are presented it Annex 7. These wells were used to calibrate the survey profiles with respect to depth to the water table from the surface and as an indication of the salinity of the pore fluids found in the sediments in the shallow groundwater. The interpreted datasets have then been edited to ensure the same colour scale for all sections, allowing easier comparison between sections for interpretation. The lower end of the scale indicates lower resistivity values which suggest sediments or formations with more brackish water <100 ohm-m, with the higher resistivities indicating dry sands >1,000 ohm-m.

The water table depth, measured at the wells, is superimposed on the profiles thereby providing a useful control point. The profiles do not account for topography or elevation changes, and while it is recognised that relative changes in elevation between electrodes can impact on the analysis and interpretation of the results, for the purposes of this survey, the relative changes in elevation were not considered to be significant enough to alter the overall interpretation of the results and were not included in the analysis.

Resistivity results revealed that contrary to theoretical expectation on the hydrology of the island, the freshwater lens was not thickest in the centre of the island as was initially expected, which suggests that the island geology was more complicated and is the main controlling feature of the formation of a freshwater lens. The results suggest that the northern end of Vaitupu will have a freshwater lens that can be accessed at about 2.5 m depth and will have a thickness of freshwater, at the time of the survey, of up to 4 m. This is reflected in survey profiles VTP8, VTP11, VTP12.

The contour of the interpreted base to the freshwater lens slightly increases as you move southwest from the northern end of Vaitupu along profiles VTP11 and VTP12, indicating a thickening of the freshwater lens.

VTP11 and VTP12 resistivity survey profiles were undertaken along the existing unsealed road in a NE–SW direction (Figure *21*). Profile VTP11 commenced approximately 50 m from the northern end of the unsealed road along a NE–SW track. The VTP 11 profile suggests that in the northern section of the profile, the freshwater lens is quite thin. On this section, Togalaa well is indicated, however it should be noted that this well is offset approximately 45 m to the west of the survey line and some 35 m from the start of the line, but provides a useful indication of the water table depth.

VTP12, which is a follow on and overlapping survey from VTP 11, commencing approximately 70m to the NNE along the road from Segua well and travelling in SSW direction, is interpreted as being a consistently thicker part of the freshwater lens, with an estimated average thickness of about 3 m. Towards the end of this profile it appears that the freshwater lens may thin, possibly due to the underlying geology, indicating a slight rise in the Pleistocene limestone basement.

A review of all the survey profiles suggest that the thickest part of the lens is limited to the northern part of the island on the western side, south of and including Tafue and Segua wells, with an elongated shape with a NNE and SSW strike. It is noted that on the northern-most part of the ring road where VTP9 profiling was undertaken, the NW–SE profile, indicates that at approximately 160 m along the profile, in a SE direction, the resistivity values become quite low, suggesting a thinning of the lens. Similarly, the somewhat irregular variation in the contour of the low resistivity values in VTP8, VTP10, and VTP11 suggests an irregular thickness of the freshwater lens, which is interpreted as being geologically controlled rather than from abstraction impacts.

The suggested interpretation is that the island's freshwater lens is limited by relatively higher permeable geology at shallow depths across most of the island. This is attributed to more permeable Pleistocene limestone or patch reef formations that would account for the irregular low resistivity boundary and the lack of a freshwater lens of any thickness found towards the centre and in other parts of the island. The extent of the usable freshwater lens is interpreted as being restricted to the northwestern area of the island, as indicated in Figure *22*. The contours for the freshwater lens suggest that the lens is a narrow elongated shape, with a strike of NNE–SSW of over 600 m and 100 m wide, and an estimated area of 23,210 m^2 for the 2.5 m thickness and 107,910 m^2 for the 2.0 m thickness.

VTP 13 and VTP 16 are west–east orientated profiles towards the centre of the island and farthest from the expected oceanic impacts. These resistivity survey profiles were undertaken to determine if the resistivity results supported the results from the EM34 reconnaissance survey, suggesting high conductivity readings and limited potential for groundwater. Both of these surveys indicate low resistivities and subsequently limited or no potential for the development of a freshwater lens of any usable thickness. As indicated, this is at odds with the expected hydrogeology for the island, whereby a thicker freshwater lens was anticipated in the centre of the island based on island size and shape. It is suggested that these resistivity results provide additional support for the interpretation that the island is composed of reef patches, combining over time, whereby some of the underlying Pleistocene limestone is found at relatively shallow depths, limiting the development of fresh groundwater.

Profiles VTP14 and VTP15 are resistivity surveys undertaken at Motufoua School. The survey lines were determined based on initial EM34 results and with consideration to existing infrastructure and potential future development. VTP14 is a NE–SW section that travels from the NNE across the existing rugby field in a SSW direction. Profile VTP15 starts at the edge of the rugby field and travels in a SW direction across the rugby field and past the girl's dormitory to finish just near the existing girl's well.

The interpretation of these two resistivity profiles at the school suggest that the freshwater lens is quite thin and is restricted to the area around the playing field, with a freshwater lens thickness of 1–2 m at the time of the survey. Future groundwater development around the school is limited although the best location based on the resistivity survey is the playing field, with a horizontal gallery well installed to skim the freshwater at the water table. The abstraction would need to be a very low yield to limit the potential for up-coning, and it should be expected that at times, particularly during dry weather, the abstracted water would be brackish.

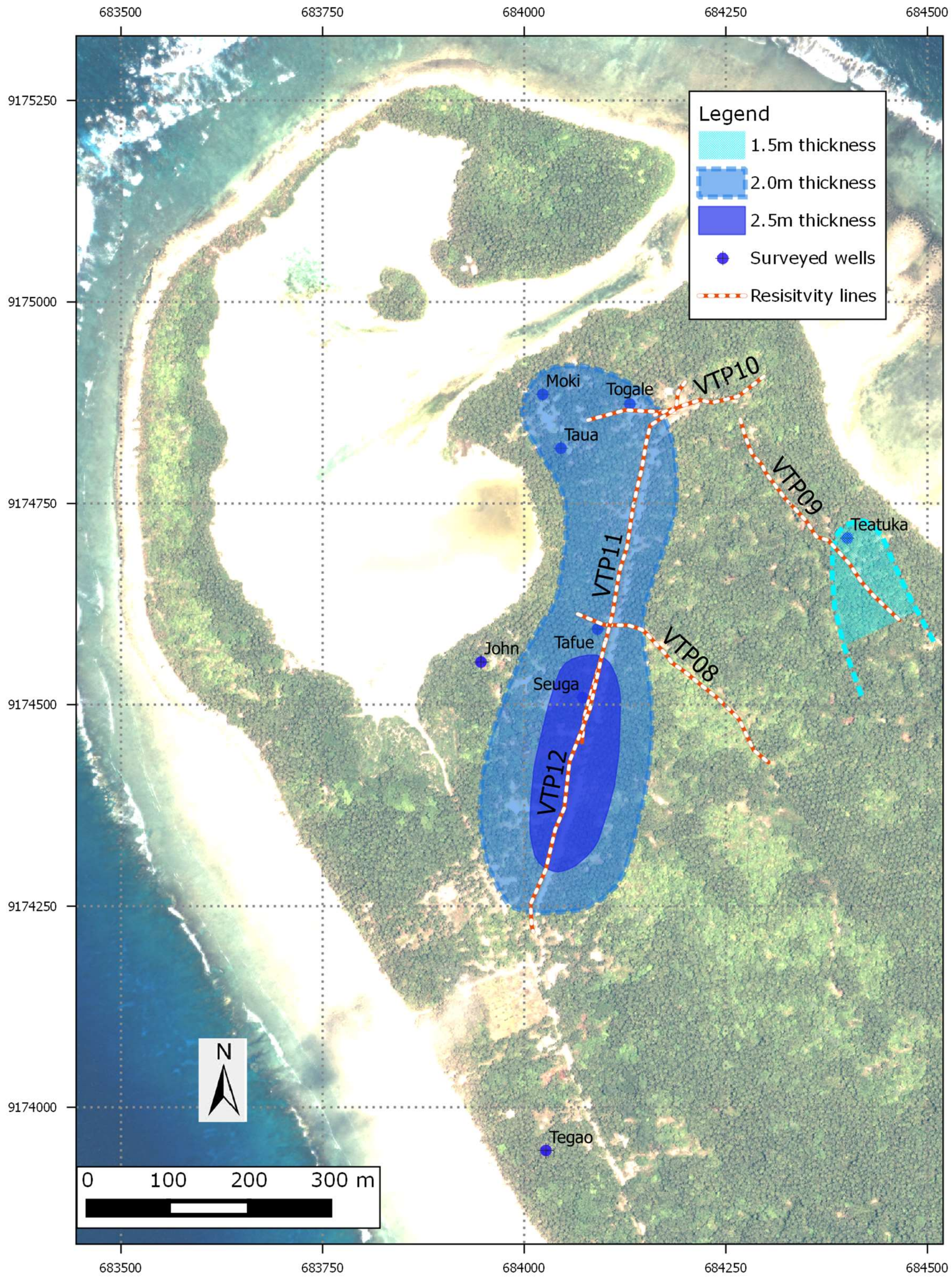

Figure 22: Interpreted freshwater lens thickness in the northern part of Vaitupu based on resistivity profiles and measured EC at existing wells. Source: Google Earth 2015

4 Interpretation

4.1 Hydrogeology

Vaitupu, with an estimated average annual rainfall of 3,210 mm/year, and an area that is more than 4 km in length and 1 km wide, with a land area of 5.62 km^2, boasts good groundwater potential. On closer investigation, however, the groundwater potential of Vaitupu is limited.

Geophysical surveys indicate that Vaitupu has limited quantities of fresh groundwater suitable for development. The survey results suggest that the fresh groundwater is mainly restricted to the northern part of Vaitupu, and within this northern area, the freshwater lens is limited in its thickness, further restricting the potential for development as a water resource. The indicative freshwater lens thickness suggests that groundwater development is predominantly controlled by the underlying geology. Low resistivity suggests that relatively high hydraulic conductivities occur at depths as shallow as 4 m, restricting any great thickness of freshwater lens from developing.

For many wells south of the identified groundwater resource the presence of reef rock was noted (Annex 4). It can be expected that the presence of reef rock will influence the recharge, whereby if reef rock is present, recharge will be impeded relative to areas where reef rock is absent. This was observed in the response to a recharge event of 100.5 mm, recorded in pressure transducers for four wells over 24 hours, between 28 and29 June 2015 (see Section 3.5.2).

Loggers installed in four wells Togalaa, Teatuka, Segua and Tegao indicated a respective delay between the time when the rainfall event commenced and the corresponding rise in the water table (Annex 5). This delay is connected to the presence of reef rock, whereby a relatively reduced or delayed response is observed in those wells when reef rock is present, compared with readings where reef rock is absent and recharge is faster and more pronounced. Annex 4 identifies the presence or absence of any reef rock and associated observations.

Similarly, the same pressure transducers deployed in existing shallow wells allowed variations in tidal lag and tidal efficiency to be calculated across the island. Areas of reduced tidal lag and increased tidal efficiency suggest areas of greater hydraulic conductivity or greater connection with the ocean, either as a function of the proximity to the ocean or underlying geology.

It was observed that brackish wells with reduced tidal lags and higher tidal efficiencies are observed in some locations more distant from the ocean, which is counter to what would be expected. This suggests that for these locations, the underlying geological factor is the dominant factor influencing and restricting the development of a freshwater lens. Based on these observations, it is suggested that an erosive shallow limestone boundary exists at depths as shallow as 4 m. The thickness of unconsolidated sand sediments is interpreted as being less than 10 m. The thickness of the unconsolidated sediments is the dominant control in the development of fresh groundwater.

Investigative drilling and construction of monitoring bores would be required to provide more conclusive evidence to support the above interpretation of geology, hydrogeology, and the measured thickness of the freshwater lens.

The geophysics indicates low resistivities at depth and this is interpreted as highly permeable limestone and saline water, with zones of unconsolidated sands in between the eroded limestone surface. This is suggestive of the development of the island and the coalescence of patch reefs, in which pockets of unconsolidated sands have been deposited in between the patch reef network. This suggested geological framework is the controlling factor for the development of any freshwater lens.

The estimated available volume of fresh groundwater is presented in Section 4.2.2.

4.2 Groundwater availability and sustainability

4.2.1 Recharge

Recharge to the groundwater system on Vaitupu is in response to the available rainfall. The rainfall analysis provided in Section 3.2 indicates that an average annual rainfall of 3,210 mm/year can be expected, and while variability in the rainfall is higher for Vaitupu than for islands to south of it, such as Funafuti, the estimated coefficient of variation (28%) indicates moderate variability when compared with other islands in the Pacific. The relatively high rainfall and moderate variability of rainfall suggests that recharge to the groundwater system on Vaitupu is moderate to high, suggesting rainfall is unlikely to be a limiting factor for fresh groundwater lens development.

Recharge cannot be expected to be uniform across the island and will vary due to the presence of reef rock (as indicated in Section 4.1), variations in vegetation densities and type, minor variations in topography, land use, and variations on where and how much rain falls. However, to assist with determining the groundwater development potential, it is useful to determine an average recharge for subsequent estimations of available water volumes for abstraction.

In the absence of specific recharge studies, a conservative estimate of recharge can be based on empirical studies. Falkland (1992) derived an empirical relationship between mean annual rainfall and calculated mean annual recharge for a number of low lying islands (Figure *23*).

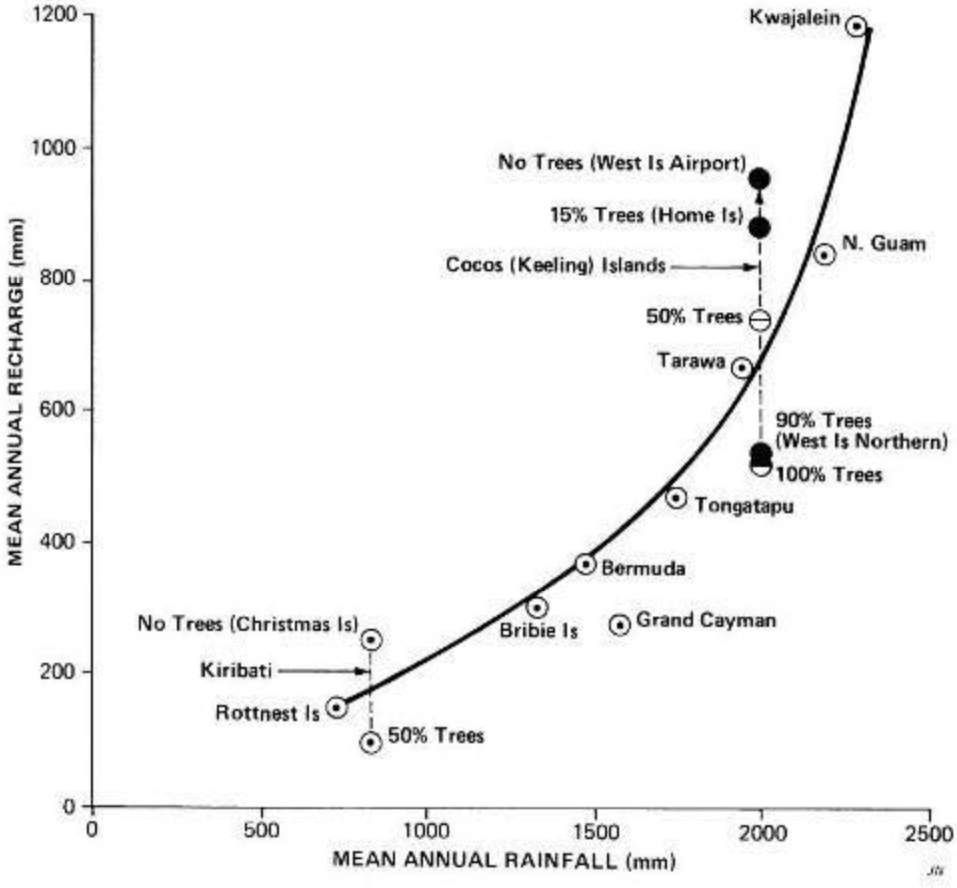

Figure 23: Annual rainfall and recharge relationship for a few studied small islands. Source: Falkland 1992

This empirical approach has been used by Falkland (2003) to develop a polynomial equation that provides an estimate of recharge based on rainfall.

$$R = 0.0002238P^2 - 0.1816P + 164.53$$

Where *P* is rainfall in mm, and *R* is recharge in mm.

Applying this approach suggests that based on a mean annual rainfall of 3,210 mm/year, an estimated recharge of 1,888 mm/year would occur across Vaitupu. This approach suggests that on an annual basis, recharge is estimated to be as high as 59% of the rainfall received on Vaitupu.

The water balance methodology is an alternative approach to calculate recharge in cases where there is no significant surface runoff.

$$R = P - ET_a \pm dV$$

Where ET_a is the actual evapotranspiration (evaporation from intercepted water on trees and other surfaces, evapotranspiration from the soil zone, and transpiration of deeply rooted vegetation directly from groundwater), and *dV* is change in soil moisture store.

WATBAL is a computer program used to simulate the water balance and derive recharge estimates. Features of the WATBAL model and how it was applied in the recharge modelling for Vaitupu include:

- Monthly rainfall data for Vaitupu used available Vaitupu rainfall records, and for missing data the rainfall records from the nearby island of Nui were used to approximate the rainfall on Vaitupu.
- Estimates of evaporation taken from McClean and Hosking 1991, and modified to accommodate seasonality based on Tarawa, Kiribati records are used in the calculations for WATBAL.
- In the absence of daily rainfall data, monthly rainfall records were evenly distributed into daily time steps for use in the water balance calculations and determination of recharge. Fry and Falkand (2011) suggest daily time steps will produce greater accuracy while monthly rainfall and water balance calculations is likely to underestimate the recharge by 5–10%.
- Other factors influencing the WATBAL equation, including soil types and vegetation cover, were determined from McClean and Hosking 1991 and Google Earth images.
- Crop factors and vegetation density used were relevant for the area of interest within Vaitupu to estimate monthly recharge.

The results from WATBAL are considered as a guide only, due to the large number of unknowns that presently can only be estimated.

The sensitivity of recharge to variations of input parameters was determined for the Pan factor, using a range (0.7–0.8), and for deep rooted vegetation ratio (DRVR), where values of 0.4 and 0.8 were used, whereby the lower the ratio of DVRV, the more cleared the land.

The output files from WATBAL are provided as both monthly estimates of recharge in mm, and as a percentage of rainfall. Given the assumptions used in the calculations, it is more appropriate to consider recharge as a percentage of annual rainfall rather than specific monthly estimates of recharge.

WATBAL estimates that the recharge on Vaitupu will be, on average, between 60% and 65% of rainfall. This estimate from WATBAL compares favourably with the recharge estimates of 59% of rainfall determined from the empirical method after Falkland (2003).

These two approaches, WATBAL and the empirical method, suggest that, on average, recharge can be expected to be high at around 60% of rainfall. Given the relatively high rainfall for Vaitupu, the volume of water recharging to the groundwater system is also high, indicating greater potential for the sustainable development of the groundwater system within its hydrogeological and geological constraints.

4.2.2 Estimated available volume

The estimated available volume of fresh groundwater can be determined by calculating the area of fresh groundwater that has a freshwater lens thickness greater than 2.5 m, and then applying a factor for the specific yield for the aquifer. Groundwater assessment work undertaken in Kiribati (GWP 2010), suggests that a freshwater lens is delineated by selecting all of the area that is estimated to have a freshwater thicknesses greater than or equal to 2.5 m. Falkland (2003) suggests that the assumed specific yield for coral sands is 0.3.

It should be noted that a drought resilient zone has been mapped in previous studies in Kiribati by GWP (2010) and Loco et al. (2015) as areas having an estimated freshwater lens greater than 6 m, whereby 5.0–5.5 m is the potential reduction in freshwater lens thickness induced by drought (GWP 2010). This guidance is based on variations of the freshwater lens thickness observed in monitoring bores located in Bonriki, Kiribati, which has some similar hydrogeological features as Vaitupu.

In the specific case of Vaitupu, the interpreted geophysics suggest that the maximum freshwater lens thickness expected is up to 4 m. Despite this relatively thin freshwater lens, the identified zone in the northern area is considered to be the thickest area of freshwater lens, and will represent the most drought resilient and useful occurrence of groundwater to be found across Vaitupu. During extended droughts, the available fresh groundwater is expected to decrease over time. However the northern area is expected to provide fresher water for a longer period than other areas due to the increased thickness of the freshwater identified in this area. If the development of groundwater for drought and water security is to be considered, the area of thicker freshwater lens identified by the geophysics in the northern part of Vaitupu is recommended for future water supply development.

The available volume is estimated as:

$$V_{available} = A \times T \times S_Y$$

Where *A* is the estimated area of the lens, *T* is the thickness of the lens and *Sy* is the specific yield. For a freshwater lens of 2.5 m thickness and area of 23,210 m^2 (see Section 3.2.2), and specific yield of 30% of the volume, the estimated $V_{available}$ is approximately 17,407 m^3 or 17.4 ML of total available water.

Sustainable yield is often considered as a function of the accepted impacts over a predetermined time frame. Section 4.2.3 discusses in more detail the concept of sustainable yield and how sustainability in atolls challenges the traditional notion of sustainable yield commonly used in continental aquifers.

Falkland (2003) developed a conservative assessment of sustainable yield that may also be considered as an acceptable long-term volumetric abstraction under average rainfall conditions. The assessment is based on a relationship between abstraction and recharge, whereby abstraction increases as the percentage of recharge increases, and is based on modelling studies in high rainfall areas, and on a Christmas (Kiritimati) Island study (Falkland and Woodroffe 1997). The relationship is:

$$Abs = R - 10$$

Where *R* is recharge as a percentage of rainfall, and *Abs* is acceptable abstraction as a percentage of recharge.

Applying this approach for Vaitupu, with a mean annual rainfall of approximately 3,210 mm and an estimated mean annual recharge of 1,888 mm, 59% of rainfall, a conservative preliminary acceptable abstraction of 49% of annual recharge is calculated, which correlates with the estimated acceptable abstraction for Vaitupu of 29% of rainfall.

The acceptable abstraction for the freshwater lens with an estimated thickness of 2.5 m over the course of a year in which average rainfall was received, is calculated as:

acceptable abstraction = area m^2 * (annual rainfall*rainfall factor for acceptable abstraction)
= 23,210m^2 * (3.210*0.29) m
= 21,606 m^3/year
= 59.2 m^3/day (59,200 L/day)

Under average rainfall, this result would suggest that an estimated abstraction of 59,200 L/day or 59 L/person/day (Motufoua School excluded), should be achievable. This volume is useful as a starting point for the design of a pumping well and gallery, noting that variations in rainfall will impact on the salinity of the groundwater abstracted. During extended dry periods, abstraction may need to be reduced to maintain an acceptable salinity of the water delivered.

The estimated acceptable abstraction is based on an average rainfall year. The stored available fresh groundwater is estimated to be 17.4 ML. If a prolonged period of drought occurs, and assuming an abstraction of 59.2 m^3/day, then it is estimated that there is sufficient stored freshwater for up to an estimated 9.5 months based on no rainfall. It should be noted that for nearby islands Nanumea and Nui, the meteorological drought is averaged to be 12 months in duration. However, even during droughts, we can expect periods of recharge to occur, which will support the estimated available abstraction volume.

4.2.3 Sustainable yield concept

Traditionally, sustainable yield estimates focus on identifying an average daily pumping that can be maintained without adversely impacting the resource, whereby impacts are subjective and time frames can vary. However, it is proposed that the sustainable management of a groundwater system should take into consideration the environmental, economic and social aspects affecting the community, and the potential and actual reliance on the groundwater systems by the community over an agreed time frame. Community needs, priorities and level of governance will, of course, influence the way a resource is managed and operated, and these factors should be an important consideration when developing a groundwater resource and a daily abstraction volume.

The main concern for a freshwater lens in a coral sand island such as Vaitupu is that of quality, specifically salinity. A freshwater lens thickness naturally reduces in response to reduced rainfall and/or pumping, with a corresponding increase in salinity. Following recharge after rainfall, the freshwater lens thickness will increase, returning in time back to previous levels. It is, therefore, critical that the community appreciates the naturally dynamic groundwater system in atolls in order to help develop an active management approach that embraces the dynamic nature of the groundwater system and focuses on water quality as the limiting parameter for groundwater management.

A community may also consider adopting different levels of salinity under emergency situations, rather than maintaining a fixed long-term abstraction volume. For instance, during an extended drought the community may be willing to accept a slight increase in salinity of the pumped water to maintain an agreed on volume of water. The alternative is to reduce the volume of water provided to ensure water quality is maintained. It should be noted that with returning rains the groundwater will freshen over time and the salinity of groundwater will return to pre-drought water quality conditions, allowing pre drought volumes to be abstracted.

The following table provides an estimate of the ranges of salinity for consideration. Note that salinity is considered by the World Health Organization to be a parameter used for aesthetic purposes only — that is, taste. There are no specific health impacts associated with salinity to affect its potability.

Table 8: Guide on salinity threshold values for consideration by the Vaitupu community and the Government of Tuvalu to provide guidance for management purposes.

Salinity (µS/cm)	% Seawater	Comments
<200	<0.5%	Rainwater
200–1100	0.5–2.2%	Slight taste of salinity may be perceptible to people at the upper end of range.
1100–1500	2.2–2.5%	Upper desirable range for drinking water, where salinity in water will be perceptible to most people, but tolerated.
1500–2500	2.5–5.0%	Salty taste in the water will be perceptible to all and unacceptable to many. Upper limit of freshwater considered to be 2500 µS/cm.
50,000	100%	Seawater

A freshwater lens in a small coral sand island environment is highly dynamic, being intimately connected to rainfall and tidal variations that naturally impact on the freshwater resource. Depending on the connectivity to the ocean tides, the size of the lens and the permeability of the sediments, changes in rainfall can start to impact on the freshwater lens within months. Significant thinning or shrinking of the freshwater lens is observed in larger fresh groundwater systems within 12–24 months of reduced rainfall. Pumping will further stress the lens and reduce the thickness of the freshwater lens, resulting in increased salinity.

Recent numerical modelling work at the Bonriki water reserve in South Tarawa, Kiribati indicates that with returning rains, the recovery of the freshwater lens can be significantly quicker than the time it takes for the freshwater lens to thin. Numerical modelling also provides confidence; that with rainfall, the lens will recover and impacts to the freshwater lens, such as salinity increases, will be reversed without permanent impacts to the freshwater lens.

Other factors, such as the social and economic costs of maintaining an acceptable salinity or ‘freshness’ of the supplied water, compared with the costs of providing an alternate water source, such as desalination, should also be considered. In some cases, the community may be willing to accept higher salinity water for a period of time in deference to the funding the cost of desalination to meet water needs.

One approach to guide the operation and management of a freshwater lens, may be to determine an average abstraction volume based on an acceptable percentage of ‘average rainfall’ conditions, using the approach presented in Section 4.2.2. This estimated abstraction volume could then be modified depending on whether the community agree to manage to a specific salinity and to keep the salinity below the agreed salinity value (e.g. 1,000 or 1,500 µS/cm), or to allow salinity to increase if water quality is less important, for example for sanitation. It is suggested that groundwater management and salinity threshold targets should be agreed on by the community and used as a basis in which operational management of the freshwater lens can be developed. An example of this is as follows:

1. Preferred maximum salinity such as <1,000 µS/cm.
2. Acceptable salinity, whereby salinity levels accepted for a 'short' period of time, given adverse climatic conditions such as a drought (e.g. 1,500 µS/cm), volumes may need to be reduced.
3. Unacceptable salinity, whereby the salinity of the groundwater should not exceed, for example, >1,500 µS/cm. Salinities above this are not acceptable for drinking water and alternatives need to be considered. Water may be suitable for alternative uses such as washing.

The volume of water abstracted may need to be varied in order to maintain acceptable salinity levels and minimise the potential for abstracting 'unacceptable' water. This approach to operational management requires monitoring the salinity of the water being abstracted from each pumping well or gallery as well as the pumping volume and the rainfall. Rules are required at predefined salinity trigger levels to permit either a reduction, or an increase, in the abstraction in pre-defined fixed amounts, depending on the salinity of the well, at a fixed interval of monitoring. For example, pumping is reduced to preserve the freshness of the water provided while salinity monitoring frequency is increased to capture changes in water quality.

In the case of Vaitupu, the volume of water available for abstraction under average rainfall conditions may be 59,000 L/day (see Section 4.2.2), where the current range of salinity is indicated to be between 440 µS/cm and 1,300 µS/cm.

As a guide, the community may like to consider an interim value of a maximum acceptable salinity of 1,500 µS/cm with an initial abstraction volume of up to 59,000 L/day, under average rainfall conditions. During droughts, this abstraction rate may need to be reduced to conform with the acceptable salinity levels agreed on by the community.

The reduction in pumping would need to be empirically determined based on observations of salinity, abstraction and rainfall. Long-term monitoring of salinity, rainfall and abstraction will be important to help determine appropriate abstraction rates.

4.3 Groundwater supply options

A pragmatic objective of the project is to improve the water security of Vaitupu with consideration to the development of a more resilient groundwater resource as a drought reserve. It is assumed that by providing greater access to a fresh groundwater source the use of groundwater as a viable and cost-effective alternative to increased rainwater collection and storage facilities or desalination options will be promoted. Improved access is also expected to reduce the costs of accessing the fresh groundwater.

An option for the development of the fresh groundwater on Vaitupu is based on initial discussions of field results with the *kaupule*. A detailed engineering study is required to determine the design of the water supply infrastructure; however, general guidelines and abstraction rates of an infiltration gallery is presented in the following section.

4.3.1 Infiltration gallery

Horizontal infiltration galleries have proved to be a very effective mean of abstracting fresh groundwater from freshwater lenses on atoll islands (Falkland 2003). The success of the infiltration gallery design is based on its ability to draw groundwater from horizontal and slotted pipes so as to minimise the drawdown on the water table at the pump station. By maintaining a small drawdown, the impact of pumping on the freshwater lens is reduced, lessening the potential for pumping induced upward movement of underlying saline water into the freshwater zone.

It is proposed to construct an infiltration gallery in the area where the freshest and thickest freshwater lens has been identified (Figure *24*). Gallery construction involves excavating a trench approximately 1 m below the lowest level of the water table from tidal impact, and installing horizontal PVC-slotted pipes that lead to a central pumping station. The infiltration gallery would be constructed parallel to the long axis of the freshwater lens, in a NW–SE direction, comprising two 100-m gallery arms (Figure *22*). The horizontal wells would be backfilled with suitably sized rounded gravel to help develop a gravel pack before being backfilled with the excavated sand. The calculated required pump rate is 40 m^3/day, which is equivalent to 0.2 m^3/day/unit length, based on similar investigations. This is considered to be a conservative value, and accounts for approximately 20% of average annual rainfall, or 68% of the calculated acceptable abstraction estimated in Section 4.2.2. Considering that a solar pump operates between six and eight hours a day, the operating pumping rate should be around 1.4 L/s for eight hours of pumping. Historical droughts for Nanumea and Nui indicate a meteorological drought duration of 12 months. An abstraction rate of 40 m^3/day would, over an average drought period, abstract 14.6 ML, which is below the estimated available volume in storage of 17.4 ML calculated in Section 4.2.2.

Annex 8 presents the design of a generic infiltration gallery proposed for atoll environments (Sinclair et al. 2015a). Details on additional infrastructure proposed for the storage and transmission of the water are presented in Annex 8.

4.3.2 Infiltration gallery construction design consideration

As indicated in Section 4.1, reef rock has been observed in a number of existing bores. The analysis of pressure transducers installed in wells indicates that the reef rock will result in a reduction and/or a delay in recharge to the underlying aquifer and freshwater lens in response to a significant recharge event (see Section 3.5.2).

As indicated in Section 4.1, if the option for investigative drilling is available an assessment of the thickness and competency of the reef rock could be undertaken to assist with construction design. In the absence of investigative drilling, test pits could be dug with an excavator along the proposed construction to help in the assessment of ground conditions.

Construction design of the gallery should take into consideration the presence of reef rock, as well as the identified thicker parts of the freshwater lens, and make provision for the reef rock during the construction. A field assessment indicates that reef rock can be expected during construction in the area to the south of Seuga well. Field observations suggest that the reef rock in Seuga well appears moderately weathered, and the pressure transducer data indicate that the weathered reef rock responds quite well to recharge events. This suggests that moderately weathered reef rock is sufficiently permeable to allow sufficient recharge to support the construction of a gallery beneath weathered reef rock.

It is suggested that during the excavation of the trench for the gallery, if reef rock is encountered and remains weathered to moderately weathered, trench construction should continue. A practical approach during construction may be that if the trench excavation can continue relatively easily through the reef rock, then trench construction should continue. If the reef rock is hard or well cemented or thick reef rock is intercepted, then the continued construction of the trench should be assessed. In the areas where thick and unweathered reef rock is encountered, it is expected that the recharge may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery. If the option exists to extend the gallery farther in the other direction, aligned with the long axis of the lens shape identified in Figure 24, and taking into account the condition and/or presence of the reef rock and the expected thickness of the freshwater lens, then extending the lens in this direction would be preferable.

The construction of the proposed gallery would occur adjacent to the Segua well site or in close proximity to it, and possibly as far north as Tafue well. In the interest of reducing the vulnerability of the proposed gallery, any well or pit that is within 50 m of the gallery trench would need to be decommissioned to minimise the potential for contamination. Decommissioning wells or pits would involve the removal of any organic matter in the well, the removal of coarse rocks protecting the well wall and any existing parapet around the well. The well would then need to be backfilled with suitably sized clean sand.

To reduce the contamination risk of groundwater lenses it is recommended that protection zones be established around the groundwater abstraction areas (i.e. wells and galleries). Falkland (2003) suggested a nominal set-back distance of 50 m for infiltration galleries. It is, therefore, suggested that a 50-m buffer zone be enforced to reduce vulnerability to the infiltration gallery. Within this buffer zone, land-use activities would be restricted, and it would not be permissible to undertake any agriculture, including *pulaka*, pig husbandry and intensive gardening, and no permanent or temporary housing would be permitted, nor the siting of cemeteries, latrines or any wastewater disposal. It is not expected that fencing is required, however agreement with land owners and a bylaw would be required to safeguard the proposed buffer zone.

Permitted land-use activities would include the harvesting of coconuts, bush food collection, and a potential sports field. Ideally, the vegetation in the area in which the gallery is located would be kept sparse because this would help maximise recharge. The current main unsealed ring road for the island passes within the proposed gallery construction and buffer zone area. It is recommended that this ring road be diverted for 300 m so that it is outside of the proposed buffer area in order to minimise potential contamination and unwanted access within the buffer area.

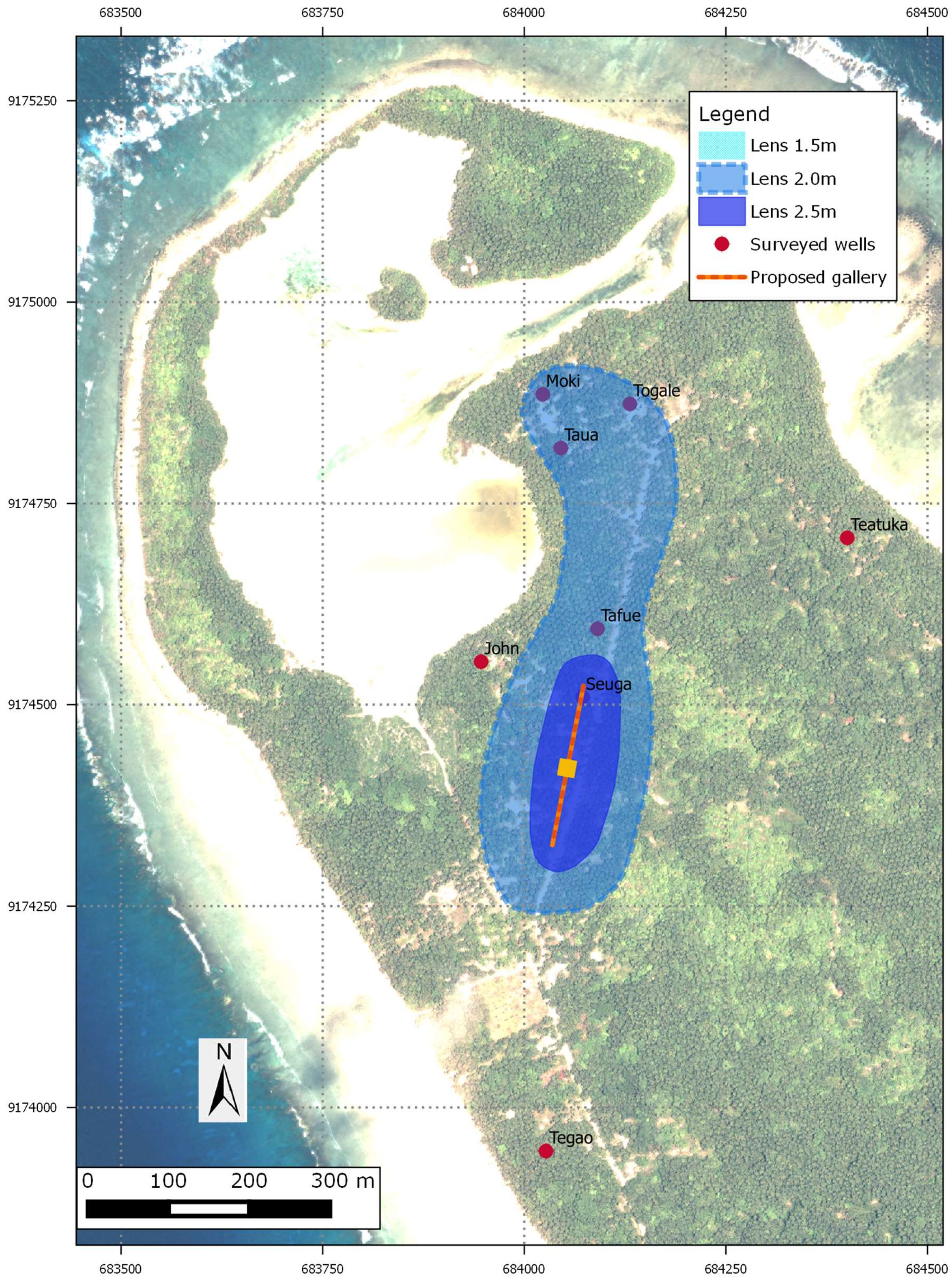

Figure 24: Proposed location of the gallery. Source: Google Earth 2015

4.4 Groundwater supply monitoring

The monitoring of the freshwater lens on Vaitupu is critical to determining the impacts of climate variability on the volumes of water available from the lens. Periodical and long-term monitoring provide significant inputs to: characterise groundwater systems and identify tendencies in groundwater quality over time; identify existing or emerging water quality issues; and improve responses to emergencies, such as overtopping events.

Loco and colleagues (2015) present guidelines to conduct water quality monitoring campaigns in outer islands.

- Representatives from the *kaupule or falekaupule,* or a 'water technician' from Vaitupu, should receive appropriate and regular training on water quality field techniques (e.g. sampling and equipment maintenance and calibration).
- Basic water quality parameters that could be monitored include water levels and salinity in existing wells, which provide a direct indicator of the occurrence, fluctuation and sustainability of this resource.
- Adequate logistical support is required, including transport, technical equipment, calibration solutions and data storage facilities.
- It is suggested that outside of a drought, quarterly monitoring of the salinity of existing frequency.

4.5 Groundwater vulnerability

Freshwater lenses are extremely vulnerable to natural processes such as storm surges, droughts and human-induced anthropogenic influences (Werner et al. 2015; Loco et al. 2015). The high vulnerability of freshwater lenses in atoll environments is mostly associated with the shallow depth to the water table and the unconfined characteristic of the aquifer.

4.5.1 Anthropogenic contamination

The *E. coli* sampling results indicate the occurrence of groundwater contamination in the majority of the existing wells at the time of the survey. Contamination can occur from the surface due to poor well construction and protection, seepage from nearby, poorly designed toilets, and improper land-use practices, such as inappropriately located piggeries and rubbish dump sites.

Wells located near inhabited areas are subject to contamination from sources such as pig pens, poorly sited and constructed sanitation systems, and general household activities such as washing and waste disposal. Contamination of groundwater resources when populations are located immediately above the water resource is very difficult to avoid although measures can be taken to reduce the impact of contamination and increase the awareness of communities, resulting in improved self-management of groundwater systems. One measure is to relocate contaminant sources to a nominal separation distance of at least 20 m from the wells.

The northern end of Vaitupu has a low population concentration; however, bacteriological contamination was detected in the majority of wells, presumably due to poor well construction and protection, including the inadequate parapet height, and a lack of apron and well covering. Special considerations to protect groundwater quality at the northern end of Vaitupu are recommended because this area has the potential to be a drought reserve water supply for the community.

4.5.2 Drought

Freshwater lenses in atoll environments are vulnerable to extended dry periods because the lens 'shrinks' in response to reduced rainfall and recharge. Long-term monitoring of rainfall, abstraction and lens thickness will assist in determining the capacity of the freshwater lens to provide groundwater of suitable salinity for domestic purposes under different climatic conditions. Monitoring and modelling results of freshwater lenses in atoll environments has increased the knowledge of the response of these vulnerable systems. The modelling and monitoring of similar systems indicates long-term resilience. While groundwater systems are susceptible to stress under extremely dry conditions, modelling and monitoring results indicate they are able to return to pre-drought conditions once rainfall returns.

4.5.3 Groundwater protection

Observations of construction features for hand dug wells in Kiribati, coupled with bacteriological water quality information, indicates that the type of construction features for the well will have a significant impact on the protection of well water from surface contamination. In particular, the presence and type of well parapet, well casing, and well cover are important in reducing the ingress of surface water and thus possible contamination of the well.

Simple design features and technologies have been proposed by Sinclair et al. (2015a) to improve well water quality. The following list summarises potential improvements than can be implemented into the existing wells on Vaitupu.

- Building a concrete casing to maintain well integrity and control the depth from which groundwater is accessed.
- Extending the concrete rings above the ground (a well parapet) is important for reducing the potential of contamination from the surface into the well.
- Fitting a cover over the well to prevent foreign objects from entering and to reduce algae growth.
- Installing a concrete apron around the well to redirect water away from the well and reduce the potential ingress of water down the sides of the well.
- Constructing fences directly around the well to improve security and reduce access by animals and unauthorised personnel.
- Using bucket stands to keep buckets from coming into contact with potential contamination sources.
- Installing hand pumps or solar pumps to increase the accessibility of water and reduce the need for direct access to the well.

5 Conclusions and recommendations

The groundwater field investigations undertaken between June and July 2014 enabled the project to expand the current knowledge of Vaitupu's hydrogeology, and the potential use of groundwater as an alternative water source for Vaitupu.

Rainfall analysis from four meteorological stations located in Funafuti, Nanumea, Niulakita and Niu suggest that in Tuvalu, droughts are more commonly associated with La Niña ENSO conditions. Funafuti, Niulakita and Nukalelae are statistically likely to experience more meteorological drought conditions than islands to the north, and drought is more commonly experienced during either La Niña or neutral ENSO conditions.

An automatic tipping bucket rainfall station was installed at the *kaupule*, with technical support provided to the *kaupule* on the operation and management of the station. The rainfall station is critical for better understanding the long-term management and development of freshwater supply systems, especially in regards to rainwater harvesting and the recharge of groundwater resources. Long-term management of the rainfall station is currently setup to be a collaborative exercise between TMS and the Vaitupu *kaupule*. On a day-to-day basis it is proposed that the rainfall station will be maintained by the *kaupule*, with the data to be transferred on a regular basis to TMS for processing and archiving. TMS will also undertake annual calibration of the rain gauge.

The well survey results indicate that in the past, groundwater has been used generally for non-potable purposes, such as washing, bathing, toilet flushing and pigs. The exception to this is during droughts when, in the absence of alternatives, it is relied on as a backup for all uses, including potable needs.

In total, 16 wells were surveyed, and their salinity measurements indicated that fresher groundwater is found towards the northern end of the island, 3 km distance from the village. This distance from village to the fresher groundwater has been a limitation in the development and use of groundwater on Vaitupu. Groundwater at the village and at Motufoua School is brackish, and its potential use for purposes apart from a source for desalination or toilet flushing is limited.

Pressure transducer loggers, installed within the wells provides valuable insight on the spatial variability of tidal impacts and aquifer–ocean connectivity. There is no clear correlation between the distance from the coast and the connectivity of the aquifer with the ocean, suggesting that the underlying geology is more complex and has greater heterogeneity than originally expected. The higher connectivity with the tides occurs towards the south end of Vaitupu at Motufoua School, while lower connectivity is found in the north, corresponding with thicker reserves of fresh groundwater occur there.

Sampling of wells for bacteriological analysis provides useful insight into groundwater quality, well design, and existing land-use activities. The majority of the wells sampled indicate moderate to high bacteriological contamination. At the village and the school the contamination appears associated with nearby anthropogenic activities such as settlements, waste disposal and land-use activities. Additional factors influencing the water quality is where structures have little protection from the ingress of surface water such as parapets, well covering or well aprons, which help prevent direct contamination from the wells to the groundwater.

Sampling of rainwater harvesting systems for bacteriological analysis indicated that the communal systems are well maintained, with no major contamination issues identified. Private systems indicated poorer water quality, suggesting the need for ongoing educational activities to inform the community about the benefits of maintaining rainwater harvesting systems in good order, including screens for inlets and outlets, and regular inspection and cleaning of gutters and storages.

Geophysical surveys identified the location and extent of the freshwater lens on Vaitupu. The usable freshwater lens is restricted to the northwestern area of the island. An area of greater freshwater thickness appears to be elongate in shape, with a strike NNE–SSW over 600 m long, and 100 m wide. The freshwater lens is interpreted as being limited by relatively low resistivity, suggestive of higher permeable geology saturated with high saline water at shallow depths across most of the island. This geological feature is suggested to be an erosive shallow limestone boundary, possibly as shallow as 4 m. The development of a freshwater lens appears restricted to areas of thicker, unconsolidated and less permeable unconsolidated sand sediments.

Empirical studies, as well as analytical analysis using WATBAL, and compared against numerical modelling results for similar environment in Kiribati, suggests that conservatively, the average annual recharge is as high as 60% of rainfall. Following on from this recharge estimation an acceptable long-term volumetric abstraction, under average rainfall conditions, suggests that 30% of rainfall (i.e. 50% of recharge) should be achievable (62 m^3/d), noting that natural rainfall variation will impact on recharge volumes in any given month

It is recommended that given the varying recharge that can be expected and the dynamic nature of groundwater in atolls, sustainable management of a groundwater system should focus on salinity water quality to guide abstraction. This approach requires the community to consider the level of salinity it is prepared to accept under different conditions, which will guide the volume of water that is abstracted in any given month, rather than consider sustainable management refers to maintaining a fixed abstraction volume. For example, during an extended drought, the community may be willing to: i) accept a slight increase in salinity of its domestic water in order to maintain a certain volume of water, or ii) reduce the volume of abstracted water to ensure lower salinity levels, and fresher water quality is maintained. The second approach requires monitoring the pumping well and gallery, and rainfall. Based on the observed relationship, it is possible to provide guidelines that allow either a reduction or increase in the volume pumped, in pre-defined fixed amounts, depending on the salinity of the well.

Where groundwater is relied on as a potential water source for day-to-day use, or where it is used as a drought reserve, then significant benefits can be achieved for the operation and management of groundwater through the long-term monitoring of rainfall, pumping, and groundwater quality. Periodical and long-term monitoring of groundwater provides useful information on the behaviour of the groundwater system and changes in groundwater quality in response to climate variability over time.

Freshwater on Vaitupu is currently provided to most of its population by rainwater harvesting. Rainwater harvesting is capable, with the high rainfall received on Vaitupu, of meeting most of the current demands of the population during average or above-average conditions. However, during times of reduced rainfall or drought, access to freshwater is reduced and fresh water shortages are experienced creating sustained hardship for many people. The occurrence of a useful thickness of fresh groundwater in the northern part of the island provides Vaitupu with an opportunity to develop this resource as a viable potential drought reserve to the benefit the larger community of Vaitupu.

As part of the *kaupule*'s strategy for water security on Vaitupu, the development of the thicker freshwater lens in the northwestern part of the island would best be developed with an infiltration gallery constructed in the thickest part of the freshwater lens, pumping to a header tank that could pipe water towards a cistern located either at the Vaitupu primary school or hospital compounds.

5.1 Recommendations

A fresh groundwater resource of useful and viable extent has been identified in the northern part of Vaitupu. The groundwater extent, while limited in size, can be developed as a drought reserve for use in times of reduced rainfall and limited freshwater, or as an ancillary alternate freshwater supply to harvested rainwater. Given the isolation of Vaitupu from alternate freshwater sources, the development of the groundwater resource as a drought reserve is recommended with regards to improved water security and drought resilience.

Following on from the recommended development of the assessed available fresh groundwater resources, the following measures are recommended.

- Maintain daily rainfall records to assist with the development and management of water sources. Further, it is recommended that rain gauges be installed across all habitable islands of Tuvalu to extend the existing network.
- Increase effort to educate the community on the benefits of maintaining efficient and clean water storage systems. In addition, educate communities that rely on groundwater of the potential for contamination from inappropriately designed wells, and in appropriate land-use practices.
- Consider developing a drought response plan that may include the following:
    - triggers and operational rules for the rationing of communal rainwater storages;
    - development of the groundwater resource identified in the northwestern part of Vaitupu as a drought reserve using horizontal galleries to maximise fresh groundwater potential;
    - give consideration to operational rules that manage abstraction during drought periods with consideration to rainfall, salinity and pumped volumes.

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Annex A - Monthly rainfall records Vaitupu, Tuvalu

VAITUPU RAINFALL (mm)																	
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**	**May - Nov**	**Dec- Apr**	**Funafuti annual rainfall**	**% difference Vaitupu to Funafuti**
1941	369.4	286.2	299.4	251.2	223.5	198.8	210.5	223.2	386.8	140.5	270.3	298.2	**3158.0**	1654	1504	3077	3%
1942	520.2	719.6	182.6	243.1	182.9	218.7	280.9	195.1	213.4	159.3	114.6	512.1	**3542.5**	1365	2178	3748	-5%
1943	215.9	130.6	111.5	175.5	154.7	198.8	210.5	223.2	175.1	171.0	181.0	320.7	**2268.5**	1314	954	3341	-32%
1944																4190	
1945																3067	
1946																3239	
1947																2860	
1948	627.5	445.5	230.4	357.6	168.3	216.3	215.5	410.3	275.6	246.8	411.9	388.1	**3993.8**	1945	2049	3660	9%
1949	613.1	380.9	378.1	174.9	113.5	283.2	142.8	214.2	389	201.9	256.8	279.5	**3427.9**	1601	1827	3610	-5%
1950	80.1	301.5	19	168.2	140.6	167		70.3	30.8	61	290.5	384.9				2614	
1951																2604	
1952																3654	
1953																4545	
1954																3467	
1955																4182	
1956																2959	
1957																4676	
1958					455.8						403.9					4656	
1959										418.2	229.1					4029	
1960	455.8	658.8	211.7	260.6	296	148.8	229.8	420.1	220.6	250.7	225.5	187.1	**3565.5**	1792	1774	3889	-8%
1961	491	366.3	911.5	262.9	301.2	230.8	221.1	66.2	160.2	404.3	342.1	231.4	**3989.0**	1726	2263	3895	2%
1962	193.7	316.4	75.5	123.7	132.9	95.5	40.1	55.3	109.9	217.5	132.3	509.8	**2002.6**	784	1219	2474	-19%
1963	162.5	65.8	202.1	196.9	97.2	243.9	172.7	237	185.8	66.6	159.3	370.1	**2159.9**	1163	997	2678	-19%
1964	483.5	423.5	255.2	130.4	88.9	188.9	129.5	39.9	37.3	33	493.3	156.7	**2460.1**	1011	1449	3227	-24%
1965	122.8	188.7	180.4	333.8	187.7	189.8	223.3	428.6	403.8	331.5	590.9	214.3	**3395.6**	2356	1040	3725	-9%
1966	381.1	296.2	239.5	271	247.6	243.9	277	308.3	103.5		275.1	552.2				3891	
1967	309.5	332.7	197.1	438.9	180.6	235.6	209.3	177.5	167.3	153	323.1	309.6	**3034.2**	1446	1588	4221	-28%
1968	295.9	455.4	280.5	164.2	171.4	149.1	137.2	120.9	224.4	179.7	421.5	136.4	**2736.6**	1404	1332	3128	-13%
1969	186.3	284.8	114.8	218.3	506.2	219.4	240.4	435.1	217.6	215.8	327.4	333.7	**3299.8**	2162	1138	3720	-11%
1970	511.3	626.5	412.5	407	266.4	295.1	123	363.7	295.2	277.4	183.4	433.2	**4194.7**	1804	2391	4832	-13%
1971	80.9	96	62.1	20.5	40.9	8.5	129.1	99.7	3.5	245.7	345.2	496.1	**1628.2**	873	756	2226	-27%
1972	340.9	77.6		226.6	168.1	115.6	168.9	182.4	468.1	557.4	275.8	316.2				2583	
1973	297.6		241.4	175	301.6	372	133.3	367.1	17.6	259	190.3	531.2				3989	
1974		82.1	94.7	69.9	23	77.4	115.4				233	229.6				2842	
1975	142.9	33.6	68.5	52.4	90.6			117.3		35.4	190.3	213.1				2858	
1976	236.7	139.4	230.4	189	134.8	129.5	59.1	63.4	59.5	176.6		477.9				2472	
1977			409.8		364.8							216				3790	
1978	411.5	437.1	280.5	322.6	206.7	212.4	158.2	335.8	192.3	100.4	468.1	431.9	**3557.5**	1674	1884	2980	19%
1979	418.9	214.6	285.6	228.1	257.3	92.4	158.7	135.5	206.9	308.8	316.3	420.6	**3043.7**	1476	1568	3083	-1%
1980	231.6	506.8	482.1	145.7	337.5	166.2	95.1	178.8	283.7	212.2	412.1	379.8	**3431.6**	1686	1746	3591	-4%
1981	246.2	724.3	293.4	496.4	251.3	216.9	205.5	247.1	242.9	47.4	177.1	511.1	**3659.6**	1388	2271	3855	-5%
1982	249	443.9	332.7	133.1	199.3	135.3	67.5	257.3	401.6	259.2	215	335.8	**3029.7**	1535	1495	3432	-12%
1983	1158	487.5	492.8	151.5	191.6	283.3	339.5	514.1	204.7	170.2	130.3	335.4	**4458.5**	1834	2625	3994	12%
1984	120.3	364.6	628.1	161.4	182.8	228.3	396.8	258.9	139.8	205.9	199.6	658.7	**3545.2**	1612	1933	3990	-11%
1985	645	88	617.9	208	238.4	178.8	197	170.1	108.5	173.6	201.7	207.7	**3034.7**	1268	1767	2891	5%
1986	511.9	242.9	171.2	272.6	316	127.3	280.5	151.1	111.4	145.9	126.3	313.2	**2770.3**	1259	1512	3505	-21%
1987	342.9	675.8	388.3	337.8	550.3	225.1	642.4	432	400.2	573.2	187	436.6	**5191.6**	3010	2181	4172	24%
1988	386.2	512.4			321.4	187.7	466.7	372.5	80	277.7	135.9	110.2				3732	
1989	357.9	148.4	349.9	226.9	306.6	126.2	97.6	170.8	383.9	161.7		192.5				2936	
1990	610.9	391.8	402.2	160.8	115.1	169.7	196.1	186.3	110.6	191.8	333.8	478.1	**3347.2**	1303	2044	3762	-11%
1991	189.5	683.9	52.3	400.2		161.2		274.9	113	231		180.1				3889	
1992	597.4	388	346.3	409.5	317.7	139.8	188.6			408.6	337.4	482.4				3732	
1993	364.6		390.2	343.7	202	245.8	363.1	212.4	264	390.2	640.8	243.3				4015	
1994	372.4		258.8	156.1	292.6	201.7	227.1	372.4	121	96.6	119.2					3292	
1995	441.1	282.6	291.3			148		317.2	166.3	179.9	364.4	355.2				3923	
1996	53.3			121.3	271.2	193.2	292.7	354.4	199.5	55.7	159.2	270.8				2930	
1997	440.8	283.3	859.8	131.5	259					296.9	168.9					5141	
1998																4135	
1999																	
2000																2409	
2001					289.9	143.1										2442	
2002																	
2003																	
2004																	
2005																	
2006																	
2007																	
2008																	
2009																	
2010																	
2011	130.9	135.5	97.4	141.2	151.8	122.4											
2012																	
2013																	
2014																	
2015						146	134										
2016	3	507	263	336.5	371	227	364.5										

146 rainfall record for the month is incomplete

No rainfall record observed for the month

STATISTICS FOR FULL PERIOD, 1941 - 2001														
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Mean	350	347	295	228	232	185	214	244	202	221	275	344	**3,210**	**Mean**
Std Dev	211	195	194	109	112	65	117	125	121	126	128	131	772	**Std Dev**
Cv	0.60	0.56	0.66	0.48	0.48	0.35	0.55	0.51	0.60	0.57	0.46	0.38	0.24	**Cv**
Max	645	724	912	496	550	372	642	514	468	573	641	659	5,192	**Max**
Min	53	34	19	21	23	9	40	40	4	33	115	110	1,628	**Min**
Median	350	333	263	208	215	189	201	223	192	204	245	335	3,347	**Median**
No. Years	44	41	43	43	46	45	40	40	39	42	42	42	27	**No. Years**

overall average	-8%
std deviation	14%
median	-9%
maximum	24%
minimum	-32%

Annex B - Rainfall data download and exchange instructions

Basic steps to downloading from ML 1 logger

1. Connect the ML1 logger to the PC using the serial cable to the serial port (or serial/USB adapter in case of USB ports).

2. Open WinComLog.

3. Click on status (this gives the information about the data logger). Check all status items are correct.

4. Record the logger time, your actual time and battery voltage from the status on your rainfall logsheet. Also note the tip size.

5. Click on Start Capture.

6. Select CSV 2 as your file format from the dialog box that comes up.

7. Select location to save to, type a name to the file e.g. 91638_20150610_RAW (station name and download date). Note both the location (directory) and the file name on the logsheet.

8. Click on Dump Rain. On your screen you will see all the times a tip occurred listing down. Wait till the logger finishes the download. The process is finished once you see 'End of Record'.

9. Click yes for View plot.

10. Click on Stop Capture (this closes the file).

11. Click on View Plot on the top most left hand corner. Select the appropriate DURN file. This shows the entire rainfall data graph and allows you to check for any significant anomalies that you could make a note of.

12. Click on the Exit at the right hand side bottom corner.

13. Open the CSV file using Notepad and check to see the data has been recorded. The RAW data file should always be retained.

14. To edit data – Open the recently downloaded rainfall data and save as an edited file, eg 91638_2015610_EDIT. txt. Check the file for 6 manual tips in the record. For the first set of 6 manual tips, delete the first five tips of 6 manual tips and replace 0.5 with 0.0 for the 6th tip. Similarly for last set of 6 manual tips at the end, delete five tips and replace 0.5 with 0.0 for the 6th tip. The data is now ready to archive.

15. Open logger file using Wincomlog. If the data has been successfully archived the logger can then be cleared of all data.

    PASSWD=BOMM <CR>
    CLR <CR>
    Y <CR>

16. Check the status of the logger, ensure that time on logger is correct, BV=3.6V, rainfall total = 0.0.
17. Scan a copy of the Site Sheet. Send a copy of the site sheet, the RAW.csv and the EDITED.txt file to SPC's water and sanitation programme's Water Resources Assessment Unit
18. File the rainfall logsheet.
19. Remove the logger and pack it for delivery to Vaitupu. This includes taping one of the fly lead wires to remove the potential for contact with the other fly lead wire, resulting in a spurious event being logged.

For more details and troubleshooting please refer to the Win Com Log Manual

Exchanging ML 1 logger at rain-gauge Vaitupu

This data download operation is carried out monthly, ideally at the beginning of the month, OR, in sync with shipping movements. That is shipping schedule may be every 6 weeks in which case the logger exchange would be carried out the day before the arrival of the ship, assuming a spare logger is available. If no spare logger is available, **no** exchange of logger is required, until a spare logger is provided.

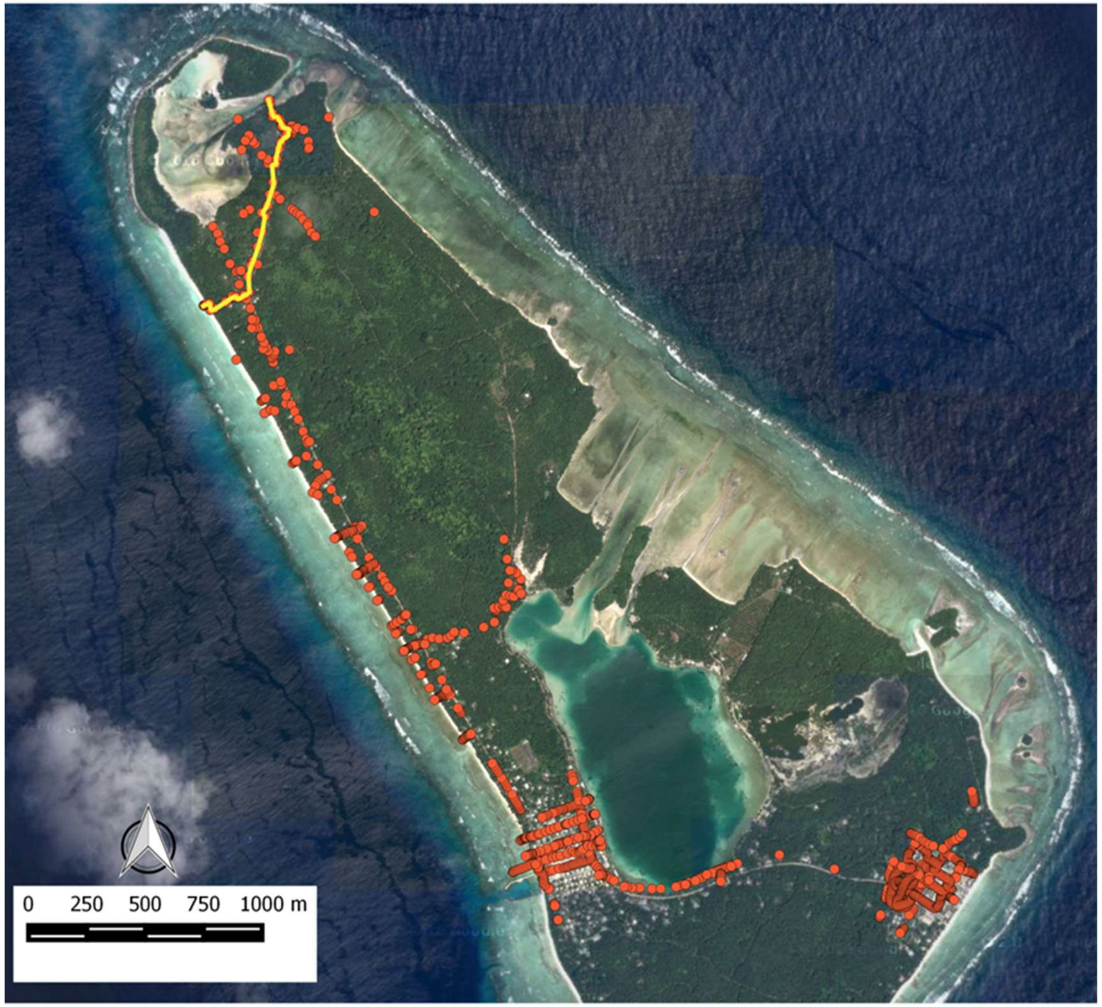
1. Open the rain-gauge cover using the 'allen' key provided.
2. Record on the rain-gauge logsheet the site name (e.g. Vaitupu_91638), tip size of the TB3 bucket (e.g. 0.5 mm).
3. Undertake 6 manual tips, to ensure the logger is operational indicated by brighter flashing red diode on the logger. Record on site sheet number of manual tips performed, the date and time and the logger serial number. For example, 6 tips at 10:20am 09/6/2015 for logger 15_202.
4. Unscrew ML1 logger lead from rain gauge, and tape the black wire of the lead wires to remove the potential for contact with the other fly lead wire, resulting in a spurious event being logged.
5. Attach the leads of new logger to colour marking on the rain gauge, blue wire to the blue marking and black wire to the black marking on the rain gauge with the small screw driver supplied.
6. Once the logger is installed, undertake 6 manual tips to ensure the logger is operational, indicated by brighter flashing red diode on the logger. Check the logger is secured and ready for logging.
7. Record the serial number of the newly installed logger on the rainfall logsheet and the date and time of installation. For example, 6 tips at 10:30am 09/6/2015 for logger 15_203.
8. Record any observations or comments and put in observers initials.
9. Put the rain-gauge cover back on and tighten using the allen key.
10. Pack the logger with a copy of the rain-gauge record sheet and address it to the Director of Meteorology, Funafuti.
11. Deliver to the writer of the ship picking up the new logger from Funafuti.
12. Rain-gauge technician in Vaitupu is to email Tuvalu Meteorological Service in Funafuti to advise that the logger has been sent with the ship's writer along with the name of the writer and the ship that it was sent on. Email (and cc Kaupule); Director of Marine, and Director of Meteorology.

13. Meteorologist is to arrange for pick up of the logger from the ship's writer and ideally meet the ship on its arrival in Funafuti.
14. Meteorology Officer is to arrange transfer of the new logger to the ships writer and inform Vaitupu's raingauge technician by email. Email (and cc Kaupule): Director of Marine, and Director of Meteorology.

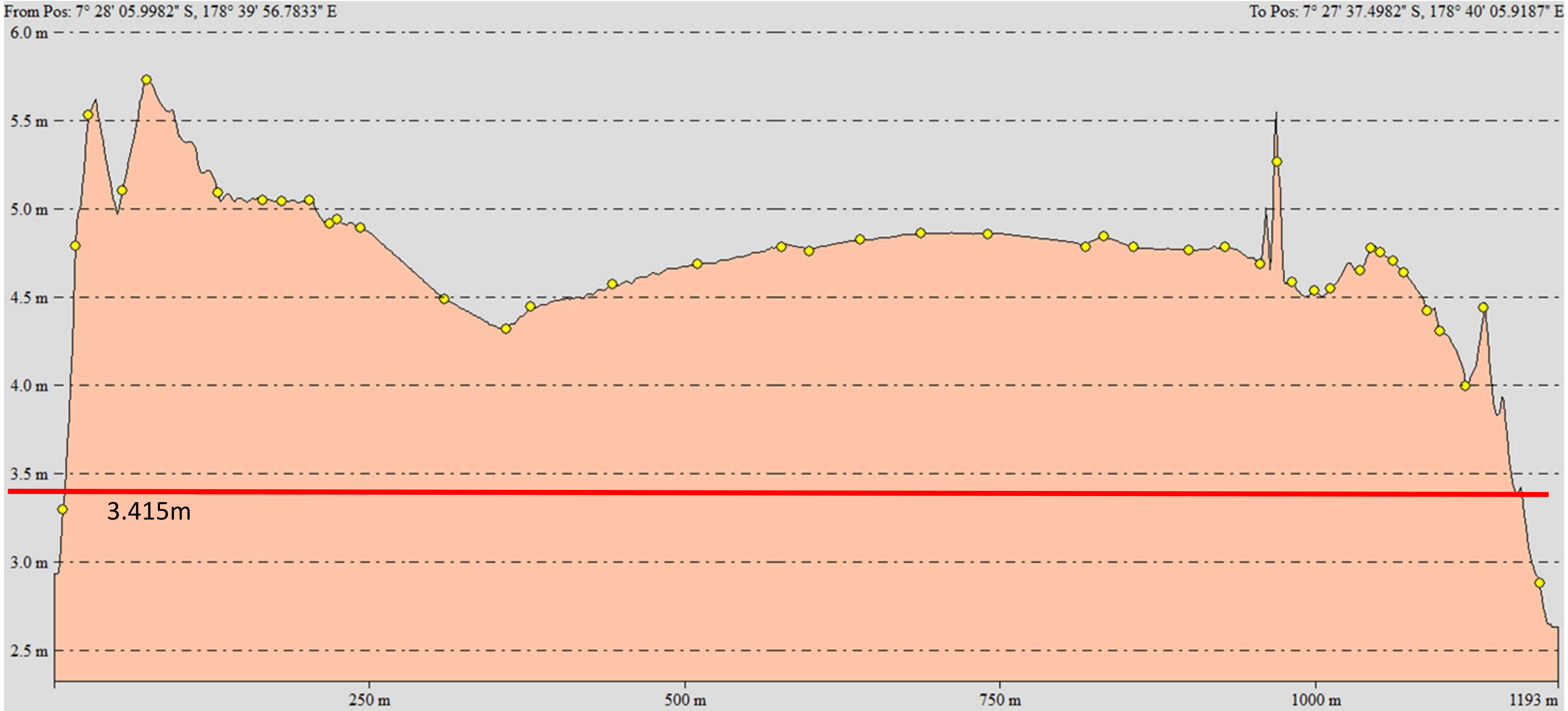
Contacts

- Director of Meteorology, Mr Tauala Katea (tauala.k@gmail.com)
- Climate Officers, Tuvalu Meteorology: Niko Iona (niko.iona@gmail.com)
- Director of Marine email and phone Taasi Pitoi Taasi.pitoi@gmail.com 20054/55 cell 900018
- Captain of vessels, Manu Folau, Nivaga II
- Vaitupu - Raingauge technician: Mr Letia K Tauetia lktauetia@gmail.com
- Vaitupu Kaupule: teapalolo@gmail.com

Annex C – Topographical survey cross sections



Topographical cross section location, Vaitupu.



Cross section across northern Vaitupu. Red line shows highest water level recorded in Funafuti, 3.415 m in 2006. Note the elevation on the Y axis is referenced to Australian Chart datum.

Annex D – Well survey results

Well name	East	North	Abstraction	Use	Casing	Well covering	Para height (m)	Diameter (m)	DTWT (m)	TD (m)	EC Top (mS/cm)	EC Base (mS/cm)	Depth from ground depth (m)	Comments
ALAAE	178.674	-7.481	None	None	Coral Rock	None	0.50	1.7	3.95	4.9	2.06	8.15	4.4	Well located within the old hospital compound. The well is not in used.
JOHN	178.667	-7.465	Bucket/tin	Pigs	Coral Rock	None	0.00	1.2	1.2	1.56	0.85	1.30	1.56	The well is exposed without protection
MOKI	178.668	-7.461	Bucket/tin	Pigs	Unlined	None	-0.76	1.5	0.42	0.82	0.48	0.48	1.24	The well is located in a swale, with para height below ground level.
SEUGA	178.668	-7.465	Bucket/tin	Washing/ bathing	Coral Rock	None	0.50	1.88	2.79	3.16	0.44	0.44	2.66	
SIAKI	178.678	-7.472	Bucket/tin	Washing/ toilet	Coral Rock	None	0.00	2.2	2.14	2.27	2.92	3.16	2.27	The well is exposed without protection
TAFUE	178.668	-7.464	None	Only in droughts	Coral Rock	None	0.60	1.38	2.94	3.28	0.50	0.52	2.68	
TALAI	178.680	-7.488	Bucket/tin	Washing/ bathing	Cement	None	0.68	1.17	1.92	2.29	0.48	0.48	1.61	
TAUA	178.668	-7.462	Bucket/tin	Washing/ bathing	Coral Rock	None	0.55	1.3	2.16	2.69	0.53	0.54	2.14	
TEATUKA	178.671	-7.463	Bucket/tin	Washing/ Pigs	Coral Rock	None	0.29	2.21	2.9	3.28	0.46	0.47	2.99	
TEGAO	178.668	-7.470	Bucket/tin	Pigs	Coral Rock	None	0.40	2.3	3.5	4.15	1.09	1.14	3.75	

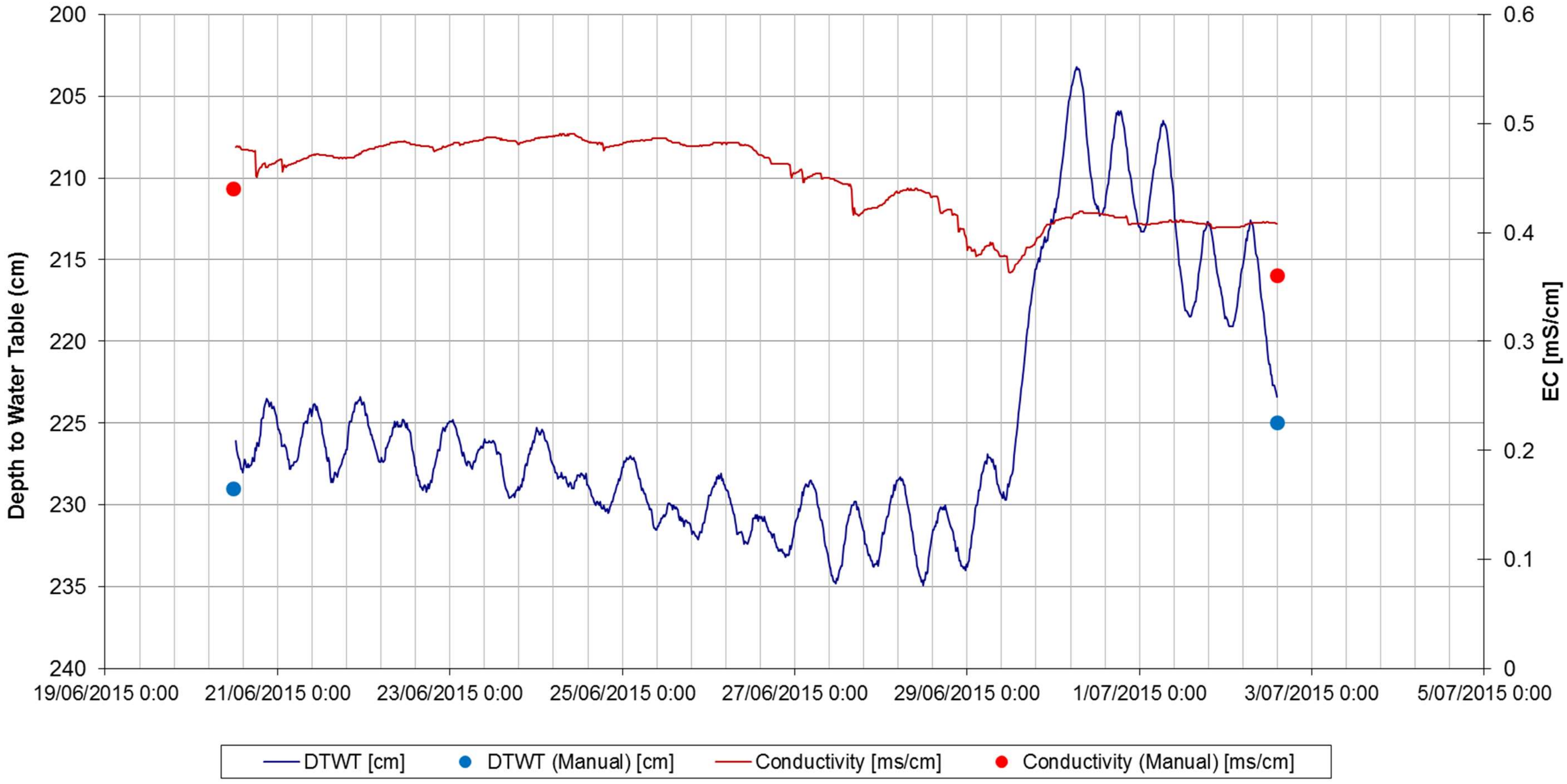
TOGALE	178.669	-7.462	Solar Pump	Drought	Blocks	Metallic cover in good conditions	-1.58	1.38	1.02	1.68	0.52	0.53	3.26	Well managed by Kaupule during droughts. This is the main well used during droughts
VAIMAUA	178.680	-7.487	Bucket/tin	Washing/ toilet	Coral Rock	None	0.28	1.12	1.6	2.14	0.35	0.33	1.86	
LETI	178.677	-7.475	Bucket/tin	Washing/ toilet	Coral Rock	None	0.19	0.84	1.62	1.84	1.01	1.01	1.65	The well is exposed without protection
MOTUFOUA DESAL	178.693	-7.489	Pump	Drought reserve	Cement	Metallic cover in good conditions	0.85	0.8	2.6	3.21	1.20	1.30	2.36	The well feeds water for the desalination plant
BOYS WELL	178.694	-7.489	Pump	Drought reserve	Cement	Metallic cover in good conditions	0.93	0.8	2.91	3.56	1.27	1.28	2.63	
GIRLS WELL	178.694	-7.491	Pump	Drought reserve	Cement	Metallic cover in good conditions	0.60	0.6	3.07	3.76	1.33	1.39	3.16	

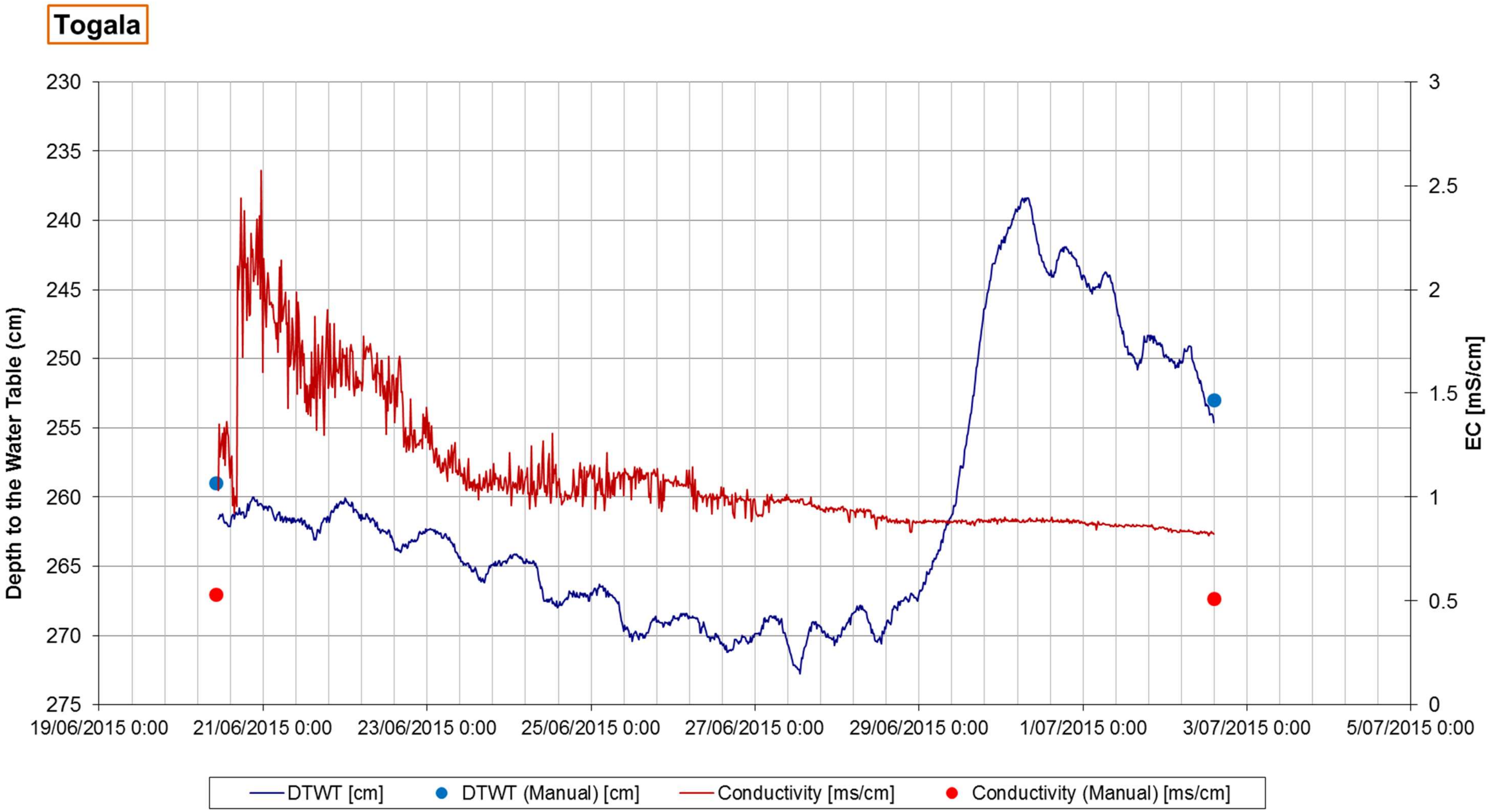
Presence or absence of reef rock for selected wells, Vaitupu.

Well name	East	North	Comments on reef rock presence or absence
ALAAE	178.674	-7.481	NA
JOHN	178.667	-7.465	NA
MOKI	178.668	-7.461	NA
SEUGA	178.668	-7.465	Reef rock present, estimated to be at watertable and 0.3 – 0.4m thick and weathered.
SIAKI	178.678	-7.472	Reef rock present, at or near watertable, fractured in nature
TAFUE	178.668	-7.464	Reef rock absent
TALAI	178.680	-7.488	Reef rock present, at or near water table, estimate 0.5m thick, hard and unweathered
TAUA	178.668	-7.462	Reef rock appears to be absent
TEATUKA	178.671	-7.463	Reef rock appears to be absent
TEGAO	178.668	-7.470	Reef rock present, estimated to be 0.4-0.5m thick
TOGALAA	178.669	-7.462	Reef rock absent
VAIMAUA	178.680	-7.487	Reef rock present, estimated to be 0.2m thick, hard and unweathered
LETI	178.677	-7.475	Reef rock present, estimated to be 0.3 – 0.4m thick, mostly unweathered but "blocky"
MOTUFOUA DESAL	178.693	-7.489	Reef rock present, estimated to be 0.3 – 0.4m thick, mostly unweathered
MOTUFOUA SCHOOL WELL			Reef rock present, estimated to be 0.4 – 0.5m thick, hard and unweathered
BOYS WELL	178.694	-7.489	Reef rock present, estimated to be 0.3 – 0.4m thick, mostly unweathered
GIRLS WELL	178.694	-7.491	Reef rock present, estimated to be 0.4 – 0.5m thick, mostly unweathered

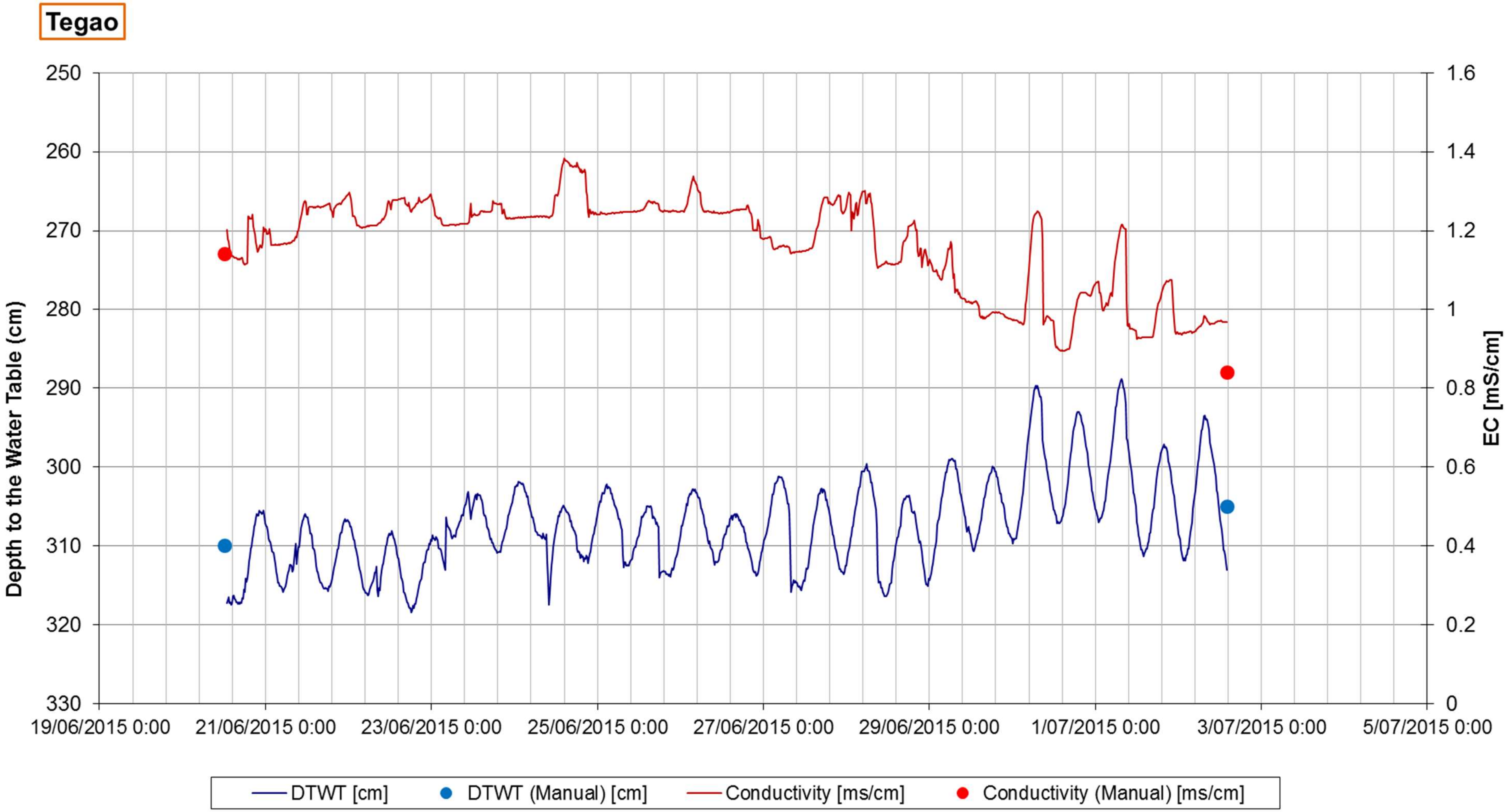
Annex E – Diver logger data, Vaitupu

Seuga

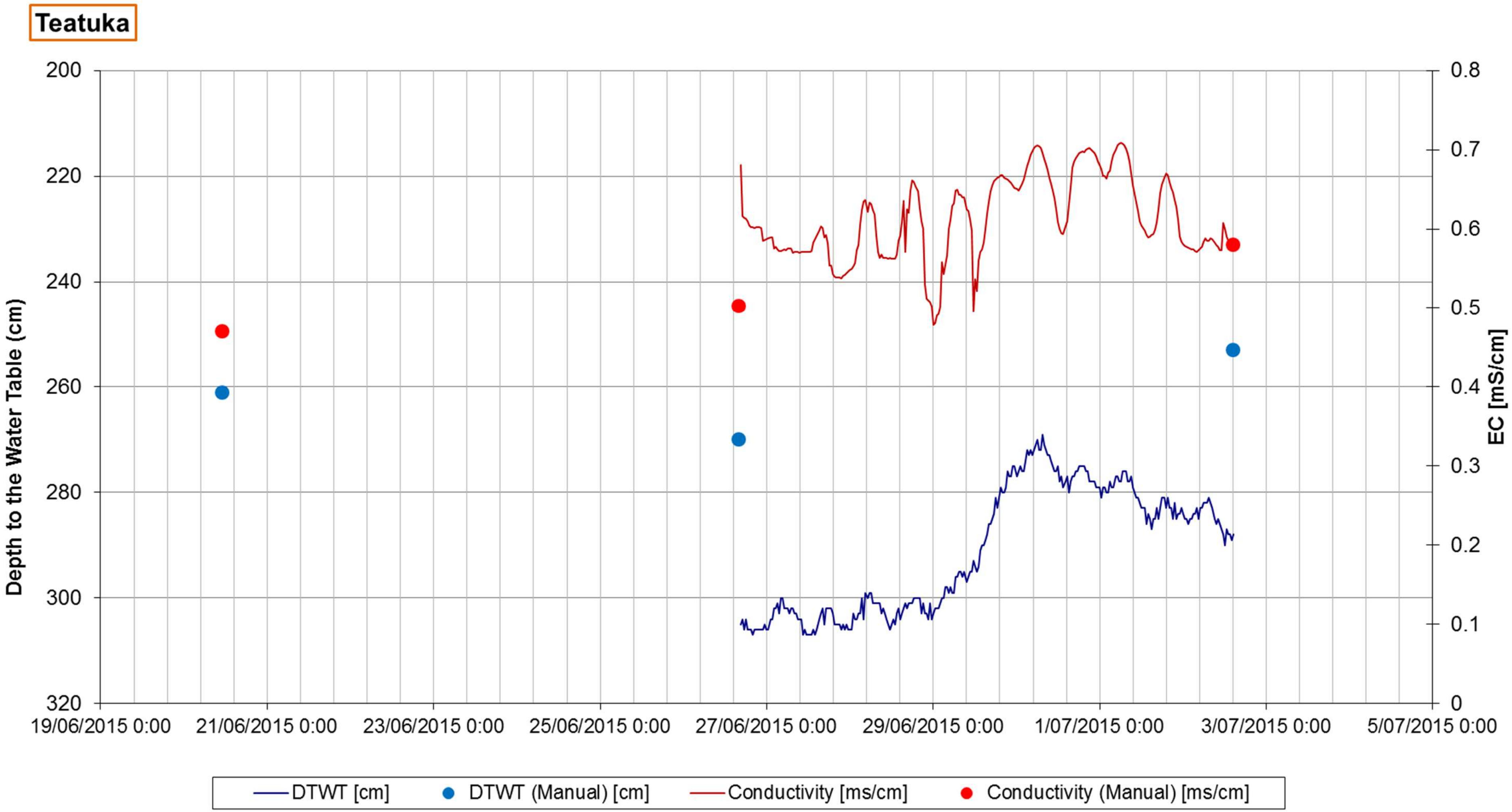




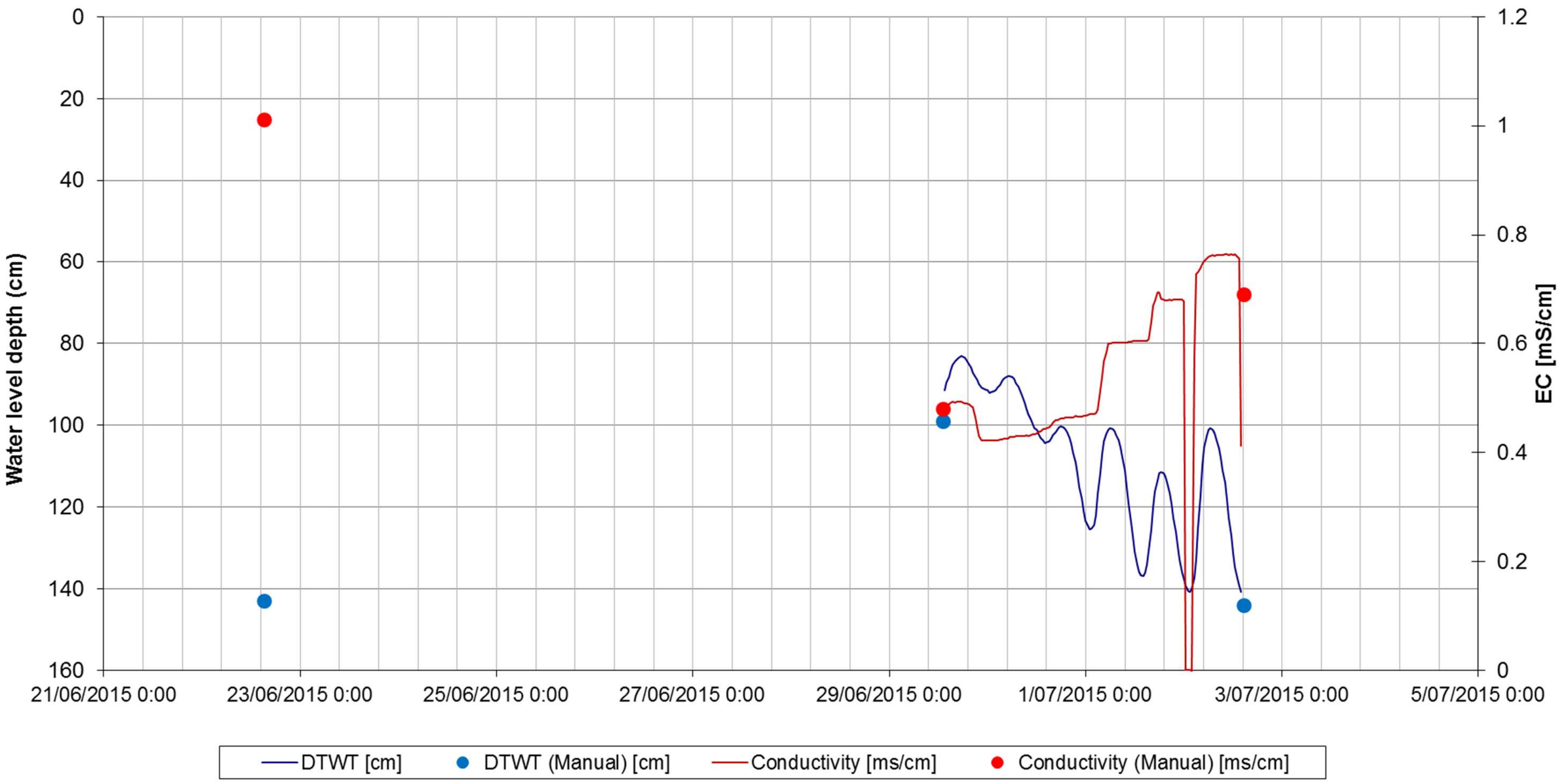
Togala
Depth to the Water Table (cm)
EC [mS/cm]
230
235
240
245
250
255
260
265
270
275
3
2.5
2
1.5
1
0.5
0
19/06/2015 0:00
21/06/2015 0:00
23/06/2015 0:00
25/06/2015 0:00
27/06/2015 0:00
29/06/2015 0:00
1/07/2015 0:00
3/07/2015 0:00
5/07/2015 0:00
DTWT [cm]
DTWT (Manual) [cm]
Conductivity [ms/cm]
Conductivity (Manual) [ms/cm]



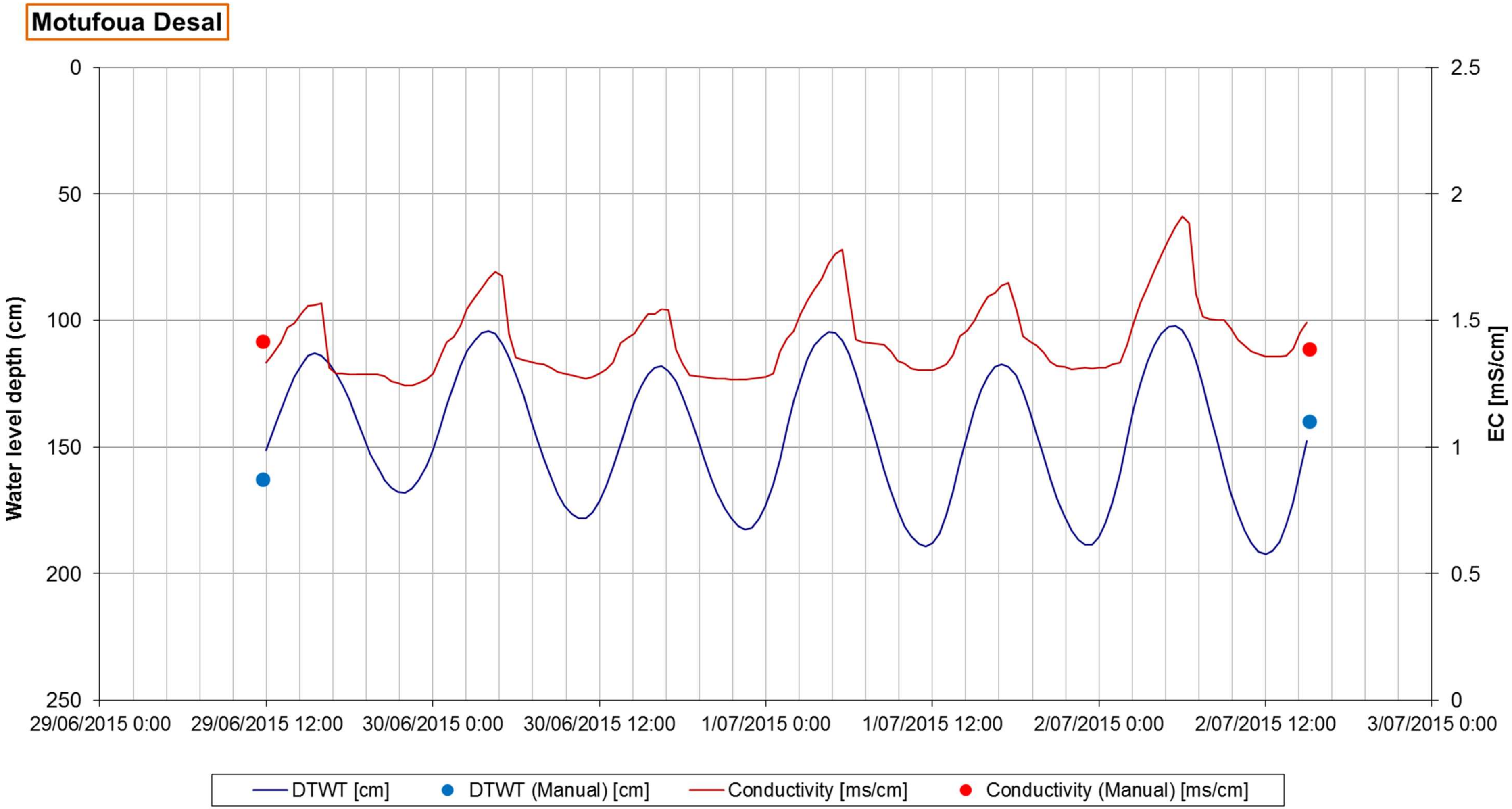
Tegao
Depth to the Water Table (cm)
EC [mS/cm]
250
260
270
280
290
300
310
320
330
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
19/06/2015 0:00
21/06/2015 0:00
23/06/2015 0:00
25/06/2015 0:00
27/06/2015 0:00
29/06/2015 0:00
1/07/2015 0:00
3/07/2015 0:00
5/07/2015 0:00
DTWT [cm]
DTWT (Manual) [cm]
Conductivity [ms/cm]
Conductivity (Manual) [ms/cm]


Teatuka
200
220
240
260
280
300
320
Depth to the Water Table (cm)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
EC [mS/cm]
19/06/2015 0:00
21/06/2015 0:00
23/06/2015 0:00
25/06/2015 0:00
27/06/2015 0:00
29/06/2015 0:00
1/07/2015 0:00
3/07/2015 0:00
5/07/2015 0:00
DTWT [cm]
DTWT (Manual) [cm]
Conductivity [ms/cm]
Conductivity (Manual) [ms/cm]

Leti



0
20
40
60
80
100
120
140
160
Water level depth (cm)
1.2
1
0.8
0.6
0.4
0.2
0
EC [mS/cm]
21/06/2015 0:00
23/06/2015 0:00
25/06/2015 0:00
27/06/2015 0:00
29/06/2015 0:00
1/07/2015 0:00
3/07/2015 0:00
5/07/2015 0:00
DTWT [cm]
DTWT (Manual) [cm]
Conductivity [ms/cm]
Conductivity (Manual) [ms/cm]


Motufoua Desal
Water level depth (cm)
EC [mS/cm]
0
50
100
150
200
250
2.5
2
1.5
1
0.5
0
29/06/2015 0:00
29/06/2015 12:00
30/06/2015 0:00
30/06/2015 12:00
1/07/2015 0:00
1/07/2015 12:00
2/07/2015 0:00
2/07/2015 12:00
3/07/2015 0:00
DTWT [cm]
DTWT (Manual) [cm]
Conductivity [ms/cm]
Conductivity (Manual) [ms/cm]

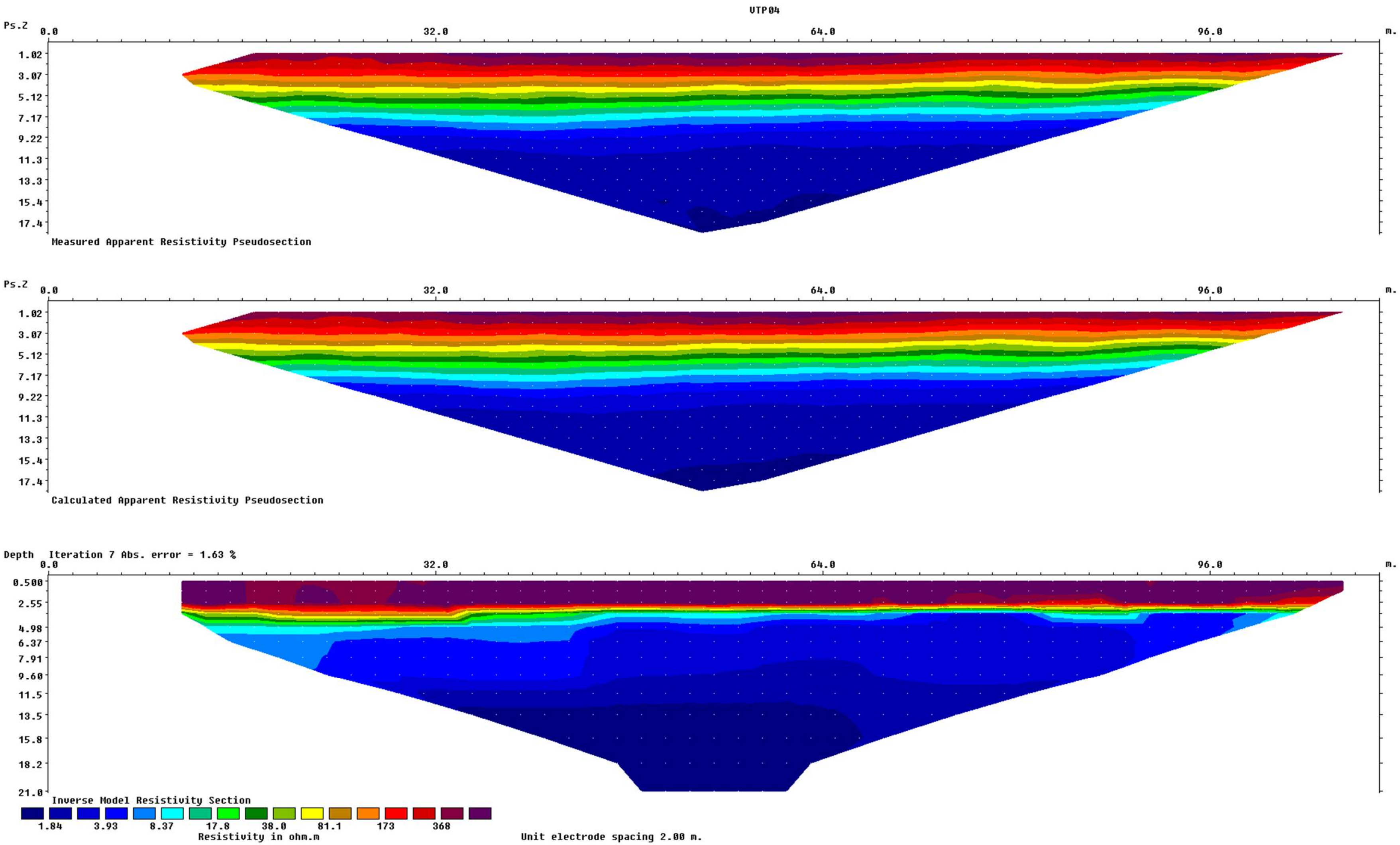
Annex F – Bacteriological sampling results – Groundwater samples

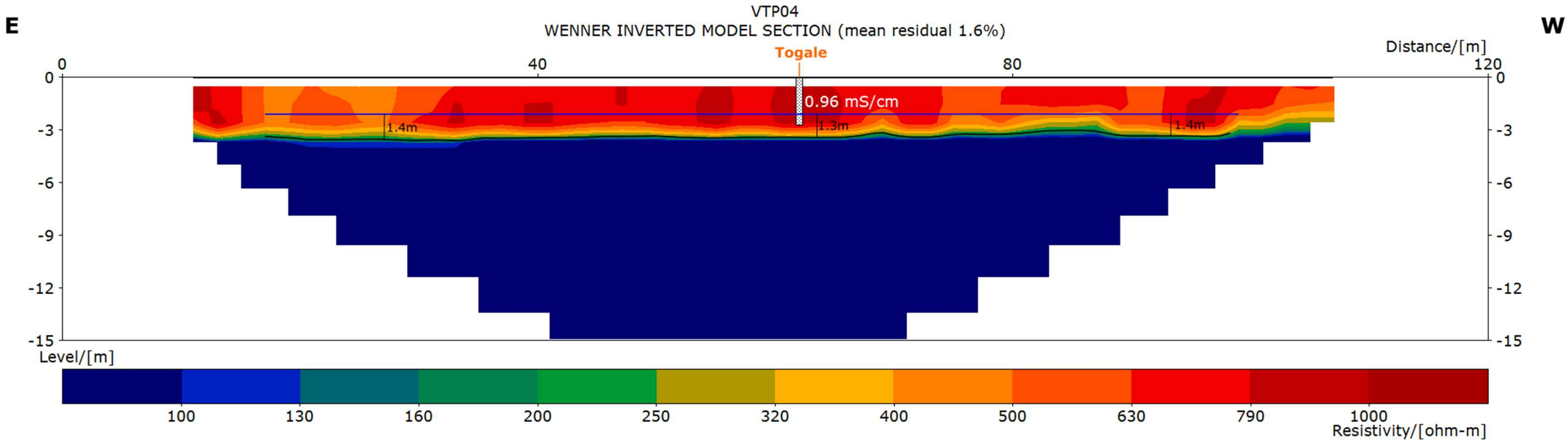
EC compact dry sample		Coliform Calculation					
Groundwater samples	**Date**	1 mL *E. coli*	1 mL Total coliform	50 mL *E. coli*	50 mL Total coliform	*E. coli* count	Total coliform count
Alaae	20/06/2015	0	TNC	46	TNC	23	TNC
John	22/06/2015	0	TNC	232	TNC	116	TNC
Moki	22/06/2015	200	TNC	168	TNC	184	TNC
Seuga	20/06/2015	100	TNC	62	TNC	81	TNC
Siaki	22/06/2015	0	TNC	26	TNC	13	TNC
Tafue	20/06/2015	200	TNC	6	TNC	103	TNC
Talai	20/06/2015	0	TNC	TNC	TNC	TNC	TNC
Taua	22/06/2015	0	TNC	30	TNC	15	TNC
Teatuka	20/06/2015	0	0	32	0	16	0
Tegao	20/06/2015	1900	TNC	TNC	TNC	TNC	TNC
Togalaa	20/06/2015	0	TNC	6	TNC	3	TNC
Vaimaua	20/06/2015	1300	TNC	TNC	TNC	TNC	TNC
Leti	22/06/2015	100	0	110	17	105	9
Motufoua desal	03/07/2015	0	900	TNC	TNC	TNC	TNC
Boys well	03/07/2015	0	700	272	TNC	136	TNC
Girls well	03/07/2015	200	TNC	TNC	TNC	TNC	TNC

Rainwater samples

EC compact dry sample			Coliform Calculation					
Rainwater Harvesting samples	Owner	Date	1 mL *E. coli*	1 mL Total coliform	50 mL *E. coli*	50 mL T. Coliform	*E. coli* count	Total coliform count
Kaupule cistern	Community	25/06/2015	0	0	14	TNC	7	TNC
Manneapa cistern	Community	25/06/2015	0	100	6	TNC	3	TNC
Tumaseu cistern	Community	25/06/2015	0	0	8	TNC	4	TNC
Asau cistern	Community	25/06/2015	300	TNC	TNC	TNC	TNC	TNC
Church cistern	Community	25/06/2015	100	TNC	160	TNC	130	TNC
Church guest house cistern	Community	25/06/2015	0	0	18	TNC	9	TNC
Solomona Maina cistern	Private	25/06/2015	0	900	TNC	TNC	TNC	TNC
Maeli Meemai tank	Private	25/06/2015	0	300	6	TNC	3	TNC
Isaac cement tank	Private	25/06/2015	0	900	6	TNC	3	TNC
Motufoua Desal Cistern	School	03/07/2015	0	4600	32	TNC	16	TNC
Boys Tank	School	03/07/2015	0	TNC	18	TNC	9	TNC
Girls Tank	School	03/07/2015	100	TNC	86	TNC	93	TNC

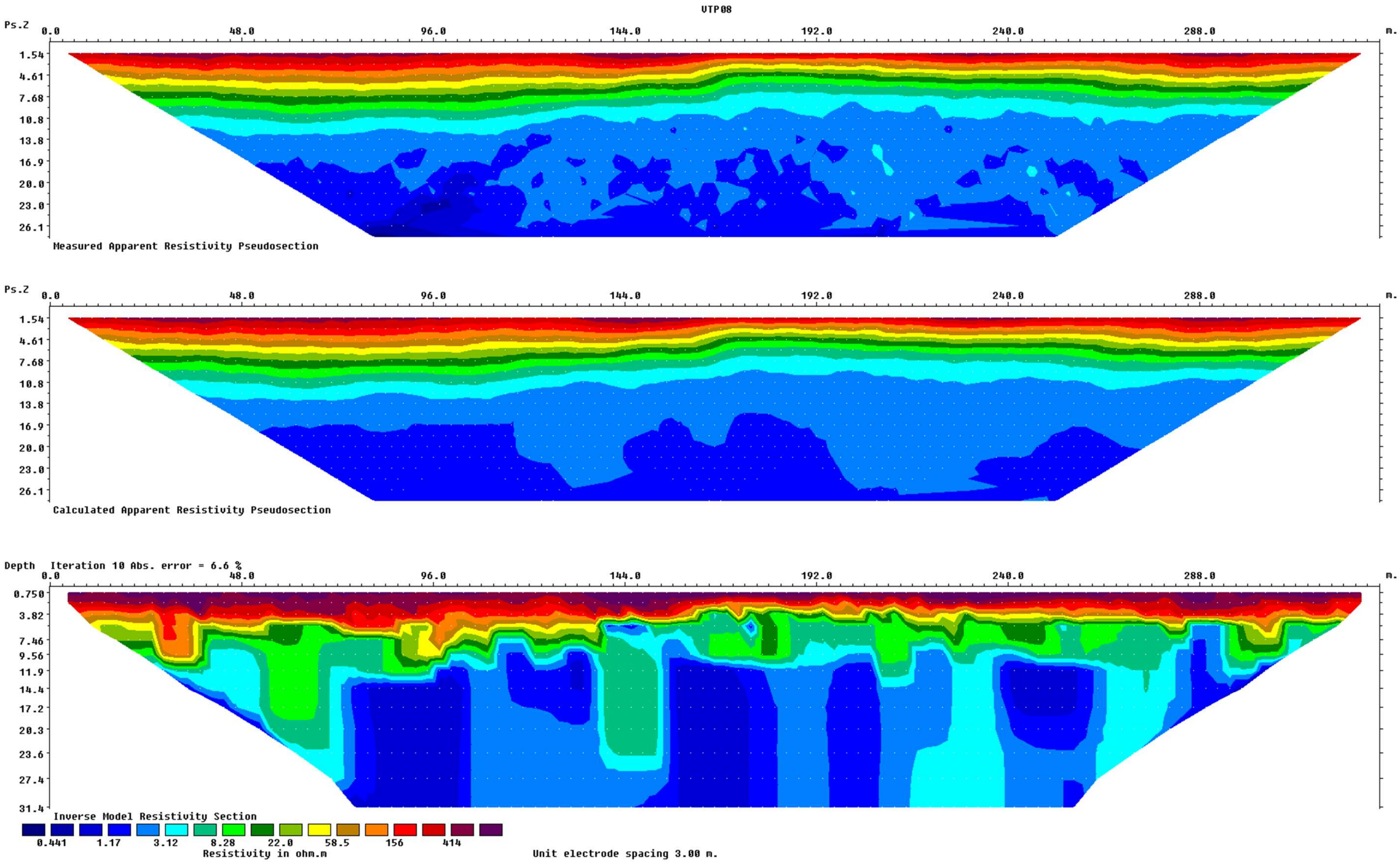
Annex G- Resistivity profile interpretations - VTP04 - Wenner

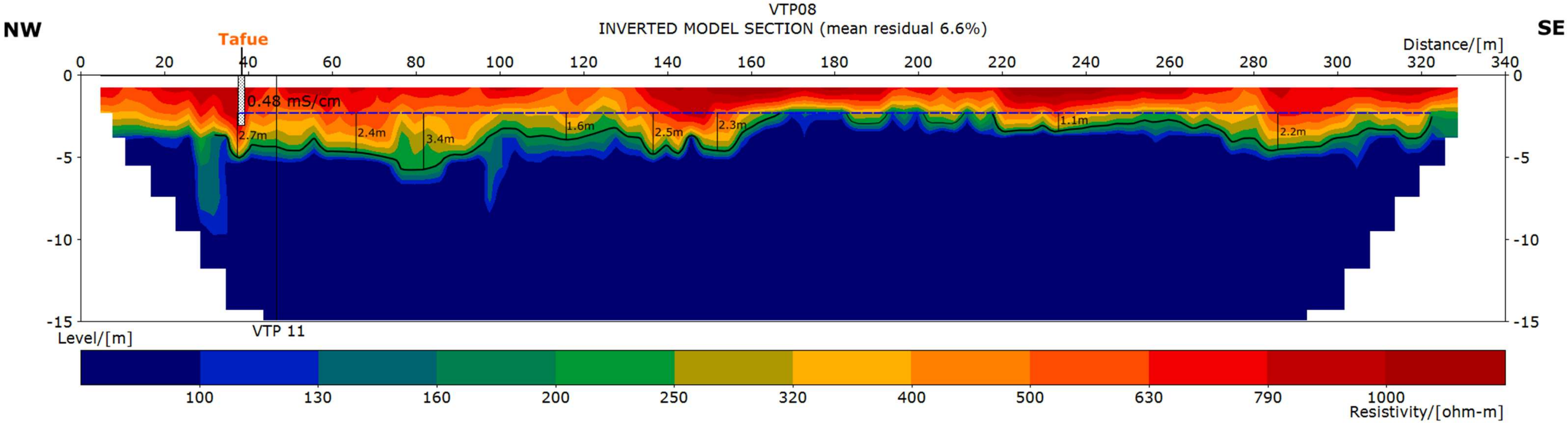




Vaitupu groundwater survey	Survey date: 24 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP04	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 120 m	

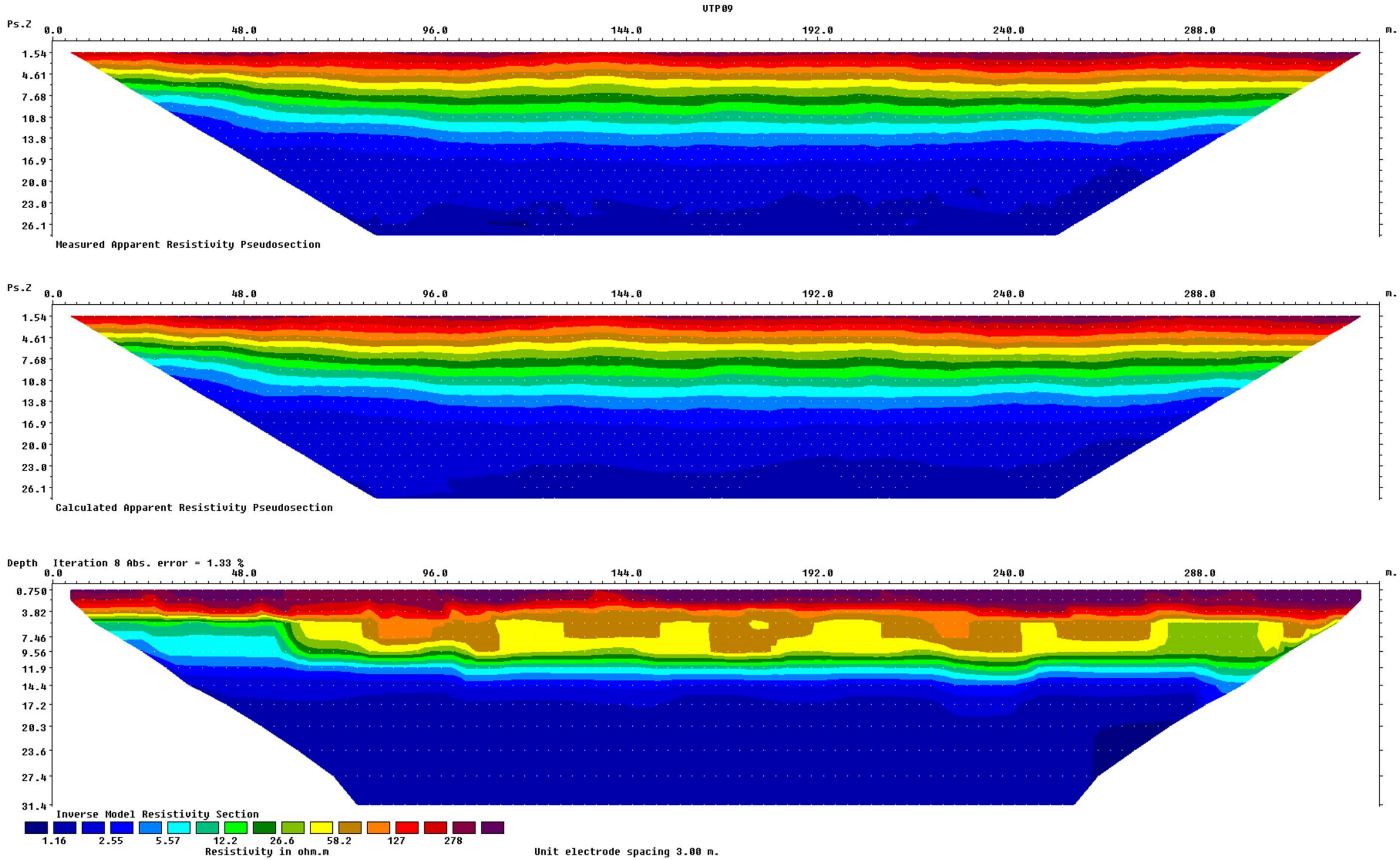
VTP08 - Wenner

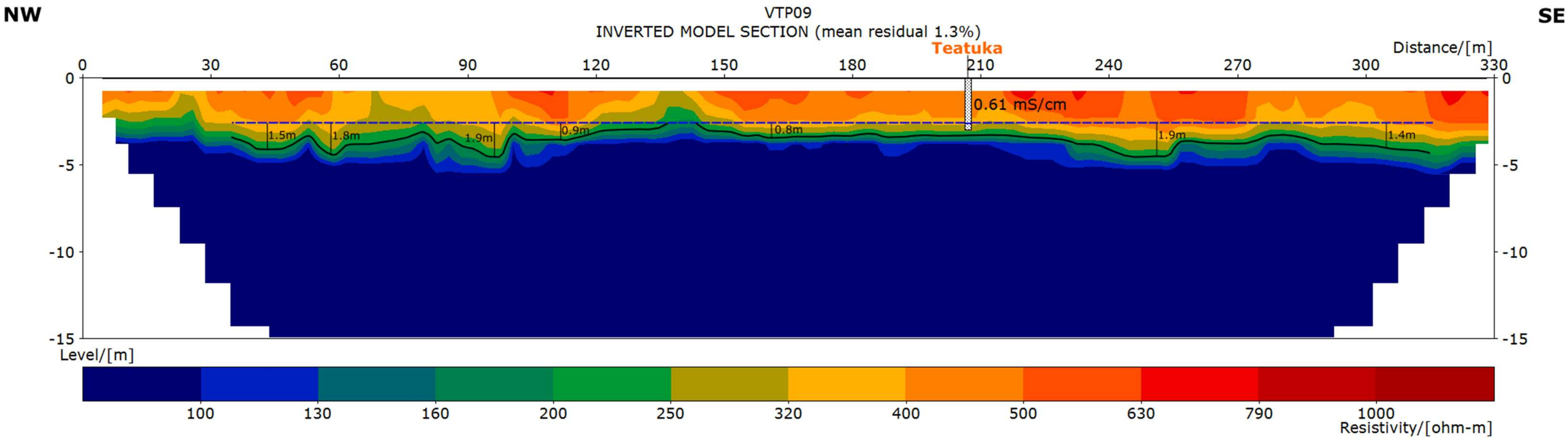




Vaitupu groundwater survey	Survey date: 25 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP08	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohmmeter	Survey length: 320 m	Roll-along survey (1 roll)

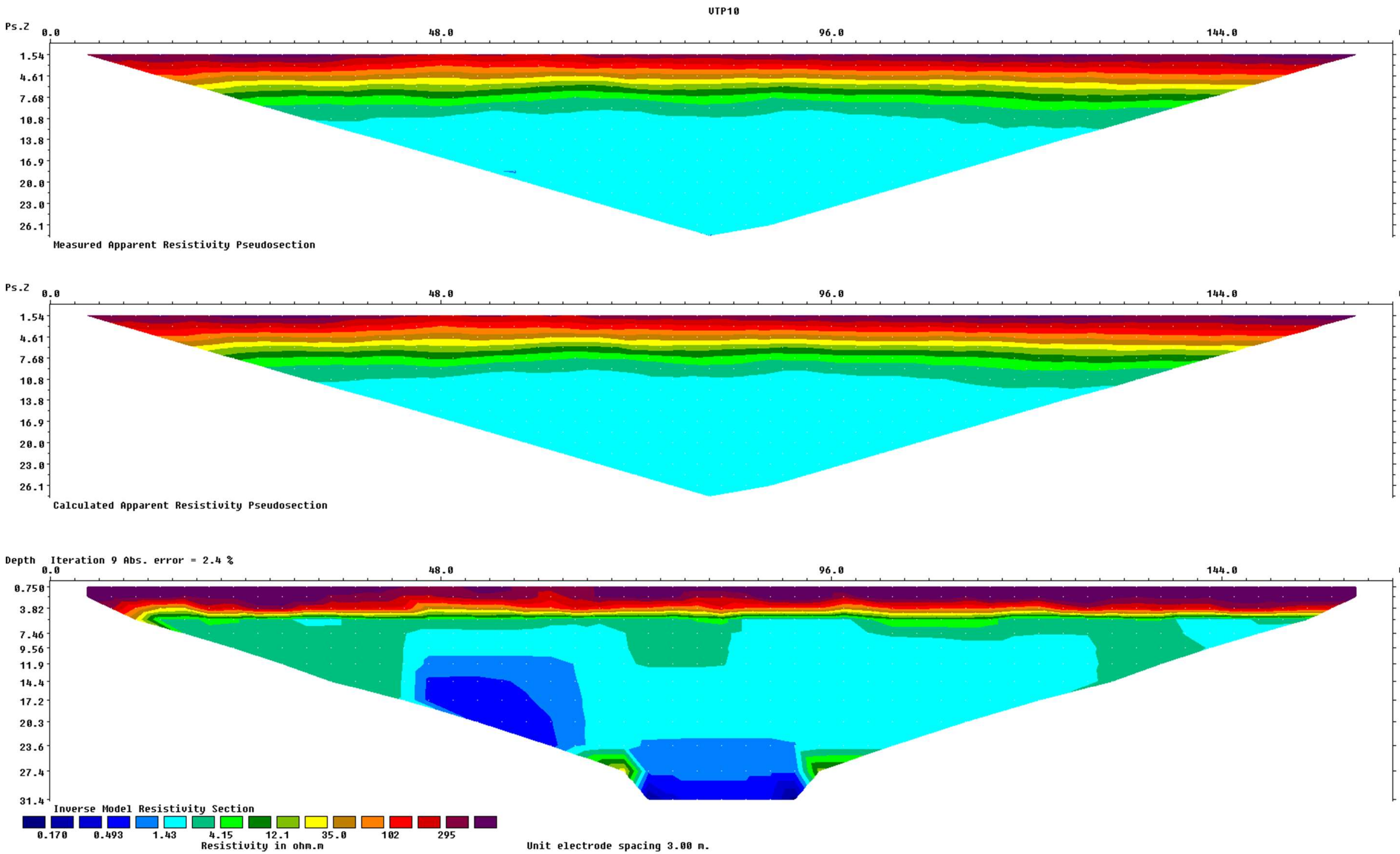
VTP09 - Wenner

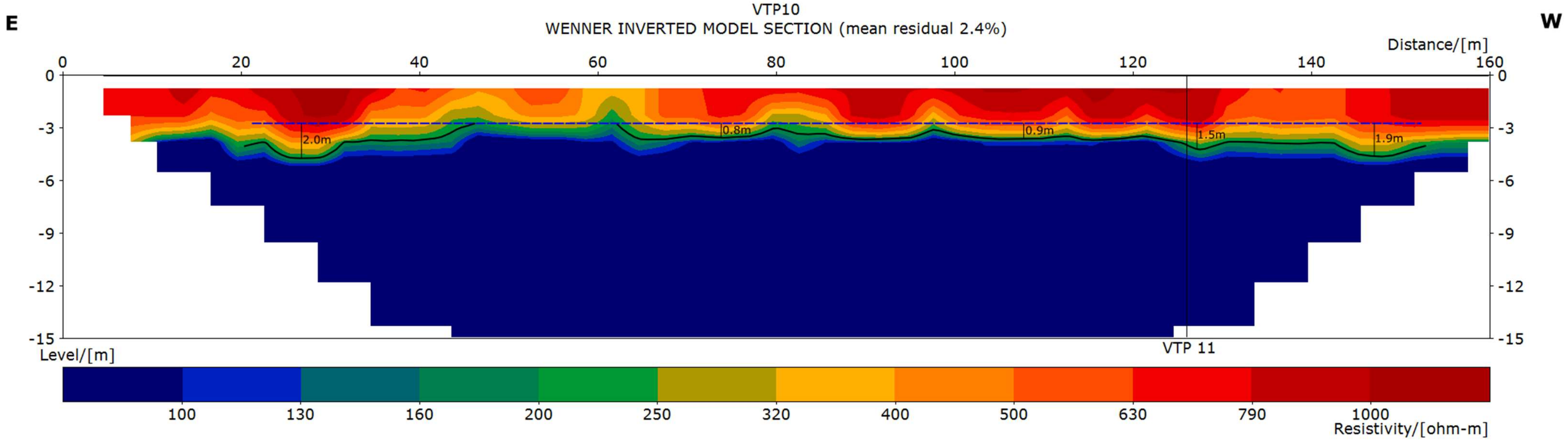




Vaitupu groundwater survey	Survey date: 26 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP09	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 326 m	Roll-along survey (1 roll)

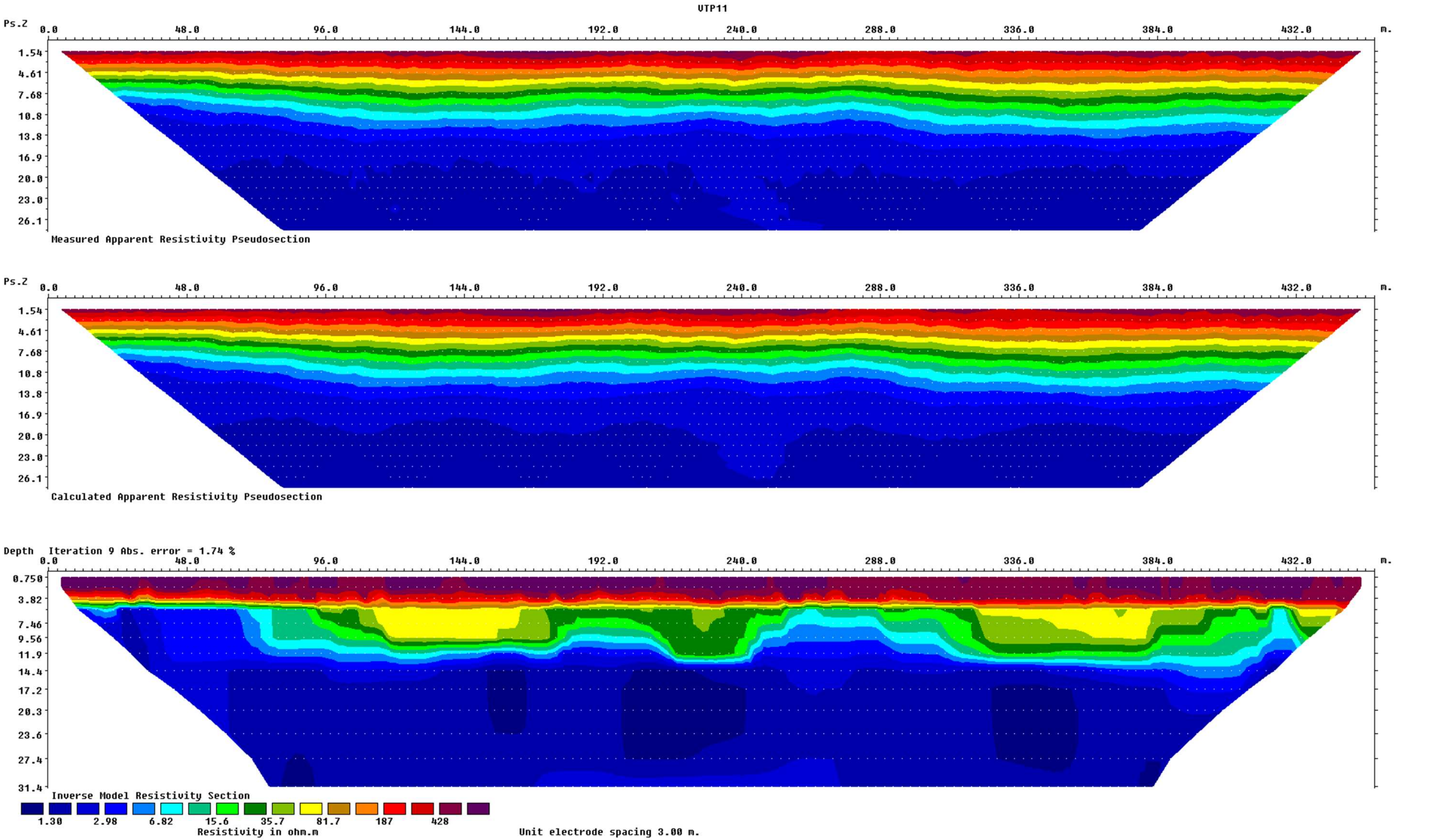
VTP10 - Wenner

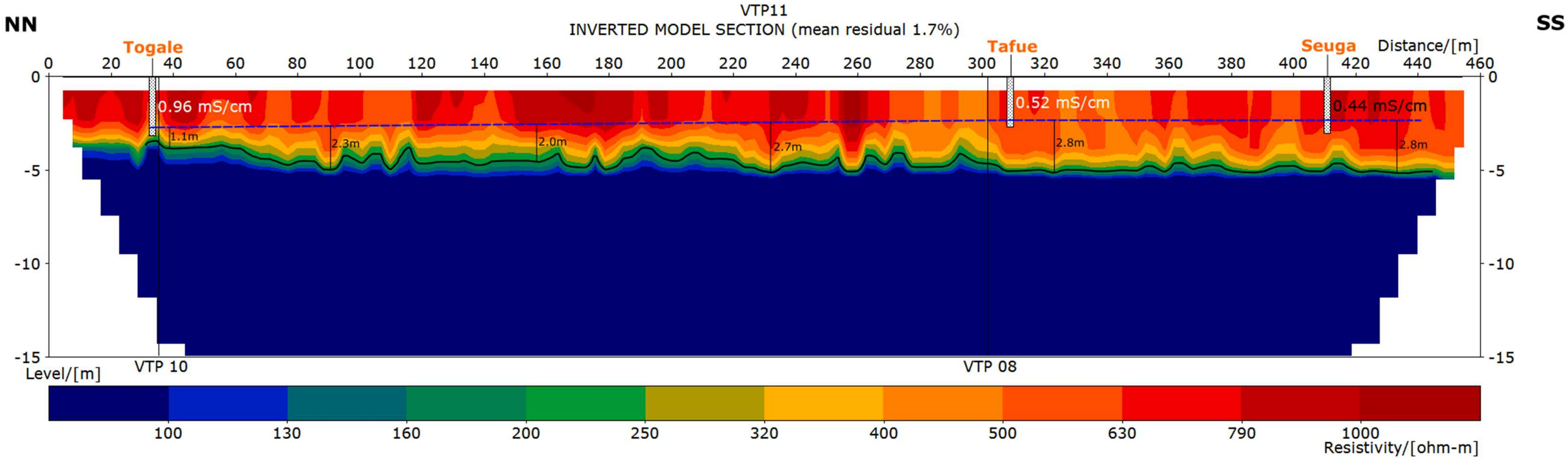




Vaitupu groundwater survey	Survey date: 26 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP10	Array type:	Res2dinvx64 and Erigraph2
Units: eters and ohm-meter	Survey length: 150 m	

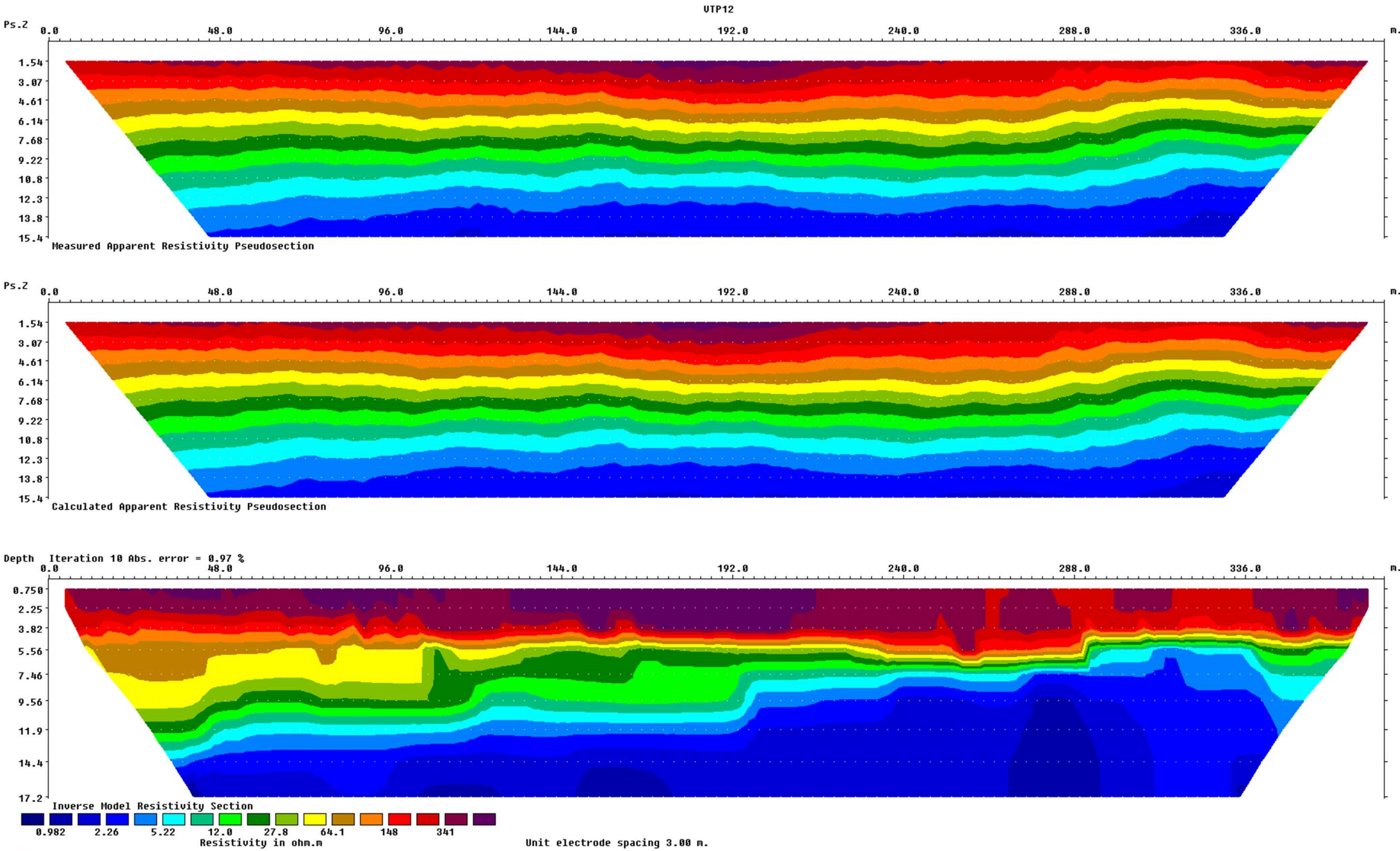
VTP11 - Wenner

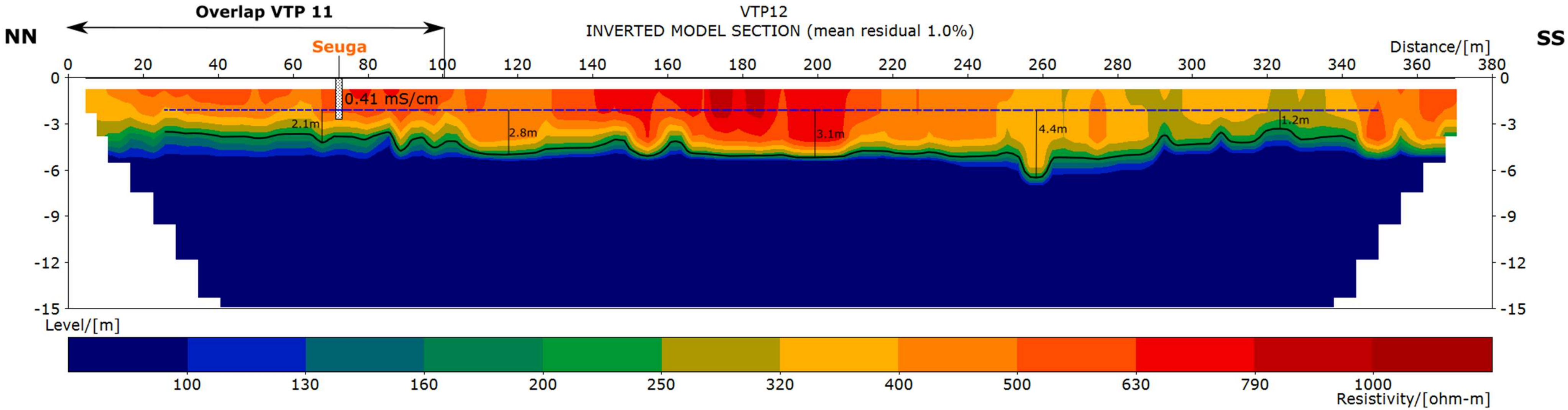




Vaitupu groundwater survey	Survey date: 27 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP11	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 480 m	Roll-along survey (2 rolls)

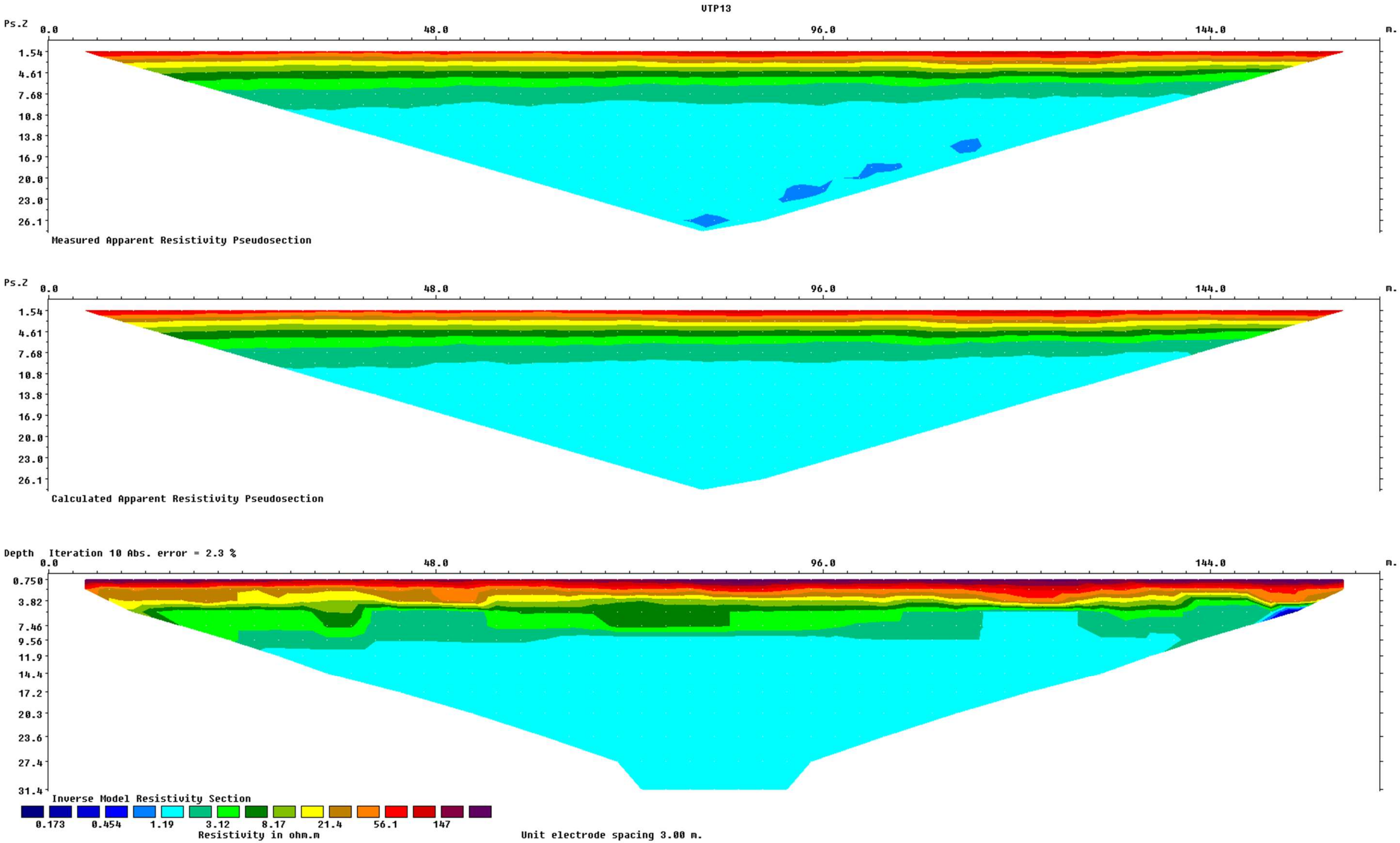
VTP12 – Trimmed Wenner

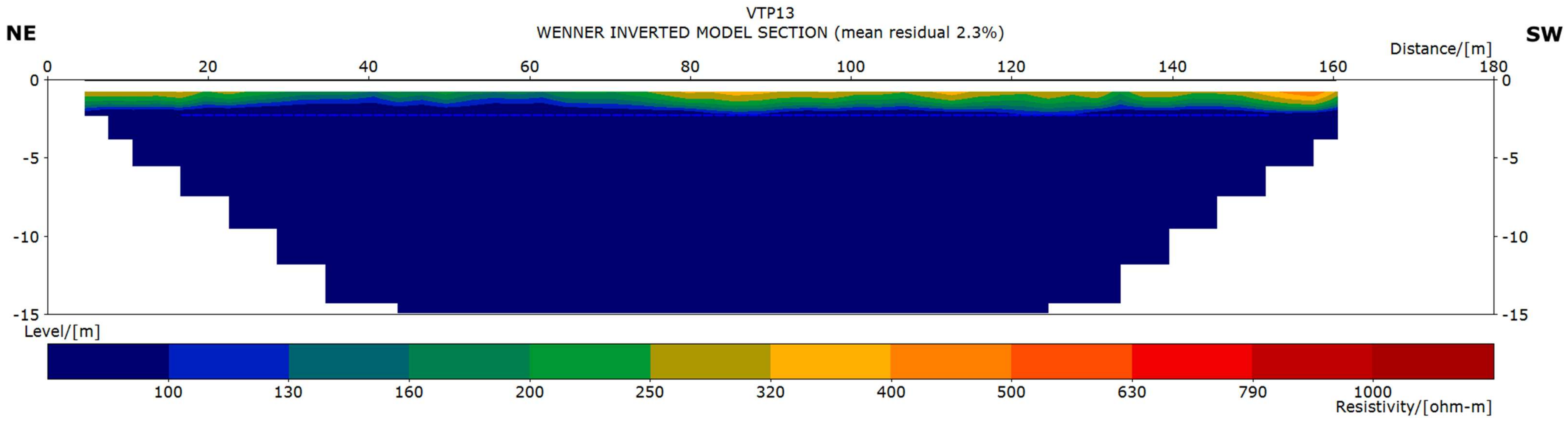




Vaitupu groundwater survey	Survey date: 30 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP12	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 480 m	Roll-along survey (2 rolls)

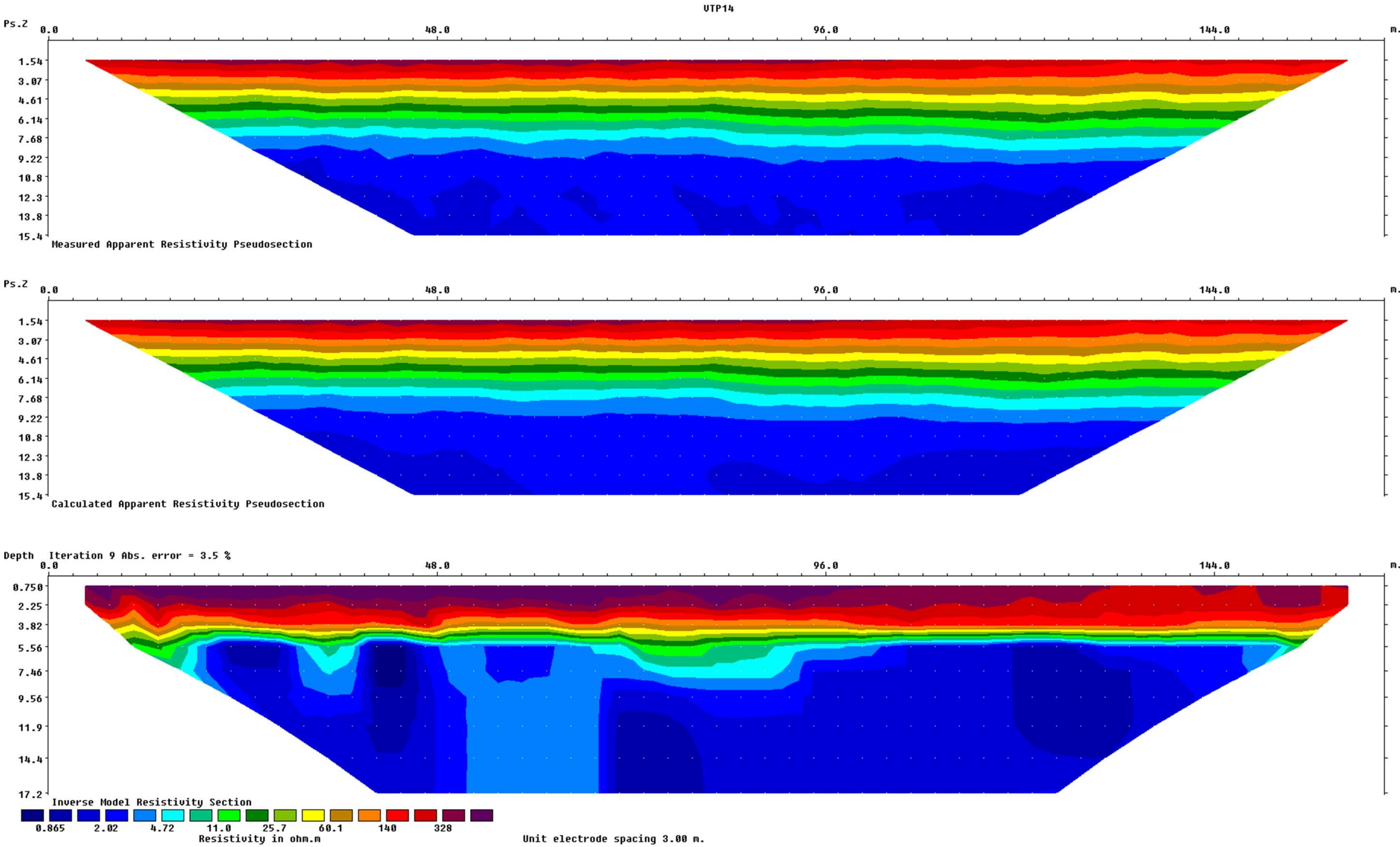
VTP13 - Wenner

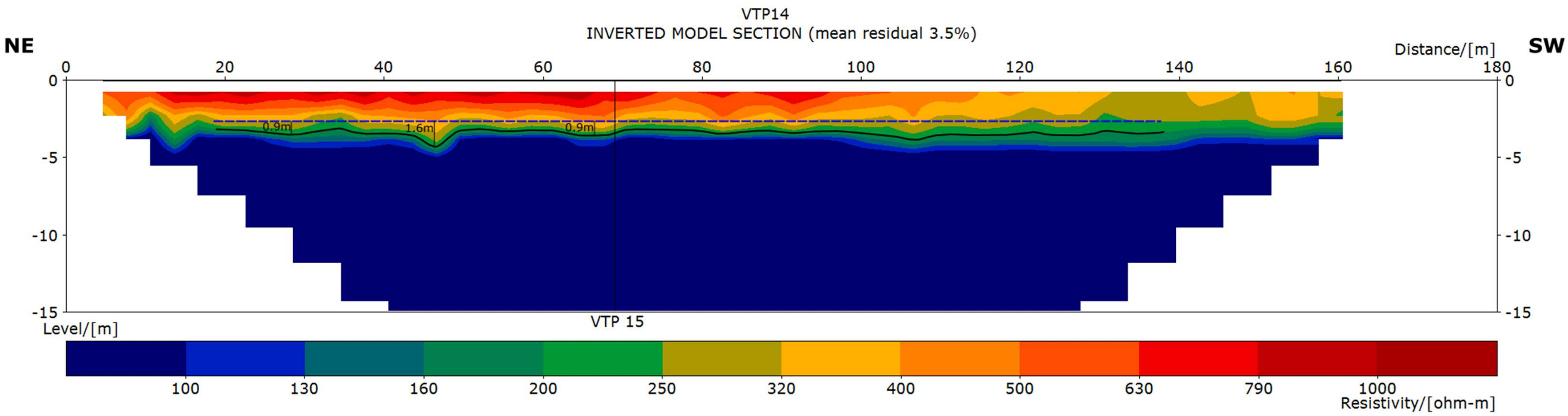




Vaitupu groundwater survey	Survey date: 30 June 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP13	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 150 m	

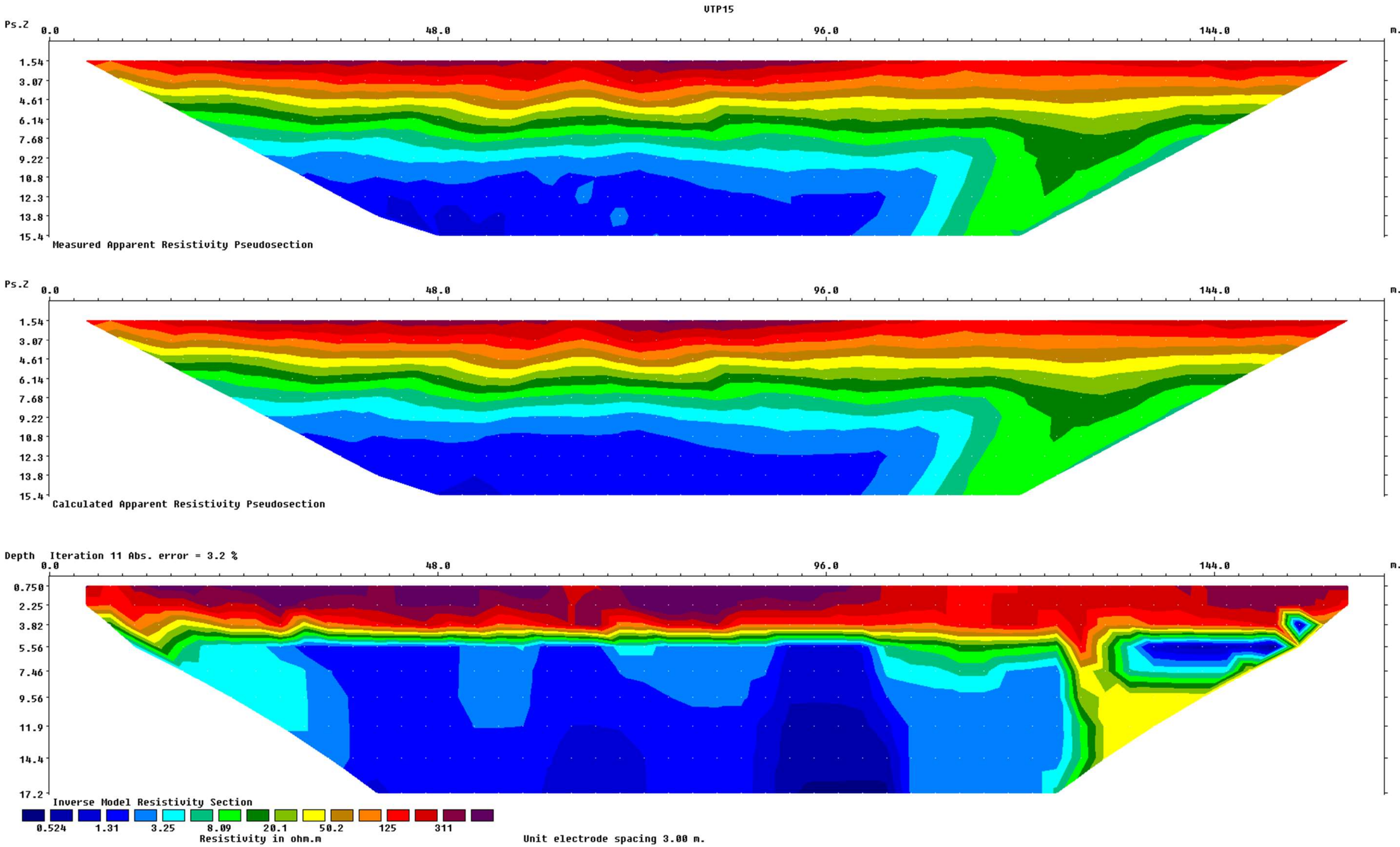
VTP14 – Trimmed Wenner

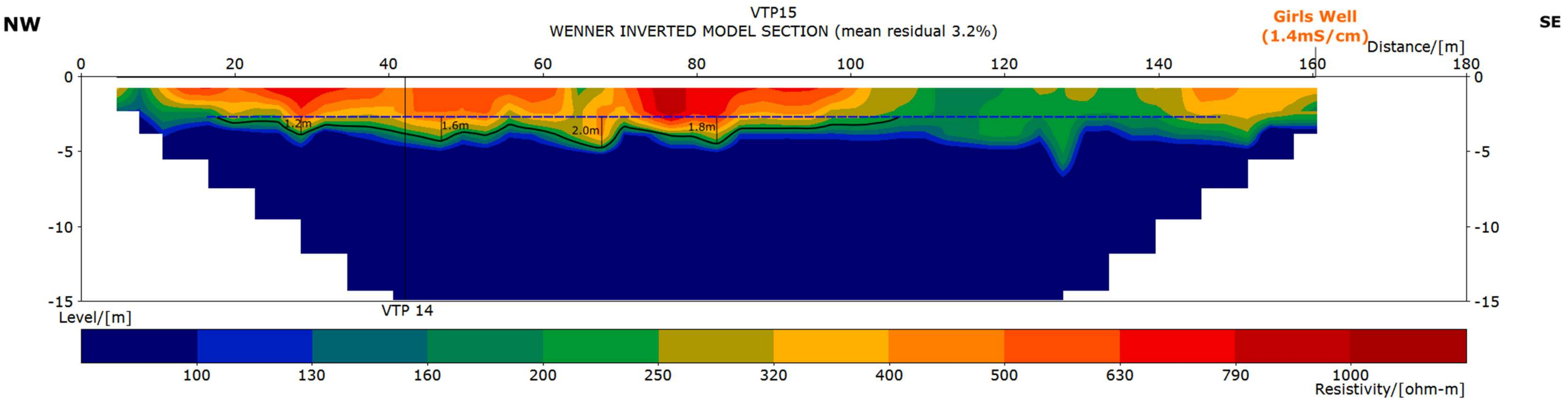




Vaitupu groundwater survey	Survey date: 1 July 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP14	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 170 m	

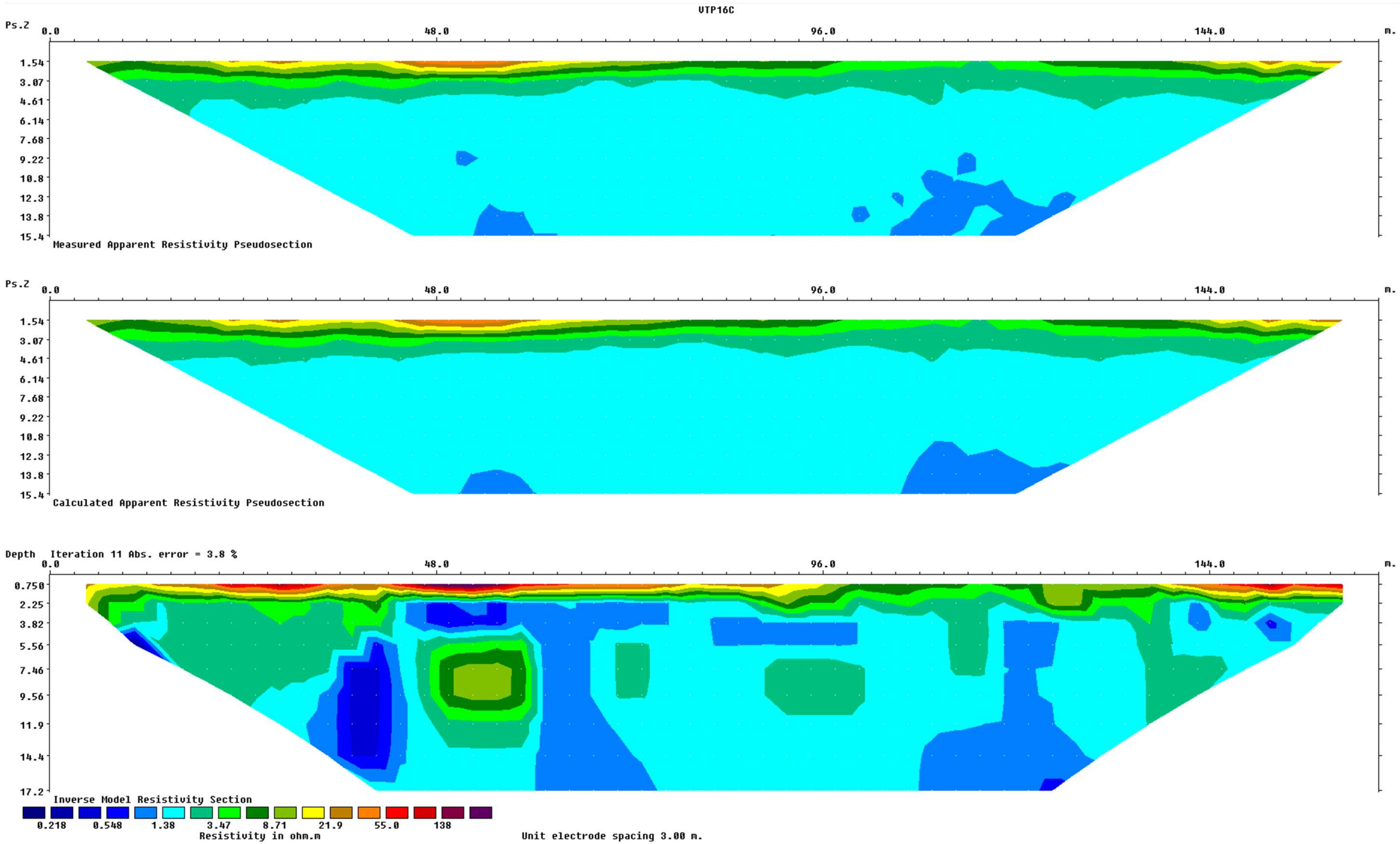
VTP15 – Trimmed Wenner

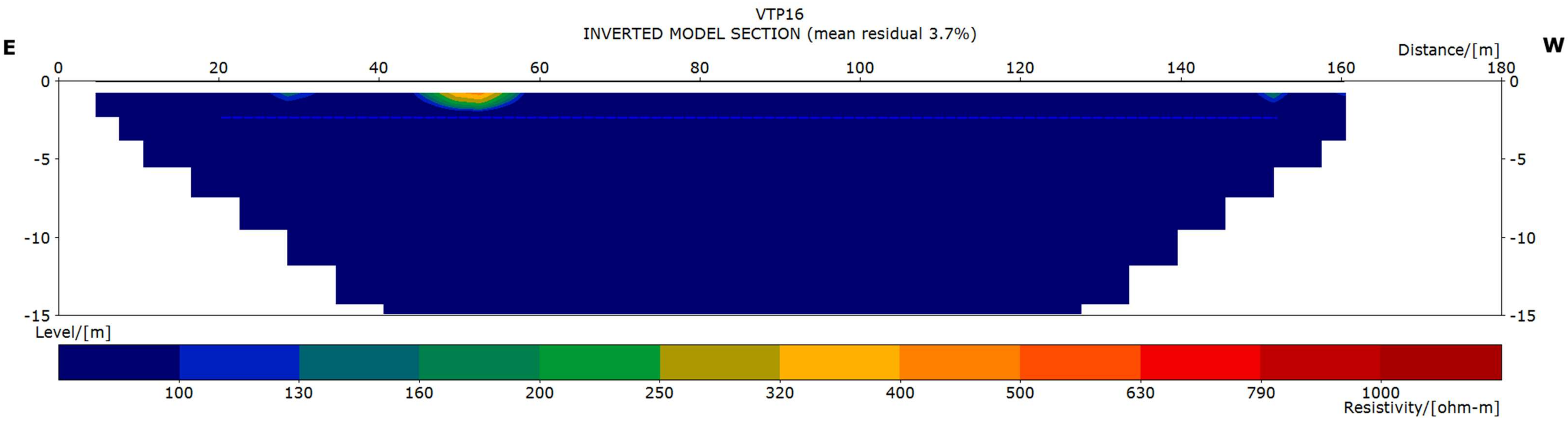




Vaitupu groundwater survey	Survey date: 1 July 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP15	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 170 m	

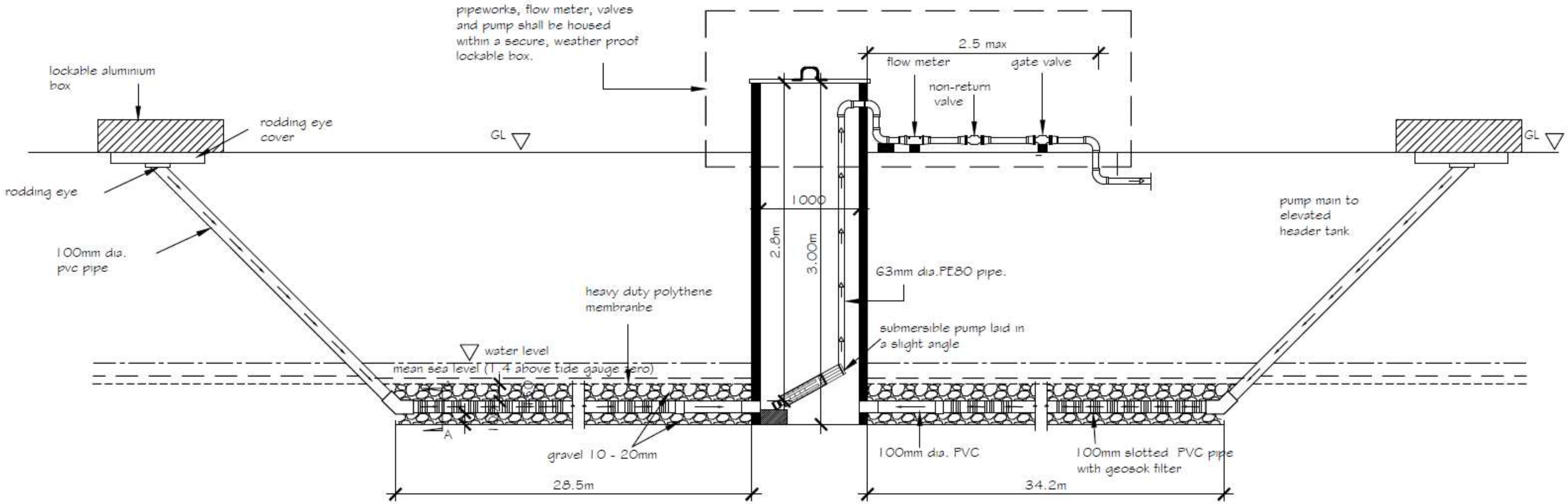
VTP16 – Trimmed Wenner



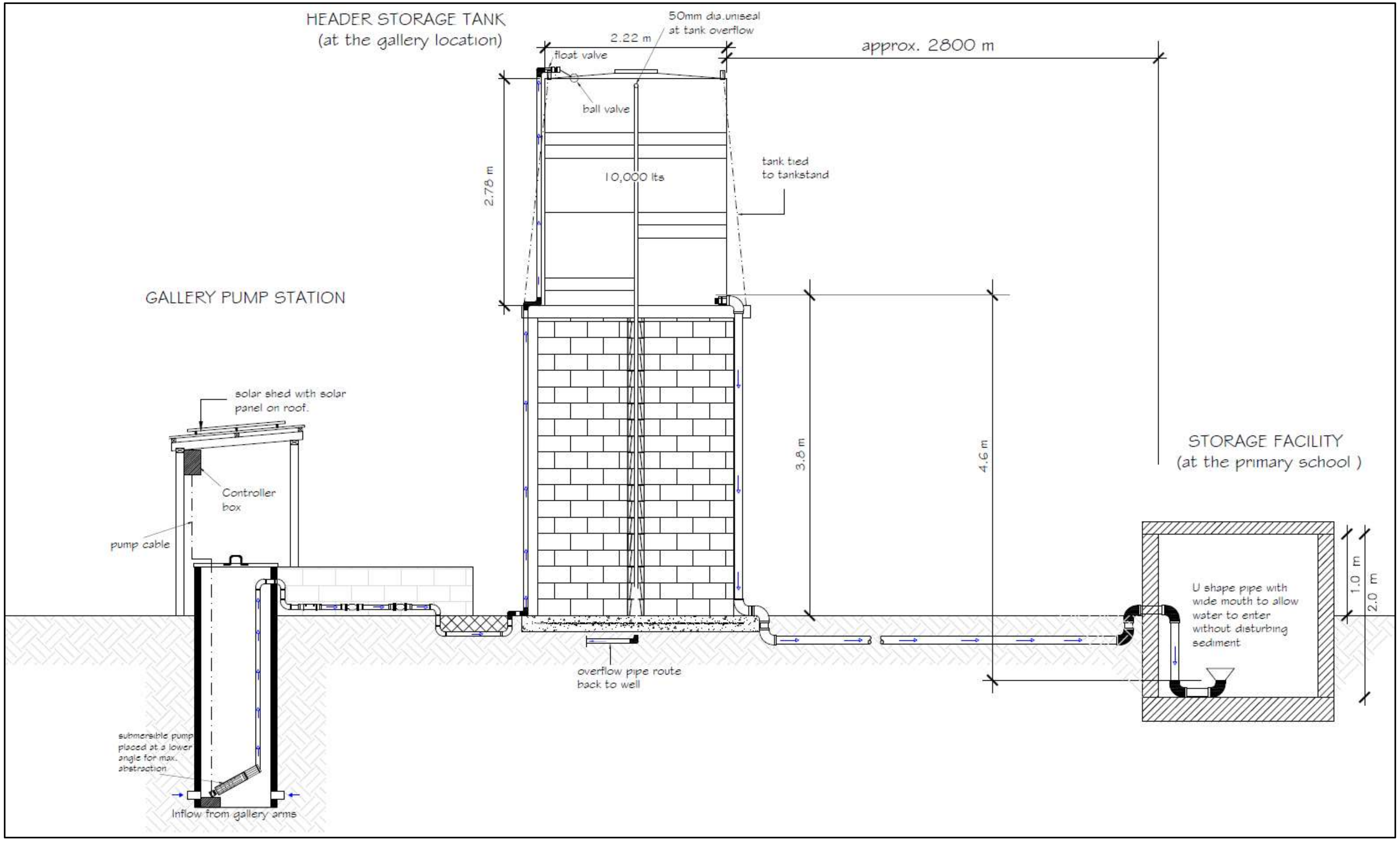


Vaitupu groundwater survey	Survey date: 2 July 2015	Instrument: Super Sting R1/56 3 m spacing
Survey line: VTP16	Array type:	Res2dinvx64 and Erigraph2
Units: meters and ohm-meter	Survey length: 150 m	

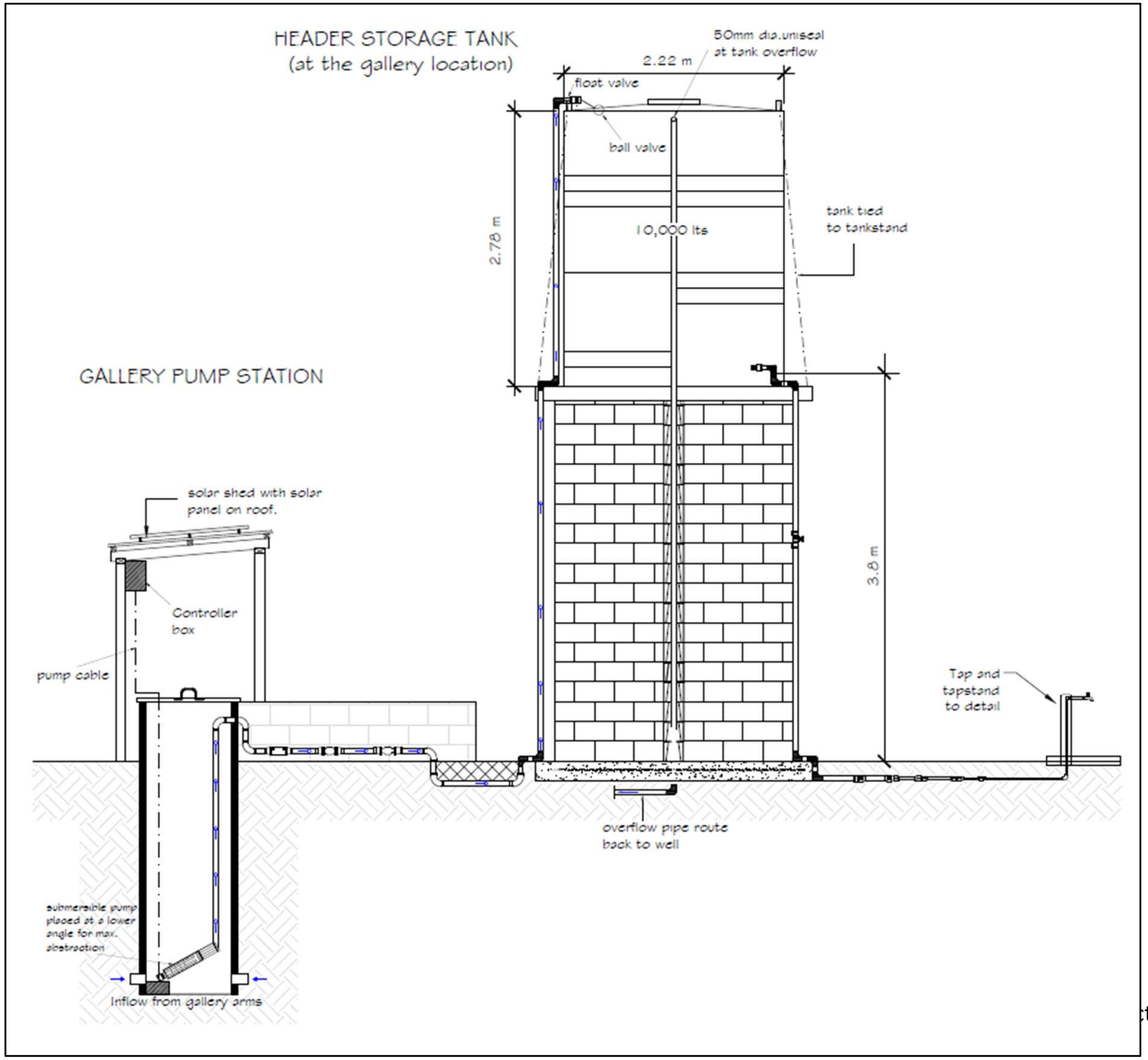
Annex H - Water supply Infrastructure designs



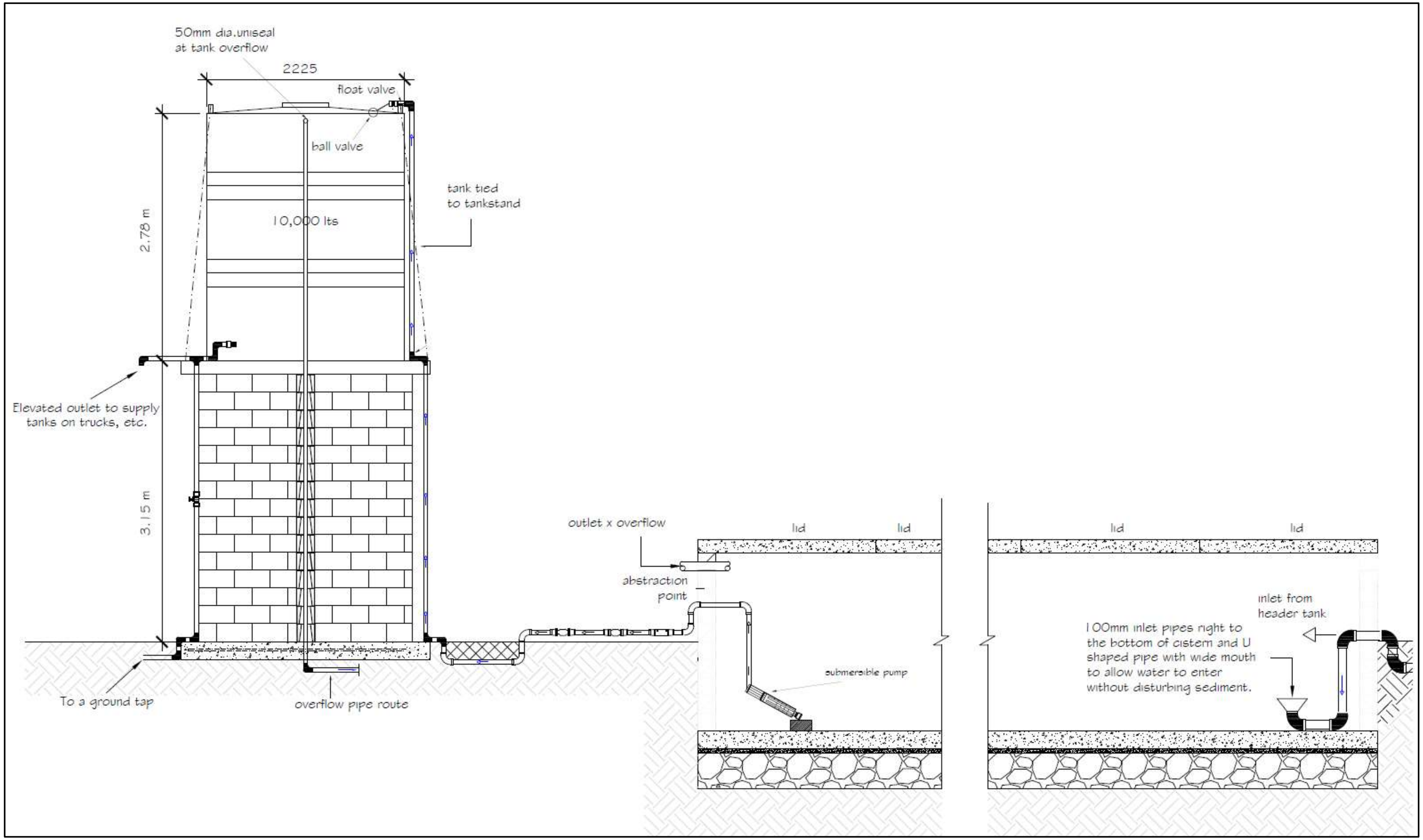
Generic infiltration gallery design proposed for outer islands under the KIRAWATSAN project. *Source: Sinclair et al. 2015a*


HEADER STORAGE TANK
(at the gallery location)
50mm dia.uniseal
at tank overflow
2.22 m
float valve
ball valve
approx. 2800 m
2.78 m
10,000 lts
tank tied
to tankstand
GALLERY PUMP STATION
3.8 m
4.6 m
solar shed with solar
panel on roof.
STORAGE FACILITY
(at the primary school)
Controller
box
pump cable
U shape pipe with
wide mouth to allow
water to enter
without disturbing
sediment
1.0 m
2.0 m
overflow pipe route
back to well
submersible pump
placed at a lower
angle for max.
abstraction
Inflow from gallery arms

Schematic representation of the proposed infrastructure including gallery, header tank, and conduction to the cistern located at the primary school or hospital area. Source: Sinclair et al. 2015a


HEADER STORAGE TANK
(at the gallery location)
50mm dia.uniseal
at tank overflow
2.22 m
float valve
ball valve
2.78 m
10,000 lts
tank tied
to tankstand
3.8 m
GALLERY PUMP STATION
solar shed with solar
panel on roof.
Controller
box
pump cable
Tap and
tapstand
to detail
overflow pipe route
back to well
submersible pump
placed at a lower
angle for max.
abstraction
Inflow from gallery arms

A tapstand point proposed to provide water to people in north Vaitupu, directly from the header tank. Source: Sinclair et al. 2015a


50mm dia.uniseal
at tank overflow
2225
float valve
ball valve
tank tied
to tankstand
10,000 lts
2.78 m
3.15 m
Elevated outlet to supply
tanks on trucks, etc.
To a ground tap
overflow pipe route
outlet x overflow
abstraction
point
lid
lid
lid
lid
submersible pump
inlet from
header tank
100mm inlet pipes right to
the bottom of cistern and U
shaped pipe with wide mouth
to allow water to enter
without disturbing sediment.

Details of elevated tank and cistern. *Source: Sinclair et al. 2015a*

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EUROPEAN UNION

The project is co-funded
by the European Union

The project is implemented
by the ACP group of states