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Pacific Community Recovery Support for Tropical Cyclone Winston

Micro Projects Programme

Hydrogeological Assessment for Rural Water Supply Ba and Ra Provinces, Viti Levu, Fiji

Aminisitai Loco, Andreas Antoniou, Anesh Kumar and Peter Sinclair

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Making a difference to Fiji's sugarcane communities

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- Fiji Meteorological Service
- Fiji Sugar Cooperation
- Ministry of Sugar
- Bureau of Statistics
- Provincial Administrators in Ba and Ra provinces, and District Officers in Ba and Tavua districts, under the Ministry of Rural and Maritime Development and National Disaster Management

The engagement and support of the advisory councillors and community members of Qerelevu, Wailevu and Nanuku, Benai, Navia and Nadhari, Malele and Volivoli throughout this hydrogeological assessment phase is greatly appreciated.

1 Introduction

As part of the European Union (EU)-funded Micro Projects Programme (MPP), a hydrogeological assessment of six cane farming communities in Ba and Ra provinces in the Western District of Viti Levu, Fiji was undertaken between February and December 2017. The assessment was part of the recovery response to category 5 Tropical Cyclone Winston that caused widespread damage in Fiji in 2016. All assessment work was undertaken in communities that were affected by the cyclone. The six communities, selected through a Fiji Government-led prioritisation process, included Qerelevu, Benai, Navia and Nadhari and Malele in Ba Province, and Wailevu and Nanuku and Volivoli in Ra Province. These rural communities have historically relied on creeks, springs and rainwater harvesting for their domestic water needs, and are prone to the adverse impacts of climate extremes. These communities are considered to be disadvantaged due to their limited water resources, often relying on water cartage for extended periods.

The assessment work utilised geophysics and, more precisely, electrical resistivity tomography (ERT), coupled with lineament analyses topographical surveys, and groundwater sampling to improve the hydrogeological understanding of the areas of interest. The main objective was to identify groundwater-bearing geological formations that would be suitable for drilling water-supply bores that would provide a secure and resilient water supply for the selected communities.

It was found that the hydrogeological framework underlying the assessed areas is dominated by fractured volcanics that influence localised groundwater flow and storage. There is the occasional presence of perched aquifers – resulting from the intrusion of volcanic dikes coupled with sedimentary formations contiguous to the volcanics – which influence the preferential storage of groundwater along the geological interface.

In total, 49 high-resolution ERT profiles were conducted to investigate the lateral and vertical variability in electrical resistivity response. These profiles revealed a number of geological features that indicate groundwater potential. Areas of potential groundwater occurrence are represented in the profiles by a low-resistivity response in the range of 20–50 Ohm.m, and are displayed by well-defined, near-vertical or horizontal zones that possibly indicate concentrated fracturing or weathering of the geological formation, or even fractured geological contacts where preferential groundwater flow and storage is permitted. Resistivity responses outside this range may indicate: 1) very low resistivity (5–15 Ohm.m) capping silty loam and clay layers with limited groundwater potential; 2) medium resistivity drilling targets (50–100 Ohm.m), representing either perched or saturated fracture systems; and 3) high-resistivity (>100 Ohm.m) fresh and unaltered bedrock. As geophysical targets are drilled, actual resistivity ranges should be correlated against drilling results to further refine the site-specific resistivity range for the specific rock formation and geological setting.

Twenty-five drilling targets were identified and proposed within the surveyed communities. Prioritisation was based on the interpreted (through ERT) groundwater potential of the geological units, coupled with site accessibility and close proximity to existing water-supply infrastructure.

The designation of drilling targets was made by synthesising information from different sources, including geology, existing bores, geophysics, structural features, land accessibility, and other physical and socioeconomic conditions and constraints. As additional information becomes available (e.g. supplementary borehole data), it is recommended that this be incorporated into a reassessment of the identified resistivity targets to assist with calibrating resistivity and improving confidence when recommending future drilling targets.

1.1 Project overview

The MPP was designed and implemented under the EU's Accompanying Measures for Sugar Protocol Programme to mitigate the adverse effects of sugar price reform and the overall decline of Fiji's sugar industry on the most disadvantaged groups, particularly sugar cane farming communities. The MPP programme was implemented by the Pacific Community (SPC) with the specific objective to reduce the social, economic and environmental vulnerability that sugar cane farmers and mill workers face due to the sugar price reform. The project's activities were reviewed by the EU following the devastating impacts of the category 5 Tropical Cyclone Winston, which struck Fiji on 20 February 2016. The review allowed for a broadening of project components to contribute towards the much-needed recovery response for the affected communities of Viti Levu. Target beneficiaries were disadvantaged communities from Rakiraki to Ba town, where the impacts of the cyclone were recorded as being the most severe. The MPP's scope was reshaped with the following additional components: 1) improve access to safe and disaster-resilient water supplies, sanitation and hygiene facilities and practises; and 2) improve access to affordable electricity for income-generating opportunities.

To address component 1, and with direct links to Goal 6 of the 2030 Agenda for Sustainable Development of "ensuring access to safe and affordable drinking water and access to adequate and equitable sanitation and hygiene for all", it was proposed that a hydrogeological assessment be conducted in six farming sectors to investigate new and exploitable groundwater supplies. The assessment was undertaken by SPC's Water Resources Assessment (WRA) Unit within the Geoscience, Energy and Maritime Division, and in collaboration with the Mineral Resources Department (MRD) of Fiji's Ministry of Land and Mineral Resources. The assessment technique included the use of geophysics and, more specifically, the electrical resistivity transect (ERT) method, to assess the potential of groundwater occurrence in the geological formations underlying these communities. The main objectives were to identify new groundwater sources for drilling, and construct water supply bores to improve the longer term water security of vulnerable and prone-to-droughts communities

1.2 Selection of target communities

The prioritisation and selection of communities was undertaken following a consultation with the Ministry of Sugar and the Fiji Sugar Cooperation. An objective selection process was developed in collaboration with MRD using the following criteria:

- drought vulnerability based on the frequency of emergency water carting;
- groundwater potential based on recent and historical investigations and drilling campaigns to determine the likely failure or success of the planned assessment;
- population density and expected per capita water demand; and
- land use.

Consequently, six disadvantaged cane farming communities were selected as candidates for the proposed hydrogeological assessment work: Qerelevu, Benai and Navia and Nadhari in Ba District (Ba Province), Malele in Tavua District (Ba Province), and Wailevu and Nanuku and Volivoli in Rakiraki District (Ra Province). Please note that Navia and Nadhari communities, although having separate governance bodies, were surveyed in the same period because of their closeness to one another and for logistical reasons. This was also the case for Wailevu and Nanuku.

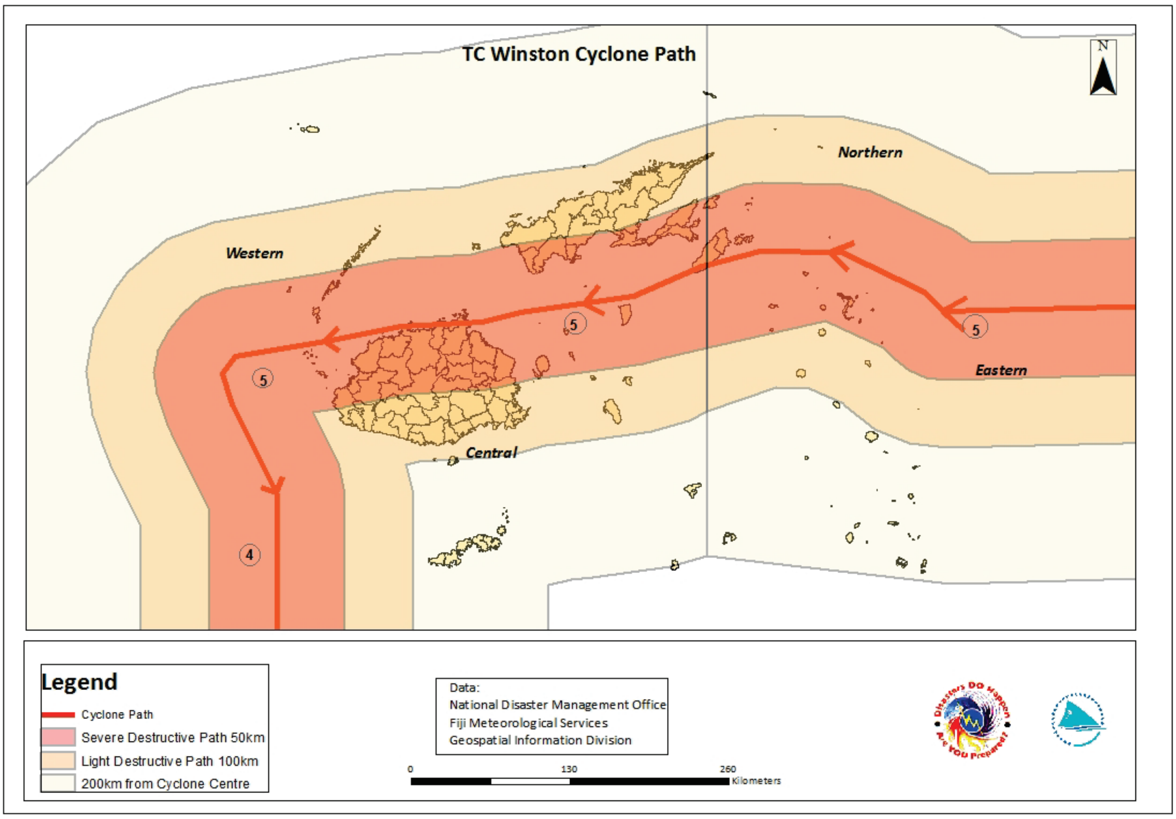

Figure 1. Fiji Islands and the path of Tropical Cyclone Winston.

1.3 Field assessment schedule and survey team

Table 1 shows the communities that were visited as part of the proposed field assessments between February and December 2017.

Table 1. Field assessment schedule in the Micro Projects Programme target communities.

Area	Survey period 2017
Field reconnaissance	30 January–3 February
Qerelevu	20–23 February, 22–26 May
Wailevu and Nanuku	29 May–2 June
Benai	17–22 September
Navia and Nadhari	2–6 October
Malele	19–24 November
Volivoli	25–30 November

In addition to the hydrogeological assessment trip, a pre-survey consultation trip was undertaken on 13–14 September in four communities: Benai, Navia, Malele and Nadhari. This consultation was essential to increasing the awareness of the communities and relevant government authorities about the objectives, approach and scope of the proposed hydrogeological assessment, and to ensure that the communities' expectations and the project's objectives were aligned.

The survey team from SPC's WRA included Peter Sinclair, Andreas Antoniou, Amini Loco and Anesh Kumar; and from MRD, hydrogeology staff members who were rotated throughout the course of the assessment included Ilaitia Dokonivalu, Ilaitia Bulai, Vono Salusalu, Anawaite Vuetaki, Manoa Pio, Timoci Bese, Epeli Bola, Penijamini Mataitoga and Isimeli Koroi.

1.4 Proposed three-phased approach for groundwater development

The hydrogeological assessment was the first of three phases of complete groundwater development and use. The three phases involved the:

1. identification of groundwater-bearing formations and drilling targets through a hydrogeological assessment using geophysics (the objective of this component);
2. drilling and construction of water-supply bores, including pumping tests, water quality analysis, sizing of pumps, and safe yield determination (unfunded future work); and
3. setting-up water-supply infrastructure and management in consultation with communities (unfunded future work).

The first phase, which was undertaken as part of the MPP, aimed at assessing the groundwater potential of underlying geological formations. High-resolution ERT profiles were undertaken to identify potential groundwater-bearing formations and drilling targets that could be drilled with the intention of developing new potable water supplies.

The second phase will consist of drilling and developing the identified groundwater targets. While not directly funded by the MPP, this phase is critical to assessing the groundwater resource potential, and will include water bore construction and development. Drilling allows for a further detailed assessment of geological materials in terms of depth, thickness, and characteristics of potential groundwater-bearing formations, which in turn helps calibrate the resistivity profiles and further improve the hydrogeological understanding and confidence of the assessment. The Government of Fiji has formally indicated its support of this phase through a signed memorandum of understanding between SPC and MRD. MRD is likely to lead this important phase, subject to funding availability, through the use of appropriate drilling methods, quality construction materials, and safe practices. This will also include other aspects of the hydrogeological assessment such as borehole development, aquifer drawdown and recovery tests, and chemical and microbiological tests to evaluate the yield and quality of groundwater. These tests ensure that the bores can withstand extreme climatic conditions and, simultaneously, can provide long-term safe drinking water for the communities.

The third phase will include equipping bores to support the distribution of groundwater from the source to end-users. This will include installing appropriately sized pumps, either solar or electrical powered, connecting with existing or newly constructed water tanks, installing additional storage tanks, and installing reticulation systems. Although this phase is also outside the scope of the project, potential donors have expressed interest in supporting the communities in achieving the overall objective of improved access to safe and reliable water. An important part of this phase will be the education, mobilisation and empowerment of community members towards the long-term maintenance and operation of water supply systems. There is a need to clearly define roles and obligations, including funding, by community members in order to ensure the sustainability of these systems.

1.5 Purpose of this report

This report provides a summary of the groundwater field investigations conducted in and around the target communities. It also documents major survey techniques, key datasets and findings, and recommendations related to the potential of groundwater occurrence underlying the study areas.

This report is expected to facilitate discussions between key stakeholders, including district officers and provincial administrators within the Ministry of Rural and Maritime Development and Nation Disaster Management, utility providers such as the Water Authority of Fiji (WAF), Fiji Sugar Cooperation (FSC) field officers, and community leaders, on the hydrogeological conditions underlying and surrounding the target communities. This report offers valuable information on groundwater potential, drilling targets, options for improved and resilient water supplies, and guidance on the sustainable development and management of the water supplies.

1.6 Report scope

This report is divided into eight sections:

- Background information of target communities, including site locations, population and land use, rainfall and regional geology and hydrogeology, water challenges, and field methodologies and considerations
- Qerelevu survey results and drill targets prioritisation
- Wailevu and Nanuku survey results and drill targets prioritisation
- Benai survey results and drill targets prioritisation
- Navia and Nadhari survey results and drill targets prioritisation

- Malele survey results and drill targets prioritisation
- Volivoli survey results and drill targets prioritisation
- Summary and recommendations
- Detailed interpretation of ERT profiles (Annex 1)

2 Background information

2.1 Geographic location and social structure

The target communities were selected from the cane farming areas between the provinces of Ra and Ba on Viti Levu, Fiji's largest island (Fig. 2). Four communities were selected from Ba Province: Qerelevu, Benai, Navia and Nadhari (all from Ba District), and Malele (Tavua District). The remaining communities were selected from Ra Province: Wailevu and Nanuku (Raviravi District) and Volivoli (Rakiraki District). All of these communities, which ranked among the most vulnerable in terms of poor access to a reliable water supply, were severely impacted by Tropical Cyclone Winston (Fig. 1).

Figure 2. The target communities (shown by yellow polygons) between the provinces of Rakiraki and Ba.

The social structure of these communities is such that the advisory councillor in each community provides leadership and acts as the community focal point for any development work or initiative, be it government or other partners (Fiji Government 2014). The councillors not only coordinate and are directly involved in development activities for the communities, but also promote and implement proper governance for the benefit of the communities. For this hydrogeological assessment, the engagement of the advisory councillors was initiated early on in the implementation phase in order to assist with the project's execution. This early engagement proved critical in ensuring that the project's objectives were understood and to facilitate access to important information pertaining to the status of water challenges within the communities, and where the assessment work may best be carried out.

Qerelevu is an FSC farming sector, located 15 km inland from Ba town. The community is within native-owned land and covers a land area of 12 km^2 around which flows the Ba River. The sector has six self-governed areas – Nakavika 1, Nakavika 2, Nakavika 3, Nabatolu, Qerelevu and Namau – with each area having separate community councillors. Qerelevu is located between latitudes 17.59ºS and 17.63ºS, and between longitudes 177.73ºE and 177.79ºE.

Wailevu and Nanuku are two farming sectors located along the King's Road Highway, approximately 10 km west of Vaileka town. These adjoining sectors are situated on a coastal plain next to Vunitogoloa Village, where land-ownership is totally free-hold land. The sectors, although having separate community councillors, cover a land area of 6 km^2 and comprise coastal plains, valleys and a network of rugged hills. The sector boundary extends between latitudes 17.37°S and 17.46°S, and between longitudes 178.04°E and 178.07°E.

Benai farming sector is located north-northwest of Qerelevu and approximately 7 km from Ba town. Benai, covered by native leases and dominated by rolling and low-lying areas, has an area of around 3 km^2, and has its own advisory councillor. The sector boundary extends between latitudes 17.56°S and 17.58°S, and between longitudes 177.73°E and 177.75°E. Although 40% of the community's population is covered by the WAF distribution scheme, residents of the areas of Benai 22 and Benai End are disadvantaged by the lack of access to the reticulated water supply, and suffer water challenges throughout most parts of the year.

Navia and Nadhari, similar to Wailevu and Nanuku, are two neighbouring farming sectors within Ba Province and are 1.5 km inland from the Kings Road Highway between the villages of Sasa and Natunuku. The sector is covered by native leases and is dominated by hilly terrain with restricted valleys in places. This sector has an estimated land area of 8 km^2 and consists of two self-governing communities. The community boundary extends between latitudes 17.47°S and 17.49°S, and between longitudes 177.73°E and 177.78°E.

Malele is the largest sector and is located southeast of Vatukoula Village and between Nadelei and Davota villages. The community boundary extends between latitudes 17.47°S and 17.54°S, and between longitudes 177.86°E and 177.93°E.

Volivoli is the most populated sector among the ones investigated during this project. It is northeast of Rakiraki town on the peninsula that extends north of Kings Road Highway between latitudes 17.31°S and 17.34°S, and between longitudes 178.18°E and 178.20°E. The area is dominated by extensive cane farms with the establishment of a number of resorts around the coast marking a relative increase in tourism.

2.2 Population and land use

The population estimates presented in Table 2 are based on census information obtained from Fiji's Bureau of Statistics (Fiji Government 2017) and supported by the Fiji Sugar Cane Growers Council (FSCGC), which keeps updated records of the cane farming communities.

Table 2. Population of the target communities.+

Area	Population	Expected minimum daily water demand* (L/d)	Expected maximum daily water demand* (L/d)
Qerelevu	270	13,500	27,000
Wailevu/Nanuku	61	3,050	6,100
Benai	130	6,500	13,000
Navia/Nadhari	270	13,500	27,000
Malele	173	8,650	17,300
Volivoli	340	17,000	34,000

+ Source: Fiji Sugar Cooperation Grower's Council 2016.
* Expected water demand is calculated based on the World Health Organization recommendation of 50 L/d/capita as a minimum water requirement for potable needs and washing, while the maximum per capita demand of 100 L/d/capita is used if the water supply is used for sanitation, farming and animal grazing (Reed and Reed 2011).

Table 2 illustrates the variability in population within the different farming sectors. The estimated daily water demand is based on the World Health Organization (WHO) guidelines on minimum water requirements, and includes all water needs (WHO 2017). It was concluded that the current water use around the sectors, based on the emergency water carting records of the Tavua District Office (Maria Osborne, pers. comm. 2017), covers the minimum daily water demand of 50 L/d/capita. Emergency potable water is only delivered during severe dry periods in areas that rely on intermittent streams and low-flowing springs. These records, coupled with the extent and terrain description of these communities (Section 3.1), will have implications on water demand and usage, and will be important considerations when designing appropriate and reliable water supply systems.

Land use around these areas is dominated by sugar cane farming with minor cash crops and fruits, such as pineapple and vegetables, coupled with animal grazing. The recent community consultation with FSC field officers revealed the emphasis on intercropping, which entailed the simultaneous cultivation of sugar cane and other crops in the same space (Timoci Sila, FSC field officer, pers. comm. September, 2017). These alternative crops, despite providing some financial stability to the farmers during the cane growing period and prior to harvesting, require water for irrigation for optimum plant yield. Therefore, increasing water demand and use is now experienced in areas where intercropping is practised, which necessitates the need for an improved and reliable water supply.

2.3 Climate and rainfall analysis

Fiji's climate is strongly influenced by its geographical location around the Intertropical Convergence Zone and the moisture-laden southeasterly prevailing winds. Fiji has a pronounced wet and dry season from November to April and from May to October, respectively. The presence of submountainous and hilly landforms around central Viti Levu influences local climate conditions. The submountainous landforms create a barrier to the southeast trade winds and contribute to rain shadow conditions in most parts of the western provinces, where sugar cane farming is dominant.

An analysis of rainfall around the study areas over time is necessary in order to determine the frequency and trend of normal and extreme weather conditions and impacts on freshwater sources, including groundwater. Historical monthly datasets provided by Fiji Meteorological Services for five of its recording stations (Rarawai Sugar Mill in Ba, Penang Sugar Mill in Rakiraki, FSC sector office in Tavua, Laucala weather station in Suva, and the Nadi International Airport) proved useful in helping to establish general historical rainfall patterns. However, because of the distances between the sites and stations, and the inherent spatial variability of rainfall triggered by local and physical conditions, the analysis and interpretation of these data should not be used in place of site-specific data. Suva and Nadi have been included to provide a comparative perspective of the situation around other parts of Viti Levu, particularly with the known rain shadow effects. Suva is the only station located on the windward side of Viti Levu.

Table 3. Summary of monthly rainfall from meteorological rainfall stations in Rakiraki, Ba, Tavua, Suva and Nadi.

Months		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rakiraki	Max	1261.9	937.1	820.5	790.5	583.6	278.2	162.7	200.8	323.6	379.4	430.2	817.1	3956.8
	Min	9.4	62.8	71.9	32.4	7.8	2.6	0.8	3.4	0.4	1.3	8.8	40.7	1218.5
	Average	394.70	364.33	358.69	259.13	154.41	87.84	48.01	74.18	78.68	96.49	146.29	279.18	2350.77
	Standard deviation	302.92	178.30	202.18	172.10	140.20	76.26	38.93	52.14	77.08	93.01	114.64	197.14	703.48
	CV*	0.77	0.49	0.56	0.66	0.91	0.87	0.81	0.70	0.98	0.96	0.78	0.71	0.30
	No. of years	38	38	38	37	38	38	38	38	36	37	37	36	34
Ba	Max	1907.8	951.9	1067.2	777.5	402.4	302.1	211.1	377.3	312.2	374.5	515.2	646.2	3614.7
	Min	35.2	33.3	47.6	20.6	0	0	0	0	1.1	1.8	0.8	25.9	910.9
	Average	388.81	366.79	400.73	199.17	91.44	74.31	40.41	59.31	74.49	95.11	147.50	228.95	2162.95
	Standard deviation	294.72	191.65	230.49	129.01	85.52	69.06	41.56	65.84	66.91	83.09	125.77	146.85	635.95
	CV	0.76	0.52	0.58	0.65	0.94	0.93	1.03	1.11	0.90	0.87	0.85	0.64	0.29
	No. of years	76	76	76	76	76	76	76	76	75	75	75	75	75
Tavua	Max	1539	958.1	1162.3	574	330	234	208	238.5	297.7	227.2	523	887	3861
	Min	31	0	12	2	0	0	0	0	0	0	0	18.3	655
	Average	315.11	316.81	360.70	171.99	83.84	63.08	38.13	54.45	72.55	65.84	108.48	172.00	1818.03
	Standard deviation	260.85	194.29	246.48	109.09	82.49	59.90	43.76	55.88	68.07	57.67	103.27	160.87	620.59
	CV	0.83	0.61	0.68	0.63	0.98	0.95	1.15	1.03	0.94	0.88	0.95	0.94	0.34
	No. of years	78	77	77	75	76	76	73	77	72	74	74	73	68
Suva	Max	731.9	832.1	799.2	1116.1	917.9	441.7	408.8	522.8	480.5	900.3	790.2	761.8	4561.7
	Min	42.9	78.9	82.8	50.5	49.9	18.6	24.1	20.2	16.5	27.3	24.5	51.9	1581.5
	Average	331.83	295.68	363.38	355.54	241.68	166.34	139.77	150.86	190.91	214.64	247.59	289.13	2988.11
	Standard deviation	158.22	128.21	151.17	197.44	145.00	108.91	85.20	103.27	123.44	163.71	176.07	139.96	550.01
	CV	0.48	0.43	0.42	0.56	0.60	0.65	0.61	0.68	0.65	0.76	0.71	0.48	0.18
	No. of years	76	76	76	76	76	76	76	76	75	75	75	75	75
Nadi	Max	1180.6	787.9	918.2	580.1	332.1	311.9	189.8	286	278.8	341.8	460.6	562.4	3547.9
	Min	12.7	45.5	75.6	21.6	0.7	0	0	0	0	1.8	3.6	21.6	863.4
	Average	324.64	307.78	343.99	179.15	89.00	66.30	48.23	63.44	77.96	91.19	133.12	188.25	1904.39
	Standard deviation	219.80	169.40	172.15	111.26	75.70	67.94	46.68	62.36	65.21	77.78	85.27	120.94	537.19
	CV	0.68	0.55	0.50	0.62	0.85	1.02	0.97	0.98	0.84	0.85	0.64	0.64	0.28
	No. of years	76	75	74	75	75	76	76	76	75	75	74	75	74

* coefficient of variation

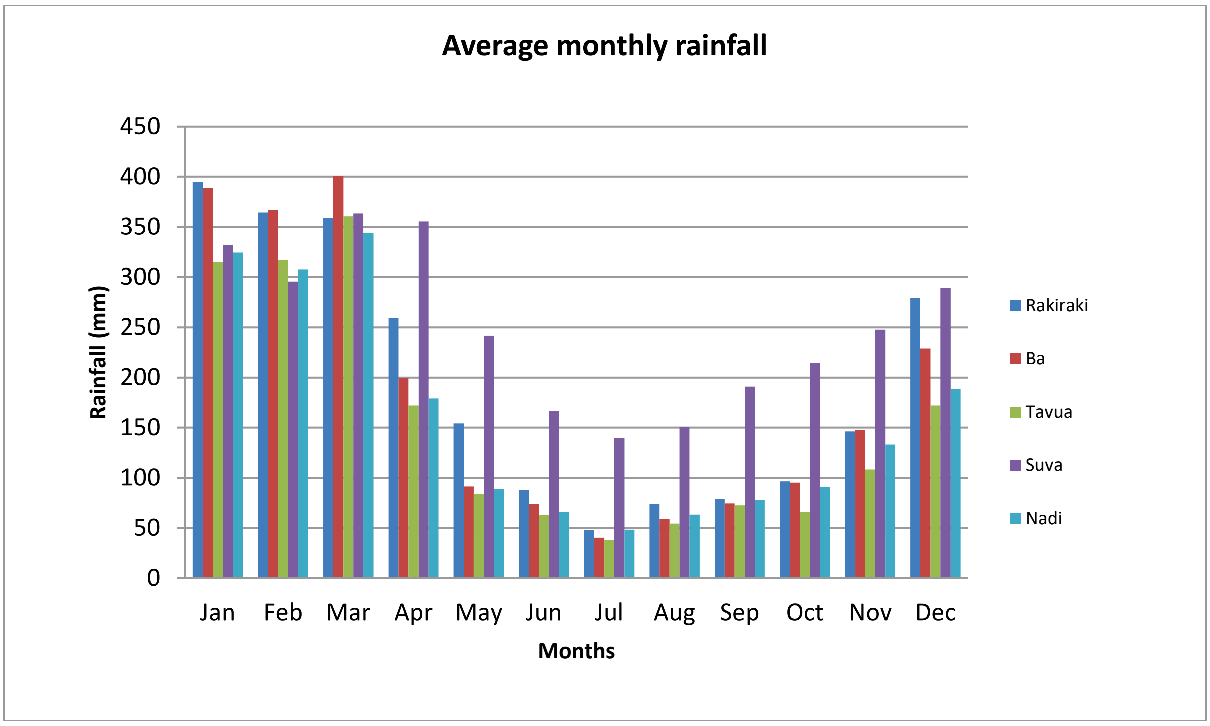

Figure 3. Average monthly rainfall for five meteorological rainfall stations on Viti Levu.

Figure 3 illustrates the variability in monthly rainfall at five stations, with leeward rainfall stations measuring high rainfall during the wet season (November to April) and considerably less rainfall recorded during the dry months. Around 80% of the annual rainfall in Rakiraki, Ba, Tavua and Nadi is recorded from November to April during episodic, high rainfall events that usually result in flooding, and when surface water may become contaminated and unusable for drinking water. The dry season, from May to October, is characterised by low rainfall and increased periods of water scarcity. Suva on the other hand, although showing similar trends of wet and dry seasons, records relatively high rainfall throughout the year. This demonstrates the strong impact of the rain shadow effect, resulting in pronounced low rainfall patterns in the leeward part of the island, particularly during the dry months, compared with the Suva stations.

The coefficient of variation (CV) is a measure of deviation of the monthly rainfall from the long-term mean. Table 3 shows that Suva records lower variance of rainfall throughout the year, while greater rainfall variance is observed at the rainfall stations in Rakiraki, Ba, Tavua and Nadi. The increasing variance in rainfall during the dry period for the stations of Tavua and Ba suggests that rainfall-dependent water sources (e.g. rivers, creeks and springs) will be commonly stressed during these periods, and that alternate, more resilient water sources are needed.

The El Niño-Southern Oscillation (ENSO) strongly influences rainfall patterns in the Pacific, and is widely accepted as a key driver of extreme climatic conditions. Thus, analysis of rainfall records around the target sectors is necessary to determine the frequency and severity of ENSO conditions over time. Using the software SCOPIC (Seasonal Climate Outlook in Pacific Island Countries), a statistical analysis of the frequency and intensity of drought events was performed on the historical monthly rainfall records. All but one of the rainfall stations had monthly rainfall data for the period 1942–2017. The Rakiraki station, despite having records from only 1980 to 2017, meets the 30 years data period required for this statistical analysis. A drought analysis was then conducted using the three-month aggregate drought index and percentile method. The results are presented in Table 4. Note that the analysis considers the definition of drought as being when the combined received rainfall for a three-month period is within the lowest 10% of all rainfall received for that three-month period.

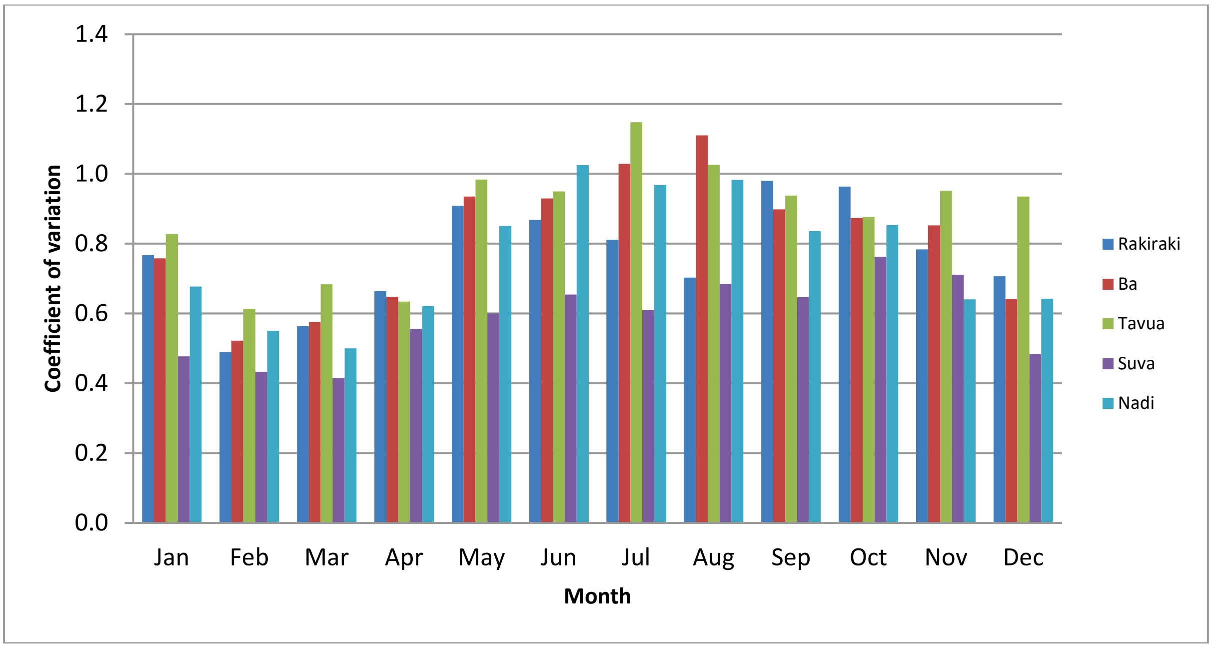

Figure 4. Coefficient of variation for five rainfall stations on Vitu Levu.

It is clear from Table 4 that La Niña periods have the lowest probability of generating droughts while El Niño and neutral periods have generated some of the most severe events. Neutral conditions generated more drought events as recorded from four out of five rainfall stations based on measured monthly rainfall records, with Tavua, Nadi and Suva stations recording markedly different rainfall amounts during neutral conditions. This may be sufficient information to suggest the potential severity of neutral conditions for the cane farming regions, if not for the whole of Viti Levu. Rakiraki is the only station recording more El Niño-driven events, which might be attributed to the limited rainfall datasets available.

Table 4. Statistical analysis of the drought and ENSO condition for Rarawai, Tavua, Rakiraki, Nadi and Suva.

Station	Total number of droughts 1942–2017	Number of droughts during El Niño	Number of droughts during La Niña	Number of droughts during neutral	Annual mean rainfall 1942–2017 (mm)
Rarawai	31	14 (46%)	1 (4%)	16 (50%)	2163
Tavua	28	9 (32%)	0	19 (68%)	1818
Rakiraki	17	9 (53%)	0	8 (47%)	2350
Nadi	34	11 (38%)	2 (3%)	21 (59%)	1904
Suva	45	15 (33%)	6 (14%)	24 (53%)	3496

2.4 Geology, geomorphology and hydrogeology

Detailed information on the geology of Rakiraki, Tavua and Ba areas is provided by a number of authors (Rodda 1984; Gale and Booth 1993; JICA 1995) and the reader is directed to these documents for a more detailed explanation of the geology. In summary, the regional geology illustrated in Figure 5 is composed of multiple phases of island-arc volcanism forming the Koroimavua, Tavua and Rakiraki volcanic groups, coupled with an intervening phase of marine and volcanogenic sedimentation in places. The dominant presence of north–south trending anticlines, faults and uplifts, minor dike intrusions in places, and the observed northeast–southwest and northwest–southeast lineaments are also evidence of structural changes related to the stress and/or strain linked to the break-up of the New Hebrides Plate, Fiji Plate and the Lau and Tonga plate, and the subsequent anti-clockwise rotation of the Fiji platform (Rodda 1994). The presence of these structural controls is of great hydrogeological interest because they may control the formation of fracture-controlled springs and creeks, and indicate the presence of localised or regional groundwater sources. Illustrated in Figure 5 and Table 5 is a summary of the regional geology and of previously documented hydrogeological investigations in the study areas.

Table 5 suggests that the geological framework underlying the study areas is the result of island-arc volcanism coupled with interceding periods of sedimentation and tectonic uplift. The physical landscapes surrounding these areas are steep and rugged, with multiple peaks and undulating landforms formed by uplifted basaltic rocks and interbedded sedimentary units. More recently, alluvium and unconsolidated marine sediments have formed adjacent to the river and creek systems as well as around the coast. Rain-fed springs and intermittent streams drain towards the major river systems of Ba and Nasivi, or towards the coast. The landforms and drainage features indicate the strong influence of historical tectonic events, coupled with long-term fluvial and coastal processes that have shaped the current landscape.

Previous groundwater assessments around the selected areas, summarised in Table 5, demonstrate the variability in groundwater potential within the geological settings. It is clear that the potential for groundwater occurrence depends on the presence and density of joints and fractures within the volcanic deposits and on the pore interflow and bedding planes within welded tuffs and interbedded sediments (Gill 1973). Based on previous drilling campaigns, it is suggested that fractured zones within the volcanics, coupled with the influence of major structural lineaments, is likely to create favourable conditions for the development of either localised or more extensive groundwater-bearing zones. These fracture-controlled systems are likely to influence the presence and movement of groundwater, while the potential for dike-impounded aquifers, perched aquifers and groundwater occurrence along geological interfaces between volcanics and sedimentary units will also be assessed.

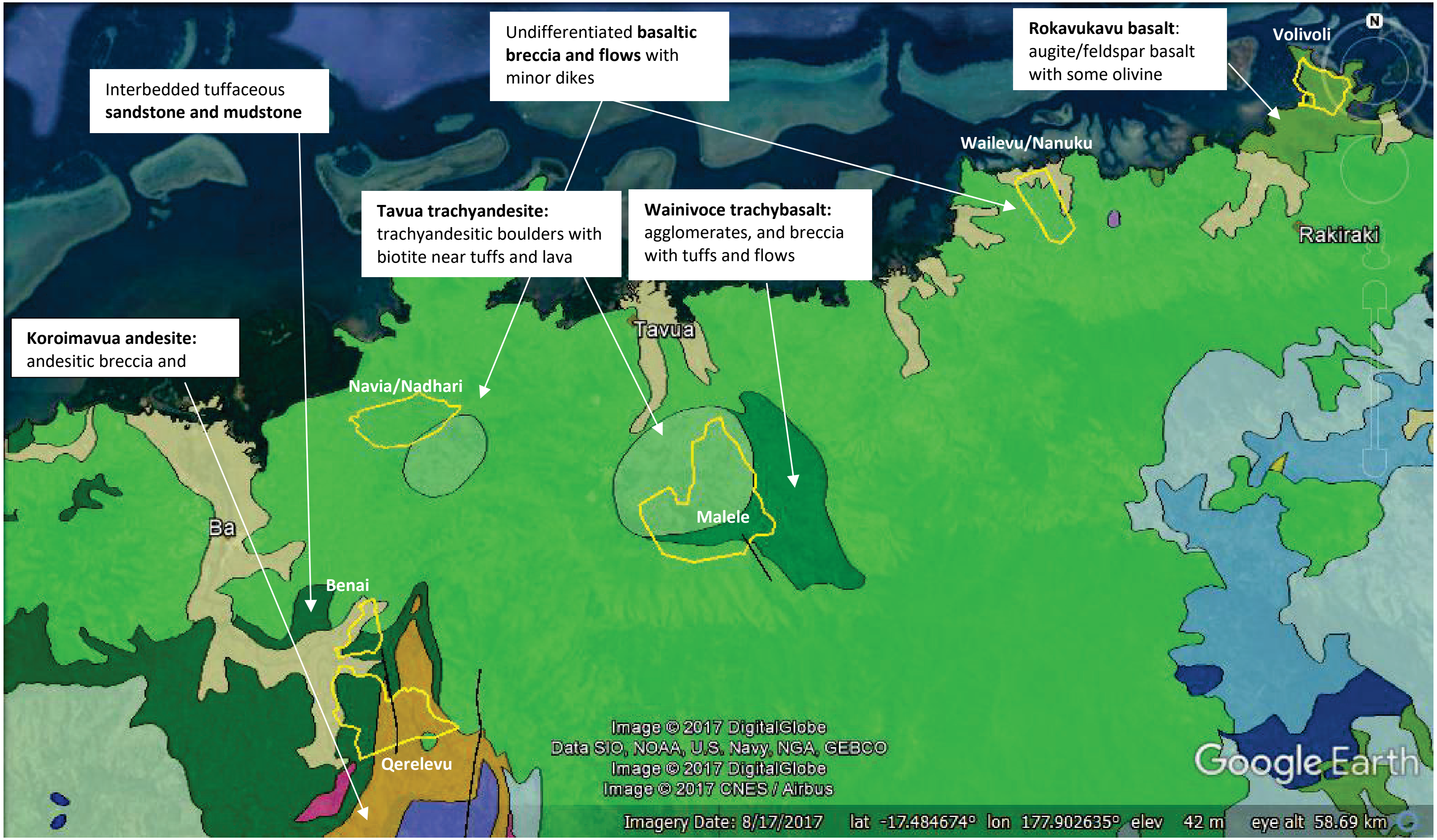

Figure 5. Regional geological map of the Rakiraki–Ba area. Mapped regional faults are shown by black lines (Rodda and Band 1966).

Table 5. Summary of the geological and hydrogeological framework underlying the study areas.

Area	Geological setting	Previous hydrogeological investigation	Targeted structural features
Qerelevu	Miocene andesitic breccia of the Koroimavua volcanic series occupying the rugged and steep areas with interbedded and moderately inclined tuffaceous mudstone and sandstone on-lapping these volcanic rocks	JICA (1995) drilling into the fissured interbedded sedimentary resulted in very low yield and poor water quality	N-S trending faults and anticlines and E-W lineaments and potential fractures within the andesitic breccia and the geological interface between the andesite and interbedded sedimentary.
Wailevu and Nanuku	Volcanic breccia, agglomerates and basaltic flows and volcaniclastic with basaltic dikes observed in places with coastal areas covered with marine and swampy materials	JICA (1995) reported three bores drilled into the basaltic fractures having transmissivities of 0.5–1 m^2/day and estimated yield of 0.4–0.8 L/s with the overall groundwater development potential classified as low	Localised fractured zones and dike impoundment that may be controlling groundwater formation
Benai	Miocene andesitic breccia and basaltic flow with juxtaposed interbedded sedimentary units and alluvium materials around the low-lying areas	The drilling of four privately-owned bores installed into the basaltic flow with depth, yield and electrical conductivity estimates of 50–55 m, and 0.8–1.0 L/s and 550–650 µS/cm	Fractured andesite
Navia and Nadhari	Basalt and basaltic breccia with minor interbedded and welded tuffs observed in places	Exploratory drilling in the 1970s resulted in a 40 m bore with static water level of 8 m and discharge rate of 0.4 L/s with suggestion that the bore was incorrectly sited into welded tuffs (Gill 1973)	Fractures or weathered fractures
Malele	Pliocene massive and bedded trachybasalt pyroclastic, agglomerate and breccia of the Tavua volcano with dominant NNW-SSE trending faults and dike intrusions	Two privately owned-bores between 1981 and 1982 with depths 33 m with recorded water level of 8 m and 18 m (Nandan 1983).	Fractures or weathered fractures
Volivoli	Rokavukavu basalt with adjacent coastal low-lying areas comprising of unconsolidated marine sediments	Groundwater investigation by the Mineral Resources Department between 2005 and 2006 resulted in the drilling of three low-yielding bores for community water supply	Fractures or weathered fractures

2.5 Current water supply

As previously stated, the farming sectors targeted in this study face severe water problems during much of the year due to the unreliability and/or inadequacy of existing water sources. Table 6 presents a summary of the current water supply situation as provided by the relevant government officials and advisory councillors. Table 6 demonstrates that the severity of water crises experienced in the communities has been long-standing. Emergency water carting has provided a long-standing, short-term solution at significant cost to the community and government. In an interview with the District Officer of Ba, Mr Abenisiga (pers. comm., September 2017), it is understood that the Fiji Government, through the Ministry of Rural, Maritime Development and National Disaster Management and WAF, spends around FJD 100,000 per month on emergency water carting to farming communities.

The present work provides an opportunity for the review of the current scheme through the possible development of long-term water supply solutions that are focused on sustainable management and offer community resilience to natural disasters and extreme climatic events. A direct benefit would be the substantial financial savings within the government through the reduction of water carting.

The extension of the WAF water distribution schemes in the Ba and Rakiraki areas is focused on the town centres, with limited extension to surrounding areas, including the study areas (Fig. 6). These farming communities will, in the foreseeable future, remain disadvantaged and continue to suffer due to an unreliable water supply. This hydrogeological assessment will support the identification and development of new and alternative groundwater sources to improve access to safe drinking water for these communities.

Table 6. Summary of water supply status in the selected communities.

Community	Current water status as of December 2017
Qerelevu	A spring located around the hills surrounding Toge Village was developed and piped into a 20,000-L ferrocement tank that currently serves Nakavika while privately-owned rainwater tanks and hand-dug wells are used in Qerelevu and Nabatolu, mainly during rainy periods. Emergency water carting is provided throughout the entire sector during prolonged dry periods. Mr Abenisiga (District Officer, Ba, pers. comm., February, 2017) stated that recent groundwater exploration in 2013 and 2014 around the Nabatolu area resulted in four low-yielding bores installed in the sedimentary units. Some of these bores are no longer working due to pump malfunctions. A borehole, installed within the andesitic flow and exhibiting artesian characteristics during rainy periods, was used for the Qerelevu Primary School but is currently non-operational as the submersible pump is damaged.
Benai	A community water supply, consisting of a borehole, with two reservoirs originally covered 80% of the community but the system was damaged. The WAF distribution network covers 30–40% of the population while the unconnected houses in two major areas, namely Benai 22 and Benai End, either have clustered spring-fed water projects established in 2015, or rely on privately-owned boreholes, hand-dug wells and rainwater tanks. Emergency water carting is common in prolonged dry periods.
Malele	The communities had a number of boreholes where water was pumped to Ferro cement tanks before being distributed to connected households. This project failed due to damaged pumps which were not replaced by the community. Thirty-six shallow boreholes existed around the area, most of which recorded reduced capacity in dry seasons (JICA 1995). Other water sources include dug-wells and rainwater tanks, which become unreliable during dry periods. River water is commonly fetched by farmers and communities located near the Nasivi River. Emergency water is usually supplied every year between August and December on a weekly or biweekly basis.
Wailevu and Nanuku	Although the JICA (1995) work resulted in the drilling of a number of low-yielding bores, none were used for water supply purposes. Two bores drilled in the 1990s are currently used by two communities within Nanuku. The Wailevu area utilises overflow water from the nearby school tank, sourced from a spring dam located in the hills. A kindergarten located in Wailevu has a borehole that exhibits artesian conditions during rainy periods. Emergency water carting is frequently demanded by the surrounding households (30) for potable needs.
Volivoli	A number of groundwater boreholes were drilled by MRD between 2005 and 2007 to serve parts of the sector. These sources are either low yielding or produce brackish water, and as a consequence, emergency water carting is frequently relied on. While the WAF main water distribution line runs past the area, the community still remains unconnected.
Navia and Nadhari	A spring dam located around the Waibuka uplands was developed in 1967 and piped through gravity into a 20-KL tank located on the Nadhari hill, prior to piped distribution to surrounding households. There is an increasing demand for water for irrigation purposes. This competing demand for available water and leakage within the system has resulted in a number of households not having reliable water supplies due to reduced pressure. Emergency water carting has always been demanded throughout the dry periods of the year.

Source: after JICA 1995.

Figure 6. Coverage of Water Authority of Fiji distribution schemes near, and across parts of, the target farming sectors.

3 Field survey methodology

3.1 Conceptual geological setting for groundwater occurrence

Available historical geological reports and maps were reviewed to establish the major geological framework and to develop a conceptual model for groundwater occurrence and transmission. The existing 1:50,000 geological map of Ba, Tavua and Rakiraki (Rodda and Band 1966), the 1:250,000 hydrogeological report and map of Viti Levu by Gale and Booth (1993), and lineament analysis using Google Earth images, all suggested a number of possible conceptual models describing the occurrence of groundwater-bearing zones underlying the study area.

1. The presence of localised fractures and fissures occurring within the mapped volcanic units. Fractures, which may or may not be linked to regional structural features, such as anticlines or faults, create conducive conditions for preferential groundwater flows and storage.
2. The contact between the volcanic units and the moderately-inclined sedimentary units may enable groundwater occurrence.
3. Potential dike-impounded groundwater systems, as observed in volcanic frameworks in Vanuatu and elsewhere, are likely to be developed in areas where dike intrusion appears to be concentrated.

3.2 Field assessment method

3.2.1 Electrical resistivity tomography

The ERT geophysical technique was used to assess, visualise and identify the lateral and vertical variability in electrical resistivity response within the tested geological systems. The method works on the principle of injecting direct current into the ground using a pair of electrodes. This current causes a potential voltage difference in the ground, which is measured by a separate pair of electrodes. The voltage measured can then, using the parameters of the survey, be converted into an apparent resistivity value. Resistivity is a function of the porosity of a geological medium, hydraulic permeability, electrical conductivity or salinity of pore fluids, and clay mineralisation, and can provide insight into the underlying geology and hydrogeology.

The ABEM Terrameter LS (Guideline Geo Inc.) was used in combination with the multiple gradient array as the preferred survey protocol offering a high horizontal and vertical data resolution (Dahlin and Bing 2006). The depth of investigation is a function of the electrode spacing and the Earth's resistance; in general, the greater the electrode spacing, the deeper the investigation. An electrode separation spacing of 3–5 m was selected, depending on the situation, to investigate depths ranging from 35 m to 80 m. The orientation of the survey profiles was planned in such a way so as to adequately investigate the observed structural targets.

Model inversions were performed using the software RES2DINV (Loke 2000). The programme automatically creates a two-dimensional model by dividing the subsurface into rectangular blocks, and subsequently calculating the apparent resistivity of these blocks using either a finite difference or finite element method, and then comparing these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual measurements. A uniform colour bar was used to allow comparisons between the inverted profiles.

Figure 7. The ABEM Terrameter LS.

In the inverted resistivity profiles (Annex 1), potential groundwater-bearing formations are identified as well-defined zones of low to medium resistivity (20–50 Ohm.m) surrounded by high-resistivity zones. This is based on documented resistivity calibration results conducted in basalts in India, as shown in Tables 7 and 8, where resistivity responses of 20–50 Ohm.m have been interpreted as a moderately weathered or fractured rock mass that is saturated with water. Lower values represent weathered basalts containing clay, while higher-resistivity values suggest weathered dry or massive basaltic units (Chaturvedi et.al. 1979; Rai et.al. 2013).

Table 7. Resistivity ranges in Ohm.m of Deccan Trap basalts, Maharashtra, India (Chaturvedi et al. 1979).

Resistivity range (Ohm.m)	Basalt type
5–15	Weathered with clay
15–30	Highly weathered and/or fractured saturated with water
30–50	Moderately weathered and/or fractured saturated with water
50–70	Slightly weathered and/or fractured that may contain some water OR highly weathered and/or fractured devoid of water
70–100	Weathered dry
>100	Massive

Table 8. Resistivity ranges in Ohm.m for Deccan Trap basalts, India (Rai et al. 2013).

Resistivity range (Ohm.m)	Basalt type
5–10	Bole beds (interbasaltic clay)
20–40	Weathered and/or fractured vesicular saturated basalt
40–70	Moderately weathered and/or fractured vesicular saturated basalt
>70	Massive basalt

The assessment of low-resistivity zones at depth in coastal areas, such as Wailevu and Nanuku and Volivoli, were treated with caution because the reduced resistivity response may indicate brackish or saline groundwater at depth, which may render the groundwater unusable.

3.2.2 Groundwater sampling and assessment of existing bores

Existing groundwater wells were sampled and analysed for major cations and anions in MRD's geochemical laboratory in order to: 1) determine the groundwater hydrogeochemistry from existing bores and geological formations, and 2) assess selected chemical parameters in relation to WHO drinking water guidelines.

Information collected from the privately drilled bores included total depth below ground level, static water level, and pumping rate. This allowed the approximation of useful hydrogeological parameters such as the potential depth of groundwater-bearing formations and the expected depth to the water table around the bores to assist with calibrating the obtained resistivity results. Moreover, the potential yield of identified groundwater sources in the vicinity of the existing bores could be approximated.

Figure 8. Groundwater chemical sampling in Benai.

A bacteriological analysis of samples from existing bores was not undertaken because the samples could not be delivered to the laboratory within the necessary time frame. A bacteriological analysis will be necessary though when the new groundwater targets are drilled and developed. This report will provide guidance on the suitability of groundwater for potable needs.

3.2.3 Topographical survey

Figure 9. A Trimble R10 GPS rover unit in use.

A post-processed kinematic (PPK) elevation survey style was used to determine absolute elevation at 20-m intervals along each ERT line. PPK surveys require data from at least two receivers: a base (reference) receiver and a rover (moving) receiver. Base receivers were installed at central locations in the study areas to allow for good communication with the rover receiver. Elevation data were then used to simulate the surface topography during the processing of the resistivity data obtained in the field.

The topographical elevation of each survey line is critical to avoid distortion of the inverted resistivity model and errors in the interpretation (Mariita 1986). An accurate survey of absolute elevation as well as of the relative change along the profile is also critical.

3.2.4 Consideration for survey locations

3.2.5 Favourable geological and structural features

A literature review coupled with lineament analyses of high-resolution satellite images aided the identification of favourable geological conditions and suitable areas to perform the groundwater assessments. Site reconnaissance proved valuable when validating geological characteristics and determining the orientation of structural and lineament features to be targeted during the survey.

3.2.6 Learning from previous assessments

Lessons learned from previous investigators provided guidance on the possible success and failure of groundwater assessments in the study areas. The JICA (1995) exploratory drilling and more recent drilling around the Nabatolu and Nakavika area, confirmed that the boreholes penetrating the sedimentary units at the Qerelevu site had low yields of and, at times, poor groundwater quality.

The fractured nature of the Ba basalts and breccia, including the Koroimavua andesite, and the concentration of springs and creeks around the area suggest the potential for preferential groundwater storage and flow in geologically constrained fractures. Therefore, the investigation focused on the volcanic units and around the geological structures.

The low elevation and coastal proximity of the Wailevu and Nanuku and Volivoli sectors, coupled with the presence of saline water in hand-dug wells, provided guidance to undertake the geophysical assessment around elevated ground to avoid or minimise the potential threat of adjacent tidal processes and saltwater intrusion.

3.2.7 Information from community councillors and relevant authorities

The dispersed nature of the target communities and their individual water needs were critical considerations in determining the type of survey that would be most suitable within the inherent project time constraints. In consultation with the project management unit and district authorities it was agreed that the surveys would focus on those communities within the sectors that were identified as being the most disadvantaged. District officers, provincial administrators and site visits with community advisory councillors provided useful information in delineating those areas with more severe water problems.

3.2.8 Site accessibility

Site accessibility was critical to allowing geophysical surveys and future drilling to take place. High-resolution satellite imagery was initially used to determine the presence of access roads and tracks relative to the identified geological targets of interest. ERT profiles require a relatively straight survey line and suitable conditions to allow adequate grounding of the electrodes. Other factors complicating the survey design and implementation included undulating topography and dense vegetation.

3.2.9 Existing water supply infrastructure and water demand

Assessing the location and status of existing water-supply infrastructure was an important criterion during the survey design. Utilising existing infrastructure such as storage tanks and pipe networks was considered in the design of the geophysical surveys so as to minimise future community costs and potential land access issues.

3.2.10 Elevation

An accurate assessment of elevation is required in order to guide the potential drilling and development of a groundwater supply and to optimise the use of existing infrastructure. Additionally, in the assessment of coastal areas such as Wailevu and Nanuku and Volivoli, careful consideration of absolute topographical elevation was required to assess the potential for saltwater intrusion that could easily jeopardise the usability of a fresh groundwater body. In this latter case, ERT profiles were assessed in relation to mean sea level where any significantly reduced resistivity zones below this reference may indicate brackish or saline water.

4 Qerelevu

Qerelevu geophysical surveys were undertaken 20–22 February and 22–26 May 2017. The assessment consisted of eight ERT profiles covering the Nakavika, Qerelevu and Namau areas. The analysis and interpretation of the survey lines evaluated the groundwater occurrence with regards to the geologically controlled settings. It should be noted that heavy rainfall events were encountered during fieldwork. The saturated conditions may have influenced the geophysics and resulting interpretation, which in turn may display differences during dry conditions. The relative assessment between target locations would be expected to remain unchanged. A detailed interpretation of the ERT profiles is given in Annex 1 and the inverted resistivity profiles are presented in Annex 2.

4.1 Survey location

ERT profiles were planned and their locations were based on satellite imagery analysis and existing hydrogeological information. Conceptually, groundwater is expected to be present in fractures within the andesitic flow and breccia and in the geological interface between the interbedded sedimentary units and the volcanic formations as shown in the Figure 10. Geological structures were identified based on existing geological maps and from lineament analysis of remotely sensed images.

4.2 Hydrogeological conceptual model

Based on the geophysical interpretations (Annex 1) and field observations it is proposed that groundwater in Qerelevu occurs in three different hydrogeological settings.

- Fractured andesite is expressed as low-resistivity zones, indicating saturated volcanics. These fracture zones, although limited in width (i.e. 5–10 m) in some areas, increase in width in others (> 20 m in Namau) and are thought to form conduits that allow for groundwater flow and storage. The absolute dimensions of these water-bearing fractures may have been underestimated, particularly at depth where the resolution and accuracy of resistivity models is reduced. The lateral and vertical extent of these features was evaluated during this survey but the hydraulic parameters cannot be estimated without drilling and aquifer testing.
- Small perched, dike-impounded systems encountered at Namau and Nakavika and also at higher elevations are expected to hold limited amounts of fresh groundwater. Most of the springs that are located around the hills, which record low to negligible flow during dry periods and are regarded as unreliable water sources, fall within this category. Low-permeability layers (weathered or massive volcanics) allow groundwater to be held between the dikes or fine materials infilling these subvertical features. These systems seem to offer the best option for small, but reliable, groundwater development at the community level.
- Semi-confined systems along the weathered geological contacts of the andesitic flow and sedimentary units may result in the formation of a zone of concentrated weathering and fracturing, with increased potential for groundwater flow via secondary porosity in the weathered sediments and fracturing for preferential groundwater flow. Groundwater potential in these contacts may vary over space and time, and will be dependent on the storage capacity of the sedimentary formation towards the weathered interface.

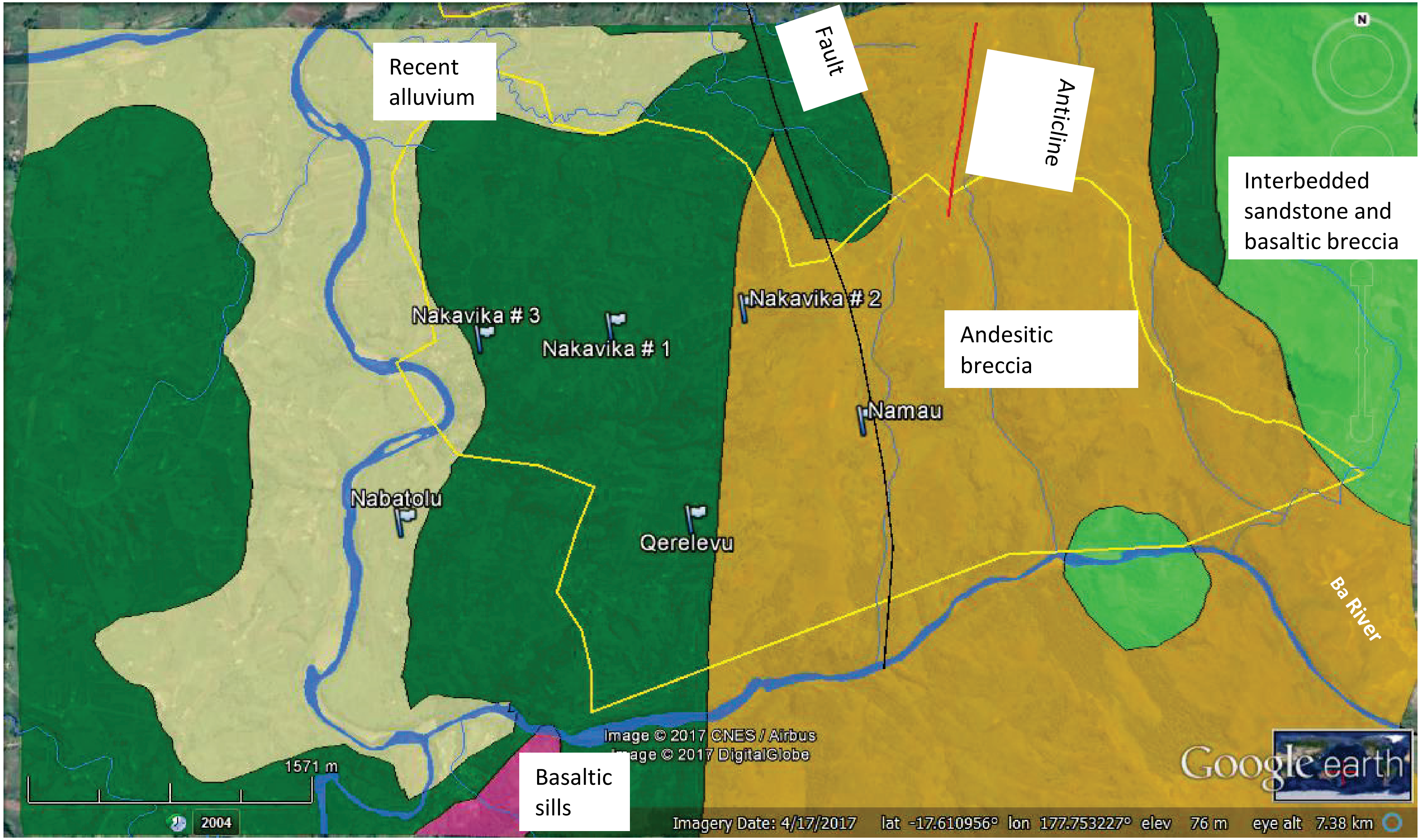

Figure 10. Geological formation underlying Qerelevu.

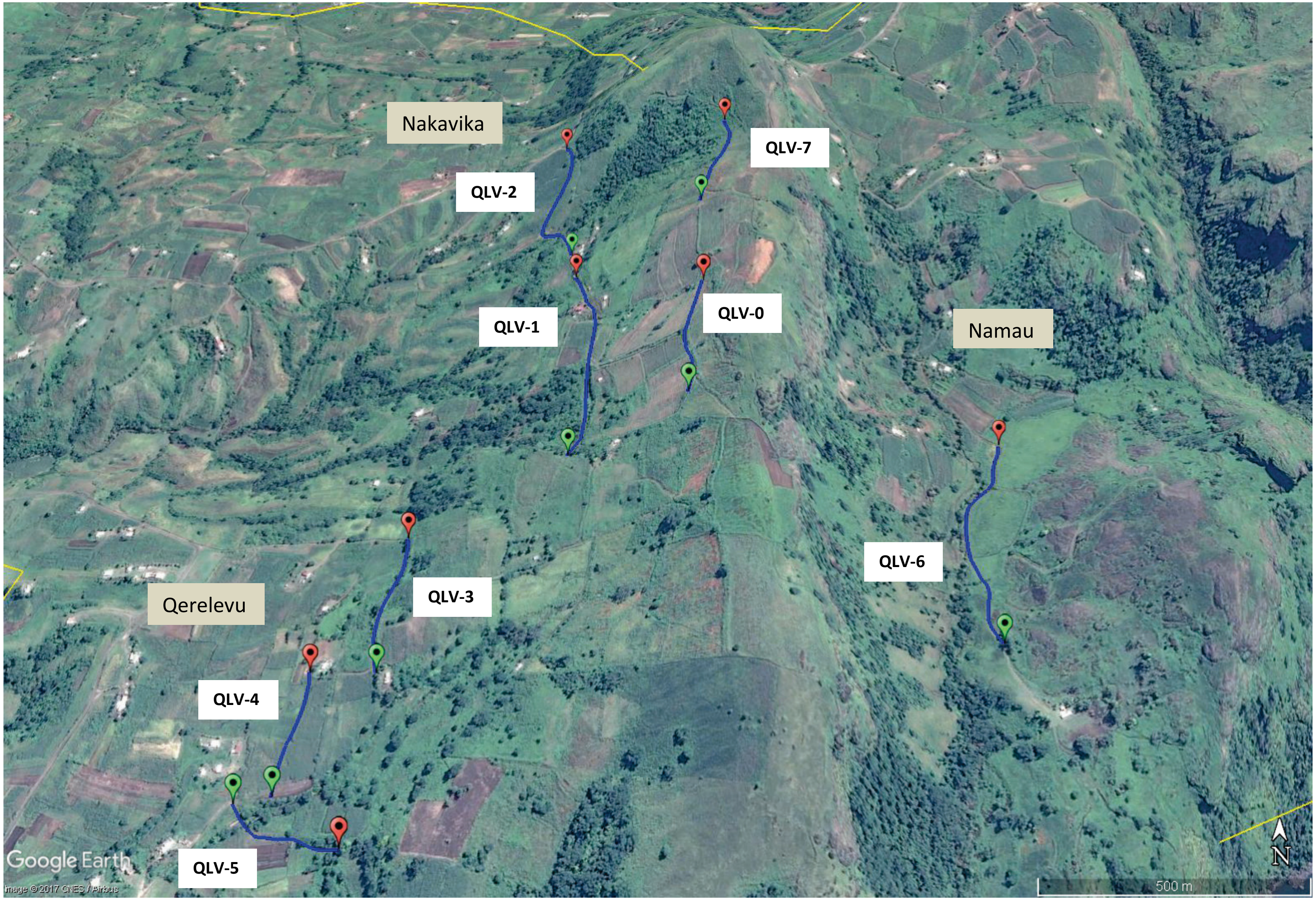

Figure 11. Qerelevu survey profiles (green and red marks indicate, respectively, the start and end of each profile). Source: Google Earth

4.3 Groundwater resources development options

4.3.1 Expected water quality

Groundwater samples were not obtained during this survey, although three existing boreholes in the Qerelevu and Nabatolu areas were surveyed for groundwater depth below ground level and electrical conductivity.

Table 9. On-site measurements of boreholes in Qerelevu and Nabatolu.

Site	Area	Year drilled	Depth (m)	Formation	Water level	Electrical conductivity (µS/cm)
Vinod Prasad	Nabatolu	2016	60	sedimentary	borehole locked	not measured
Ramesh Chand	Nabatolu	2010	67	sedimentary	0.81	200
Qerelevu Primary School	Qerelevu	unknown	50	volcanic	artesian	452

Table 9 presents depth and EC measurements of two privately-owned bores installed into the sedimentary formation in Nabatolu and a borehole currently serving the Qerelevu primary school and drilled in volcanic formations. These data suggest that the geological formation underlying Qerelevu have EC values suitable for drinking water purposes. The low EC recorded for the sedimentary formation may indicate infiltrating rainwater with low residence time while the increased EC recorded in the primary school bore may suggest a deeper water-bearing source with more residence time to allow the dissolution and enrichment of ionic content.

The poor groundwater quality encountered during the JICA (1995) drilling through the sedimentary formation would suggest limited potential for groundwater development. However, the geological interface between the andesite and sedimentary and the fractured-system within the andesitic flow seems to exhibit favourable conditions for groundwater as a community water supply.

4.3.2 Expected yield

Limited information on the yield of the targeted andesitic flow is known. Groundwater flow potential of the volcanic formation will be dependent on the porosity and permeability of the observed fractures and their interconnectedness and extension both horizontally and vertically as influenced by local structures and lineaments (Singhal and Gupta 2010).

Aquifer properties are difficult to estimate as they depend on the connectivity between fractures, vesicles. Borehole yield in basaltic rocks depends on the rock type encountered and on various parameters such as well location with respect to lineament intersections and acceptable drawdown. These properties can only be calculated from aquifer testing. Table 10 presents a range for porosity and hydraulic conductivity in volcanic rocks (Singhal and Gupta 2010).

Table 10. Porosity and hydraulic conductivity values in volcanic rocks (Singhal and Gupta 2010).

Rock type	Porosity (%)	Hydraulic conductivity (m/s)
Dense basalt	0.1–1.0	10^{-11}–10^{-8}
Vesicular basalt	5–11	10^{-9}–10^{-8}
Fractured/weathered basalt	10–17	10^{-9}–10^{-2}
Pyroclastics (tuffs)	87	10^{-6}-10^{-4}

4.3.3 Prioritisation of drilling targets

Three primary drilling targets were prioritised. The prioritisation was based on the pronounced and extensive zone of low resistivity (20–50 Ohm.m), suggesting: 1) the potential of the fractured andesite to provide useable groundwater; 2) accessibility of the site for drilling operations; and 3) proximity to an existing water-supply infrastructure, such as tanks and piping networks, which should yield significant financial savings. Hence, lines QLV-0 and QLV-7 were not considered due to their inaccessibility and high elevation, even though both profiles showed a number of promising targets.

Table 11. Proposed drilling targets in Qerelevu.

Profile	Location	Priority	Site no.	Target distance (m) along the survey line	Expected water-bearing depth target (m)	Drill target coordinates
QLV-1	Nakavika	Secondary	QLV-S1	170–190	15–25	177.757°E, -17.612°S
QLV-1	Nakavika	Primary	QLV-P1	60–75	15–25	177.757°E, -17.613°S
QLV-2	Nakavika	Primary	QLV-P2	85–100	30–50	177.756°E, -17.607°S
QLV-3	Qerelevu	Primary	QLV-P3	70–80	20–40	177.753°E, -17.616°S
QLV-3	Qerelevu	Primary	QLV-P4	170–190	15–35	177.754°E, -17.616°S
QLV-6	Namau	Secondary	QLV-S2	160–180	15–40	177.763°E, -17.615°S
QLV-6	Namau	Secondary	QLV-S3	230–260	20–80	177.764°E, -17.614°S
QLV-6	Namau	Secondary	QLV-S4	330–340	30–80	177.764°E, -17.614°S

For Nakavika, it is proposed that **QLV-P1**, located along survey line QLV-1 (Fig. A2) be the primary drilling target because it indicates adequate depth and lateral extension, suggesting potential for greater storage capacity and usable groundwater even during extreme climatic conditions. The site is located on andesitic breccia, indicating that the top 20 m will provide challenging drilling conditions before the potential groundwater source is encountered. It is recommended that **QLV-P2** along survey line QLV 2 (Fig. A3) be explored and tested, should QLV-P1 be found to be either too difficult to drill or low-yielding.

For Qerelevu, **QLV-P3** along survey line QLV 3 (Fig. A4) is the preferred drill target, based on the increasing thickness of weathered or fractured andesite and its location near a potential fault, indicated by the adjacent vertically steep fresh basement. These suggest that the underlying area is likely to be moderately fractured or jointed and may have a greater storage area, thus allowing this site to provide more reliable and usable groundwater over time. This target is sited on andesitic breccia, suggesting that challenging drilling conditions can be expected before the potential groundwater-bearing formation is encountered at depths below 15 m.

Targets in Namau have been prioritised although there are no existing tanks or piping network. The selection of these targets is based on the depth and lateral dimensions of the potential groundwater systems represented on the profile. **QLV-S4** along survey line QLV-6 (Fig. A7) was indicated as the preferred target. Again, challenging drilling conditions should be expected, mainly because of fractured andesite and the layer of increased resistivity between 20 m and 30 m capping the possible water sources. The presence of the groundwater target along the Namau profile is encouraging but may require significant cost and sound engineering to develop and reticulate the system.

The use of a down-the-hole (DTH) hammer bit with a high-pressure air compressor is strongly recommended for these drilling targets due to its suitability for hard formations. Appropriate drilling protocols such as: 1) logging rock-cuttings with special attention on the fractured zones; 2) estimating groundwater yield through airlift and the use of a V-notch weir; and 3) using proper construction materials, including pea-sized gravel and class-12 PVC casing, are recommended industry best practices and should be used. It is recommended that a 24-hour pumping test be performed to determine the hydraulic parameters to inform the sustainable development for community water supplies with yields greater than 1 L/s. Yields less than 1 L/s could rely on a 12-hour pumping test for determining long-term pumping rates.

5 Wailevu and Nanuku

Investigation around the Wailevu and Nanuku sectors were undertaken from 5 to 9 June 2017, resulting in eight survey lines across the area. The survey, undertaken one week after the Qerelevu mission, coincided with high and frequent rainfall events. Caution should, therefore, be taken when analysing the ERT profiles because the investigated basaltic framework may be at near-saturation and this is expected to change significantly during dry periods, particularly with near-surface or rainfall-dependant sources.

5.1 Survey locations

Following the advice of the advisory councillor from Nanuku and Wailevu, coupled with information gathered from the lineament analysis and survey visits, a number of survey sites were identified. The site selection considered the location of people residing around the western and central parts of Nanuku, and the north-central part of Wailevu surrounding the school as being the most disadvantaged. Selected existing groundwater sources were assessed for groundwater depth and yield, which provided useful information on site conditions favourable for groundwater occurrence. Figures 12 and 13 show the locations of the eight survey profiles conducted around the neighbouring sectors relative to the mapped geological framework and assessed groundwater bores.

5.2 Hydrogeological conceptual model

Based on the geophysical interpretations and field observations it is proposed that groundwater in Wailevu and Nanuku occurs in two different hydrogeological settings.

- Fractured basalt, as represented by well-defined incised and/or near-vertical low-resistivity zones, indicates saturated volcanics. These fracture zones, although limited in width (i.e. 5–20 m) can form conduits allowing for groundwater flow and storage. The full dimensions of these water-bearing fractures may have been underestimated, particularly at depth where the resolution and accuracy of the inverted resistivity models is reduced. The lateral and vertical extent of these features was evaluated during this survey but their hydraulic parameters cannot be estimated unless drilling and proper pumping tests are undertaken.
- A number of shallow and perched formations were observed within the basaltic framework. These systems may represent shallow zones of weathered regolith or fractures that are underlain by low-permeability basalt with little to no fracturing influencing the development of limited storage systems that may be recharged directly by rainfall but may be vulnerable during dry periods.

5.3 Groundwater resources development options

5.3.1 Expected water quality

Groundwater samples were obtained from Mr Satish Kumar's bore in Nanuku and from the kindergarten bore in Wailevu. The analysis of major anions and cations was undertaken at MRD's geochemical laboratory. Other on-site physicochemical properties were assessed, including total borehole depths, static water levels and electrical conductivity (EC). These are shown in Table 12.

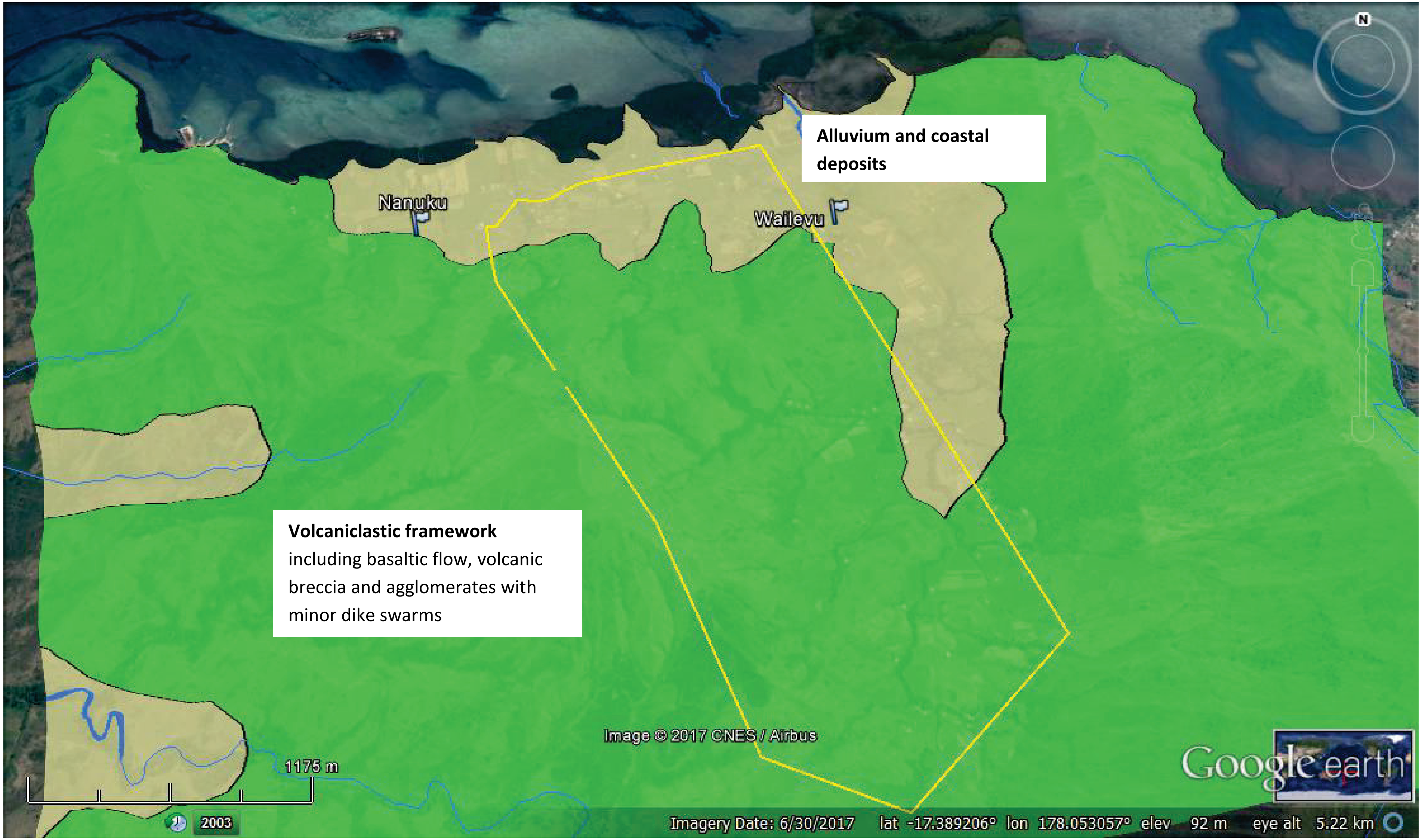

Figure 12. Geological formation within Wailevu and Nanuku.

Figure 13. Nanuku and Wailevu survey profiles. Source: Google Earth

Table 12. On-site measurements of boreholes in Nanuku and Wailevu.

Site	Satish Kumar	Wailevu kindergarten
Total depth (m)	31.2	28.6
Static water level (m)	10	0.32
EC	244	418
Estimated discharge rate (L/s)	0.8	0.8
Hydrogeochemical properties		
Magnesium (mg/L)	15.61	24.6
Sodium (mg/L)	10.47	12.88
Potassium (mg/L)	0.43	0.157
Manganese (mg/L)	<0.01	<0.01
Iron (mg/L)	<0.01	<0.01
Bicarbonate (mg/L)	168.77	250.1
Carbonate (mg/L)	< detectable limit	< detectable limit
Sulphate (mg/L)	< detectable limit	3
pH	7.23	7.37

Satish Kumar's bore, although slightly deeper than the kindergarten bore, shows significantly lower EC, possibly due to low magnesium and sodium at that site. The Wailevu kindergarten bore exhibited high EC and enriched magnesium and sodium. This variability may suggest heterogeneity in groundwater flow and storage within the basaltic framework, coupled with the close proximity of the abstraction point to the recharge sources and the groundwater residence time to allow the dissolution and enrichment of ionic content. The measured cations and anions show permissible limits in relation to WHO drinking water guidelines. A full bacteriological assessment of groundwater is required to determine its safety.

Documented in the JICA (1995) drilling report were a number of existing groundwater bores installed into the fractured basalt around the Wailevu coastal plain, recording an EC range of 320–630 µS/cm. Although the groundwater development potential of the chloritised trachybasalt was deemed poor, it is clear that the localised nature of fractures would generate favourable conditions to yield usable groundwater.

5.3.2 Expected yield

Table 12 shows that both of the sampled bores were pumped at 0.8 L/s. The JICA (1995) report noted that existing bores in the Wailevu coastal plain have an estimated transmissivity and well yield of 0.5–1.0 m^2/day and 0.4–0.8 L/s, respectively, suggesting that groundwater potential may be poor. The variability of fractures in terms of depth extent, width and level of interconnection, dictate the preferential groundwater flow. The location of the profiles within the capture zones of all the targeted catchments areas, coupled with the dimensions of potential fractures observed on the profiles, may suggest the potential for good groundwater yield from the fractured basalts, which would be ideal for the community water supply.

5.3.3 Prioritisation of drilling targets

Four primary drilling targets were prioritised, two for Nanuku and two for Wailevu. The prioritisation was based on the pronounced and extensive zone of low resistivity (20–50 Ohm.m), which is indicative of fractured and possibly saturated basalt that has the potential to provide adequate groundwater. Survey line 2 (NNK-2) was not considered due to its inaccessibility and high elevation. Five secondary targets were also indicated due to their depth and potential for groundwater storage. The drilling of these sites is strongly suggested if additional funds are available to further enhance water security for local communities.

Table 13. Proposed drilling targets around Wailevu and Nanuku.

Profile	Location	Priority	Site label	Profile distance (m)	Expected depth for water-bearing target (m)	Drilling target coordinates
NNK-1	Nanuku	Primary	NNK-P1	175–190	15–40	178.040°E, -17.380°S
NNK-3	Nanuku	Primary	NNK-P2	115–125	15–30	178.035°E, -17.381°S
NNK-3	Nanuku	Secondary	NNK-S1	175–185	15–30	178.035°E, -17.381°S
NNK-4	Nanuku	Secondary	NNK-S2	190–240	10–30	178.047°E, - 17.379°S
NNK-4	Nanuku	Secondary	NNK-S3	250–260	20–30	178.048°E, -17.379°S
WLV-5	Wailevu	Primary	NNK-P3	85–105	15–45	178.057°E, -17.381°S
WLV-6	Wailevu	Secondary	NNK-S4	95–110	30–50	178.059°E, -17.381°S
WLV-7	Wailevu	Secondary	NNK-P4	320–370	10–40	178.061°E, -17.382°S
WLV-7	Wailevu	Primary	NNK-S5	500–680	5–40	178.061°E, -17.380°S

For Nanuku, it is proposed that **NNK-P1**, located along survey profile NNK-1 (Fig. A9) be the primary drilling target because it shows a significant depth extent, suggesting that it may have greater storage capacity for groundwater. The expected depth to reach groundwater is 15–30 m. This site is prioritised over **NNK-P2** (survey line NNK-3, Fig. A11) mainly because the households clustered around the western part of Nanuku and adjacent to the Direndra residence do not have any water supply systems in place, whereas areas around survey line NNK-3 are in proximity to a productive bore where an active water supply system serves the surrounding households. If NNK-P1 proves to be low-yielding or difficult due to either inaccessibility or a non-supportive landowner, then NNK-P2 should be considered. Both sites are within basaltic flow and breccia, and hence challenging drilling conditions should be expected.

For Wailevu**, NNK-P3** is preferred based on the size of the fractured and possibly saturated basalt along survey line WLV-5 (Fig. A13), which may be hydraulically linked and recharged from higher in the catchment, as is suspected of the kindergarten bore. The density of houses adjacent to the area that do not have access to reliable water sources is another of the main reasons why the site has been prioritised. Should this area be low-yielding, then the drilling of **NNK-P4** (survey line WLV-7, Fig. A15) is proposed, which exhibits encouraging results in terms of lateral and vertical extension, has good accessibility along the Wailevu Road, and is closely situated to existing electricity lines. Again, the sites are located within basaltic frameworks, hence challenging drilling conditions should be expected. The use of a DTH hammer with a high-pressure air compressor is, again, strongly recommended for these drilling targets due to its suitability for hard formations, with the other hydrogeological and drilling protocols and data collection practices recommended for Qerelevu be upheld.

6 Benai

Benai geophysical surveys were conducted 18–22 September 2017 with nine survey lines undertaken around the sector. As stated earlier, two areas within Benai suffer from long-term water shortages due to their disconnection from the WAF distribution schemes. These areas include Benai 22 and Benai End, and based on the advice of Advisory Councillor Deo Sharan, the current survey was designed to ensure that these sparse areas are adequately covered. It should be noted that the survey was undertaken during dry conditions, which is ideal for identifying and delineating relatively deep groundwater systems that may be able to yield usable and safe groundwater throughout the year.

6.1 Survey locations and profile summary

The selection of survey lines was guided by the extent of the fractured andesitic and basaltic formations around the Benai 22 and Benai End areas. These geologies are considered to be the target formations that may possess favourable conditions for groundwater flow and storage. Hence, seven lines (BEN-1 – BEN-7), of the nine profiles were planned around volcanic formations. Survey lines 8 and 9 were completed in the interbedded sedimentary formations, and targeted the possible occurrence of groundwater either within the sedimentary rocks or along the interface between sedimentary deposits and the underlying basaltic breccia. The extension of the NNW-trending regional fault into the Benai area also generated interest in terms of creating localised fractures that may yield usable groundwater. Table 14 and Figures 14 and 15 illustrate the summary and location maps of the ERT profiles.

Table 14. Description of Benai survey lines.

Profile	Location	Geology	Distance covered (m)	Electrode separation (m)	Target(s)
BEN-1	Benai22	Andesitic breccia and flow on the southeast end, and basaltic breccia on the north end, with the rolling and undulating area from the southwest and extending to the central area underlain by interbedded sedimentary and alluvial materials that are concentrated around the low-lying areas	400	4	Fracture zones within volcanics
BEN-2	Benai22		384	4	Fracture zones within volcanics
BEN-3	Benai22		320	4	Fracture zones within volcanics
BEN-4	Benai22		500	5	Fracture zones within volcanics
BEN-5	Benai-End		320	4	Fracture zones within volcanics
BEN-6	Benai-End		320	4	Fracture zones within volcanics
BEN-7	Benai-End		500	5	Fracture zones within volcanics
BEN-8	Benai-End		500	5	Geological contact between sedimentary deposits and basaltic breccia
BEN-9	Benai-End		400	5	Geological contact between sedimentary deposits and basaltic breccia, and assess the extent of N-S trending regional fault

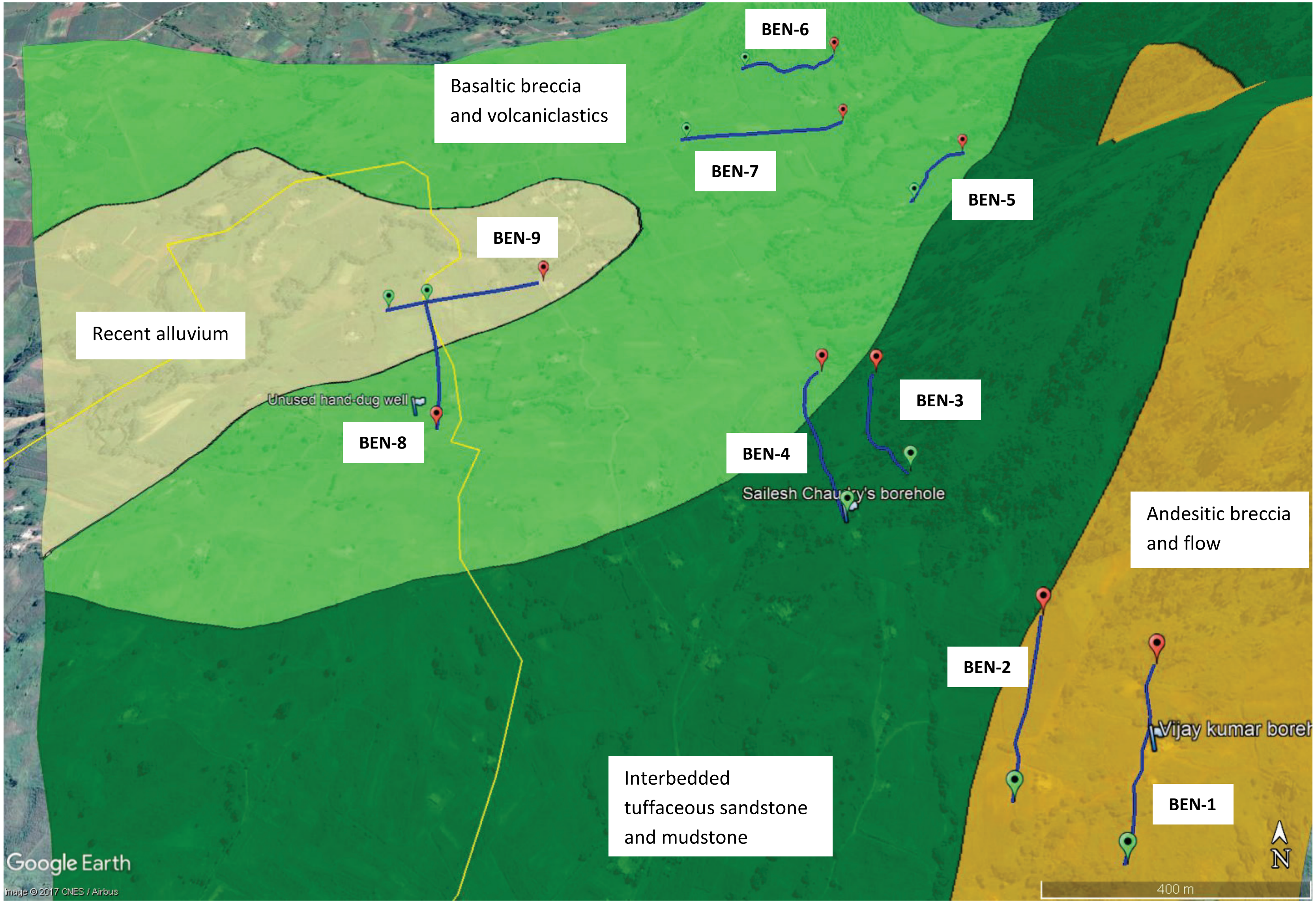

Figure 14. Geological framework underlying and surrounding Benai and locations of electrical resistivity transect profiles.

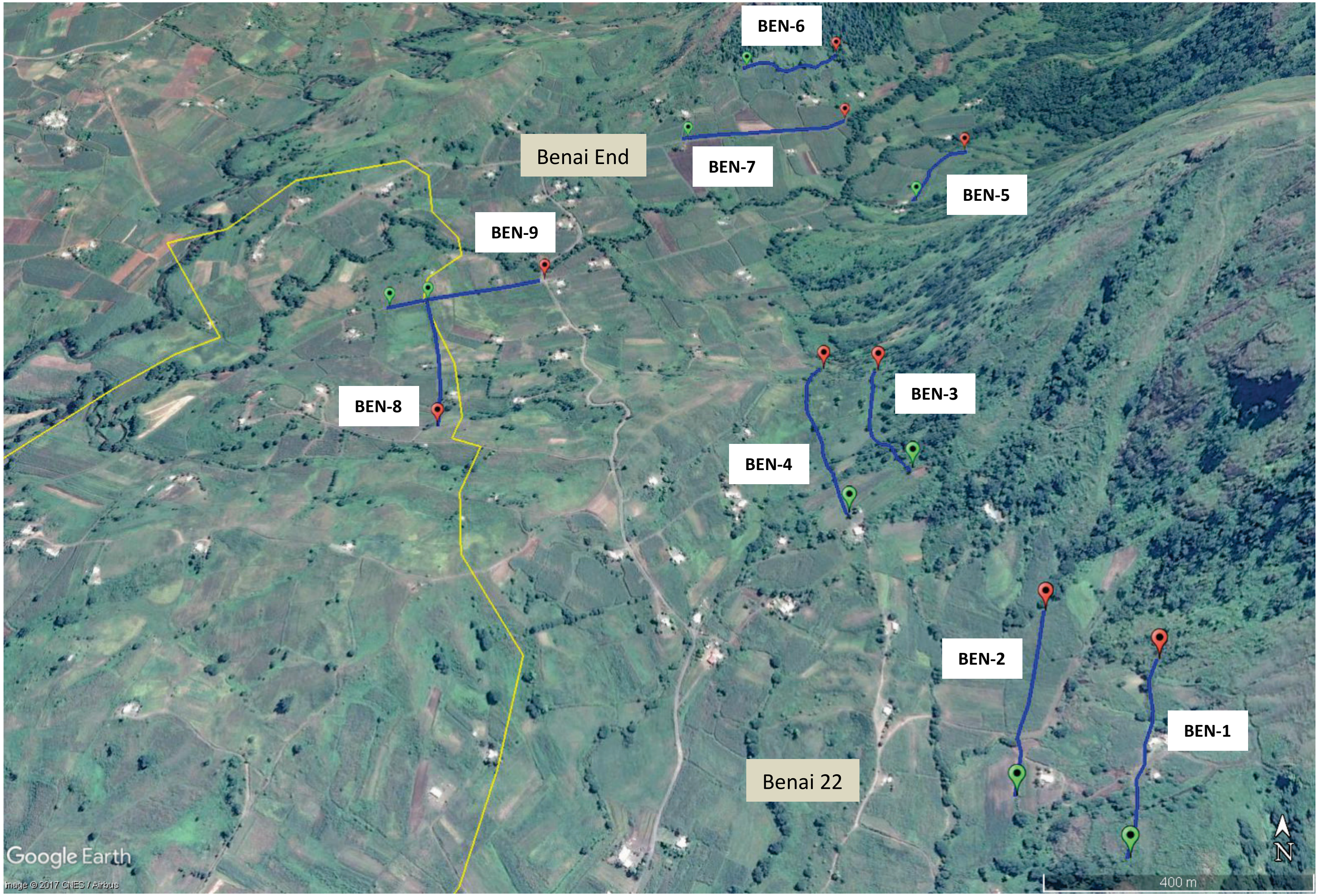

Figure 15. Benai survey profiles.

6.2 Hydrogeological conceptual model

Based on the resistivity profiles, the occurrence of groundwater around the Benai area, as suggested by the resistivity results, appears to coincide with the presence of fractured andesitic and basaltic flows, thus providing enhanced porosity and permeability and creating preferential groundwater flow and storage.

6.3 Groundwater resources development options

6.3.1 Expected water quality

The on-site sampling and analysis of three existing bores in Benai, as shown in Table 15, suggests that the underlying basaltic and andesitic units investigated are capable of providing potable water quality. While there have not been any reported cases of water-borne diseases from groundwater-reliant households, it is imperative that a complete water chemistry and bacteriological analysis be conducted should any of the identified groundwater targets is considered for development for community water supply. This is mainly to ensure the safety of groundwater for human consumption and to comply with WHO guidelines for drinking water.

Table 15. On-site and hydrogeochemical measurements of three sampled boreholes in Benai 22.

Site	Kumar's bore	Chaudhry's bore 1	Chaudhry's bore 2
Area	Benai 22	Benai 22	Benai 22
Total depth (m)	55	56	54
EC (µS/cm)	451	606	525
Estimated discharge rate (L/s)	0.8	0.7	0.8
Hydrogeochemical properties			
Calcium (mg/l)	45.5	44.9	24.1
Magnesium (mg/l)	20.02	13.99	3.68
Sodium (mg/l)	19.98	73.51	91.79
Potassium (mg/l)	4.567	3.405	2.083
Manganese (mg/l)	0.021	0.021	< detectable limit
Iron (mg/l)	< detectable limit	< detectable limit	< detectable limit
Bicarbonate (mg/l)	231.8	337.5	314.2
Sulphate (mg/l)	32	22	16
Chloride (mg/l)	14.2	13.3	6
pH	7.19	7.38	7.72
Ionic balance (%)	0.4	2.4	0.9

6.3.2 Expected yield

Table 15 shows the physicochemical properties of the three sampled bores. Installed in the fractured andesitic formation, the bores are currently used for household water supply and do not seem to have problems in relation to the current abstraction rates. An unused, hand-dug well was also observed at around 440 m profile distance along survey line 8 (BEN-8, Fig. A24). The well, installed within the basaltic breccia, had a total depth and static water level of 5.0 m and 4.6 m, respectively, while recording an EC of 393 µS/cm. This source does not run dry and seems to be used by nearby households only during extremely dry conditions. This suggests that the surrounding basaltic and andesitic formations have favourable characteristics for groundwater flow and storage, and it is strongly recommended that: 1) the identified targets are drilled to assess groundwater potential, and 2) successful bores be tested for hydraulic properties to ensure the accurate estimation of groundwater yield. Again, the variability of fractures in terms of vertical and lateral extent, together with their level of interconnection, will dictate the preferential groundwater flow (Singhal and Gupta 2010).

6.3.3 Prioritisation of drilling targets

Three primary drilling targets were prioritised. The prioritisation was based on the pronounced and extensive zone of low resistivity (20–50 Ohm.m), which suggests the potential for fractured andesite to provide adequate groundwater volumes. Other considerations include access and proximity of the sites to an existing water-supply infrastructure. These factors were assessed in relation to the ease of access for a 16-tonne, truck-mounted rig to the selected areas and the possibility of connecting the borehole to existing tanks or piping networks, which should yield significant financial savings.

Table 16. Proposed drilling targets in Benai.

Profile	Area	Priority	Site label	Target distance (m) along the survey line	Expected water-bearing depth target (m)	Drill target coordinates
BEN-1	Benai 22	Secondary	BEN-S1	290–310	10–20	177.764°E, -17.577°S,
BEN-2	Benai 22	Secondary	BEN-S2	55–75	30–40	177.763°E, -17.578°S
BEN-2	Benai 22	Primary	BEN-P1	140–220	30–50	177.763°E, - 7.577°S
BEN-3	Benai 22	Secondary	BEN-S3	185–210	25–40	177.761°E, -17.571°S
BEN-4	Benai 22	Primary	BEN-P2	340–380	15–70	177.760°E, -17.570°S
BEN-7	Benai End	Secondary	BEN-S4	40–120	15–60	177.758°E, -17.559°S
BEN-7	Benai End	Primary	BEN-P3	335–385	10–60	177.760°E, - 7.559°S
BEN-9	Benai End	Primary	BEN-P4	80–135	20–80	177.751°E, -17.566°S
BEN-9	Benai End	Secondary	BEN-S5	215–265	15–60	177.752°E, -17.566°S

For Benai 22, drilling targets **BEN-P1** and **BEN-P2** along survey lines BEN-2 (Fig. A18) and BEN-4 (Fig. A20) were deemed as primary, mainly because of the dimensions of the potential groundwater-bearing zones identified by resistivity, and the minimal work required to make the site accessible. For BEN-P1, the expected depth-range of the groundwater-bearing formation is 30–50 m, while for BEN-P2 it is 15–70 m. BEN-P1 is sited on fractured andesite and BEN-P2 is sited on a sedimentary and andesitic formation, hence challenging drilling conditions will be expected prior to reaching the expected groundwater depths. Based on the extent of the Benai 22 area, it is strongly suggested that both of these primary sites are drilled to ensure the coverage of water supply to the surrounding households. The secondary targets, **BEN-S1** (survey line BEN-1, Fig. A17), **BEN-S2** (survey line BEN-2,

Fig. A18) and **BEN-S3** (survey line BEN-3, Fig. A19), albeit showing promising resistivity responses, will require significant work in order to access them. Should BEN-P1 and BEN-P2 prove to be low-yielding, the relevant authorities will need to be contacted to improve site accessibility for groundwater drilling of other targets.

For Benai End, drilling targets **BEN-P3** (survey line BEN-7, Fig. A23) and **BEN-P4** (survey line BEN-9, Fig. A25) were deemed as primary based on the dimensions and potential of the fractured basaltic formation to yield groundwater for the surrounding communities. The secondary targets, **BEN-S4** (survey line BEN-7, Fig. A23) and **BEN-S5** (survey line BEN-9, Fig. A25), although having good accessibility, will only be considered if the primary targets prove to be low-yielding. Again, the basaltic framework, be it fractured or fresh, will present challenging and difficult drilling conditions.

The use of a DTH hammer bit with a high-pressure air compressor is strongly recommended for the drilling of these targets due to its suitability for hard formations. Appropriate drilling protocols are essential for estimating the hydraulic parameters of these targets, which will inform the sustainable development of these groundwater-bearing formations, if successful, for the community water supply. These drilling protocols include: 1) logging rock-cuttings (with special attention to fracture zones); 2) estimating groundwater yield through airlift and a V-notch weir; 3) using proper construction materials, including pea-sized gravel and class-12 PVC; and 4) conducting a 24-hour pumping test.

7 Navia and Nadhari

Geophysical surveys were completed for the neighbouring communities of Navia and Nadhari, and extending into the nearby settlement of Waibuka, between 1 and 6 October 2017. Seven ERT profiles were conducted across the two areas, covering as much representative ground as possible with consideration to access and the location of households. In the following section, the modelled resistivity distribution is interpreted in terms of hydrogeology and groundwater potential.

The study area is located in the low, undulating hills between the Ba uplands in the southwest, the Matalevu uplands in the northeast, and the Vatia-Lousa coastal plain in the northwest. According to the JICA (1995) report, the hilly areas are underlain by consolidated pyroclastic rocks and lava of Miocene-Pliocene age, partly intercalated with sedimentary rocks. More specifically, Tertiary basalts and basaltic breccia dominate the Ba uplands region, while the Matalevu uplands region is composed of fresh and hard basaltic lava and weathered soil. The Vatia-Lousa coastal plain consists mainly of Tertiary basaltic and andesitic rocks. Tertiary volcanics are generally considered poor in terms of groundwater potential due to the advanced weathering they have undergone and the sedimentation of secondary minerals into fissures. Fractured or sheared zones may, however, form good aquifers. Intercalated sedimentary rocks in the study area consist mainly of tuffaceous mudstones with several fractured zones forming confined aquifers with moderate to high permeability.

7.1 Groundwater resources development options

7.1.1 Expected water yield

JICA (1995) documented the exploration of three bores around the basaltic formation at GW35 in Vatuyaka, TW008 in Kunirewa and TW009 in Drumasi. Although these areas are relatively far from Navia and Nadhari, the tested yield and chemical analysis provide an approximation of the groundwater potential of basaltic flows and breccias underlying the area. The yields of these historical bores are provided in Table 17.

Table 17 shows the variability of the bores attributed to highly fractured basalts and the interconnectivity of the conduits to store and transmit usable groundwater (JICA 1995). It is expected that the potential targets identified in this survey will produce similar yields, which should meet the drinking water needs for the communities of Navia, Nadhari and Waibuka. Once the proposed targets are drilled, groundwater yields can be assessed.

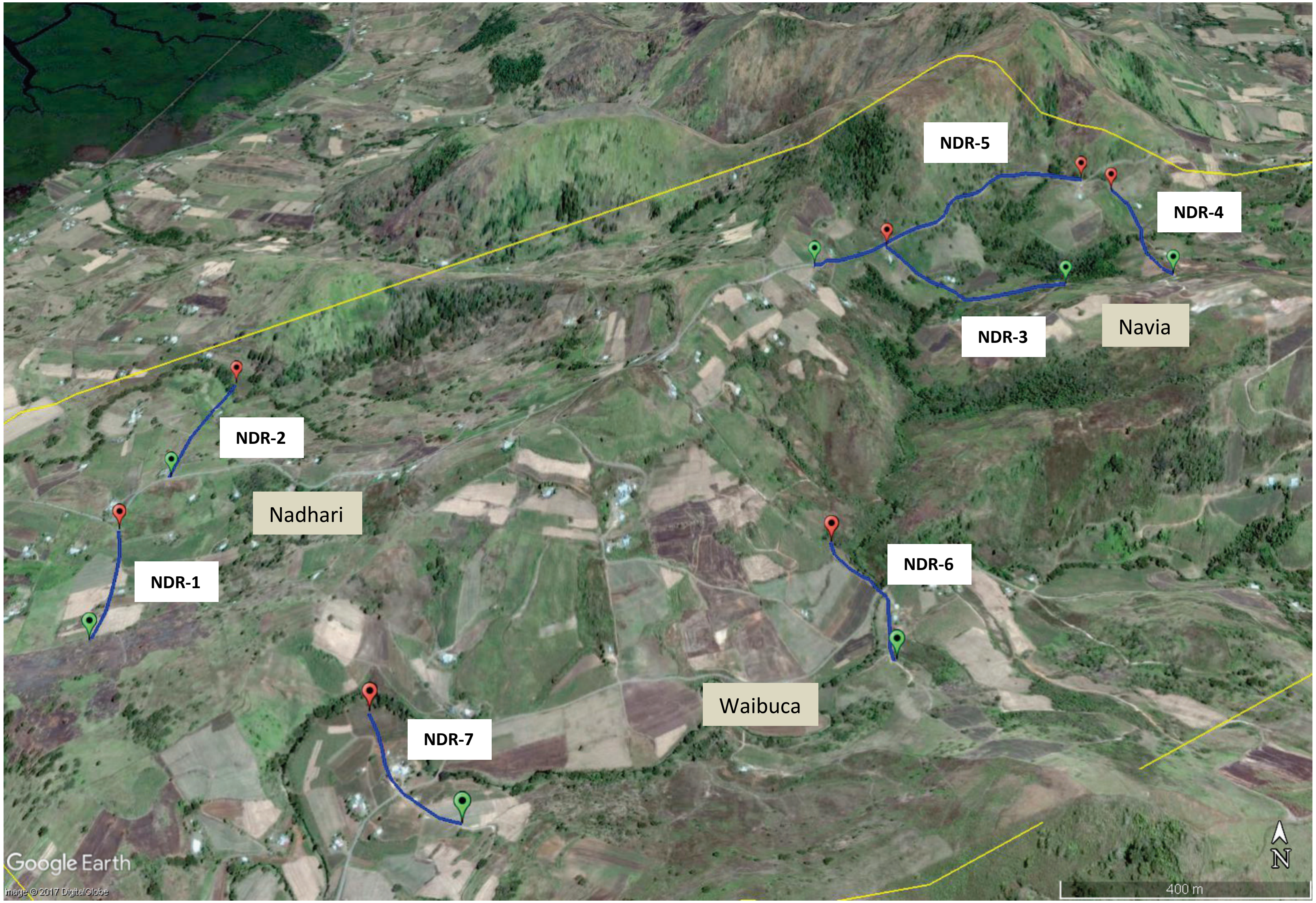

Figure 16. Navia and Nadhari survey profiles. Source: Google Earth

Table 17. Summary yield and quality of historical bores drilled into basaltic breccia and lava flows within the Ba series (JICA 1995).

Site	TD004	TD005	GW035
Total depth (m)	57.7	60.3	45
Static water level (m)	8.12	9.81	7.52
EC	188	54	340
Discharge rate (L/s)	2.89	2.35	4.81
Hydrogeochemical properties			
Magnesium (mg/L)	65	18	11.2
Sodium (mg/L)	10	4	10
Potassium (mg/L)	1.8	0.9	0.2
Calcium (mg/L)	40	6	36
Iron (mg/L)	0.2	0.5	0.1
Manganese (mg/L)	<0.001	0.25	<0.01
Chloride (mg/L)	8	5	18
Sulphate (mg/L)	6	20	2.186
Bicarbonate (mg/L)	125.6	19.5	250.1
TDS (total dissolved solids)	150	34	200
pH	6.81	6.28	6.81

7.1.2 Expected water quality

Table 17 shows groundwater chemical composition in terms of major cations and anions, and aggregating these through EC and total dissolved solids. It is clear that most of the measured parameters in the three sources exhibit variability that may be attributed to local ionic dissolution processes. However, all sources seem to be within WHO's drinking water guidelines. The groundwater targets proposed through this assessment will undergo similar sampling and analysis to determine their compliance with WHO standards, while additional bacteriological analysis will be needed to determine the safety of these sources with regard to health.

7.1.3 Prioritisation of drilling targets

Eight targets were identified, of which four were categorised as primary and four as secondary, based on their expected yield. Along survey line 1 (NDR-1, Fig. A26), two primary targets (**NDR-P1** and **NDR-P2**) were indicated as being relatively close distance to each other. The targets were both marked as primary because the yield is expected to be substantial; however **NDR-P2,** should take priority if only one of the targets is to be drilled. The relatively small distance between the two sites (~75 m) and the absence of subsurface features that could act as boundaries or groundwater divides, may have implications in terms of the two sites influencing each other if they are both drilled and operated simultaneously. The water-bearing formation is expected to be encountered at 10–15 m depth at both sites, although drilling should continue down to 50–55 m depth.

Along survey line 2 (NDR-2, Fig. A27), one secondary groundwater target (**NDR-S1**) is marked at 265 m profile distance in an area where fissured volcanic deposits possibly underlie a 10-m-thick layer of saturated clay. It is recommended to continue drilling down to at least 45 m depth.

No promising drilling targets were identified along survey lines 3 and 4 because the overall resistivity response was relatively high, indicating low groundwater potential. Survey line 5 (NDR-5, Fig. A30), on the other hand, proved quite successful, and three drilling targets were proposed: two primary and one secondary at 195 m, 560 m and 750 m, respectively. The first two targets (**NDR-P3** and **NDR-P5**) were marked as primary drilling sites due to their higher groundwater potential. The water-bearing formation at target NDR-P3 is expected to be encountered at a depth of more than 30 m, and drilling through basaltic lava and/or pyroclastic rocks should be expected until the aquifer is reached. Drilling should continue until sufficient air-lift yield is achieved. Drilling in the other two sites is expected to be easier and the water-bearing formation should be encountered at shallower depths of 10–15 m. The three sites are not expected to influence each other due to the presence of subsurface boundaries acting as groundwater divides.

Finally, two secondary sites were marked along survey lines 6 (NDR-6, Fig. A31) and 7 (NDR-7, Fig. A32) to cover the demands of the Waibuca farming community. It should be noted that survey line 6 shows general groundwater potential along its entire length, and site **NDR-S3** is located at the best location if only one target is to be drilled. Groundwater is expected to be found at shallow depth (~5 m) although drilling should continue until at least 30 m. Drilling anywhere along the 130–300-m interval along the profile is expected to yield average groundwater volumes. Moderate yields are also expected along survey line 7 and the secondary target (**NDR-S4**) was marked at 258 m distance along the profile. The water-bearing formation is expected at 15 m depth and it is recommended to continue drilling to at least 50 m depth.

Table 18. Proposed drilling targets in Nadhari, Navia and Waibuca.

Profile	Location	Priority	Site label	Target distance (m) along the survey line	Expected water-bearing depth target (m)	Drill target coordinates
NDR-1	Nadhari	Primary	NDR-P1	135	10–50	177.744°E, -17.487°S
NDR-1	Nadhari	Primary	NDR-P2	208	15–55	177.744°E, -17.487°S
NDR-2	Nadhari	Secondary	NDR-S1	265	5–45	177.745°E, -17.481°S
NDR-5	Navia	Primary	NDR-P3	195	30–70	177.763°E, -17.478°S
NDR-5	Navia	Primary	NDR-P4	560	10–80	177.766°E, -17.476°S
NDR-5	Navia	Secondary	NDR-S2	750	15–40	177.768°E, -17.475°S
NDR-6	Waibuca	Secondary	NDR-S3	282	5–30	177.763°E, -17.487°S
NDR-7	Waibuca	Secondary	NDR-S4	258	15–50	177.752°E, -17.492°S

The expected presence of basaltic breccia and flow with minor welded tuffs suggests that difficult drilling conditions will be encountered around most of, if not all, the sites. Appropriate drilling methods and practices, along with the necessary hydrogeological assessment will be required to warrant the sound characterisation, construction and development of the potential water-bearing targets, as well as the accurate evaluation of groundwater yield and quality.

8 Malele

Geophysical surveys of the Malele farming sector in Tavua were undertaken between 20 and 24 November 2017. The visit resulted in the realisation of 10 survey lines around the area. Parts of Malele already have reliable water supplies while the most remote part, Malele #3, is not connected to a reliable water supply system and is reliant on carted water from WAF during much of the year. Due to this long-standing situation of water carting, FSC identified Malele #3 as a vulnerable community, which was later prioritised as a target community during this project. According to the community Advisory Councillor Balbant Singh, four areas within Malele #3 suffer long-term water security issues: Malele north, Natolevu, Davota and Bangladesh. The severity of the limited water supply around Malele #3 is evident by the frequent water carting trips undertaken by the contracted WAF delivery trucks to the area during the field assessment.

The location and orientation of the resistivity survey lines were chosen to: 1) target potential regional and local fracture systems that may influence the groundwater potential of the underlying geological framework; and 2) identify prospective groundwater drilling targets that would provide long-term solutions to the prevalent water problems. The following sections summarise the main geological framework underlying the area, and provide information on survey locations

8.1 Survey locations and profile summary

The selection of survey lines was guided by the extent of the juxtaposed trachybasalt and trachyandesite, both having agglomerate, breccia and multiple flow characteristics. These units are located within (and possibly a product of) the collapsed Tavua caldera, having a dominant lineament trends of SSE-NNW and NE-SW and could influence the potential storage and flow of groundwater around the area. Also, the close proximity of the Island Chill's water bottling source and the Vatukoula gold mine were encouraging indicators of the possible presence of multiple geological structures and formations that enhance groundwater movement and storage potential. Table 19 and Figures 17 and 18 illustrate the summary and location of the survey profiles.

Table 19. Description of Malele survey lines.

Profile	Location	Geology	Distance covered (m)	Electrode separation (m)	Target
MLL-1	Khalsa	Multiple phases of biotite trachyandesitic flow and pyroclastic and augite trachybasalt around the Tavua Caldera, with NNE and NNW trending lineaments, indicating potential faults and fracture systems and increased groundwater flow	400	5	Fractured volcanics
MLL-2	Malele		300	5	Fractured volcanics
MLL-3	Malele		300	5	Fractured volcanics
MLL-4	Natolevu-Davota		500	5	Fractured volcanics
MLL-5	Davota		500	5	Fractured volcanics
MLL-6	Natolevu south		500	5	Fractured volcanics
MLL-7	Davota-Vanga		500	5	Fractured volcanics
MLL-8	Natolevu north		500	5	Fractured volcanics
MLL-9	Vuqele		600	5	Fractured volcanics
MLL-10	Bangladesh		400	5	Fractured volcanics

8.2 Hydrogeological conceptual model

Based on the resistivity profiles), the occurrence of groundwater around the Malele area appears dominated by fractured volcanics and controlled by the presence of regional and localised faults. Being part of the collapsed Tavua caldera, where multiple structural events have occurred, the mapped trachybasaltic and trachyandesitic flows would have been subject to displacements and deformations, thus providing conditions for preferential groundwater storage and flow in places.

8.3 Groundwater resources development options

8.3.1 Expected water quality

The on-site sampling and analysis of three existing bores in Malele (Table 20) suggests that the underlying basaltic and andesitic units investigated are capable of providing potable water to the Malele communities. However, full water chemistry and bacteriological sampling and analysis should be conducted prior to establishing community water supplies.

Table 20. On-site and hydrogeochemical measurements of three sampled boreholes in Malele.

Site	Balbant Singh	Jay Chand	Jai Ram
Area	Malele #2	Malele #3	Malele #3
Total depth (m)	50	40	55
EC (µS/cm)	807	523	567
Estimated discharge rate (L/s)	0.7	1	0.8
Hydrogeochemical properties			
Calcium (mg/L)	90.85	27.46	51.49
Magnesium (mg/L)	47.83	2.60	9.9
Sodium (mg/L)	14.99	65.65	41.91
Potassium (mg/L)	0.645	1.141	1.762
Manganese (mg/L)	0	0	0
Iron (mg/L)	0	0	0
Bicarbonate (mg/L)	370.07	239.43	259.3
Carbonate (mg/L)	0	0	0
Sulphate (mg/L)	54.8	32	17
Chloride (mg/L)	23.92	10.19	22.16
pH	7.2	7.6	7.2
Ionic balance (%)	7.4	4.4	0.3

Figure 17. Geological framework underlying and surrounding Malele #3, and locations of electrical resistivity transect profiles.

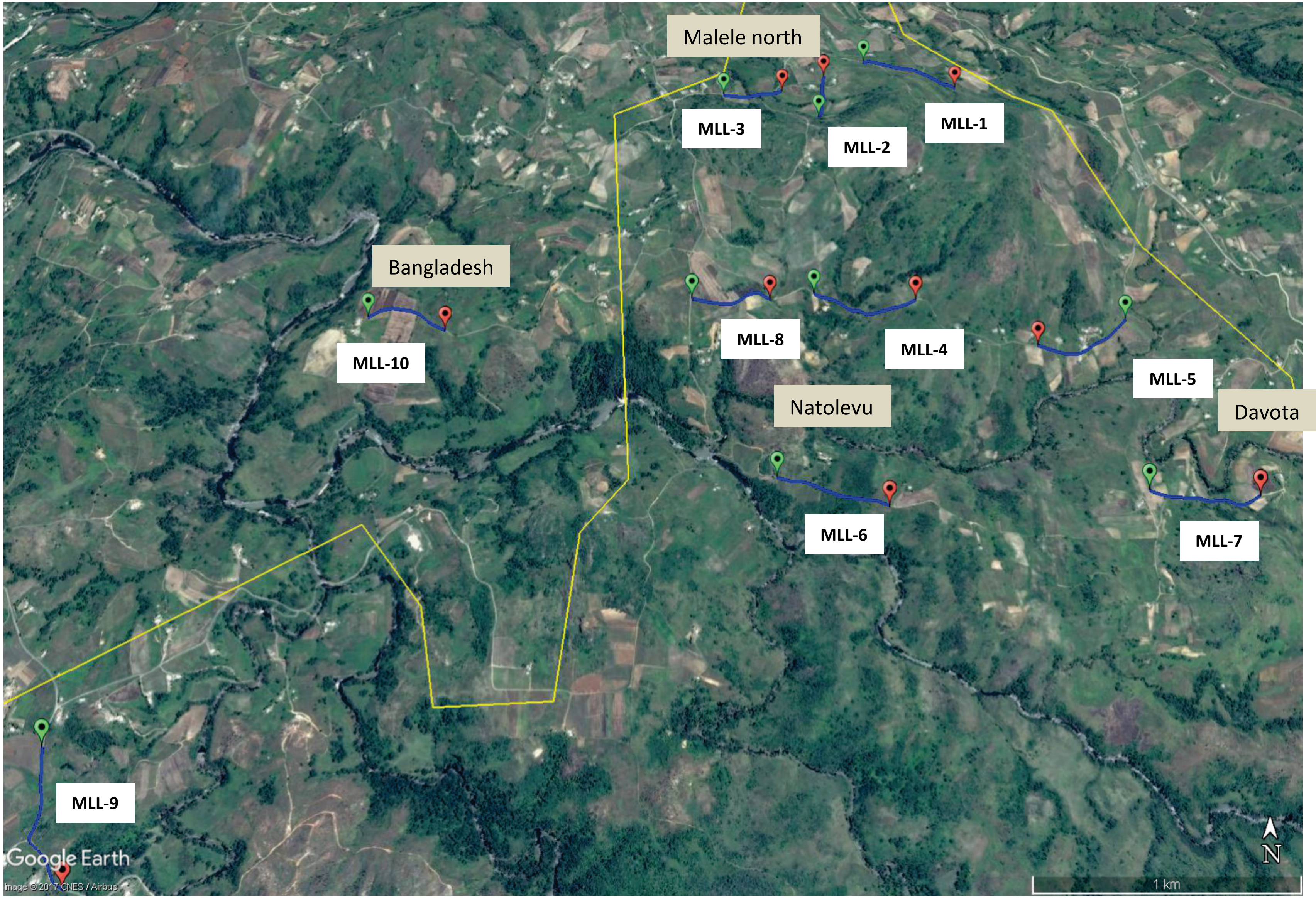

Figure 18. Malele survey profiles.

8.3.2 Expected yield

Table 20 shows the physicochemical properties of the three sampled bores. Installed in the fractured volcanic formations, the bores are currently used for household water supply and appear capable of maintaining quoted abstraction rates. These observations suggest that the surrounding basaltic and andesitic formations should have favourable characteristics for groundwater flow and storage, thus increasing the chances of drilling successful water supply bores at identified targets with similar lithological characteristics. The variability of fractures in terms of depth extension and width, together with how these are interconnected, either locally or extensively as influenced by structures and lineaments, will dictate the preferential groundwater flow (Singhal and Gupta 2010).

8.3.3 Prioritisation of drilling targets

Five primary drilling targets were prioritised. The prioritisation was based on the identified zone of low resistivity (20–50 Ohm.m), suggesting fractured andesite with the presence of groundwater. Other considerations used during the prioritisation include the access, number and concentration of families around each area, and proximity of the sites to existing water-supply infrastructure. These factors were assessed in relation to the ease of access for a 16-tonne truck-mounted rig to the selected areas and the possibility of connecting the borehole to existing tanks or piping networks, which should yield significant financial savings.

Table 21. Proposed drilling targets in Malele.

Profile	Area	Priority	Site label	Target distance (m) along the survey line	Expected water-bearing depth target (m)	Drill target coordinates
MLL-1	Khalsa	Secondary	MLL-S1	125–140	60–80	177.903°E, -17.492°S
MLL-2	Malele North	Primary	MLL-P1	70–100	30–50	177.900°E, -17.495°S
MLL-3	Malele North	Primary	MLL-P2	180–200	30–50	177.897°E, -17.493°S
MLL-4	Natolevu/Davota	Secondary	MLL-S2	310–340	40–60	177.902°E, -17.505°S
MLL-5	Davota	Secondary	MLL-S3	140–170	30–50	177.911°E, -17.506°S
MLL-6	Natolevu	Secondary	MLL-S4	360–400	30–50	177.900°E, -17.513°S
MLL-7	Davota	Primary	MLL-P3	360–400	40–60	177.915°E, -17.513°S
MLL-8	Natolevu	Primary	MLL-P4	280–320	20–60	177.896°E, -17.504°S
MLL-9	Vuqele	Secondary	MLL-S5	40–100	20–40	177.869°E, -17523°S
MLL-10	Bangladesh	Primary	MLL-P5	120–150	25-60	177.881°E, -17.504°S

For Malele North, survey profiles 2 (MLL-2, Fig. A34) and 3 (MLL-3, Fig. A35) yielded two primary targets **MLL-P1** and **MLL-P2** based on the dimensions of the potential groundwater-bearing zones identified, the concentration of houses, and the minimal work required for site accessibility. Similarly, for Natolevu and Bangladesh, two primary drilling targets, **MLL-P4** (survey line MLL-8, Fig. A40) and **MLL-P5** (survey line MLL-10, Fig. A42) were considered, mainly due to the severity of water problems around the area. However, due to their remote locations inland and the existence of secondary access roads, weather conditions should be a consideration prior to mobilising drilling machines to the sites. Site **MLL-P3** (survey line MLL-7, Fig. A39) in Davota-Vanga was deemed as a primary drilling target due to the high number of houses and available access. Most secondary drilling targets, albeit showing promising resistivity responses, may require improvements to allow access to the sites. Although there is good access to site **MLL-S3** (survey line MLL-5, Fig. A37), and while there are a high number of houses without water, this site may need to be further investigated due to its possible movement around 50 m away from the profile due to close the site's proximity to potential contaminant sources. Site **MLL-S5** (survey line MLL-9, Fig. A41), although not part of Malele, was considered as a secondary drilling target based on the site's promising resistivity responses.

Drilling at all Malele sites should be conducted with caution due to the expected challenging site conditions usually associated with volcanic systems, such as multiple flows and brecciated and agglomerate composites. Similar to all of the other target communities, the use of a DTH hammer bit with a high-pressure air compressor is strongly recommended for these drilling targets due to its suitability for hard formations. Appropriate drilling protocols such as: 1) logging rock-cuttings with special attention on fracture-zones; 2) estimating groundwater yield through airlift and using a V-notch weir; 3) using proper construction materials, including pea-sized gravel and class-12 PVC; and 4) conducting a 24-hour pumping test are essential for estimating hydraulic parameters of these targets, which, in turn, will inform their sustainable development for the community water supply.

9 Volivoli

The Volivoli farming sector in Rakiraki District was surveyed between 25 and 30 November 2017. Seven geophysical survey lines were completed in locations selected after consultation with the community advisory councillor. The selection process took into account the location of households that are not connected to the public water supply network, and site accessibility in terms of the presence of roads to facilitate surveys and, especially, access for a drilling rig in the future. Geomorphology and characteristic geological features that may reflect high groundwater potential were also considered, in combination with local knowledge on the presence of springs, existing wells and shallow water tables.

The Volivoli peninsula is in the northeastern part of Rakiraki District. The Rakiraki area shows distinct features that reflect important volcanic activity such as numerous dikes and small plugs that have been exposed by erosion. According to JICA (1995), the area of Rakiraki is underlain by chloritised trachybasaltic rocks of the Ba series, and surrounded by a steep small mountain composed of intrusive rocks, about 5 km east of Rakiraki. According to Rodda and Band (1966), the main volcanic formations present to the east of Rakiraki are the Nakorotumbu and Rokavukavu basalts, which constitute part of the broader *Mba basaltic group* and which cover most of the northern range of the island. The Nakorotumbu basalts are described by Rodda and Band (1966) as basaltic conglomerate and breccia, with some pillow lava near the base and tuff in some places. The Rokavukavu basalts are described as flows and fragmentals, occasionally chloritised and altered (Rodda and Band 1966). Seeley and Searle (1969) argue that the degree of alteration appears to be related to the site's proximity to intrusions rather than to the relative ages of basalts; therefore, associating all the bodies of flows and fragmentals with the Nakorotumbu basalts. Igneous rocks in the area that are substantially exposed by erosion include andesites and basaltic dikes. According to Gale and Rao (2015), the Nakorotumbu basalt was observed protruding along the northern fringes of the study area, where it forms the Nakauvadra and Nakorotubu ranges, separated by the topographic trough of Viti Levu Bay.

Many boreholes have been drilled in the basalt and basaltic breccia of the low hill areas around Rakiraki. The groundwater potential in these boreholes strictly depends on the intensity of the fractures. Several boreholes were drilled in the coastal area, although the majority were low-yielding or prone to saltwater intrusion. According to the geological log of two test wells drilled in the Rakiraki area (JICA 1995), the groundwater development in the region was considered poor due to the hard compaction of basement rocks. These two bores did not encounter any fractured intervals, thus limiting them as potential sources of groundwater. The aim of the current survey was to identify, through the use of geophysics, subsurface hydrogeological conditions suitable for the accumulation of groundwater. Fractured or sheared zones can form confined aquifers with moderate to high permeability.

Figure 19. Volivoli survey lines. Source: Google Earth

9.1 Groundwater resources development options

9.1.1 Prioritisation of drilling targets

Five drilling targets were identified in the study area (Annexes 1 and 2), of which four were designated as primary and one as secondary, based on the expected groundwater yield. In Volivoli east, only one target was designated and was marked as secondary due to the moderate yield expected. Nevertheless, because no other targets were identified in this area, site **VL-S1** (survey line VLV-1, Fig. A43) should be drilled to verify groundwater potential. It is suggested to drill at 170–175 m along the profile and to a maximum depth of 50 m.

In Volivoli central, two sites (**VL-P1** and **VL-P2**) were designated as being primary drilling sites along survey lines 3 (VLV-3, Fig. A45) and 5 (VLV-5, Fig. A47). It should be noted that only one target is recommended, and priority should be given to VL-P1 due to its higher elevation and, thus, smaller likelihood of possible saltwater intrusion. The site can be placed anywhere between 80 m and 165 m along the profile, and drilling can continue down to 70 m. If site VL-P1 proves to be inaccessible by the drill rig then site VL-P2 should be selected. The site can be selected anywhere between 120 m and 180 m along the profile. Given the low elevation of this site, however, drilling should not continue beyond 40 m depth, and thorough pumping tests should be conducted to verify that no saltwater intrusion will take place in the future.

In Volivoli east, one primary drilling site (**VL-P3**) is suggested along survey line VLV-6 (Fig. A48). The site should be located between 245 m and 260 m along the profile and, again, given the low elevation, drilling should not continue beyond 40 m depth.

Finally, one drilling site (**VL-P4**) is recommended in the Raratapu sector along survey line VLV-7 (Fig. A49), anywhere between 80 m and 180 m along the profile. Due to the presence of a pit latrine upstream of the survey line at 200 m distance, it is recommended to maintain a certain distance; the site should be located between 80 m and 180 m distance along the ERT profile. Drilling can continue down to 50 m depth.

Table 22. Proposed drilling targets in Volivoli.

Profile	Location	Priority	Site label	Target distance (m) along the survey line	Expected water-bearing depth target (m)	Drill target coordinates
VLV-1	Volivoli west	Secondary	VL-S1	170–175	5–50	178.180°E, -17.318°S
VLV-3	Volivoli central	Primary	VL-P1	80–165	10–70	178.189°E, -17.328°S
VLV-5	Volivoli central	Primary	VL-P2	120–180	5–40	178.190°E, -17.327°S
VLV-6	Volivoli east	Primary	VL-P3	245–260	5–40	178.197°E, -17.336°S
VLV-7	Raratapu	Primary	VL-P4	80–180	5–50	178.191°E, -17.334°S

10 Summary and recommendations

A hydrogeological assessment was undertaken in six target communities between February and December 2017. The objective of this assessment was to identify new groundwater sources to improve access to safe and reliable water in these disaster-prone areas. The assessment focused on the use of ERT geophysics and traditional water resources assessment methods including:

- a review of the geology, structures and rock types;
- a lineament analysis using high-resolution satellite images;
- an assessment of the physical and hydrogeochemical conditions of existing bores; and
- a topographical assessment of field areas in relation to mean sea level.

The preparation and completion of this assessment and logistical arrangements was a result of strong collaboration with MRD, particularly its hydrogeological team, with additional support from district officers, provincial administrators, FSC field officers, and advisory councillors for each target community.

10.1 Assessment results and prioritisation of groundwater drilling targets

In total, 49 ERT profiles were completed around the target communities with consideration to survey locations based on:

- favourable geological and structural features;
- previous groundwater assessments and development;
- information from community councillors and relevant authorities;
- site accessibility;
- existing water supply infrastructure and water demand; and
- topographical elevation.

The ABEM Terrameter LS kit was used for electrical resistivity with an electrode spacing range of 2.5–5.0 m interchangeably, depending on available space and the localised nature of some of the structural features. Vehicle traverses were undertaken to access these remote communities while foot traverses towards nearby hills were undertaken occasionally for site reconnaissance and ground-truthing of features either previously mapped or observed in satellite images. Several topographical elevation technologies, including the Trimble R10 series, Garmin GPS, and the Trimble 6000 series, were used to estimate the relative topographical variation along the profiles and to determine ground elevation above mean sea level, particularly for coastal communities such as Wailevu/Nanuku and Volivoli, where saltwater intrusion is likely to threaten groundwater quality.

Summarised in Table 23 are the survey profiles completed in each target community with additional information pertaining to the geological and structural settings investigated, and the number of groundwater drilling targets identified around the areas. It should be noted that potential groundwater-bearing formations, be they fractured volcanics or a geological interface between mapped units, the resistivity range of 20–50 Ohm.m was selected to help guide the initial identification of groundwater potential based on groundwater exploration in similar geological settings in other parts of the world. As geophysical targets are drilled, actual resistivity ranges should be correlated against drilling results to further refine the site specific resistivity range for the specific rock formations and geological setting.

The designation of drilling targets is based on a synthesis of information from different sources, including geology, existing bores, geophysics, structural features, land accessibility, and other physical and socioeconomic conditions and constraints. As additional information is made available, such as supplementary borehole data, it is recommended that this be incorporated into a reassessment of the identified resistivity targets to assist with calibrating the resistivity and improving confidence when recommending future drilling for water supply purposes.

Table 23. Summary of electrical resistivity survey work conducted in each community.

Community	Survey dates	Key geological and structural features	Number of survey lines	Total distance covered (km)	Number of primary drilling targets	Number of secondary drilling targets
Qerelevu	20–22 Feb, 22–26 May	Fractured andesitic flow and geological contacts between volcanics and overlying sedimentary unit	8	2.8	4	4
Wailevu/ Nanuku	29 May–2 Jun	Fractured basaltic framework	8	2.9	4	5
Benai	18–22 Sept	Fractured andesite and basaltic breccia	9	3.6	4	5
Navia/ Nadhari	2–6 Oct	Fractured basalts	7	3.5	4	4
Malele	20–24 Nov	Fractured trachybasalt and trachyandesite	10	4.5	5	5
Volivoli	27–30 Nov	Fractured basalt	7	2.6	4	1

The prioritisation of identified potential drilling targets was undertaken based on site accessibility, distribution of household clusters in relation to water demand, and close proximity to existing water-supply infrastructure.

Groundwater sampling analyses from existing bores around some of the communities resulted in favourable physical and hydrogeochemical properties in compliance with WHO guidelines for drinking water. This suggests the potential of the target geological frameworks in providing usable groundwater. However, it is paramount that additional water-quality testing, including chemical and bacteriological analyses, be conducted should the prioritised drilling targets are drilled and new groundwater-bearing zones intersected.

10.2 Groundwater resource development considerations

10.2.1 Land ownership

Land ownership is a critically important element in determining the feasibility and sustainability of a community water supply system. This is because the nature of land ownership could either allow or restrict land usage and long-term accessibility to a water supply. The land-ownership status within the target farming sectors covered in this field assessment falls under three categories. Qerelevu, Benai and Navia/Nadhari are located in native-owned land leases. Malele and Volivoli are located within crown leases, while Wailevu/Nanuku is on freehold land. These different land-ownership categories present varying challenges and complexities with regard to the usability and long-term accessibility of the land for groundwater assessment and development. The pre-survey consultation undertaken during the assessment period was a success in that all community members and land-owners showed strong support for groundwater drilling and water supply improvements, and hence were willing to give a portion of their land for the installation of water supply infrastructure, be it boreholes, solar accessories or distribution pipes.

It will be critical that proper land agreements be documented because landowners will either have minimal or limited access to these lands to warrant the installation and smooth operation of community water supply system infrastructure. These infrastructural elements will include (but are not be limited to):

- groundwater drilling and borehole construction;
- pump installation;
- transmission pipelines from source to tank;
- a solar-powered infrastructure;
- a suitable area for the construction or placement of storage tanks;
- a distribution pipe network; and
- service pipes to house connections.

Considering the potential costs of installing such infrastructure and the associated land area required, a pragmatic and inclusive consultation approach will be essential to adequately informing and engaging the affected landowners in order to solicit their early and long-term support. The following considerations need to be addressed in the land agreement to ensure the system's minimal or negligible disruption and damage:

- a consent letter to be signed by all affected landowners, allowing the usage and continued access of their land for the construction, operation and long-term maintenance of any of the above components;
- a clear agreement on whether the land is given voluntarily, or whether a periodical payment or some sort of compensatory arrangement is expected by the landowners for relinquishing their access and use of the land; and
- consideration to introducing a law limiting the type of land-use activities that are allowed in and around the borehole site and expected recharge areas.

10.2.2 Accessibility for drilling rig

Accessibility to the selected drill sites is important, especially given the highly-incised and rugged terrain and limited road network in and around communities. It is critical that the 16-tonne truck-mounted drilling machine, its compressor, drill rods and accessories, and support truck be able to reach the selected drill target locations with minimal concerns or damage. Given these factors, the communities and Government of Fiji should be prepared to allocate adequate resources towards improving site accessibility through road clearance and track improvement. Given the localised nature of the productive groundwater formations, drilling must take place at the selected and prioritised target sites. This drilling will also help in validating geophysical results and conceptual groundwater models, which is useful for future hydrogeological assessments.

It is clear that all of the farming communities have existing networks of field access roads that are usually prepared and have improved conditions during the harvesting season. If drilling is conducted during this time, then the only improvement work required will be to connect these access roads to the exact target sites, if these are located some distance away from a road. These often need minor improvements such as clearing trees. Otherwise, significant roadwork will be required and with potentially high costs.

10.2.3 Water governance and safety planning

The governance, protection and sustainable management of water sources and facilities is essential to ensuring that the water quality — chemical, physical and microbial composition — is fit for human consumption (Mudaliar et al. 2008). This requires awareness raising, participation and engagement of all community members, with the support of community leaders, to allow consistent access and usage of a community water supply system so that it benefits all users. This includes making sure the groundwater quantity and quality is usable and safe, and establishing rules and mechanisms to ensure the consistency of water supply and safety to consumers. This may also extend to the design and development of a community water safety plan that:

- looks to establish a team within the community to build a good understanding of the water supply system, from source to consumers;
- characterises and/or identifies risks, hazards and hazardous events; and
- identifies the means for controlling these risks and hazardous events, and establishes a monitoring system (Mudaliar et. al. 2008).

10.2.4 Operation and maintenance

An understanding of the operation and maintenance needs for a community water supply system is essential for its protection and longer term sustainable management. Some of these needs include:

- training, upskilling, and equipping members of the community to coordinate and sustain the operation and maintenance of a community water supply system;
- generator fuel charges for submersible pumps, if a generator is a power-source, or the installation cost and regular repair of solar panels and accessories (if solar power is used);
- repairing and possibly replacing submersible pumps; and
- repairing and replacing leaking distribution pipes and any other part of the system.

The above needs highlight the major responsibilities and associated costs inherent to the operation and maintenance of a water-supply system. It is critical that members of the target communities are adequately informed about and trained on these responsibilities, while pragmatic mechanisms should be designed to ensure that all beneficiaries understand these obligations, and to get their support when the collection, management and disbursement of funds is needed.

Preliminary survey results were presented to, and received by, most of the community advisory-councillors, district officers and provincial administrators. The inclusive consultation with the communities clarified the project’s scope and yielded positive support and increased awareness on the necessity of adopting a community-based approach, including the operation and maintenance of these new or alternate water systems. Landowners expressed their support and willingness to secure and maintain the sites once they become available.

10.2.5 Hazards

Identifying hazards is intrinsically linked to water safety planning but focuses on those hazards, either geological or hydrometeorological in origin, and the potential adverse effects to water supply facilities.

The recent increasing frequency and intensity of tropical cyclones in Fiji, such as Tropical Cyclone Winston in 2016, coupled with the vulnerability of cane farming areas to numerous ENSO-driven droughts, demonstrates how prone the cane farming areas are to massive damages to buildings, infrastructure and communities. The devastation of Tropical Cyclone Winston resulted in an estimated loss of more than FJD 75 million to the sugar cane industry, with the agricultural sector recording an aggregate loss and damage of around FJD 540 million (Esler 2016).

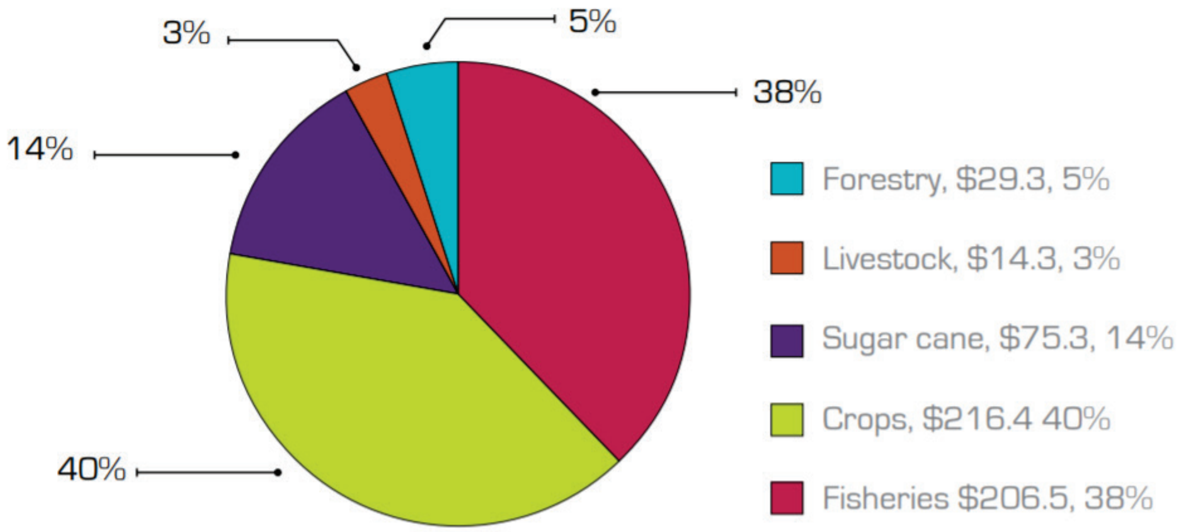

Figure 20. Estimated costs to the agricultural sector after Tropical Cyclone Winston, with sugar cane recording a loss of FJD 75.3 million (Esler 2016).

The water sector recorded a total cost of FJD 24.8 million in damages and losses, with FJD 16.9 million of that in damages alone (Esler 2016). The assessment of damages, losses and needs after Tropical Cyclone Winston illustrated that the western areas, where cane farming is dominant, recorded the highest amounts (Fig. 21). Although the damages and losses assessment may have focused on urban areas connected to the WAF water supply and sewerage systems, it is likely that rural communities have infrastructural damages due to flooding and strong winds.

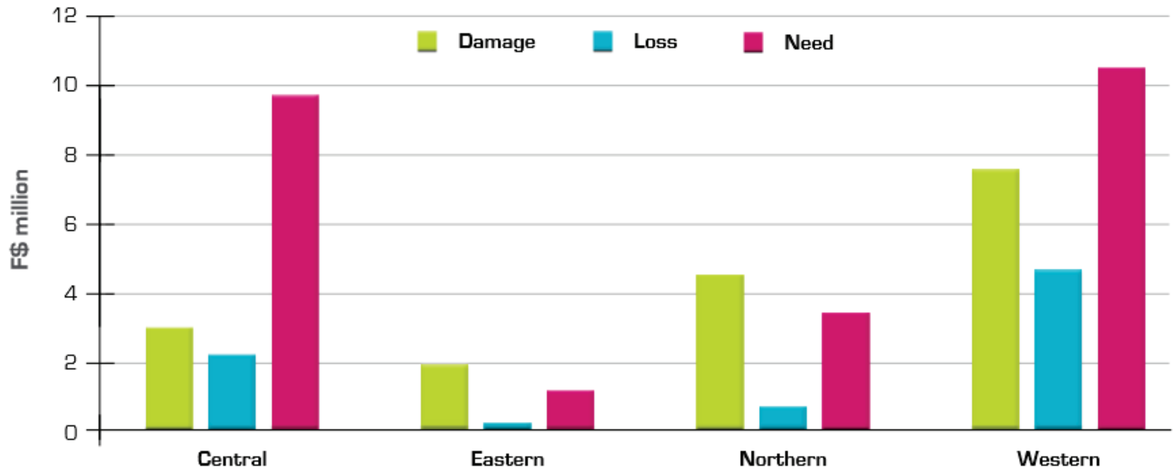

Figure 21. Damage, loss and need recorded in the water and sanitation sector after Tropical Cyclone Winston (Esler 2016).

Fiji has also recorded numerous ENSO-driven drought events in the last four decades, with increasing intensity and substantial economic cost as a consequence. These events were recorded in 1987, 1992, 1997/98, 2003 and 2010 (Australian BOM and CSIRO 2011). The 1997/98 event, one of the worst on record, resulted in 50% loss in production (unknown, 2017) and, in turn, demonstrated the vulnerability of farming communities when these extreme climatic events occur.

Considering the above-mentioned hazards and their potential impact and financial costs, it is necessary that thorough planning in the design and construction of water supply systems and facilities is carried out. This is to ensure that facilities are constructed to sustain minimal damages during and immediately after extreme climatic conditions, and/or to minimise any potential water-supply disruption, which in turn, strengthens the communities' resilience.

10.3 Recommendations

In view of the objectives of the hydrogeological assessment and the proposed three-phased approach for community water supply improvements, the following are recommended.

1. Primary drilling targets identified as part of the Phase 1 hydrogeological assessment will need to be further explored and validated through drilling, and as part of Phase 2. MRD has indicated support to undertake this phase at five sites based on limited budgets within the government. An appropriately sized drilling machine, preferably equipped with a DTH hammer bit, will need to be engaged for this purpose and be operated by suitably-trained drillers and assistants, given the challenging geological systems expected.

2. As part of Phase 2, adherence to the following groundwater investigation aspects are suggested.

    a. Proper assessment and characterisation of drill cuttings in terms of lithological properties and hydraulic potential will be required in order to determine the depth and thickness of any groundwater-bearing source, if encountered, and to guide the proper construction of these bores.

b. The estimation of groundwater yield during the drilling process using a V-notch weir is required to assist with the selection of suitably sized pumps to be used later in the groundwater evaluation.
c. The use of concrete grouting in the top 6 m, and adequate head protection such as a concrete apron, will be essential to prevent surface water ingress.
d. Proper well construction materials – including washed, well-rounded and suitably sized gravel, class 12 PVC-U pipes (both slotted and plain) and concrete – will be required for optimum well efficiency and to ensure the longevity of the groundwater sources.
e. The introduction and long-term implementation of collectively agreed groundwater source protection mechanisms, such as the building of fences, restrictions on land-use activities, and the establishment of stringent rules around boreholes will be required to ensure their protection from potential anthropogenic contaminants.
f. Groundwater yield evaluation – through constant-rate pumping on an acceptable duration be it 8, 12 or 24 hours – will be required and followed by a recovery test. This will determine the potential of the groundwater source(s) via drawdown and residual drawdown assessment to allow the estimation of the hydraulic properties of the aquifer and permit the establishment of long-term pumping limits for these sources.

3. As part of Phase 3, the bores will be equipped with either solar or electricity powered submersible pumps. Thus, it will be imperative that training in the operation and maintenance of these water supply systems be conducted by all communities. Training should be tailored to enhance gender-balanced participation with a focus on selecting and upskilling community water committees and water safety planning, and is undertaken to ensure the long-term operation of water supply systems with minimum disruption, which, should ultimately strengthen the resilience of these communities.

4. Due to MRD's limited financial capacity to conduct drilling in all of the communities, it is suggested that more work be conducted by other relevant stakeholders, such as the Ministry of Rural Maritime Development and Natural Disaster Management, and FSC, to enlist potential donors and ensure that potential drilling targets are fully investigated through drilling and pumping tests.

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12 Annex 1 – Detailed interpretation of electrical resistivity transect results

Qerelevu – Figure A1

Line 0 (QLV-0): Pineapple farm, Nakavika

This survey profile was performed on the eastern side of the north-trending andesitic hill. Survey line 0 used an electrode separation of 3 m, and covered a distance of 300 m on a S-N orientation. The profile, investigated down to 45 m below ground level, targeting a potential E-W trending fracture systems. The survey was conducted at around 180 m elevation and targeted an E-W trending fracture systems perpendicular and possibly linked to the S-N fault and adjacent regional anticline, recorded to be tending parallel to the fault.

The resistivity profile showed a highly variable response laterally and at depth, suggesting the heterogeneity of the andesitic breccia. Low-resistivity response dominated the first 140 m of the profile down to 30 m depth although subtle differences in low resistivity around this area - very low response (5–15 Ohm.m) could suggest the presence of thin layers of clay. Immediately below this low-resistivity response is an extensive area of slightly increased resistivity (20–40 Ohm.m), which may indicate an area of enhanced porosity or concentrated fractures that is either fully or partially saturated with groundwater. This zone is observed along profile distances 0–144 m and 5–40 m subsurface depth with a low-resistivity zone (5–10 Ohm.m) at profile distances of 120–140 m and at 10–20 m depth.

A contrasting anomalous response was observed beyond 145 m from the start of the survey line, where a 10-m-thick, near-vertical structure, recording intermediate to higher resistivity values (50–70 Ohm.m) was intersected. The structure may represent a dike or possible fault, with differing lithology or different weathering features of similar lithology. It is interpreted that this vertical structure may act as a barrier where the southern end suggests highly fractured conditions favourable for preferential groundwater flow and storage. The northern section of the profile suggests a geophysical divide of relatively low resistivity along profile distances 155–252 m and subsurface depth range of 0–15 m, suggesting possibly an impounded perched aquifer, with underlying less altered andesite, characterised by 70–100 Ohm.m resistivity range, appearing to be less permeable. The interpreted perched aquifer formation, although appearing fully saturated, may not yield adequate groundwater due to the limited dimensions and its reliance on rainfall-recharge would make it vulnerable to drought conditions.

The resistivity anomaly identified from this section was of sufficient interest as to undertake an additional profile down gradient of the feature to assess its extent and potential as a fracture zone with consideration as a groundwater target. The down gradient profile would be better suited for drill rig accessibility. Hence, survey line 1, which used a 4-m electrode spacing and covered a distance of 560 m, was conducted 100 m downslope and parallel to survey line 0.

Line 1 (QLV-1): Access road towards Mr Chand's residence, Nakavika – Figure A2

The survey profile was conducted along an existing access road, across grazing land and sugar cane cropping, before connecting to the Nakavika road near Mr Prem Chand's residence. The survey line was planned to confirm lateral extension of the features observed in survey line 0.

The profile indicated highly variable resistivity response suggesting a heterogeneous volcanic formation with some indications of multiple groundwater storage and flow areas. Zones of very low resistivity at near-surface depths may mean fully or partly saturated silty and clayey loam from recent rainfall events. While the high-resistivity areas dominating the deeper zones may indicate fresh and unaltered volcanic, two zones of possible groundwater storages, characterised by resistivity responses of 20–40 Ohm.m, were observed. The first geophysical anomaly is observed between 58 m and 74 m along the profile at subsurface depths of 10 m to 30 m, and is expected to continue with depth. The second zone is observed between 170 m and 200 m along the profile at depths of 15–30 m. The geophysics suggests that these potential groundwater sources may be limited in dimensions and are not hydraulically connected.

The application of the 4-m electrode spacing permitted the investigation at depth where the dimensions of the potential groundwater-bearing formation in relation to the surrounding fresh and unaltered formation was well defined. This profile indicated that the vertical-like structure seen in survey line 0 was not visible, and did not extend down gradient to survey line 1, suggesting the observed structural feature in survey line 0 was potentially localised and may influence the flow of groundwater.

Line 2 (QLV-2): Along Nakavika Rd, Nakavika – Figure A3

Survey line 2, continuing with a S-N trend, was conducted along the Nakavika Rd and started 100 m away from where survey line 1 was terminated. The line was designed to identify and assess the groundwater potential of the geological contact between the andesitic breccia and on lapping sedimentary unit. The survey line crossed a flowing creek at 105 m. The profile using a 4-m electrode separation covered a total distance of 400 m.

The profile showed a highly variable response, indicating the characteristics of the two geological formations. The first 100 m displayed the heterogeneity of the volcanic unit with the following characteristics:

- a thin veneer of saturated silty loam soil capping the formation at profile distance 10–40 m and 86–116 m down to 5 m showing very low resistivity,
- a perched zone characterised by 15–40 Ohm.m resistivity and between 42 m and 78 m profile distance at 5–10 m subsurface depth showing limited dimensions and may be vulnerable to dry conditions
- a deep and confined fractured zone characterised by a lobe of low resistivity (15–20 Ohm.m) at profile distances of 86–100 m and 30–50 m depth. This area exhibits an overlying resistivity zone of medium to high resistivity, possibly indicating a highly indurated andesitic layer. It is observed that this potentially highly fractured and fully saturated area is surrounded by an extensive zone of low resistivity (30–40 Ohm.m). This suggests that the contact or interface between the andesite and sedimentary units and the low resistivity may indicate a degree of

saturation after the recent rainfall events whereby there is hydraulic connection of fractures controlling the movement of groundwater with an expression of groundwater discharge at 105 m.

From 100 m profile distance to the end of the survey line, it is clear that there is a significant change in resistivity response dominated by medium range resistivity (40–100 Ohm.m), which may indicate more homogeneous low permeability sedimentary units. A number of medium resistivity values (40–50 Ohm.m) were observed at profile distances 160–210 m, 250–330 m and depths 20–50 m, and exhibiting vertical to subvertical features within the sedimentary units. These zones have been interpreted as being saturated but with low permeability limiting the potential of a usable groundwater source. Very low resistivity was again observed at shallow depths, possibly indicating saturated silty soil.

Line 3 (QLV-3): Mr Samagra Prasad's (Babu) residence, Qerelevu – Figure A4

Survey line 3 was carried out in a S-N direction near Mr Prasad's residence, close to Qerelevu Primary School. The survey used a 4-m electrode spacing and covered a distance of 296 m. The survey was conducted atop the andesitic flow, although the area is very close to where geological contact between the volcanic formation and the sedimentary units exist. The profile was planned to intersect the localised groundwater-bearing fracture systems that feed the Qerelevu Primary School borehole and are possibly connected to the fracture networks detected by survey lines 0 and 1. A borehole was identified near to where the survey line was run, which exhibited artesian characteristics during rainy periods with a measured EC of 452 µS/cm. The depth of the borehole is 35 m and has no drill log or water-bearing zone information.

The resistivity profiles again showed variable resistivity response laterally and at depth. The following features can be observed:

- zones of very low resistivity (15–20 Ohm.m) representing saturated soil on the surface.
- an extensive and shallow zone of low resistivity increase thickness of up to 20 m in the southern end and tapers off to 5 m thickness beyond 160 m. This may represent the vadose zone as well as weathered regolith, which may be fully saturated by the recent rain.
- a layered zone of 30–50 Ohm.m resistivity response, forming an extensive layer 30–160 m profile distance and around 10 m thick, although this thickness reduces significantly from 120 m profile distance. After 160 m, this zone suddenly increases in thickness up to 40 m between profile distance 160–190 m and 210–240 m, although the spatial extent is limited. This zone may indicate a zone of moderate fracturing beneath the regolith where groundwater water flows and is stored. However, the observed increasing thickness beyond 160 m may suggest some geological and structural control that allows increased and concentrated fracturing and consequently, conducive for groundwater flow and storage.
- the sudden increase in resistivity towards the highest recorded resistivity possibly indicates fresh volcanics at depth. The morphological change of this high resistivity area from gently sloping on the southern end to an abrupt near-vertical is of great interest and may indicate the presence of a regional fault or a zone of concentrated fractures, although not fully saturated, which, in turn, may explain the presence of the artesian conditions from the borehole at the northern section of the profile.

Line 4 (QLV-4) and line 5 (QLV-5): Sedimentary Unit, Qerelevu – Figures A5 and A6

Survey lines 4 and 5 were undertaken in the same area but with different orientation. Line 4, using a 4-m electrode spacing and covering a distance of 232 m, was oriented S-N to investigate the potential of the interbedded sedimentary unit. Survey line 5, oriented W-E, targets the geological contact between the sedimentary units and the adjacent volcanic.

Line 4 showed very low-resistivity responses (10–15 Ohm.m) at shallow depths, possibly indicating a thin veneer of silty loam or the soil profile that has soil–water interflow from recent rainfall events. At increasing depth from around 7–45 m, the homogeneous and low-resistivity response (30–40 Ohm.m) suggests a sedimentary unit that is extensive both laterally and with thickness, and with no significant variation observed to suggest any anomalous structural discontinuity or groundwater preferential flow/storage to suggest usable groundwater. This relatively homogeneous response suggests that the sedimentary formation, although porous and likely to contain some groundwater, has low permeability, which does not allow any appreciable groundwater transmission into any drilled borehole. This is validated by the recent installation of several low-yielding bores in Nabatolu which penetrated the interbedded sediments. The depth of the geophysical survey did not permit the investigation of the geological contact between the sediments and the expected underlying andesite.

Survey line 5, having a 4-m electrode spacing and W-E orientation, commenced at a low elevation hill and continued towards elevated ground covering a distance of 240 m. Similar resistivity response as measured in survey line 4 was observed in survey line 5, suggesting the interbedded sedimentary formation. Several pockets of increased resistivity were observed within the extensive low-resistivity response. These higher resistivity responses were observed along the profile at distances 54–64 m, 86–102 m, and 170–240 m, with corresponding subsurface depths of 7–15 m, 10–25 m and 5–18 m. These contrasting resistivities are interpreted as representing either zones of concretions with a higher degree of lithification and reduced porosity or areas where volcanic boulders were emplaced during the sedimentation and cementation process. A pronounced zone of lower resistivity was observed along profile distance 100–128 m and at depths beyond 35 m. This contrasting resistivity may represent the interface between sedimentary and the basal volcanic formation, which may signify increased groundwater potential whereby an increased weathering and fracturing may create favourable conditions for improved preferential groundwater storage and flow.

Line 6 (QLV-6): Namau – Figure A7

Survey line 6 survey was conducted along the road around the Namau area, which is on the western end of the andesitic hill where profiles 0 and 1 were undertaken. From Namau, the hill appeared as a cliff or an uplifted escarpment where massive fractures and jointing networks were observed suggesting increased storage and transmission of groundwater. The survey line was undertaken along the road following a S-N trend, with an electrode spacing of 5 m and coverage a distance of 500 m. Namau, while experiencing similar water issues as the other areas within Qerelevu, is usually neglected during emergency water carting due to its relatively difficult access and more isolated and distant location.

Similar to all the profiles conducted around the volcanic formations, Profile 6 showed highly variable resistivity. An extensive area of very low resistivity (10–20 Ohm.m) was observed at shallow depth, indicating the saturated soils as well as the influence of nearby running creeks and streams with pronounced response from profile distances 190–340 m and 450–500 m. Three zones of low-medium resistivity (20–50 Ohm.m) response were observed along the profile:

- the first is was observed along profile distances 120–185 m and around 20–30 depth. This area appeared to be a well-defined and limited zone and demonstrated signs of hydraulic connection to the shallow depth system, suggesting groundwater movement between the areas through fracture networks.
- the second zone was observed at profile distances 210–280 m and appeared to be an near-vertical structure with depths from 20 m to 90 m, possibly representing a fault zones where the degree of fracture is moderate to high, allowing high level of storage and flow through drainage of shallow and surface sources.
- the third zone, observed along profile distances 320–410 m at depths extending from 30 m to 90 m, exhibits both vertical and horizontal morphology indicating the concentration of fractures and is capped by a layer of higher resistivity, suggesting minimal to negligible connection with the surface. The zones may represent a more confined groundwater storage which has moderate to high level of fracturing. It is possible that this zone is recharged by deeper fracture systems.

The high-resistivity response (60–120 Ohm.m), with undulating morphology across the profile, may represent fresh and unweathered volcanics showing variability in permeability and possibly with some lithological and mineralogical differences with the formation.

Line 7 (QLV-7): near the trig station, Nakavika – Figure A8

The survey line was conducted near the hill top at around the topographical elevation of 190 m. The profile was oriented S-N and used a 5-m electrode spacing, covering a distance of 300 m. The profile was planned to be parallel to Line 2 with an objective of identifying the geological boundary between the andesite and sedimentary deposits, a target for possible groundwater storage and flow.

The first 150 m are dominated by variable and high resistivity responses indicating the heterogeneous nature of the andesitic formation. A small and shallow zone of low resistivity was observed in between profile distances 0–70 m and 5–15 m subsurface depths is possibly linked to a perched zone that may be discharging towards the south and beyond the start of the survey line. Apart from this low-resistivity zone, all areas are dominated by high-resistivity responses (80 Ohm.m to more than 700 Ohm.m), with very high measurements observed between 80 m and 130 m profile distances and at a shallow depth of 3 m. The variability in response shown by the basal layer may indicate differences in lithological and mineralogical composition within the andesitic flow and breccia without any noticeable water-bearing structure running through.

A distinct north trending low-angle (~15–20°) boundary of low-resistivity boundary (35–50 Ohm.m) was observed between profile distances 150 m and 255 m. This significant contrasting layer compared to the surround high resistivity zone immediately south may represent the geological contact or interface between the andesitic breccia on the south and sedimentary units on the north. This area of low resistivity has increased thickness towards the north between 8–10 m and maybe more, had the survey line extended; this was observed beneath profile distances 245–255 m and may indicate increased weathering and/or fracturing along the interface allowing preferential flow and storage of groundwater.

Wailevu and Nanuku

Line 1 (NNK-1): Mr Satish Kumar, Nanuku – Figure A9

This survey profile was performed at the western end of Nanuku through a highly-incised valley and crossing a dry creek. The E-W profile, covering a distance of 400 m and using a 4-m electrode spacing, was designed to target N-S trending fracture systems. The profile started from one of the hillsides, at 40 m elevation, and descended gradually, crossing the creek and terminating at around 25 m elevation. On the other side of the creek is a groundwater bore drilled into the basaltic framework and yielding 0.8 L/s. The bore was drilled in the 1990s and is currently serving seven houses within the Nanuku area.

The resistivity profile showed a highly variable resistivity response both laterally and at depth characterised by a zone of very low to low response (10–50 Ohm.m) overlying an area of moderate to high resistivity (55–120 Ohm.m), with an undulating interface. Very low-resistivity response observed at shallow depth may refer to highly weathered basalt containing clay and overlying unconsolidated soil strata having high porosity containing interpore groundwater, but not necessarily permeable and available as a useful source. The water table measured at the nearby bore was found at 10 m depth, is in good agreement with the modelled resistivity distribution.

Five noticeable zones of low resistivity (20–50 Ohm.m) are observed:

a. An area around the basaltic bed-rock high, at 32–64 m profile distance and subsurface depths from 10 m to possibly beyond 30 m. The modelled resistivity suggests the possible presence of fractures that may be associated to the tectonically uplifted, stressed basaltic body. This area has potential to extend at depth but was truncated by the model due to the survey line configuration.
b. Between 90 m and 150 m profile distance and extending from the surface down to 25 m depth is a shallow zone generating a resistivity response of 15–30 Ohm.m. This may represent an area of weathered and with substantial clay content with high moisture content.
c. An area between 168 m and 220 m profile distance and subsurface depth of 20–60 m represents an incised feature that was intersected. This feature possibly represents a zone of fractured basalt that is expected to contain some groundwater and appears to be hydraulically connected to the dry creek. The width of the zone and the surrounding bedrock showing a near-vertical morphology suggests that the fracture zone may extend beyond 60 m with a possibility that fractures at depth may be tight and more constrained with regard to the transmission of groundwater, hence the slightly increased resistivity beyond 55 m depth.
d. The area between 224 m and 274 m profile distance and subsurface depths 10–30 m shows a pronounced low resistivity (15–40 Ohm.m), suggesting a zone of weathered or possibly fractured basalt that may contain some useful groundwater supplies. This area aligns with Mr Satish Kumar's bore (measured depth of 31 m and with a recorded static water level of 10 m).
e. A zone between 300 and 400 m profile distance and subsurface depths of 0–50 m showing a low resistivity of 15–40 Ohm.m, possibly indicates another zone of fractures that may contain useful groundwater.

The underlying zone of relatively high resistivity (70–150 Ohm.m) may represent fresh and low permeability basalt. The undulating surface may represent the degree of deformation the basaltic unit has undertaken with a network of potentially groundwater-bearing fractures developing in several areas highlighted above.

Line 2 (NNK-2): Upper catchment from Line 1, Nanuku – Figure A10

This survey profile, covering a distance of 300 m and using an electrode separation length of 4 m, was conducted along an access road in the upper catchment from Line 1 following a S-N trend to target E-W trending dikes observed to be outcropping on the hillsides. It is proposed that the presence of these dikes may cause localised groundwater impoundment, a possible groundwater target.

The resistivity profile was dominated by a basal zone of high resistivity response of 80–500 Ohm.m appearing to have minor discontinuity along the profile and located at depths between 10 m to beyond 90 m. This zone probably indicates basaltic bedrock with reduced permeability/porosity and potential for groundwater yield. Two zones of discontinuity exhibiting a potential depth extension, characterised by significantly reduced resistivity (20–50 Ohm.m), were observed within the bedrock highs. These features, appearing along profile distances of 32–50 m and 230–250 m, may represent weathered fracture zones with increased moisture content and possible groundwater. The shallow depths is characterised by low to very low resistivity (10–20 Ohm.m), which may represent weathered regolith and soil profile probably partly saturated.

The hypothesised model of dike-impounded and perched aquifers was not visible. Although a number of dikes were observed outcropping around the area, none were identified from the resistivity profile, which suggests a more localised nature of these features, if present.

Line 3 (NNK-3): Direndra Nand's land, Nanuku – Figure A11

The W-E trending profile, covering a distance of 300 m and using a 2.5-m electrode separation, was conducted across a valley and crossing a boulder-filled creek at 100 m; the creek was dry at the time of the survey. The survey line aimed at identifying possible N-S trending lineaments and structures that may control localised groundwater-bearing fractures connected to the creek.

The profile presented a highly variable dataset with investigation depth of down to 40 m. A pronounced zone of low resistivity (10–20 Ohm.m) was observed between 0–100 m profile distance and subsurface depths of 0–15 m. The low response at very shallow depth may represent saturated soil profile with some clay within the weathered basalt. The slight increase in response at 10–15 m depth may indicate weathered and fractured basalt with less clay. The area, although part of a bigger catchment, seems to have limited recharge and, hence, is highly likely to be impacted by dry conditions.

A shallow and noticeably small zone of moderate to high resistivity is observed between 100 m and 120 m profile distance and 0–5 m subsurface depths. This represents the boulder-filled creek that was crossed by the survey line, and underlain by saturated zones which are connected to deeper systems.

There is a shallow, near-horizontal and up to 10-m thick layer, with moderate to high resistivity (80–120 Ohm.m) observed around 140–186 m profile distance. This may represent a zone of fresh and low-permeability basalt that has neither exhibited any weathering nor being fractured. This zone of low permeability may lead to the development of shallow perched-like systems atop this feature and would accelerate the saturation level and the formation of swampy conditions during rainy periods.

Immediately below this feature is a zone of low resistivity (10–15 Ohm.m), which may indicate weathered basalts infilled with clay materials with higher porosity and moisture content but the low permeability of clay will not allow groundwater movement.

Two distinct zones of near-vertical features, showing low resistivity (20–40 Ohm.m) were observed along the profile. The first was observed between 120–140 m profile distance and subsurface depths from 7 m and may extend beyond 40 m. The second is observed between 180 m and 193 m profile distance and subsurface depths from 15 m and may extend beyond 40 m. These features, bounded by moderate to relatively high resistivity areas, have near-vertical morphology, which may represent parallel and hydraulically connected fracture zones that possibly extend into the upper catchment containing groundwater. Their depth extension suggests the possibility of groundwater recharge from deeper sources that may be connected to other fracture networks and may represent interesting resistivity anomalies for further investigation with drilling.

A shallow and perched-like feature with low resistivity (10–30 Ohm.m) is observed around 230–270 m profile distance and down to 10 m subsurface depth. The low-resistivity response (10–15 Ohm.m) areas near the surface may represented weathered regolith or increased moisture content in the soil profile while the increased resistivity (15–30 Ohm.m) may indicate strata of weathered fractured basalts with varying level of permeability and saturation. The area, although promising in terms of groundwater presence, is likely to be vulnerable to dry periods due to its limited size and shallow depth.

A highly variable and discontinuous zone of medium to high resistivity zone (55–70 Ohm.m) constitutes the profile's basement. This may represent basaltic bedrock. The variable and relatively low-resistivity response shown in the basement formation suggests that the area is part of the highly deformed and fractured basaltic catchment linked to the degree of tectonically-driven deformation undergone by the basaltic framework over time.

The high-resolution profile generated by the 2.5-m electrode separation, albeit the associated reduced ground coverage, provided more lateral and depth details in terms of structural features that may or may not have been identified by longer separations..

Line 4 (NNK-4): Mr Ganesh Rao's cane field, Nanuku – Figure A12

The W-E trending profile was conducted following an access road through Mr Ganesh Rao's cane field to capture any N-S trending fractures or feeder zones to the nearby creek. The profile used an electrode spacing of 4 m and covered a distance of 320 m.

The inverted profile showed multiple zones of low resistivity (15–50 Ohm.m) across the profile. The shallow zones observed along profiles distances 16–64 m and 168–230 m and depths of 0–5 m recorded 15–20 Ohm.m and is interpreted as soil profile and high weathered basalt that may be saturated with water. Along profile distance 42–84 m and subsurface depths of 0 m to possibly beyond 20 m is a pronounced zone of low-resistivity response 20–40 Ohm.m, which may represent a more fractured basaltic zone that may contain water. It is possible that this zone extends down to greater depths, indicative of a potential groundwater source, but was truncated by the inverted model due to the profile configuration. Between 128 m and 168 m and depth range of 0–15 m, a low-resistivity zone of 20–30 Ohm.m having a near-ellipsoid shape cuts into the high resistivity basalt. This may represent a zone of localised fracturing and weathering extending at an angle into the low permeability basement and may contain some groundwater, albeit limited.

An extensive zone of low resistivity (20–40 Ohm.m) was observed along 164–240 m profile distance and appeared to be partly confined under a higher resistivity basalt formation up to a profile distance of 214 m. This zone showed a depth range of 25 m to beyond 70 m. Within this zone are two pronounced areas of contrasting response. The first, observed along profile distance 166–182 m and 50 m to beyond 70 m depths, exhibits low-resistivity measurements of 20 Ohm.m. This may represent a zone of concentrated fracturing containing groundwater likely to be recharged from deeper zones. Although being a promising site, its depth extension and the close proximity to the coast poses a threat of saltwater intrusion into the groundwater system. However, the immediately overlying formation (30–40 Ohm.m) still appears to have a significant potential for groundwater storage. The second anomalous zone, observed between 220 m and 230 m profile distance and similar depth range to the first zone, recorded medium to high resistivity (60–125 Ohm.m), which may indicate fractured basalt with reduced permeability, which is of less interest as a groundwater target.

Another zone of low resistivity (20–40 Ohm.m) is observed from 240 m to the end of the survey line with a pronounced zone of low response (20 Ohm.m) appearing at a profile distance of 248–260 m and depths of 15–30 m. This pronounced and well-defined zone of contrastingly low response suggests weathered or fractured basalt containing groundwater and possibly recharged by both nearby sources (creek) or deeper zones that drain towards it. Within this zone a high-resistivity feature (70–150 Ohm.m) may indicate massive and low permeability basalt.

Substantial part of the basalt composite along 64–224 m profile distance and from 5 m to beyond 70 m depth has a moderate to high resistivity (75–500 Ohm.m). This indicates a more massive basaltic flow that has low to no fracturing and hence having low to negligible permeability.

Line 5 (WLV-5): Upper catchment to the kindergarten bore, Wailevu – Figure A13

This W-E trending profile was undertaken using a 4-m electrode separation length and covered a 300 m distance, crossing a SW-NE trending and elongated catchment where the subartesian or artesian bore of the Nanuku kindergarten is located. This confined catchment seems to be branching from a SE-NW trending bigger catchment area that has thick vegetation cover. The profile started from the western hill and ran through a depression before gradually ascending along a SW-NE trending hillside.

The inverted profile is dominated by low-resistivity response with a pronounced and elongated zone of medium to high resistivity (60–250 Ohm.m) that tapers towards the end and may suggest massive basalt related to the eastern hill. The domination of low-resistivity response may suggest a high level of fracturing within the basalt and variability in the degree of groundwater contained within. The near-surface zones of very low-resistivity response (10–15 Ohm.m) observed around 16–66 m profile distance and 0–5 m depth and profile distance of 128–170 m and depths down to 8 m may represent saturated soil and highly weathered basaltic fractures containing water. Two well-defined zones of low resistivity were found and are summarised below.

- Around the depression at 80–110 m profile distance and 20–50 m subsurface depth, a low-resistivity zone may represent a confined area of highly fractured basalt containing groundwater. It is possible that this well-defined, low-resistivity area illustrates the groundwater flow path and storage that is connected to, and possibly recharged from, the adjacent catchment. This is likely to be the main flow and capture zone through which the kindergarten well is directly recharged. This site has groundwater potential that can be developed to meet the community's water needs.

- A low-resistivity zone observed on the hillside around 180–220 m profile distance and depths from 45 m to beyond 60 m appears to be underlying the massive basaltic areas, and may indicate another fracture network with groundwater. This represents another good groundwater potential formation that is likely to gain recharge either through deeper sources or other hydraulically connected fractured systems. The relatively close proximity of this area to the coastal plain and the coastline would suggest some caution in the possible development of a freshwater body around this elevation with potential for saltwater intrusion.

The domination of low-resistivity along this profile is of great interest. It is suggested that the basaltic framework is moderately fractured with groundwater expected to be contained within the fractures which may yield sufficient water for water supply purposes. This is possibly related to the level of tectonically-driven deformations and the resultant structural changes that the underlying basaltic flow has been subject to over time.

Line 6 (WLV-6): through a cane farm, Wailevu – Figure A14

This S-N trending profile used a 4-m electrode separation and covered a distance of 240 m along the eastern part of the same hillside covered by the western part of survey line 5. The profile, undertaken at 60 m elevation, was planned to target E-W trending lineaments or fractures that may influence groundwater occurrence, as indicated by nearby creeks and drainage features having similar trends.

The profile is dominated by low-resistivity responses (15–50 Ohm.m) with minor zones of high resistivity (70–170 Ohm.m). The high-resistivity zones may represent more massive and lower permeability basalts appearing as either a near-vertical structure around 124–140 m profile distance or as horizontal near-surface zones of low permeability surrounded by low-resistivity areas. The steep or near-vertical nature of the former may suggest the presence of a fracture or possibly a fault where the southern end appears to be highly fractured and highly saturated, a possible reason of low-resistivity measurement generated around the south.

The areas of low resistivity in the top 2–3 m indicate weathered clays with varying moisture content. The extension of this zone is probably related to the land use activity where the entire land is frequently cultivated and hence the top surface is always disturbed and with varying moisture content. Two contrasting zones of low resistivity (30–40 Ohm.m) with a long-angle interface were observed between 10 m and 118 m profile distance and depths extending beyond 60 m. These zones could represent basaltic flows with varying degree of fracturing and weathering and thus with a permeability contrast. It is likely that the underlying layer has a higher permeability with greater potential for groundwater development, and is recharged by fractured networks from the south. The substantial extent makes this zone a potential groundwater target. Beyond 128 m to the profile's end, the areas of low resistivity appeared as shallow features (0–10 m depth) that are underlain by the moderately fractured basalt recording a resistivity of 50 Ohm.m. These features are perched-like with some groundwater potential but may be easily compromised during prolonged dry periods. There is potentially another deep fractured and saturated zone between 192 m and 240 m profile distance but was truncated due to limited data.

The near-vertical, high-resistivity zone around the centre had somewhat allowed or dictated the formation of a highly fractured and saturated system towards the south, although contrastingly low responses were observed in places. The north end comprises shallow, perched-like formations and a possibly fractured zone towards the end.

Line 7 (WLV-7): along the Wailevu Rd – Figure A15

This profile was conducted along the main Wailevu Road and covered a distance of 700 m. Using a 5-m electrode spacing, the S-N trending profile was designed to investigate W-E trending structural features that may be linked to nearby creeks and streams.

The highly variable resistivity response observed on the inverted model indicated the presence of moderate to high-resistivity zones (70–150 Ohm.m) along 0–340 m and 380–500 m profile distance and at 5–80 m depth, which may indicate more massive and lower permeability basalt. These zones exhibit an undulating surface and appear to have two noticeable zones of abrupt and steep discontinuities. The undulating surface may represent the high degree of deformation, possibly moderately folded, controlling the weathering profile of basalts while the discontinuity zones may represent more highly fractured zones containing groundwater.

A number of low-resistivity zones are observed along the profile. Along 0–200 m profile distance and 0–20 m depth are pockets of very low to low resistivity (20–50 Ohm.m), which may represent a combination of shallow groundwater storages with some level of confinement. The shallow depth and limited dimension of these zones may influence their vulnerability during dry periods. At profile distances of 200–320 m and 380–500 m and at 0–30 m depth, low-resistivity areas (15–40 Ohm.m) exhibit similar morphology. These two zones may indicate zones of concentrated weathering and/or highly fractured basalts that may contain groundwater in the 380–500 m area, indicating greater potential and possibly receiving more recharge from surface sources.

Two zones of possibly steep, deep, groundwater within what is interpreted as a fracture zones are observed along 320–390 m and 500–700 m, with the former appearing to be partly confined by high resistivity basalt for the first 30 m. The two zones, extending to more than 90 m depth, may indicate highly fractured areas resulting from the deformation of the basaltic framework where the development and interconnection of secondary porosity has allowed groundwater flow and storage. The northern end, at 500–700 m distance, however seems to have more contrasting zones of low resistivity (20–30 m), which may suggest slightly better groundwater potential which in turn, makes this zone a potential target that may yield usable drinking water supplies.

Line 8 (WLV-8): access road and crossing the creek, eastern Wailevu – Figure A16

This W-E trending profile was carried out using a 5-m electrode spacing and covered a distance of 385 m. The survey line was targeted to identify N-S lineaments parallel to the nearby creek, and also to determine if the creek has shifted positions over time, which should be able to show paleo-incised channels that may be infilled with gravels and which may host groundwater. The survey line started from a low hill at 200 m distance from the creek before crossing this drainage and ascended though the nearby hill for another 185 m.

The profile was dominated by a basal area of moderate to high resistivity materials (70–180 Ohm.m) extending through the length of the profile, exhibiting undulating surface and protruding the land surface as the creek bedrock. This zone potentially indicates a low-permeability massive basalt with some variability in fractures and weathering in places influencing the resistivity response. Low-resistivity materials (20–40 Ohm.m) were observed at shallow depths at 0–200 m profile distance with varying thickness of 5–15 m, with the maximum thickness measured at 160 m along the survey line. This shallow zone may indicate a thin veneer of weathered basalt and a soil profile that may be saturated and hydraulically connected to the creek. The shallow and limited nature of this zone makes it vulnerable to dry conditions and likely to have poor groundwater yield to meet the Wailevu community's water demand. It could be developed and used for a household water supply. On the eastern side of the creek, from 220 m to 385 m and going up the hill, is another relatively shallow area of low resistivity (20–50 Ohm.m). This again, is likely to indicate weathered basalt that may be saturated and appeared to be connected to the creek.

The presence of relatively shallow weathered basalt and extensive massive basalt suggest the absence of any pronounced N-S fracture zones parallel to the creek that may be highly conducive to groundwater storage and flow as displayed in other profiles. No evidence of noticeable incisions of gravel-infilled bedrock was observed to suggest that the creek may have shifted overtime. The interpreted groundwater potential along this survey profile was considered poor.

Benai

Line 1 (BEN-1): across Mr Vijay Kumar's cane field, Benai 22 – Figure A17

This S-N trending profile, covering a distance of 400 m and using an electrode spacing of 4 m, was conducted along the mapped andesitic hillside at 85 m topographical elevation. The survey line progressed downslope and crossed a dry creek at 280 m. The profile, having an investigation depth of 75 m, was planned to target E-W trending fracture zones identified around the site. Mr Vijay Kumar's bore, located at around 220 m profile distance and drilled down to 55 m, also constituted an interesting target to investigate density and depth of the fractured volcanics.

The highly variable inverted profile is characterised by a basal area of medium to high resistivity (70–250 Ohm.m) that extends throughout the entire profile length and beyond 20 m subsurface depth with an increasing depth observed after 250 m distance. This zone may represent fresh andesite with low to negligible permeability while the noticeable increasing depth may indicate increasing thickness of overlying weathered or saturated fractured andesite.

Along shallower depths (0–20 m), low-resistivity geological materials (20–50 Ohm.m) are prevalent. These might represent pockets of highly weathered or saturated fractured andesite. Several zones of shallow and confined low resistivity were observed between 50 m and 140 m profile distance at 5–15 m depth. These may indicate multiple perched-like formations that are fully saturated and limited in size. Several pronounced zones of low resistivity (20–50 Ohm.m) were observed between 150 m and 275 m profile distance at 0–30 m depth, possibly indicating areas of increased weathering and porosity with some groundwater potential. Within this low-resistivity zone is Mr Vijay Kumar's 55 m deep bore sited at 220 m profile distance. It is possible that the bore was constructed in weathered and fractured andesite with a resistivity of 50 Ohm.m, which is 20 m thick and extends beyond the creek with the thickness increasing to 40 m at around 335 m profile distance. This extensive and thick zone, with maximum thickness of 35 m recorded at 298 m profile distance, possibly represents fractured andesite, which is likely to transmit groundwater, as indicated by Kumar's bore. The increasing density and concentration of fractures may be associated with a structural feature that potentially exists around 300–310 m profile distance and depths of 50–60 m but was truncated by the model due to the survey line configuration. This zone suggests improved groundwater potential for the surrounding households without any reliable water source, but will require investigative drilling to prove the resource potential.

Line 2 (BEN-2): lower catchment from Mr Vijay Kumar's farm, Benai 22 – Figure A18

This survey profile, designed to run parallel to and downslope from survey line 1, covered a distance of 384 m and used an electrode separation of 4 m. This profile was conducted along a confined catchment and aimed at identifying E-W trending fracture zones that may promote preferential groundwater storage and flow.

The inverted profile shows highly variable responses displaying the variability of the underlying framework. A thin veneer of low resistivity (20–30 Ohm.m) was observed mostly at shallow depths with increasing thickness, possibly indicating a localised increase in the weathering profile and moisture content at around 236–298 m profile distance. The basal framework is dominated by high resistivity materials (70–250 Ohm.m), possibly representing fresh to slightly weathered andesite and having low to negligible permeability.

Two pronounced zones of low resistivity (20–50 Ohm.m) were observed within the basal formation and may suggest possible groundwater occurrence. The first was observed around 50–74 m profile distance and from 25 m to beyond 40 m. This resistivity response likely indicates highly fractured and/or weathered andesite with improved groundwater potential. A larger zone of lower resistivity observed at 145–230 m profile distance and at 20 m to beyond 60 m depths suggests more fractured andesite, with expected improved groundwater potential believed to represent E-W structural lineament intersected by this profile. The extensive lateral and vertical dimensions suggest that this fractured zone could be recharged by deep and adjacent groundwater-bearing zones and hence the groundwater source could provide usable groundwater and is recommended for further investigative drilling.

Line 3 (BEN-3): upper catchment, within Mr Chaudhry, Benai 22 – Figure A19

The survey area is part of an andesitic breccia hillside where two boreholes are located. Both bores are drilled down to 55 m, sited 10 m apart, and are currently used by Mr Chaudhry as household water supplies and for small-scale irrigation. The S-N trending profile was designed to intersect fracture zones or lineaments that may contribute and/or control the development of usable groundwater around the areas. The area is inhabited by 10–15 surrounding families that do not have a reliable water supply.

The highly variable profile shows a shallow zone of low-resistivity materials (20–40 Ohm.m) from the start of the survey line to 135 m profile distance and depths of 0–50 m. This may represent weathered andesitic breccia possibly connected to the boulder-filled dry creek crossed at 100 m, with the boulders exhibiting localised increased resistivity (150–500 Ohm.m) around the creek. The lateral extent of this low-resistivity zone is interesting from a groundwater development point of view but its shallow extent makes it potentially vulnerable to dry conditions and hence, it is not recommended for a community water supply source, but may provide usefulness as a household source.

From 135 m to 280 m profile distance and around near-surface depths is a thin strata of low resistivity (20–40 Ohm.m). This indicates a clay soil profile and weathered andesite around an area frequently cultivated for cane farming. The limited depth, however, suggests its vulnerability to dry conditions.

Underlying this shallow low-resistivity zone, is a zone of medium to very high resistivity (70–500 Ohm.m), which suggests slightly fractured and fresh andesitic breccia with low to negligible permeability. Confined within this low permeability zone is a pronounced and well-defined zone of low resistivity (30–50 Ohm.m) at around 184–216 m profile distance and depths 40 m to beyond 70 m. This zone potentially indicates a deeper fractured water-bearing andesitic breccia, possibly representing an E-W trending fracture zone. This zone may be able to provide groundwater for water supply purposes.

Line 4 (BEN-4): lower catchment, Mr Chaudhry, Benai 22 – Figure A20

This S-N trending profile, located downstream and parallel to Line 3, covered a distance of 500 m and used the electrode spacing of 5 m. The survey line was selected in order to explore the potential lateral extension of the E-W fractured and potentially water-bearing andesite identified in survey line 3.

The highly variable inverted profile shows similar distribution patterns with a downward gradient of low-resistivity materials (20–40 Ohm.m) in the first 200 m of the profile, suggesting saturated clays and weathered andesite mimicking the topography and possibly connected to the gravelly-filled dry creek crossed at 110 m. Similarly, the capping strata of low-resistivity materials observed at subsurface depths 0–5 m and from 120 m to the end of the survey line may represent clay soils and weathered regolith with the bottom and sharp interface probably representing the boundary between the vadose and saturated zone. The basal formations are characterised by medium to high resistivity materials (70–250 Ohm.m) dominating the southern end of the profile, which may indicate slightly fractured and fresh andesite with low to negligible permeability. From 200–400 m profile distance and depths from 10 to beyond 90 m, an extensive zone of low-resistivity materials (20–50 Ohm.m) exists which appears to be an unconfined, yet extensive, fractured volcanics that may yield usable groundwater. Within this zone is a well-defined and concentrated zone of reduced resistivity materials 30–40 Ohm.m around 340–375 m profile distance and depths from 30 to beyond 70 m. This zone clearly indicates a contrasting resistivity anomaly suggesting an E-W trending fracture zones, possibly linked to the conductive and deep feature in Line 3. This resistivity anomaly has the potential to yield usable and reliable groundwater and is recommended for futures investigative drilling

Line 5 (BEN-5): with Mr Manil Lal's cane field, Benai End – Figure A21

This W-E survey profile was conducted through Mr Manil Lal's cane field, covering a distance of 320 m and using a 4-m electrode separation length. The area is part of a highly incised and W-E trending catchment bounded by moderately fractured basalt where survey lines 5, 6 and 7 are located. The area remains disconnected from the WAF distribution scheme. Although around 10 households in this area are served by a spring dam, the source is recorded to be insufficient and usually records low flow and runs dry during prolonged dry conditions. The households around this area appear to be also engaged in animal grazing with farmers stating difficulty of securing the animals' drinking water during dry periods and as a result they walk for hours to fetch water for the animals as the nearby creeks are either dry or unpleasant to use.

The inverted profile shows highly variable and layered resistivity patterns. The top 20 m across the profile are covered by low-resistivity materials (15–20 Ohm.m) which may represent clays and weathered basaltic rock. A 10–15-m-thick extensive zone of weathered and possibly fractured basalt is indicated by resistivity of 30–50 Ohm.m found immediately underlying the clay and weathered regolith and may represent a different flow. This zone may represent low to moderate groundwater potential between different flows.

The basal zone is dominated by higher resistivity materials (70–150 Ohm.m) indicating a less weathered volcanics with generally low permeability and limited potential for groundwater as a community supply..

Line 6 (BEN-6): Hill behind Mr Jagdish Chand's house, Benai End – Figure A22

The W-E trending profile, covering a distance of 320 m with an electrode separation of 4 m, was conducted along the W-E trending basaltic hillside and following a cane access road uphill from Mr Jagdish's house. The survey line was planned so as to investigate potential N-S fracture systems.

The inverted profile is dominated by relatively low-resistivity materials (15–100 Ohm.m) with an anomalous outlier of 500 Ohm.m observed at 105 m profile distance and 5 m subsurface depth. The prevalence of low-resistivity materials, particularly in the range 20–50 Ohm.m, suggests that the entire hill consists of more fractured and weathered geologies. A well-defined, deep vertical zone of low resistivity (20–30 Ohm.m) is observed at around 180–195 m profile distance at depths up to 70 m. This zone, bounded by vertical structures of medium to moderate resistivity, may represent a potential N-S trending fault or a more fractured zone that may suggest potential recharge from deep and lateral sources. This promising groundwater-bearing formation would require investigative drilling to assess groundwater potential at this target site, and significant road improvement to improve site accessibility.

Line 7 (BEN-7): along the main road, Benai End – Figure A23

The W-E survey profile was conducted parallel and downslope from survey line 6 to investigate the possible lateral extension of structural features identified on the hillside. The survey profile covered a distance of 500 m and used a 5-m electrode spacing.

The profile generated low-resistivity values (20–70 Ohm.m) overall. The dominance of very low responses (15–20 Ohm.m) around very shallow depths across the entire profile may represent the vadose zone materials (soil and weathered basalt) that may be saturated and bounded at the bottom by a sharp linear interface and the potential of some perched groundwater. An extensive zone of low-resistivity materials (30 Ohm.m) with varying thickness, and maximum thickness of 25 m recorded at 145 m profile distance, is observed around 80–455 m profile distance, suggesting the increasing thickness of weathered and/or fractured basalt, which in turn may indicate the presence of groundwater. A pronounced near-vertical and highly fractured zone, recording 40–50 Ohm.m resistivity, is observed around 335–385 m profile distance and depths from 10 m to beyond 70 m. The lateral and vertical extension of this feature suggests that this is a N-S fractured zone and could form a good groundwater target.

Line 8 (BEN-8): along a cane access road near Mr Shiu Narayan, Benai End – Figure A24

The S-N trending survey line covered a distance of 500 m and used a 5-m electrode spacing. The survey line was located on the western end of Benai End where around 10 households exist without any reliable water supply. The profile was planned around the mapped basaltic breccia and crossed an unused hand-dug well at 440 m.

The inverted profile shows a highly variable resistivity distribution, characterised by several very shallow zones of low resistivity (15–50 Ohm.m) that which may indicate clay soil and weathered basaltic bedrock down to 5 m depth. This potential groundwater in weathered/fractured basalt at this shallow depth can be validated from the 5 m deep unused hand-dug, which shows a static water level at 4.6 m, located at around 440 m along the profile. A zone of multiple and potentially deep zones of very low to low-resistivity material is observed in the first 130 m of profile distance at depths down to 60 m. This possibly indicates a zone of more fractured basalt which may provide usable groundwater to surrounding households. The area from 130 m onwards is marked by the increasing dominance of high resistivity materials (70–100 Ohm.m), which may indicate the decrease in fracturing and in permeability of basalts. Interestingly, around 280–440 m profile distance and at depths of 60 m to beyond 80 m is a pronounced, extensive and confined zone of reduced resistivity (20–50 Ohm.m) which may indicate a potential groundwater at depth, recharged from more distant sources.

Line 9 (BEN-9): along railway, Benai End – Figure A25

This W-E trending survey line was conducted along a railway line, close and yet perpendicular to survey line 8. The orientation of the survey line was guided by the possible continuation of the N-S trending regional fault through the area and by the fact that this structural feature may control or influence the flow and storage of groundwater.

The 400-m-long profile showed highly variable, yet relatively low, resistivity responses of 15–70 Ohm.m. The underlying high-resistivity zone (> 50 Ohm.m), exhibiting undulating morphology, may represent an area of slightly fractured low permeability basaltic breccia and volcaniclastic sediments. Two well-defined and pronounced areas of reduced resistivity (30–50 Ohm.m) are observed at around 0–140 m and 220–270 m profile distances, with the subsurface thickness of these zones of around 50 m for the former and more than 80 m for the latter. These significantly reduced resistivity responses compared to the surrounding and underlying rock units suggest increased groundwater potential and possible fracturing. These fracture zones could be part of the inferred N-S trending regional fault initially targeted. The lateral and vertical extension of these fractures appears to reflect potential groundwater bodies that will need to be drilled for further water quality and quantity evaluation.

Navia and Nadhari

Line 1 (NDR-1): Nadhari – Figure A26

Survey line 1 was carried out in Nadhari and covered a distance of 400 m in a S-N direction. A 4-m electrode spacing was used to allow for a good balance between resolution, penetration depth, and distance covered. The survey line was undertaken perpendicularly to capture and assess the groundwater potential of possible lineaments oriented parallel to the target valley.

The model inversion revealed an interesting profile with sharp contrasts in the spatial distribution of resistivity. A near-vertical, high resistivity feature located between 220 m and 250 m along the profile suggests a dike feature with low groundwater potential. On the southern side of the dike, a low-resistivity response suggests the presence of groundwater. At either side of the intrusive dike, at close distance, groundwater potential is considered high. The first 190 m of the profile are characterised by a thick zone of low-resistivity deposits (5–40 Ohm.m), suggesting the accumulation of weathering products such as clay and silt.

An electromagnetic geophysical survey (Geonics EM-34) was additionally conducted between 100 m and 300 m along the survey line to assess the capabilities of EM-34 in comparison with the resistivity method. Two dipole configurations (horizontal and vertical) were used in combination with three different cable lengths (10 m, 20 m and 40 m) to obtain an image of cumulative conductivity at different depths. It was concluded that the vertical dipole configuration using the 20-m and, particularly, the 40-m cable resulted in a distinctive conductivity peak between 170 m and 220 m along the profile, indicating the likely presence of groundwater along the first 60 m of depth. This is replicated in the resistivity results, however the lack of spatial detail and the uncertainty related to different dipole configurations does not justify the slightly shorter survey times associated with electromagnetic methods.

Line 2 (NDR-2): Nadhari – Figure A26

Survey line 2 was also carried out in Nadhari and covered a distance of 392 m in a S-N direction. The survey line was conducted perpendicular to the neighbouring valley, north of survey line 1. Information was received by the local communities that frequent flooding occurs during rainfall events, especially towards the stream at the northernmost edge of the valley. This was considered a promising indication of a possible shallow unconfined aquifer. A 4-m spacing was again used to be consistent with the neighbouring survey line.

The profile is largely characterised by medium resistivity zones (150–250 Ohm.m) overlain by a low-resistivity shallow zone believed to reflect clay deposits. As opposed to the previous profile, the very thin interface of gradual resistivity increase surrounding the resistive zone reflects the absence of groundwater at depth. Some groundwater potential may exist at 250–275 m along the profile where lower resistivity thickness increases, suggesting increased weathering with possible groundwater suitable for domestic supply only.

Line 3 (NDR-3): Navia – Figure A27

Survey line 3 was conducted in the hilly areas of Navia community farther to the east. The survey line followed an E-W orientation, perpendicular to the valley to explore the groundwater recharge potential of the flowing stream. A 5-m electrode spacing was applied to investigate adequate depth. The total distance covered was 565 m.

The entire profile indicates higher resistivity (150–750 Ohm.m), suggesting the absence of any substantial groundwater accumulations. Only the interval 150–170 m along the profile suggests a vertically oriented feature with possible groundwater potential. The feature suggests a narrow fracture zone but the resistivity range (75–100 Ohm.m) and narrow target does warrant exploratory drilling at this stage.

Line 4 (NDR-4): Navia – Figure A29

The orientation of survey line 4 was based on the same assumption of exploring the groundwater recharge potential of the flowing stream further upstream of survey line 3. A distance of 400 m was covered using a 5-m electrode separation length.

Similarly to survey line 3, this line was governed by high resistivity (150–1000 Ohm.m), except from shallower depths of 10–20 m, where resistivity is in the range of 50–150 Ohm.m. The groundwater potential along this survey line is generally low and drilling is not recommended.

Line 5 (NDR-5): Navia – Figure A30

Survey line 5 was carried out along the main road in Navia following a W-E direction, perpendicular to lines 3 and 4. The total distance covered was 1000 m to explore potential resistivity features indicating groundwater.

The model inversion revealed some interesting patterns with a number of low-resistivity zones suggesting good groundwater potential. A low-resistivity zone (30–40 Ohm.m) was identified at 130–230 m along the profile and at depths greater than 25 m. This zone is located along a surficial depression that possibly acts as a groundwater recharge zone. Downstream of this feature, thick vegetation along the depression probably reflects shallow groundwater flowing towards the main stream.

Another interesting feature is observed at 540–580 m along the profile as a low-resistivity (30–50 Ohm.m) vertical zone, possibly a fracture, sandwiched between high-resistivity (500–1000 Ohm.m) volcanic deposits. The high resistivity indicates absence of groundwater probably due to the compact nature of the deposits. Some groundwater potential possibly exists at 750–930 m along the profile where the resistivity range is between 30 Ohm.m and 75 Ohm.m.

Line 6 (NDR-6): Waibuca – Figure A31

Survey line 6 was conducted in the Waibuka community, which forms the southern valley of the study area and the downstream part of survey lines 3 and 4. The valley was again investigated perpendicularly to its orientation to investigate any potential groundwater bodies associated with the perennial stream. A 400-m-long survey line was carried out with an electrode spacing of 4 m.

The inverted profile revealed relatively low-resistivity patterns in between 20 Ohm.m and 100 Ohm.m. The shallow half of the section revealed some interesting features with resistivity in the suitable range for groundwater accumulation and development (20–50 Ohm.m). The flowing stream is observed at 215 m along the profile and seems to be significantly recharging the underlying layers. Substantial groundwater accumulation with promising drilling potential is also observed at 260–290 m along the profile.

Line 7 (NDR-7): Waibuca – Figure A32

Survey line 7 was conducted close to the southwestern edge of the study area, further down gradient of survey line 6. In this area, the river forms a peculiar bend possibly suggesting the endurance of the valley material against erosion. The survey was conducted in a downhill SE-NW orientation towards the perennial valley stream and ended just before reaching the stream. A 400-m section was assessed with a 5-m electrode separation interval.

A relatively high absolute error, associated with the large number of "negative" resistivity recorded during this survey line, poses some concerns regarding the reliability of the results. The inverted profile indicates the presence of a 20–25-m-thick, low-resistivity (20–75 Ohm.m) layer, encountered at shallow depth in the central part of the profile. This layer may present some groundwater development potential, especially at the 240–280 m interval and possibly at 320–350 m.

Malele

Line 1 (MLL-1): Khalsa, Malele 3 – Figure A33

The profile was undertaken on a 120-m-high hill around the Khalsa area, composed of a cluster of 5–10 households on the northern part of the study area. The area was selected based on several surface expressions that suggest possible favourable fractures, while the elevation seemed ideal to provide adequate head for the households around Malele north.

The 500-m inverted profile permitted the investigation of down to 80 m depth and showed a variable resistivity response from 15 Ohm.m to 900 Ohm.m and dominated by responses of more than 100 Ohm.m. These suggest that the basaltic hill probably has multiple flows that are likely to have a very low-fracturing degree and negligible permeability and hence, may store very little to no groundwater. Several noticeable areas of reduced resistivity were observed. Three very shallow zones (5 m depth) of low resistivity (15–20 Ohm.m) were recorded at 0–90 m, 220–245 m and 270–420 m profile distances. These may represent cultivated soil profile that may be partly saturated. Three well-defined and perch-like formations with resistivity range of 20–40 Ohm.m were also observed at around 40–65 m, 120–140 m and 220–260 m profile distances and subsurface depths of 10–20 m. These shallow and perched like formations appear to be well connected to the near-surface formations, suggesting their rainfall dependence and their limited extent due to surrounding high resistivity materials indicate low–yielding formations that should not be further developed. Between 125 m and 145 m profile distance and subsurface depth from 65 m to beyond 80 m is a pronounced and well-defined zone of low-resistivity material (20–50 Ohm.m). This area, although surrounded by high resistivity materials, may represent a deep and confined area of fracturing and/or weathering that is likely to allow appreciable groundwater flow and storage. This feature indicates a potential groundwater target that will need to be validated by groundwater drilling and lithological analysis.

Line 2 (MLL-2): near Mr Jai Ram's residence, Malele 3 North - Figure A34

The S-N trending profile was undertaken on a confined catchment where an old, 53 m deep, community borehole is located, and the profile is oriented to identify possible W-E trending groundwater-bearing fractures. The borehole, recorded to provide water supply for around 30 nearby households, is no longer in operation as associated households were not able to pay the electricity bills. Prior consultation with community members suggested that the borehole did not record reduced flow during historical dry periods and hence, was considered for assessment. Also, close to the catchment is located a 35-m borehole, privately owned by Mr Jai Ram.

The 300 m profile, with a 5-m electrode spacing, yielded highly variable resistivity response from 10 Ohm.m to 750 Ohm.m, possibly signifying the variability in permeability with the survey line intersecting the old community bore at 140 m and the Mr Ram bore at 240 m. The profile has a zone of high resistivity materials sandwiched by two zones of reduced resistivity. The high resistivity area, recorded at 100–240 m profile distance, is likely to represent slightly fractured to fresh basaltic materials that continue at depth and have very low to negligible permeability.

Two zones of low-resistivity response (10–50 Ohm.m) are observed from 0 m to 110 m and from 215 m to 300 m profile distances with the both zones showing subsurface thickness of more than 50 m. These areas may represent highly fractured and weathered basalts with increased groundwater potential. The existing bores, namely the old community bore and Mr Ram's bore, are generally situated around the prospective groundwater areas but ideally a new bore would be placed at around 80–90 m where lower resistivity is observed and the potential for increased fractures and groundwater potential is suggested.

Line 3 (MLL-3): near Mr Sant Kumar, Malele 3– Figure A35

This W-E survey profile was designed to intersect several noticeable lineaments and extends into the edge of the catchment investigated in Line 2.

The 300 m profile, using a 5-m electrode spacing, generated variable resistivity response (20–250 Ohm.m) and is dominated by low-resistivity materials. Similar to the previous profiles, the higher resistivity materials (>70 Ohm.m) may represent less fractured and lower permeability basaltic flows that may have very low to negligible yield. The shallow zone (0–7 m) of very low resistivity (20–30 Ohm.m) may represent saturated or partly saturated unconsolidated materials including soil profile and regolith. Three potential deep and pronounced areas of low resistivity (20–50 Ohm.m) are observed at around 20–40 m, 80–100 m, and 180–210 m profile distances. These areas suggest the potential for increased fracturing and weathering and the presence of useable groundwater. The depth extension of the first two of these areas is not well illustrated as they were truncated by the model configuration. The third area, at 180–210 m, seems to have a depth extension beyond 60 m and hence, may represent an ideal groundwater target for nearby households, but would require validation through drilling.

Line 4 (MLL-4): Along Natolevu-Davota road, Malele 3– Figure A36

This W-E trending profile was designed to target a well-indurated and moderately inclined structure crossing a creek located around the Natolevu-Davota access road. The area is sparsely inhabited and a reliable water supply is absent. Similar to the previous survey lines, this line was planned through lineament analysis and site observation of geological structures that may influence groundwater flow and storage. The profile started as the road was descending crossing a nearby creek at 200 m before gradually ascending towards the end. The creek is part of multiple and confined catchment areas all trending perpendicularly to the survey line. An interesting feature observed from site reconnaissance was an uplifted and moderately inclined welded tuff-like formation showing bedded flows beside the creek and extending into the catchment for around 100 m. This body is trending NE and dipping towards the west and is highly fractured in areas, possibly representing a structure that would control groundwater movement.

The profile demonstrates a highly variable response from 20 Ohm.m to 250 Ohm.m and is yet dominated by measurements of more than 70 Ohm.m at 145–320 m profile distance and depths extending beyond 80 m underground. These relatively high resistivity zones may represent less fractured and less permeable volcanic materials without any indication of groundwater occurrence. The presence of a West-dipping body with a resistivity response of 70–100 Ohm.m at 200–240 m profile distance is probably the representation of the well-indurated, uplifted and included tuff-like feature described earlier. Two zones of reduced resistivity were also observed at around 110–140 m and 320–500 m profile distances. These suggest highly fractured and weathered areas, possibly representing localised structures that indicate improved groundwater potential. While the thickness of the first zone is not well constrained in the profile due to truncation by the model configuration, the thickness or depth extension of the second area (330 m) can be estimated to be more than 80 m, and shows promising signs of a deeper zone with potential recharge from deep and surrounding formations. This presents a potential groundwater target that will need to be fully validated and evaluated through drilling.

Line 5 (MLL-5): Davota, Malele 3– Figure A37

This E-W trending and 500-m-long profile was designed to cover a cluster of 10 houses with no reliable water. Lineament analysis around the area suggests that possible N-S trending structures are running through the area.

The inverted profile shows a highly variable, and yet a relatively low-resistivity response of 20–250 Ohm.m. A relatively deep zone of low resistivity (20–50 Ohm.m) is observed at around 40–280 m profile distance, with a maximum thickness of 55 m, observed between 150 m and 200 m profile distance. This reduced resistivity area, similarly to previous observations may suggest increased fracturing with possible groundwater flow and storage. A point of caution is that most of the houses are concentrated around this zone and observed discharge storm flow and used water together with the presence of pit toilets and septic tanks would mean that if drilling is conducted, it should be performed at least 50 m away from the area. The presence of shallow and low-resistivity materials towards the end of the survey line would represent a thin veneer of soil profile and highly weathered volcanics saturated from recent rainfall events. An existing hand-dug well was observed at around 400 m and adjacent to a creek. The measured water table was 2.5 m and the electrical conductivity was 165 µS/cm, suggesting interflow water from recent rainfall.

A feature of comparable lower resistivity (75–100 Ohm.m) than the surrounding resistivity (>150 Ohm.m) at 290–330 m suggests fracturing, with possible groundwater or more mafic materials. Drilling would be required to investigate the resistivity feature

Line 6 (MLL-6): Natolevu South, Malele 3 – Figure A38

This survey line was designed to assist inhabited and sparsely located households around Natolevu south and could link to the Natolevu settlement in case a potentially high-yielding bore was identified. The profile was planned to run parallel to survey line 4 to confirm the lateral continuity of fracture zones or faults identified earlier.

The WNW-ESE trending profile covered a distance of 500 m and showed similar patterns of resistivity response where underlying high resistivity materials may represent unweathered or fresh volcanic units with very low permeability. Two low-resistivity zones (20–50 Ohm.m) are also observed at around 50–90 m and 320–500 m profile distance with a maximum thickness of 40 m recorded between

320 m and 390 m profile distance. These potential fracture zones may have deeper extensions but have been truncated by the model configuration. These areas may represent fracture zones that may contain groundwater and connected to structures intersected by survey line 4.

Line 7 (MLL-7): Davota-Vanga, Malele 3 – Figure A39

This profile covered a cluster of 10 households in Davota and around Vanga Creek. The households depend on carted water from WAF contractors throughout most of the year. Similar to previous survey lines, a number of noticeable surface expressions indicated potential fracture zones and/or drainage in the area, which prompted the need for an assessment.

The 500 m profile showed similar resistivity trends as in previous lines of dominant high-resistivity areas (>70 Ohm.m) representing massive and low permeability volcanic materials while the low-resistivity responses (20–50 Ohm.m) may represent increased permeability and potential groundwater storage induced by fractures and weathering. Two zones of low resistivity were observed at around 120–200 m and 240–420 m profile distances, with the former having an increased depth extension to beyond 50 m at 120–150 m profile distance. The latter shows characteristics of a shallow and perched formation at around 240–320 m profile distance while deeper extensions can be observed at 360–420 m profile distance. It is clear from resistivity that the shallow and perched-like formation will be limited as groundwater resource and vulnerable during rainfall deficient periods while the deeper zones suggest good groundwater potential and possible recharge from regional or localised groundwater-bearing fractures.

Line 8 (MLL-8): Natolevu north, Malele 3 – Figure A40

This profile was considered mainly due to the concentration of houses around the Natolevu settlement and the request from the advisory councillor due to the heavy reliance of this community to either WAF-contracted water carting or the adjacent and highly vulnerable Nasivi River.

The W-E trending profile, covering a distance of 400 m and using a 5-m electrode spacing, generated a relatively low-resistivity dataset (20–100 Ohm.m). Multiple zones of potential groundwater targets (20–50 Ohm.m) were observed along the survey line. 120–140 m, 200–240 m and 280–400 m profile distances recorded relatively thick zones of low resistivity (20–40 Ohm.m) and possible groundwater-bearing formations. The last zone (280–400 m profile distance) indicates a higher groundwater potential because the resistivity responses are around 20–30 Ohm.m and suggest increased potential for groundwater storage and recharge. Resistivity responses will need to be validated through groundwater drilling and development.

Line 9 (MLL-9): Vuqele – Figure A41

This profile was conducted around the southwestern end of the study area, and comprises 15–20 households that have no reliable water supply and are highly dependent on WAF-contracted carted water throughout most of the year. Although Vuqele has a different advisory councillor, the area was part of the Malele sector boundary provided by FSC and the severity of water shortages faced by surrounding households necessitated that additional surveys be undertaken.

The 600-m-long profile generated highly variable resistivity responses, with promising results with multiple low-resistivity (20–50 Ohm.m) zones, suggesting a number of groundwater-bearing fracture zones. The dominance of 30–40 Ohm.m measurements between 40m and 100 m, and the depth extension to beyond 60 m underground, represent a potential groundwater body that appears to have higher groundwater potential. Similar to other lines, the high-resistivity areas are believed to represent less fractured and low permeability volcanic, while shallow low-resistivity zones may represent saturated soils and weathered volcanics.

Line 10 (MLL-10): Bangladesh area, Malele – Figure A41

This survey line is located in area comprising 5–10 households, and is considered a remote part of Malele that often does not get water from the WAF emergency procedure. Based on the Malele advisory councillor's advice, the area is deemed a priority mainly because it has always been difficult for water carting trucks to reach it. Site reconnaissance around the area suggested a number of N-trending features that might influence the groundwater development. Further, the close proximity to the Island Chill groundwater bottling sites may suggest good groundwater development potential.

The profile, covering a distance of 400 m and having a W-E trend, used a 5-m electrode spacing to target N-S trending fractures and faults that may control groundwater presence and flow. The profile shows a dataset dominated by low resistivity (20–50 Ohm.m), which may suggest fractures with increased groundwater and clay system. The inverted profile suggests a possible fracture zone at around 80–160 m profile distance while a zone of lower resistivity of gradually increasing thickness is also observed from 200 m towards the end of the profile. Investigative drilling is required to verify the resistivity targets for groundwater potential

Volivoli

All survey lines were run using a 5-m electrode separation length to allow for adequate coverage in terms of distance and depth without masking the presence of hydrogeologically interesting features in terms of groundwater potential. All model inversions showed a very low absolute error (<2.9), reflecting the high quality and reliability of measurements. The low absolute error is directly associated with the absence of "negative resistivity" errors encountered in this area.

Line 1 (VLV-1) – Figure A43

Survey line 1 was conducted along a 380-m interval in the northwestern part of the Volivoli peninsula. The location was selected despite its low elevation due to the presence of an older public water supply well, drilled by MRD in 2005 and 2006, which had a relatively good yield before the pump stopped operating. A 5-m electrode separation length was applied to explore depth adequately and possible visualize the fresh/saltwater interface.

The entire profile is governed by relatively low resistivity between 20 Ohm.m and 75 Ohm.m, indicating good groundwater potential, especially along the 160–180 m interval along the survey line. Despite the large investigation depth reaching 50 m below sea level, there were no indications of underlying seawater, thus reducing the possible risk of saltwater intrusion. Nevertheless, a constructed borehole should adequately stress the aquifer to fully assess the real risk of salinisation and determine any associated sustainable yields (i.e. the maximum pumping rate that does not cause water quality degradation due to salinisation).

Line 2 (VLV-2) – Figure A44

Survey line 2 was also carried out along a 400-m interval at close distance to survey line 1 along the low northwestern slopes of the main mountain range present in the study area. The profile revealed moderate resistivity with low groundwater potential except from a shallow low-resistivity zone present at 210–335 m along the profile. The limited depth however does not offer suitable conditions for groundwater development. Drilling is not recommended along this survey line.

Line 3 (VLV-3) – Figure A45

Survey line 3 was conducted in central Volivoli, in a catchment that was indicated by the community advisory councillor as promising in terms of groundwater potential due to the presence of a productive old well close to the lower part of the catchment and due to occasional flooding of the catchment suggesting a shallow water table. The 385-m survey line was conducted along the middle section of the catchment and crossing the main central drainage line as revealed by the elevation pattern.

The modelled resistivity profile revealed low resistivity (15–30 Ohm.m) almost along the entire survey line, suggesting good groundwater potential. Particularly the section between 80 m and 220 m along the profile shows a uniform resistivity of 25–30 Ohm.m, reflecting the uniform presence of groundwater along what appears to be a high-recharge zone, based on the large number of drainage lines along the western slope of the catchment. Drilling along this interval is highly recommended, especially considering the higher elevation, which would help reduce the risk of saltwater intrusion.

Line 4 (VLV-4) – Figure A46

Survey line 4 was carried out along a 400-m section in Volivoli east where no previous wells exist. The modelled profile revealed generally higher resistivity with an interpreted low groundwater potential, as reflected by the moderate (50–100 Ohm.m) to high (250–1000 Ohm.m) resistivity. The high resistivity formations probably reflect unweathered igneous rocks such as andesitic or basaltic dikes. No fracturing of the country rock is observed around these high-resistivity features and thus drilling in this area is not recommended.

Line 5 (VLV-5) – Figure A47

Survey line 5 was conducted as a parallel to survey line 3 to confirm the downhill extent of water-bearing formations. The steep topography may complicate the drilling rig's access to survey line 3, whereas survey line 5, located along the base of the catchment, would be much easier to approach.

The 300-m inverted profile revealed even lower resistivity (10–20 Ohm.m) along the entire section, suggesting potential groundwater accumulation in the lower parts of the catchment. Areas with very low resistivity (5–15 Ohm.m) suggest the presence of clay and/or saprolite and they should be avoided when drilling. Drilling along the 120–180-m interval along the profile is generally recommended. However, because of the low elevation and proximity to the sea, thorough pumping tests should be conducted to ensure that no saltwater intrusion manifests in the long term.

Line 6 (VLV-6) – Figure A48

Survey line 6 was conducted in Volivoli east across a catchment farther inland to increase the chances of identifying promising groundwater targets. The survey line crossed the catchment vertically to investigate any groundwater bodies associated with the creek running through the catchment.

The 400-m profile revealed a promising resistivity pattern suggesting good groundwater potential between 240 m and 280 m along the profile. Given the proximity to sea level, however, careful testing of eventual boreholes should be conducted to prevent saltwater intrusion. The resistivity pattern indicates that the creek recharges the groundwater-bearing formation, which extends immediately south of the creek.

Line 7 (VLV-7) – Figure A49

Survey line 7 was conducted in the Raratapu sector to explore the groundwater potential of the southern slopes in the study area, given the presence of households with an equally critical need for a reliable water supply.

The 400-m profile revealed low resistivity on the order of 10–30 Ohm.m, possibly suggesting high groundwater potential, particularly in the first half of the section (up to 290 m) where the resistivity range was 25–30 Ohm.m, suggestive of fractured basalts containing ground water. The second half of the section revealed lower resistivity (10–15 Ohm.m), and is not recommended for drilling due to the high probability of encountering unproductive, low-permeability layers (clay, saprolite).

13 Annex 2 - Resistivity profiles

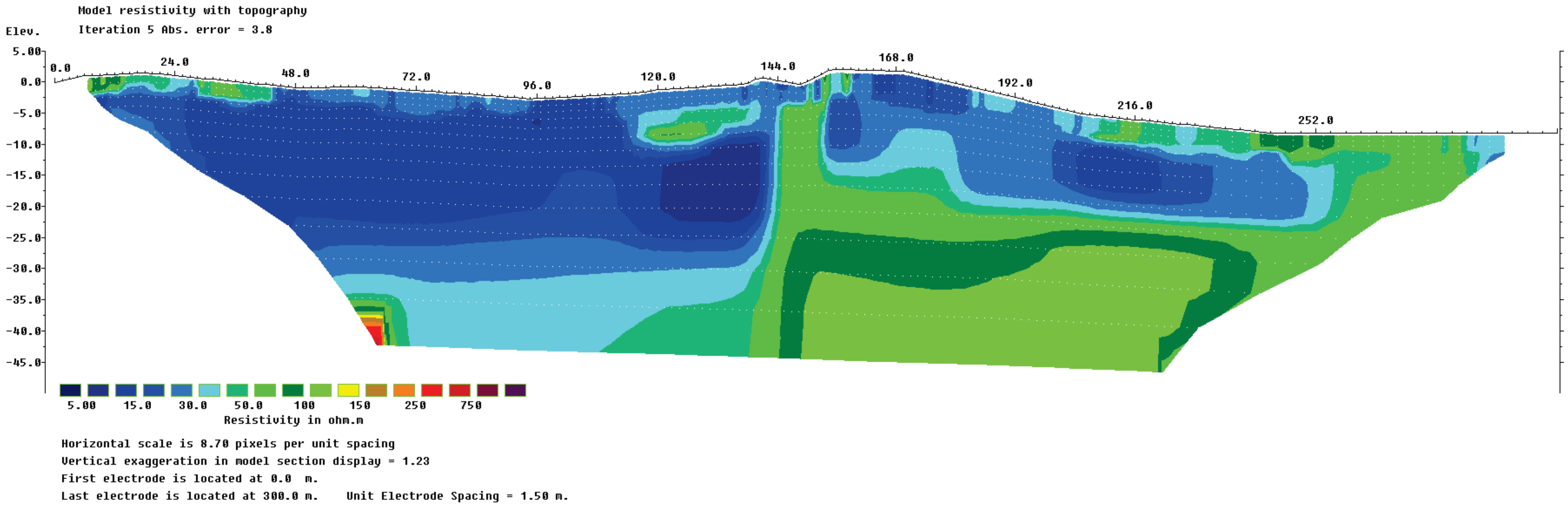


Figure A1 QLV-0

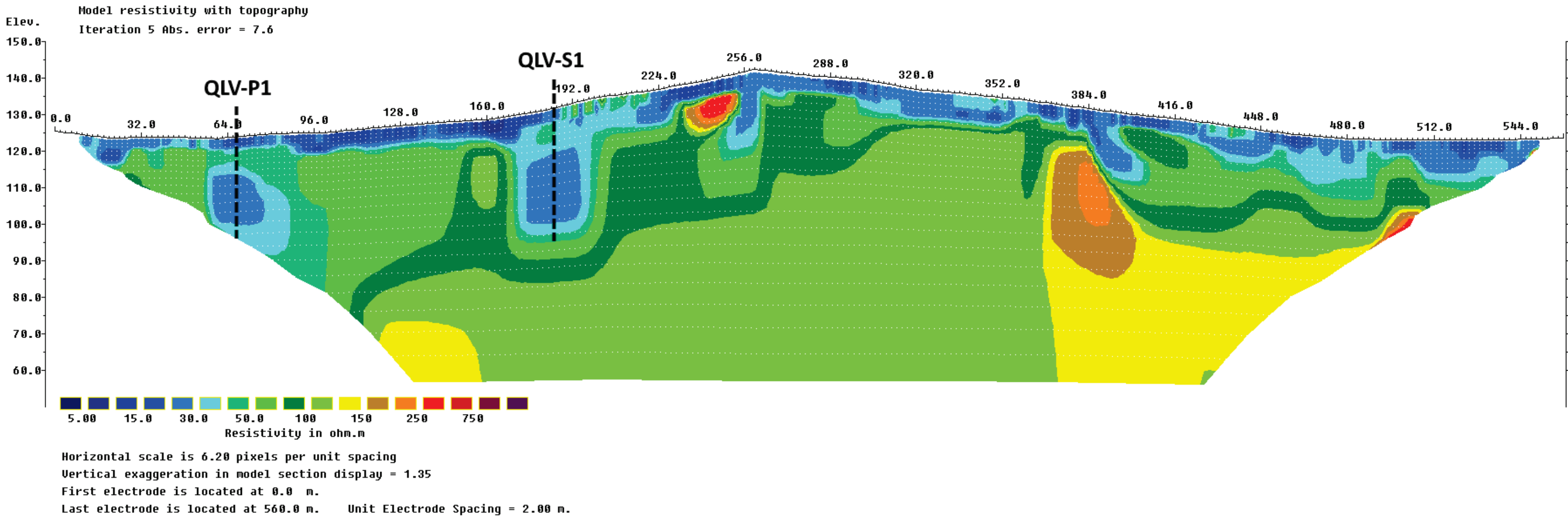


Figure A2 QLV-1

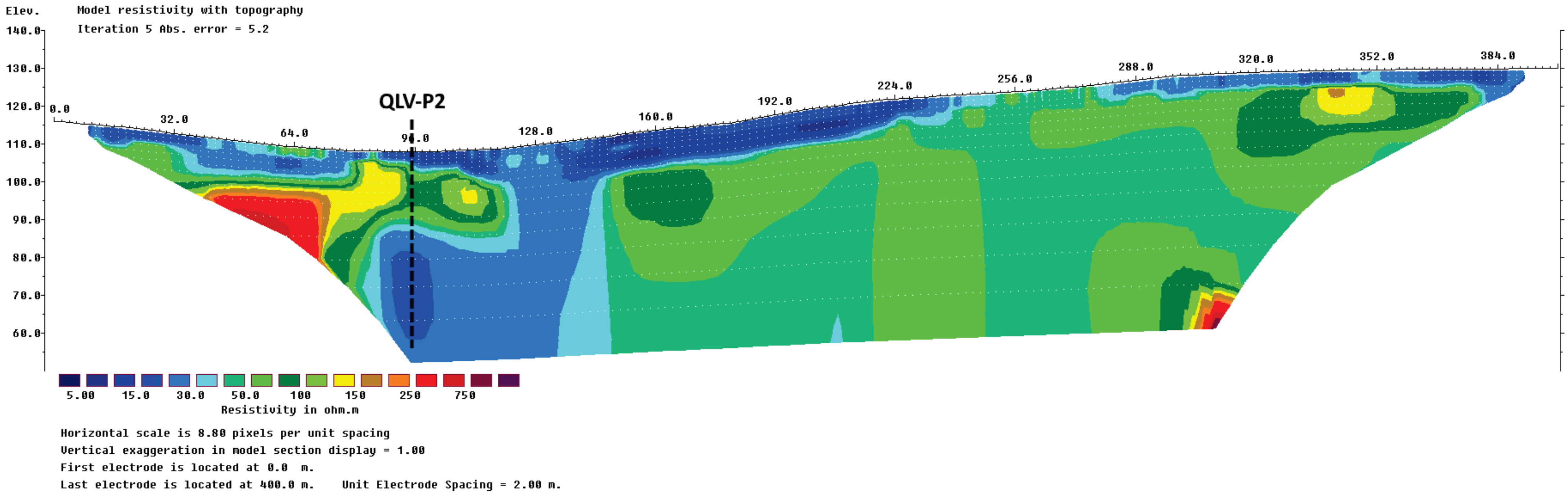


Figure A3 QLV-2

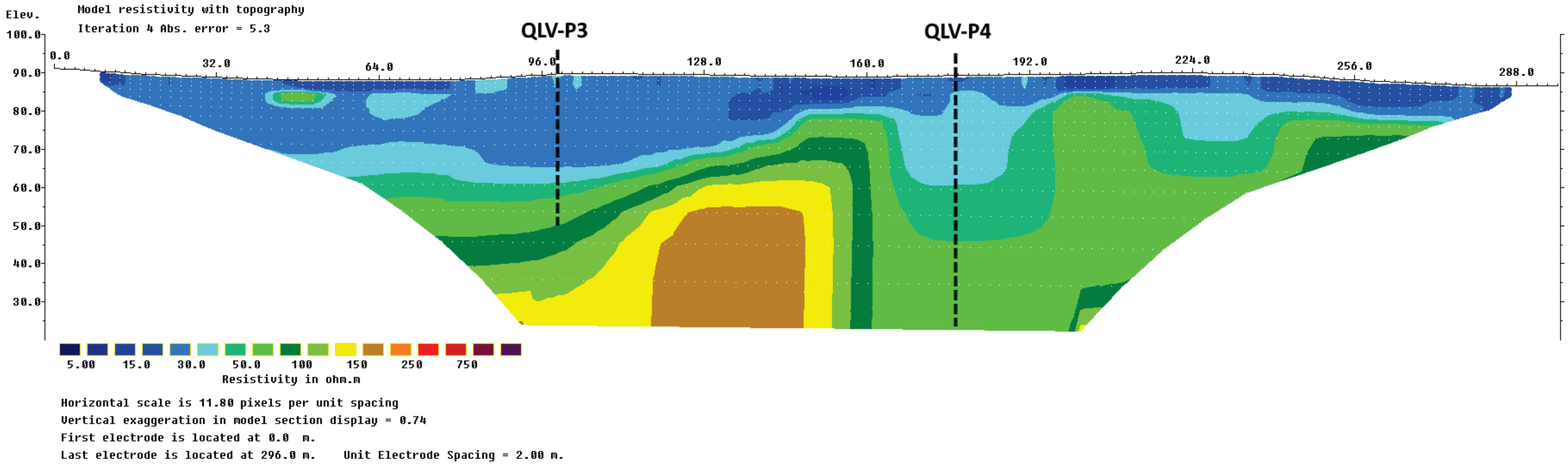


Figure A4 QLV-3

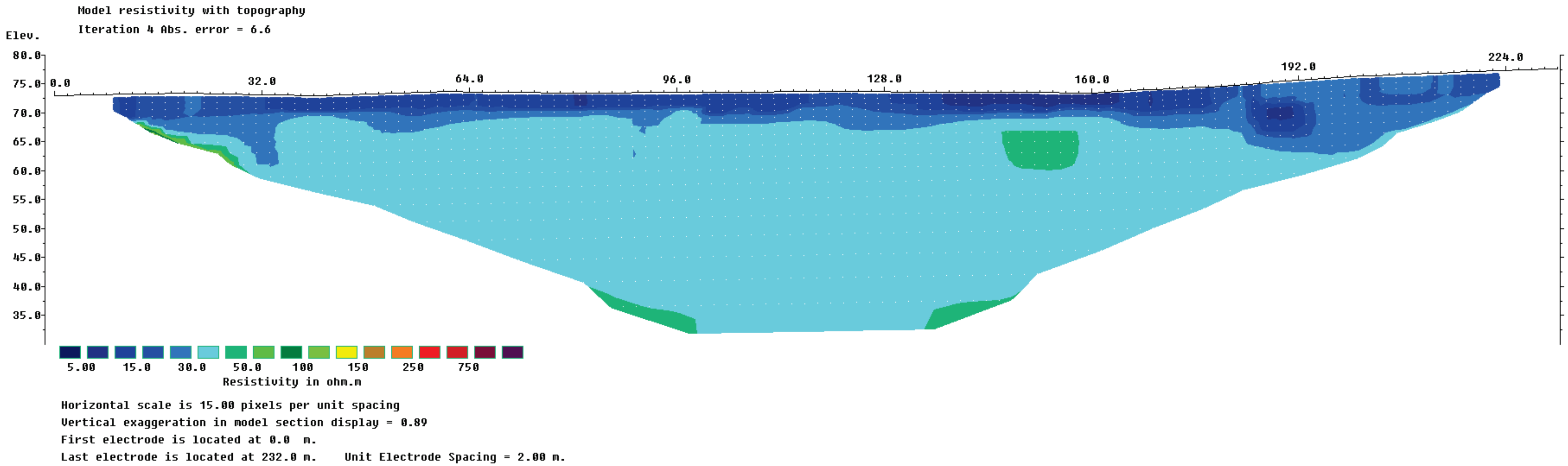


Figure A5 QLV-4

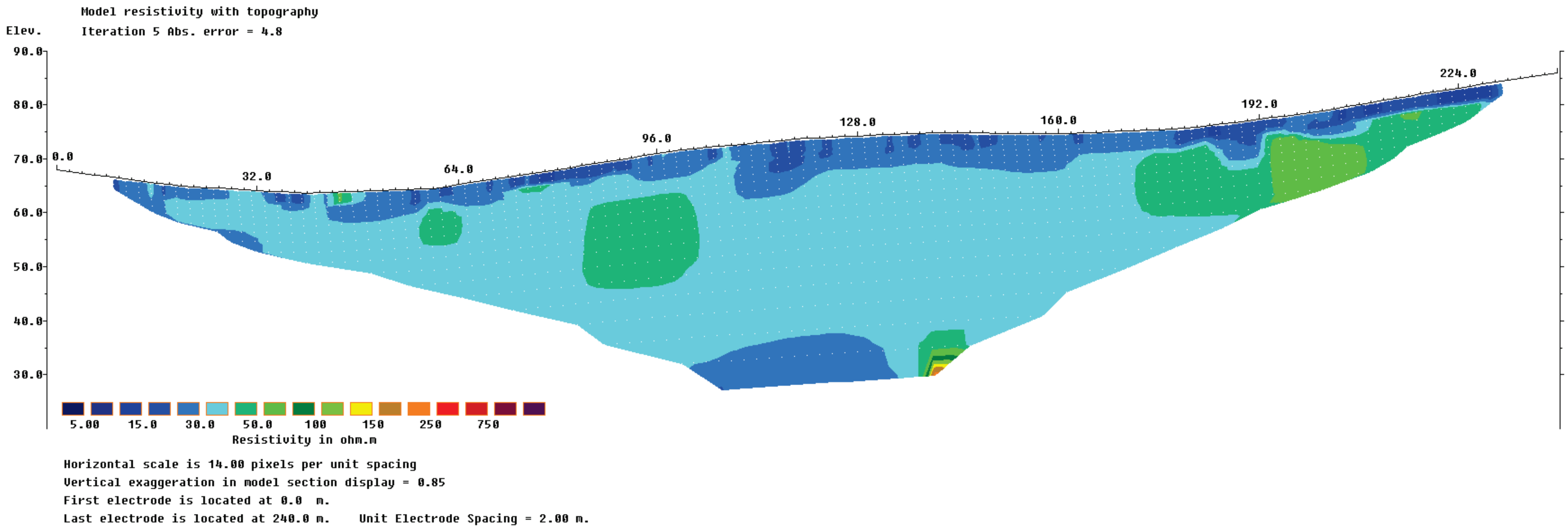


Figure A6 QLV-5

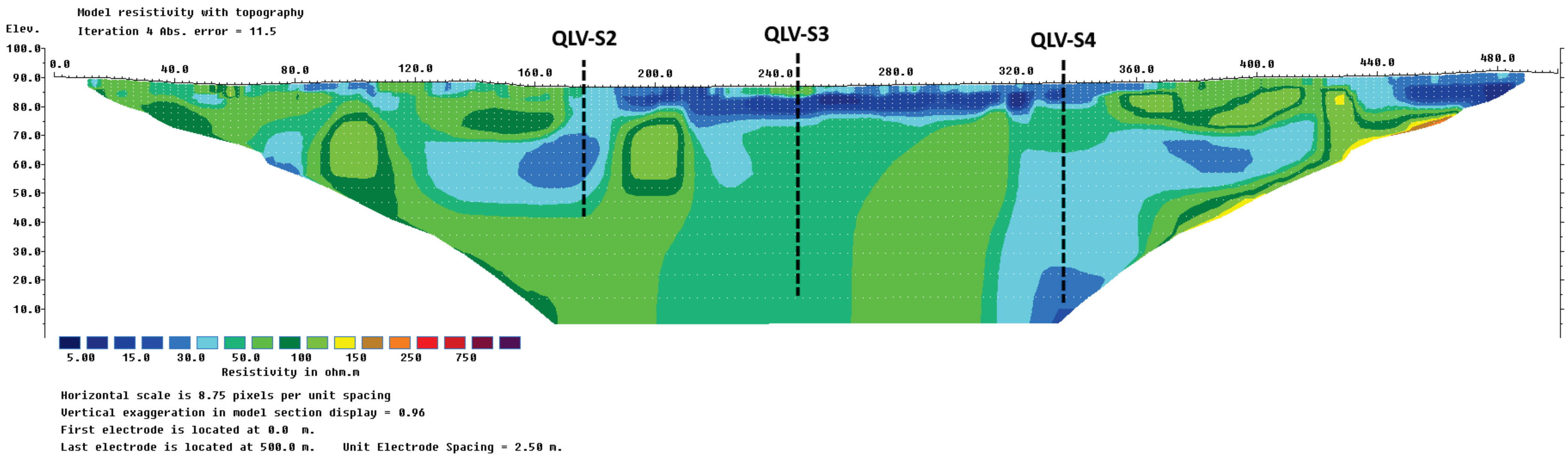


Figure A7 QLV-6

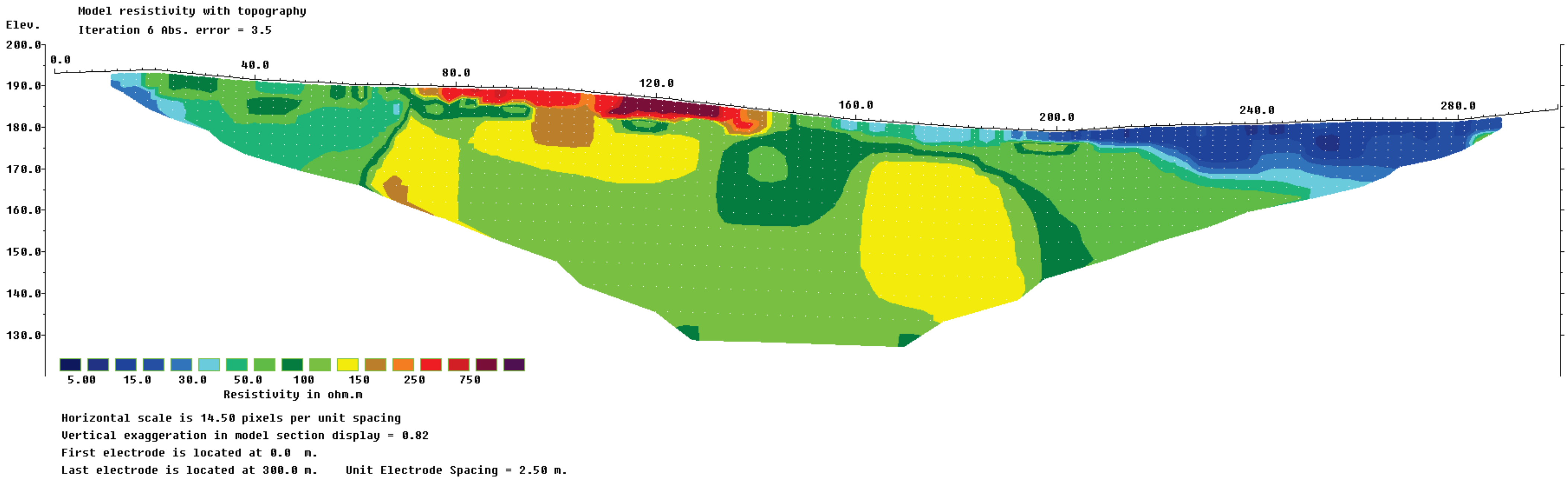


Figure A8 QLV-7

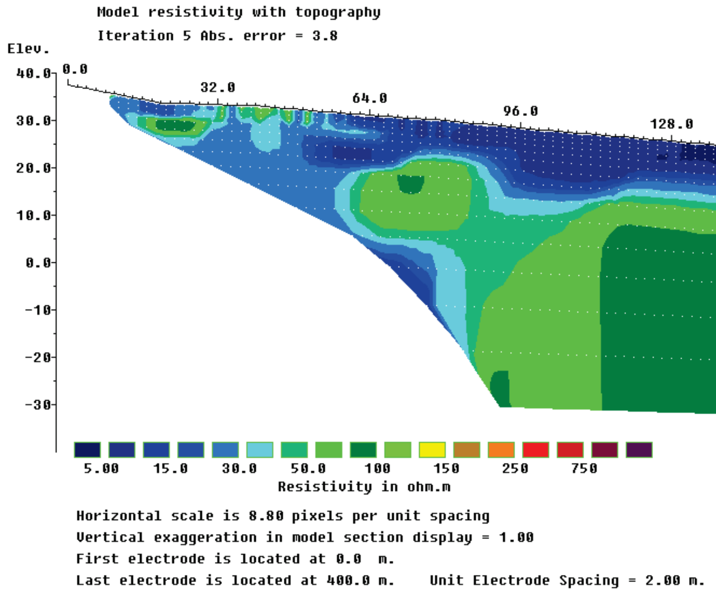


Figure A9 NNK-1

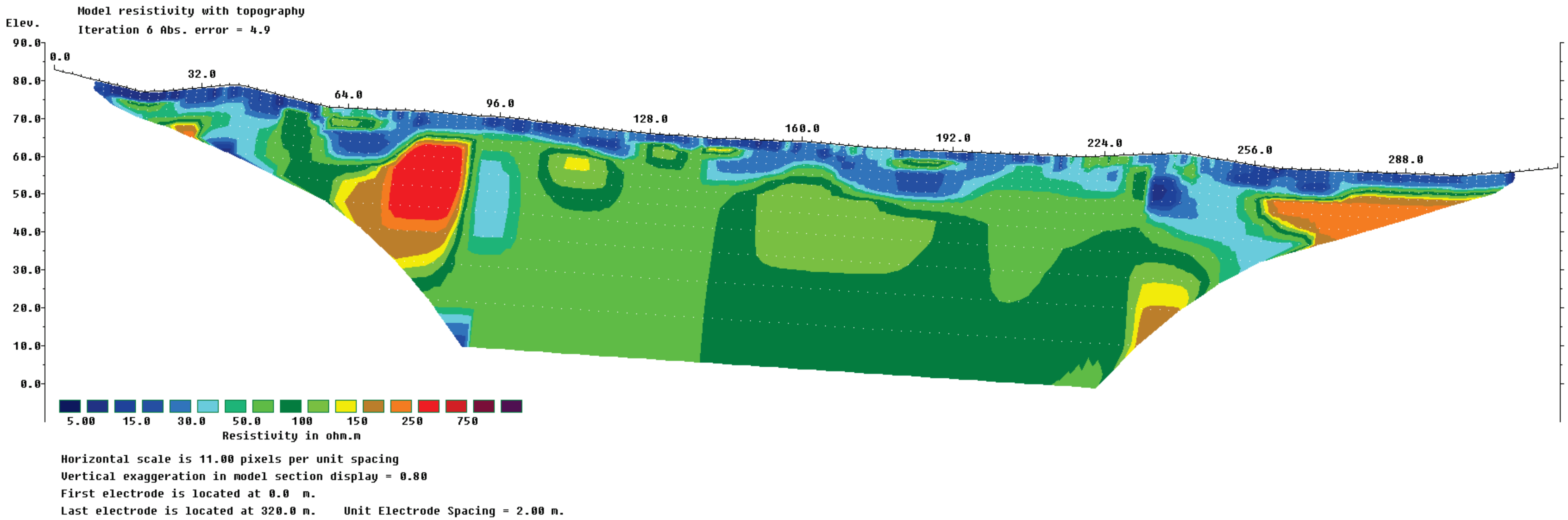


Figure A10 NNK-2

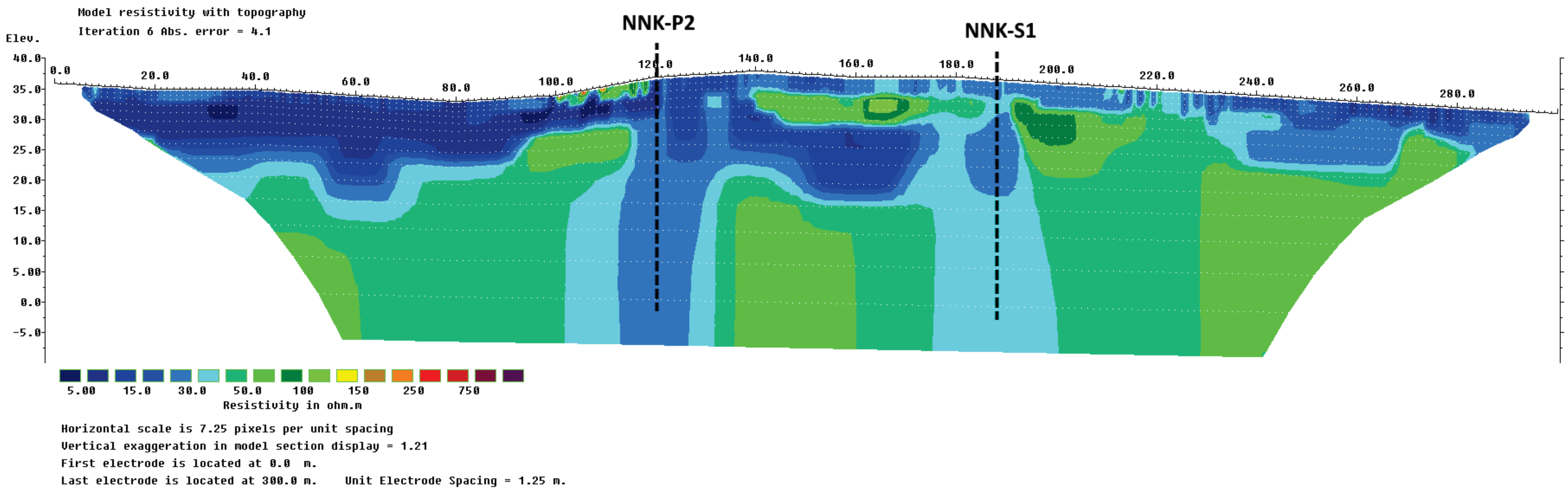


Figure A11 NNK-3

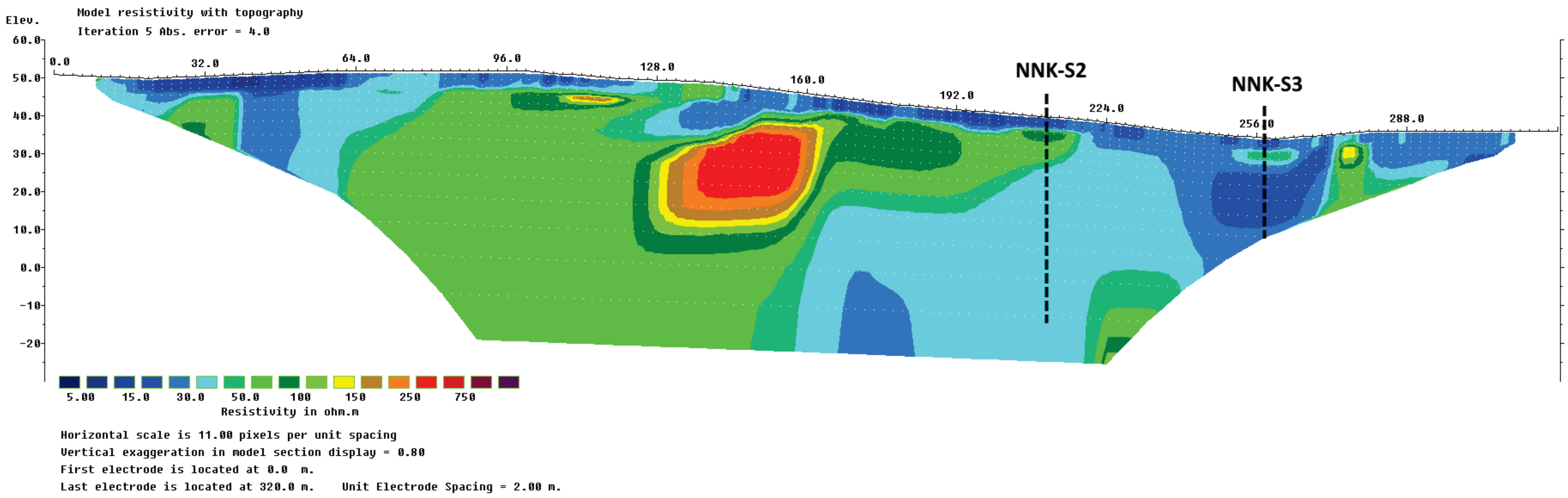


Figure A12 NNK-4

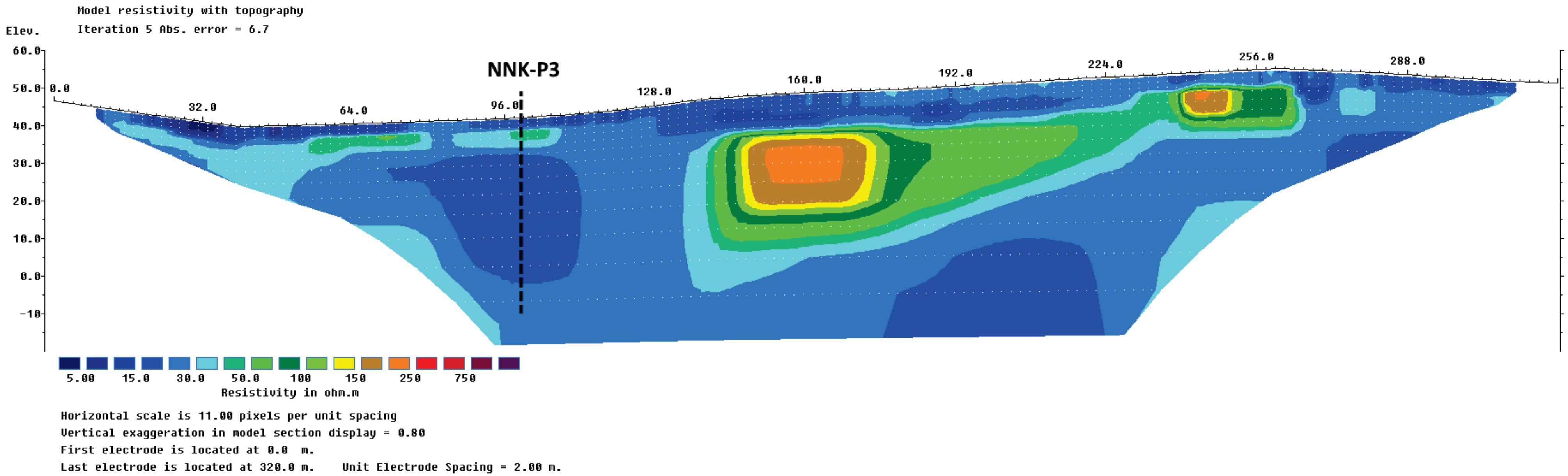


Figure A13 WLV-5

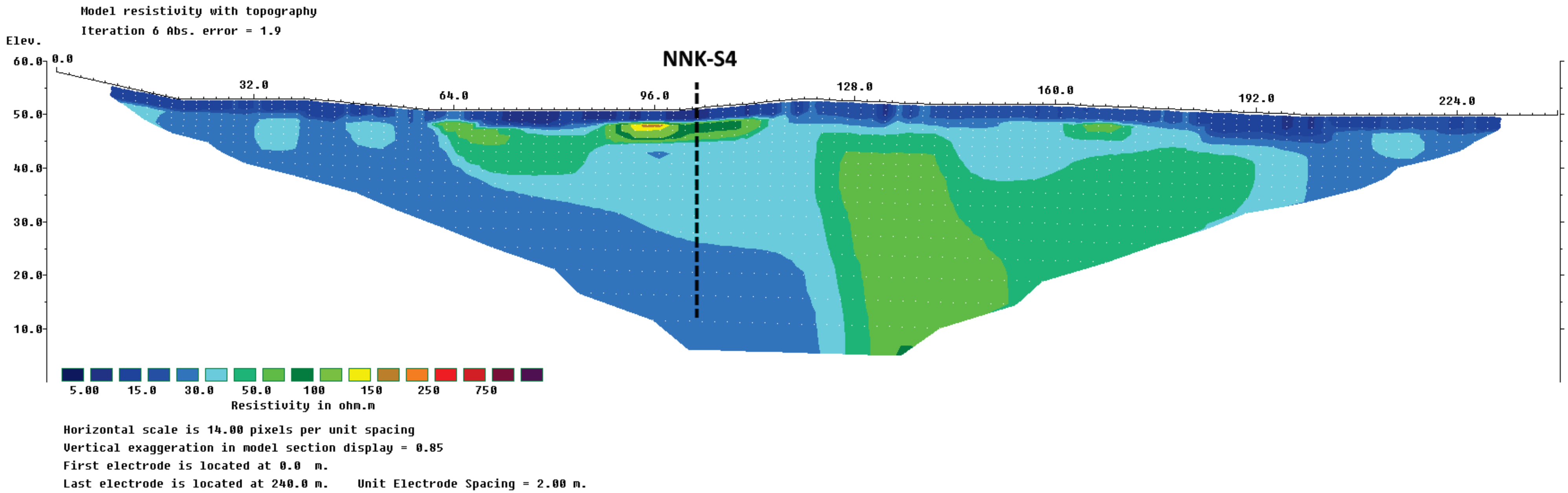


Figure A14 WLV-6

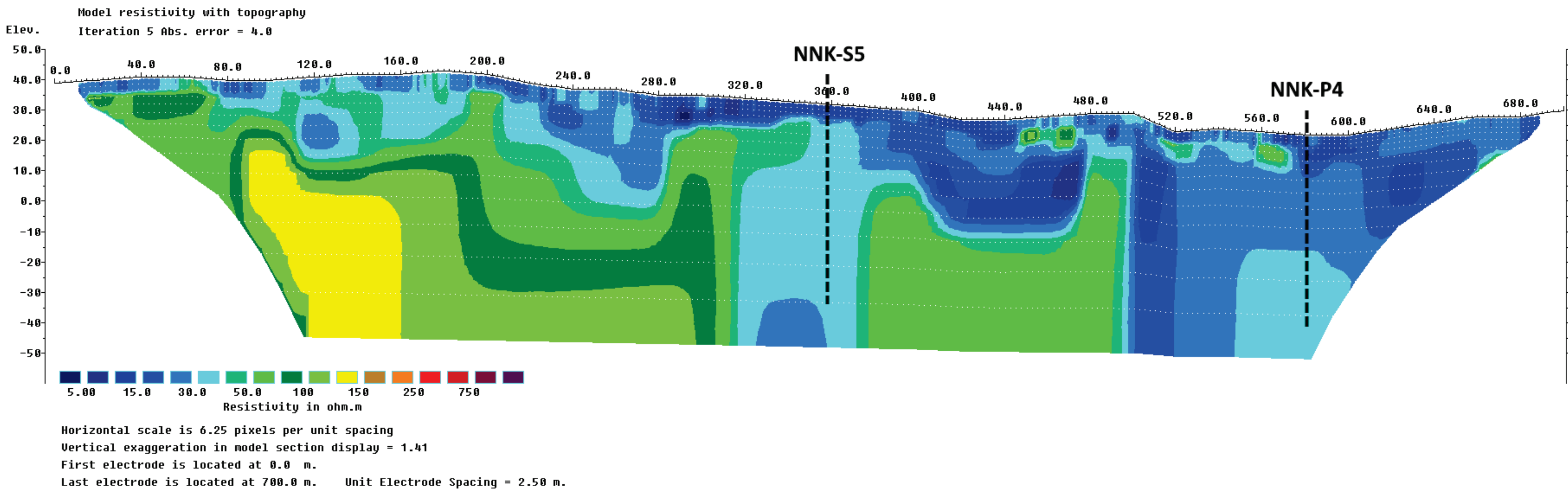


Figure A15 WLV-7

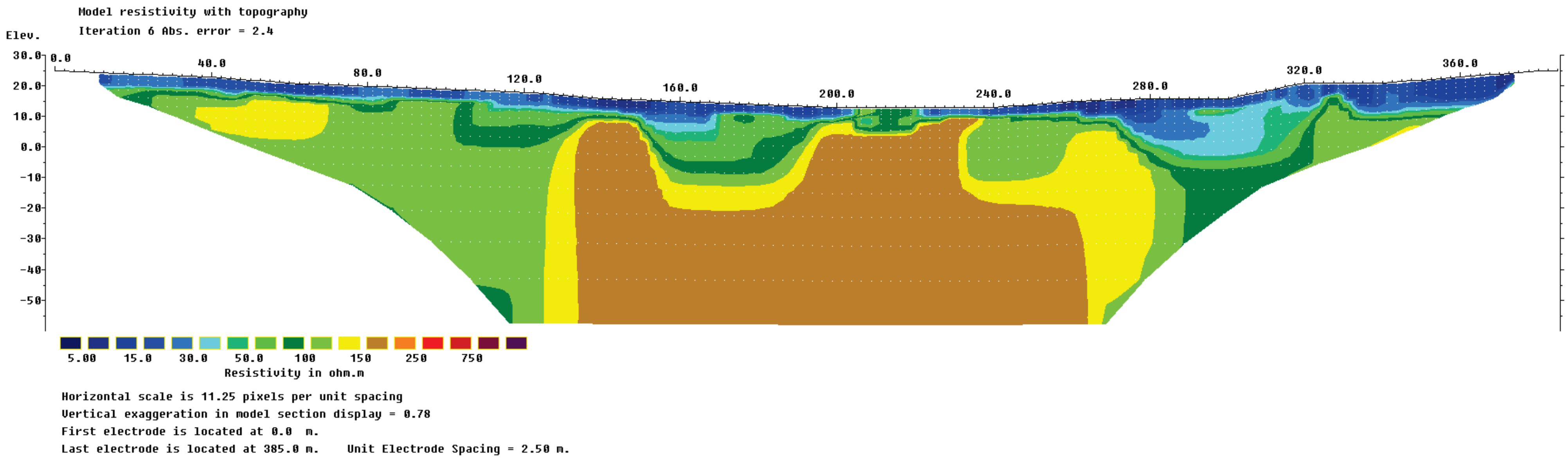


Figure A16 WLV-8

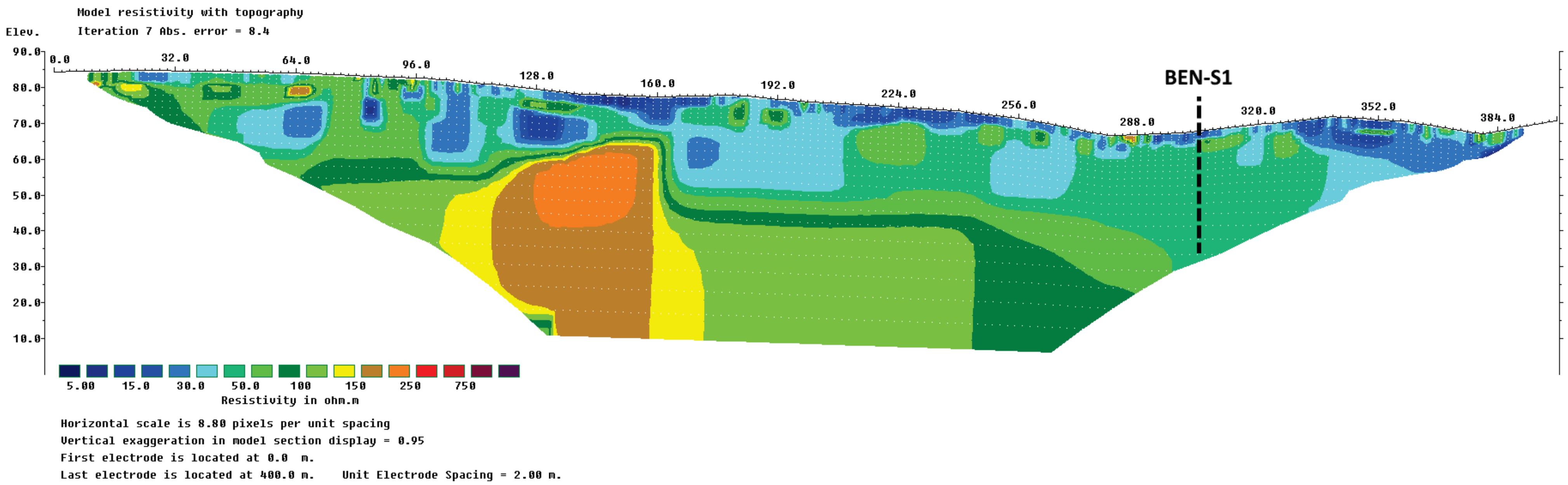


Figure A17 BEN-1

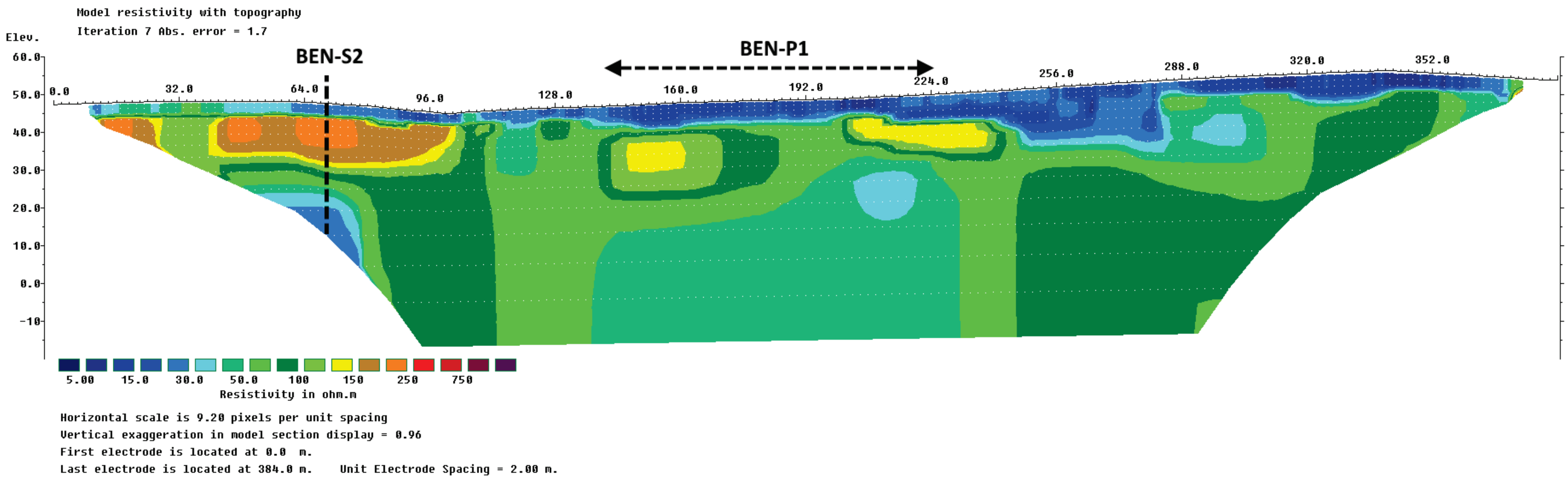


Figure A18 BEN-2

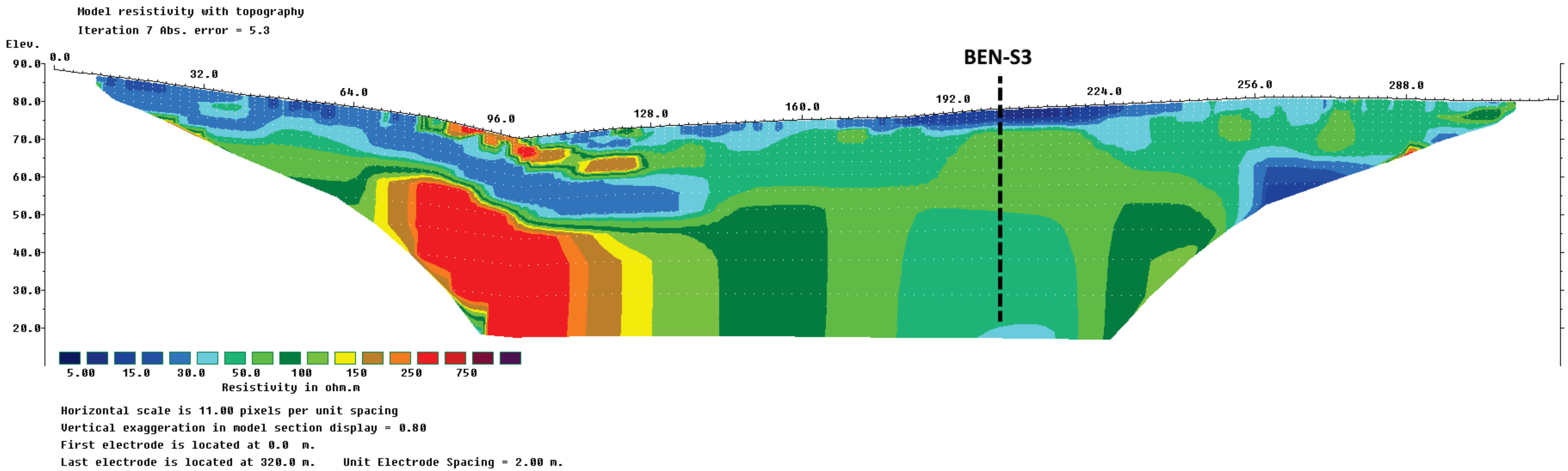


Figure A19 BEN-3

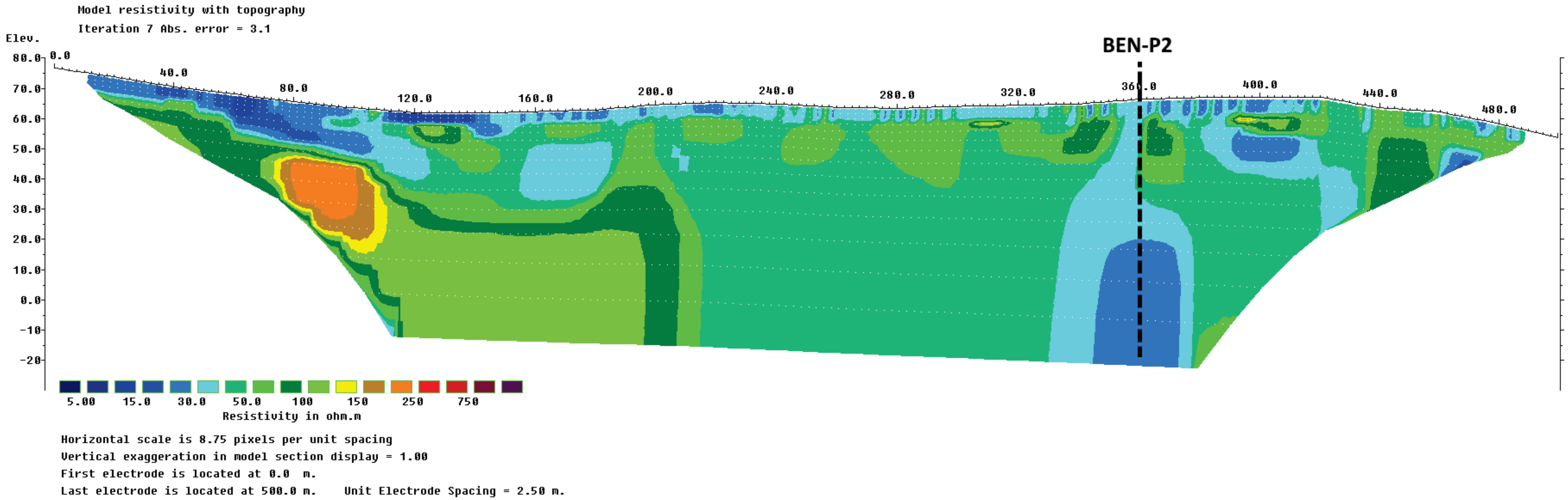


Figure A20 BEN-4

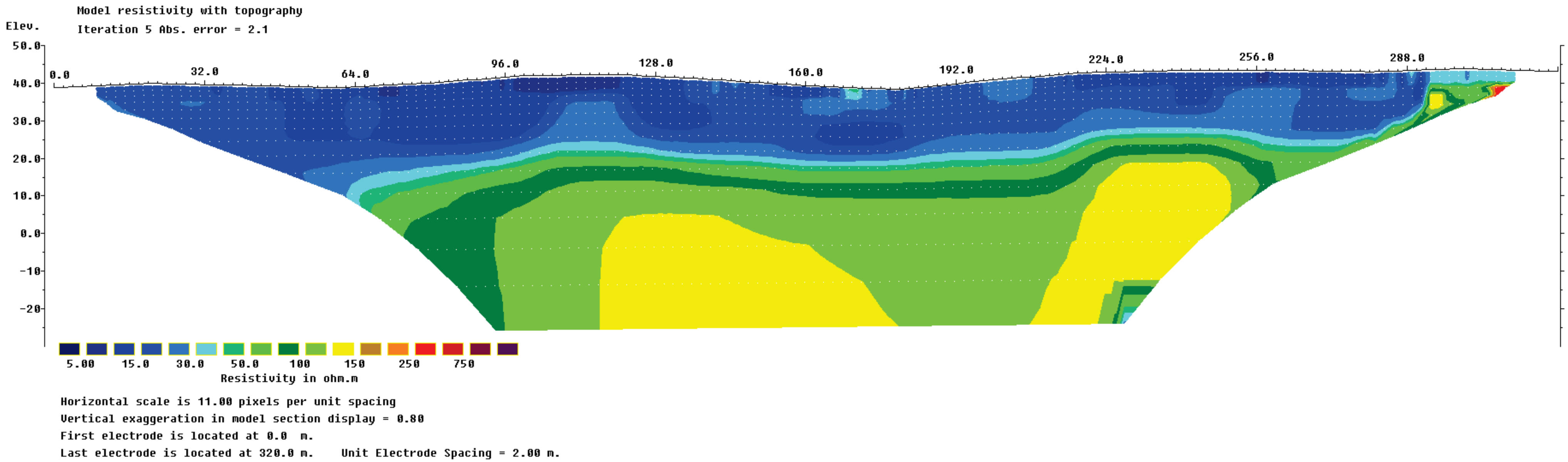


Figure A21 BEN-5

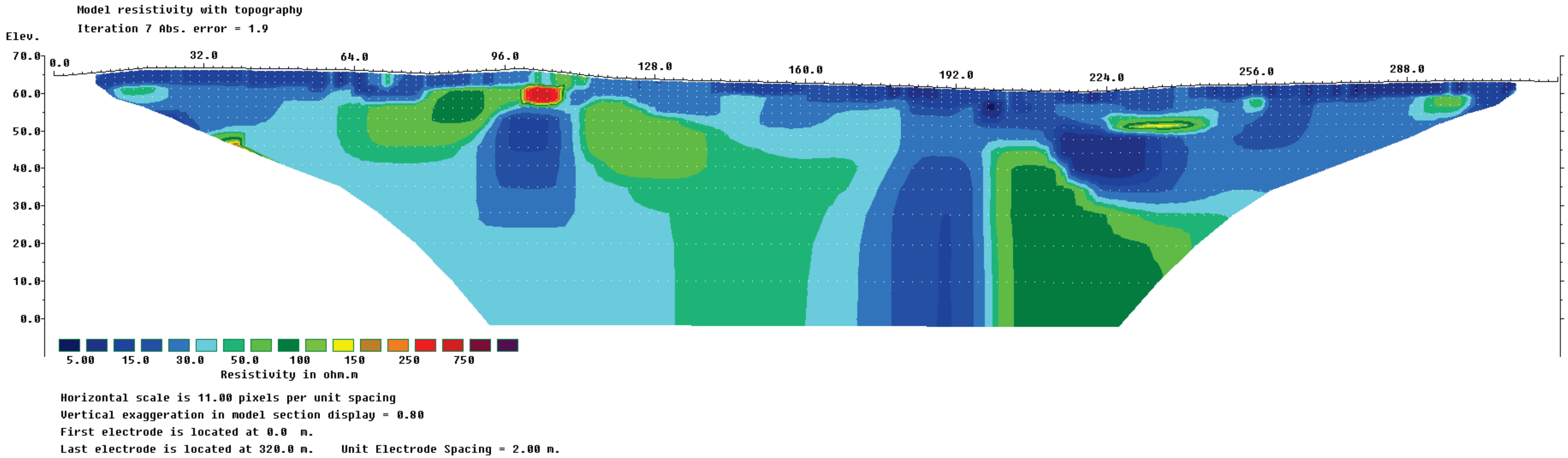


Figure A22 BEN-6

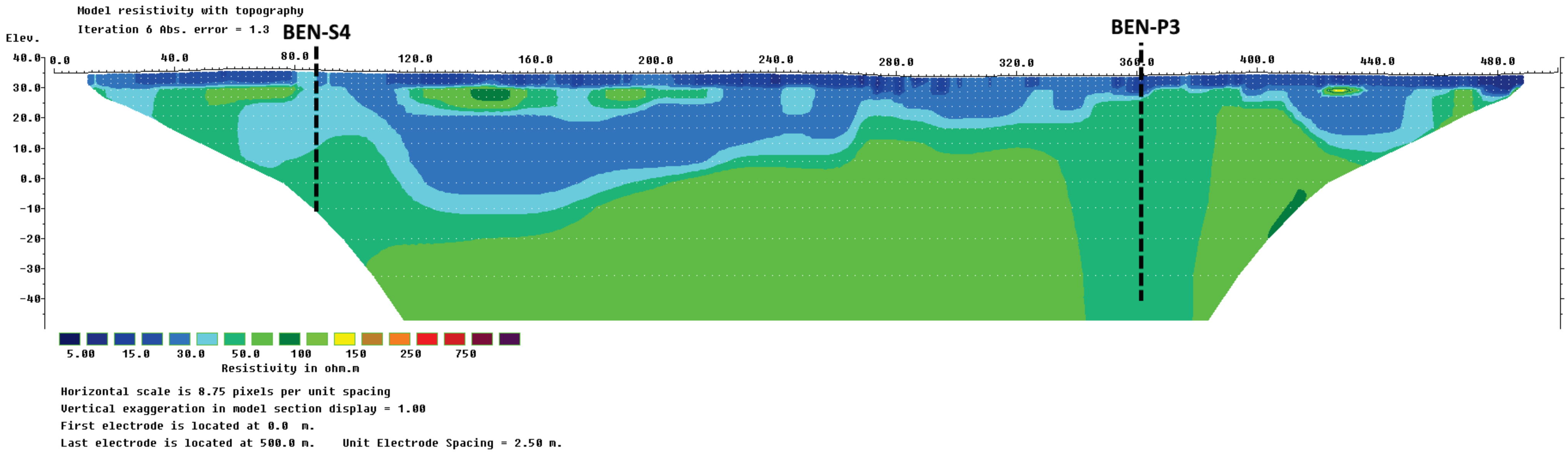


Figure A23 BEN-7

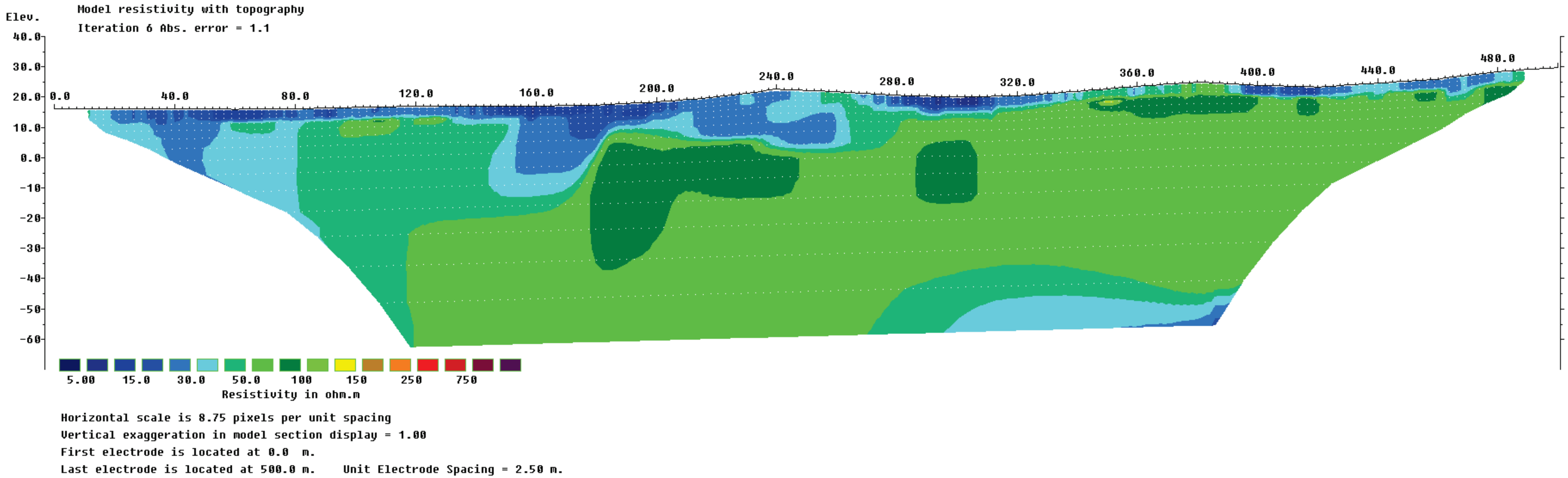


Figure A24 BEN-8

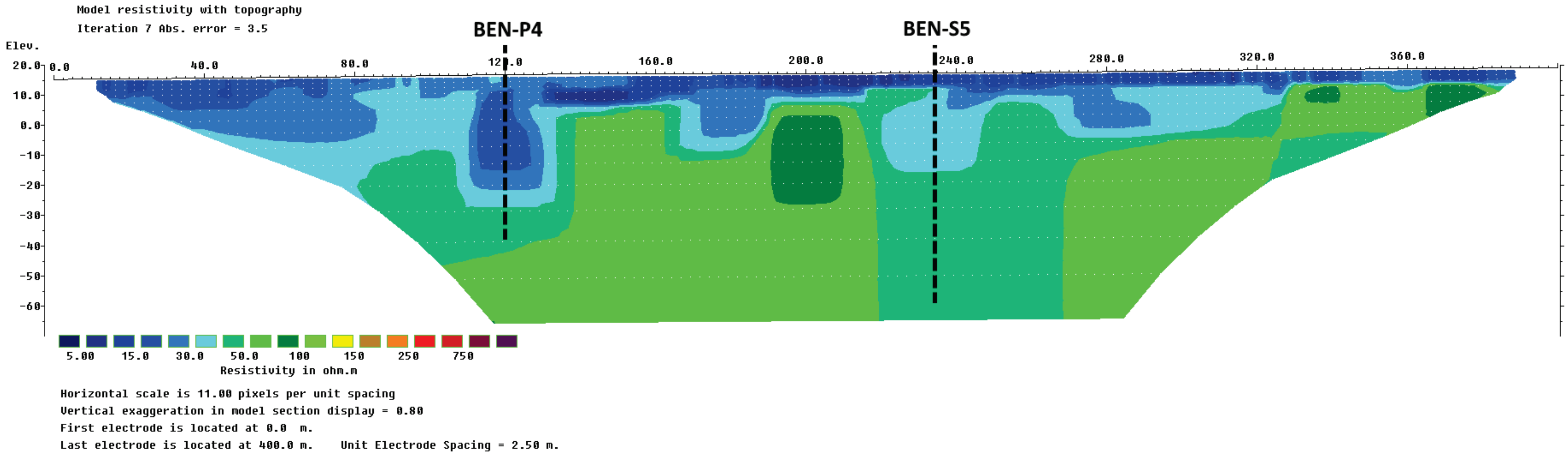


Figure A25 BEN-9

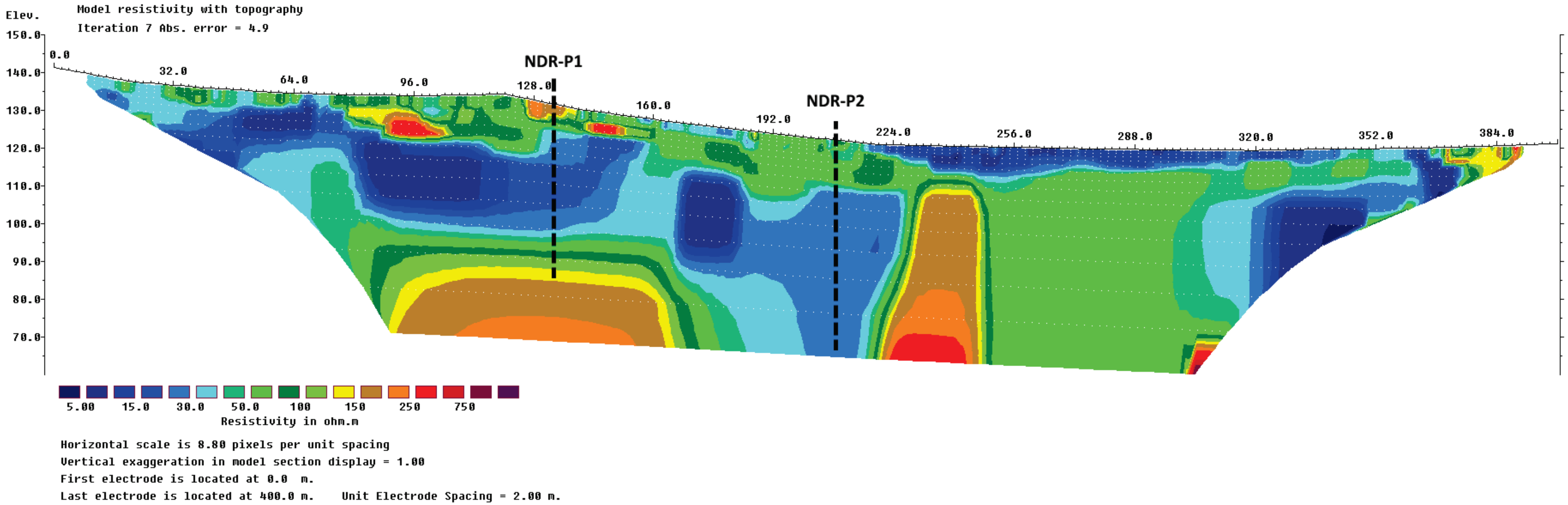


Figure A26 NDR-1

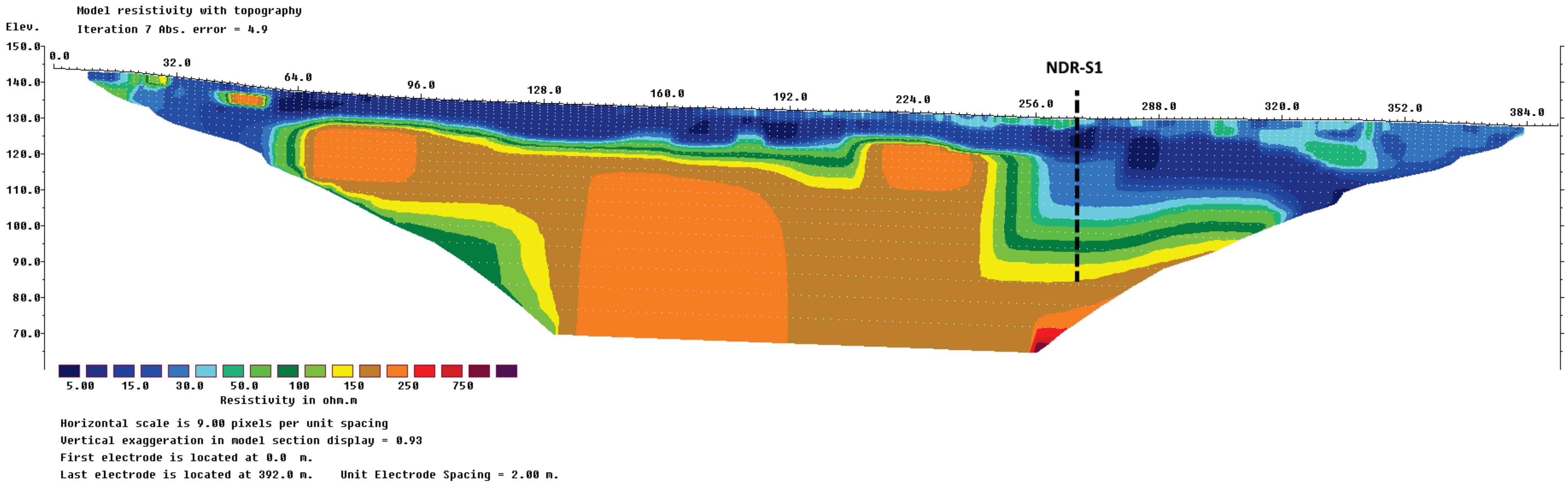


Figure A27 NDR-2

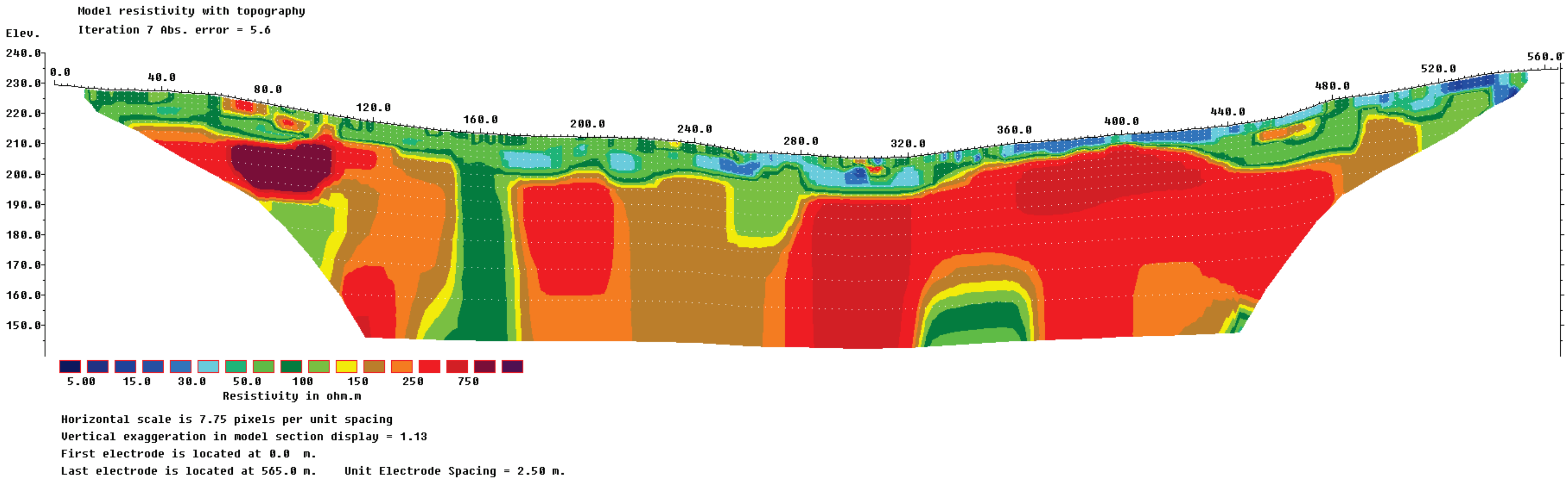


Figure A28 NDR-3

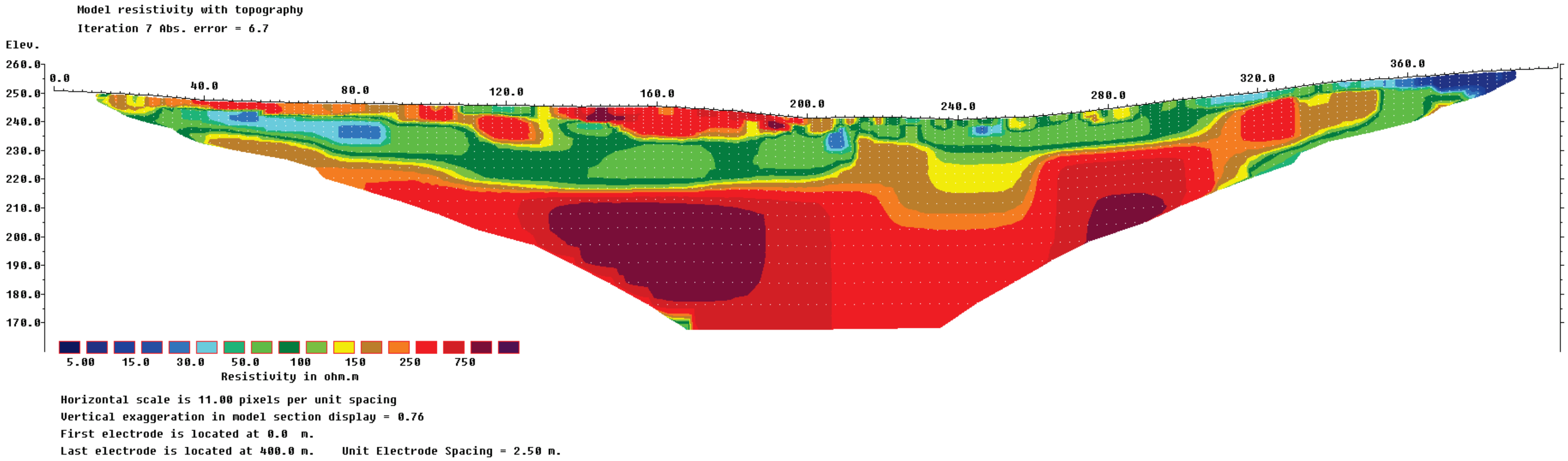


Figure A29 NDR-4

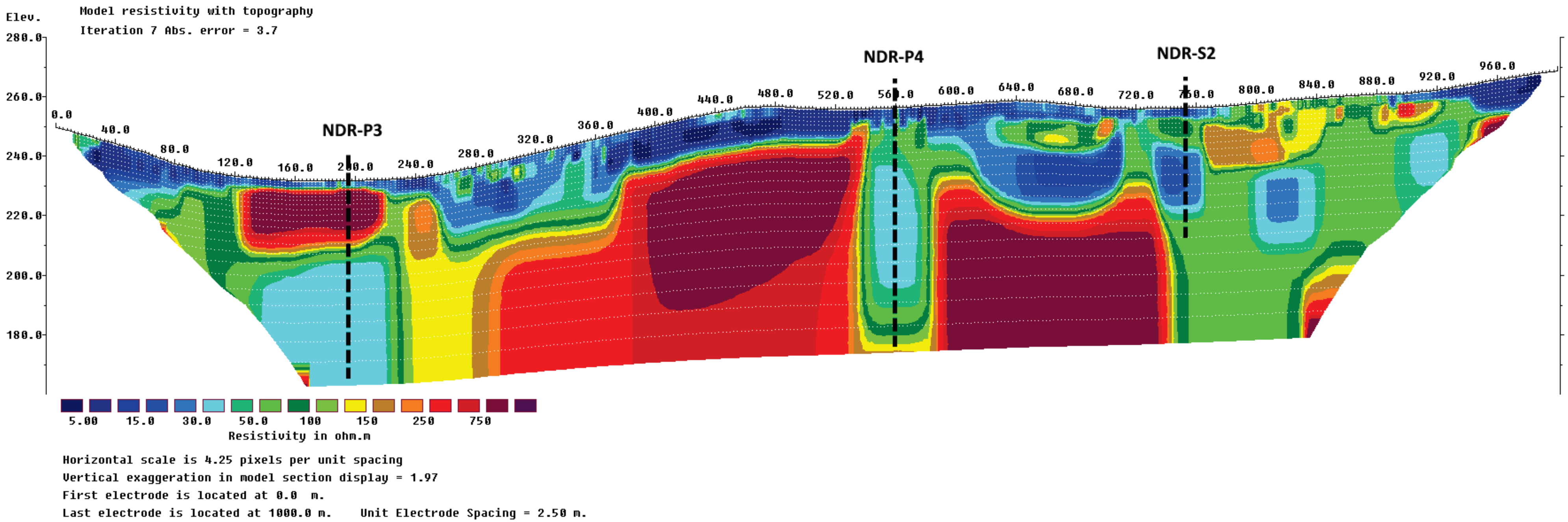


Figure A30 NDR-5

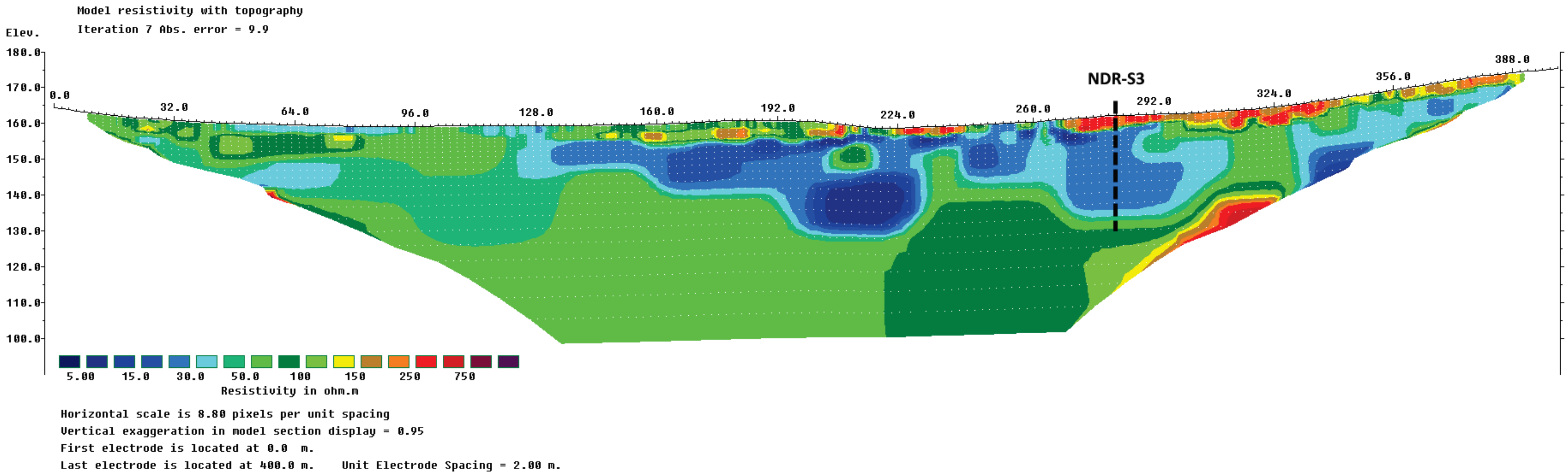


Figure A31 NDR-6

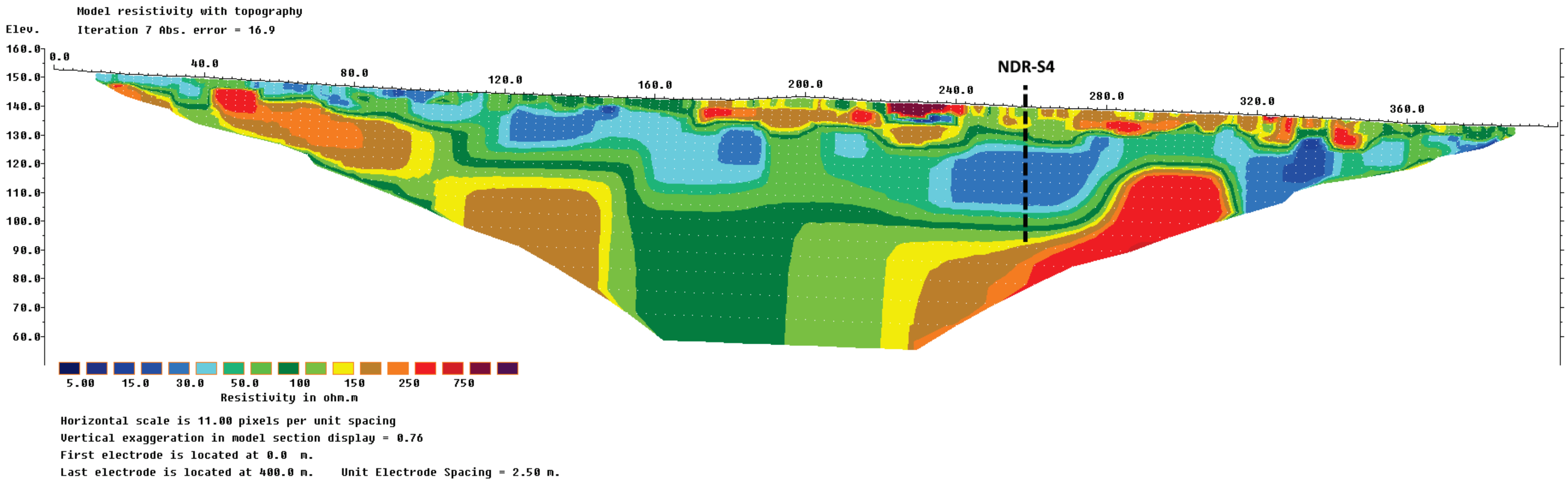


Figure A32 NDR-7

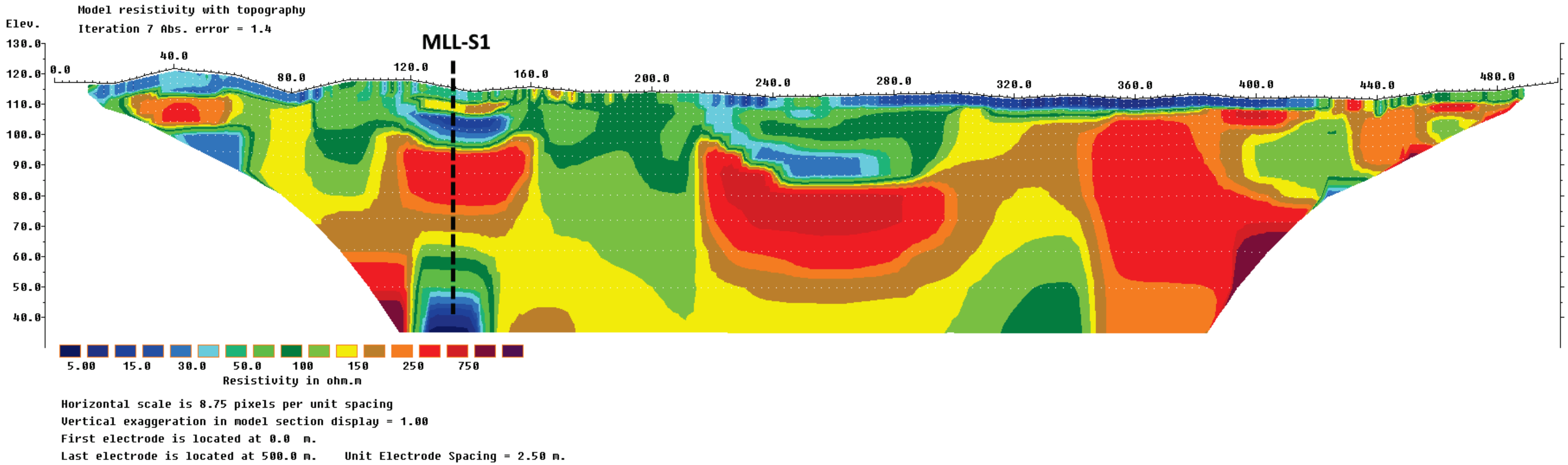


Figure A33 MLL-1

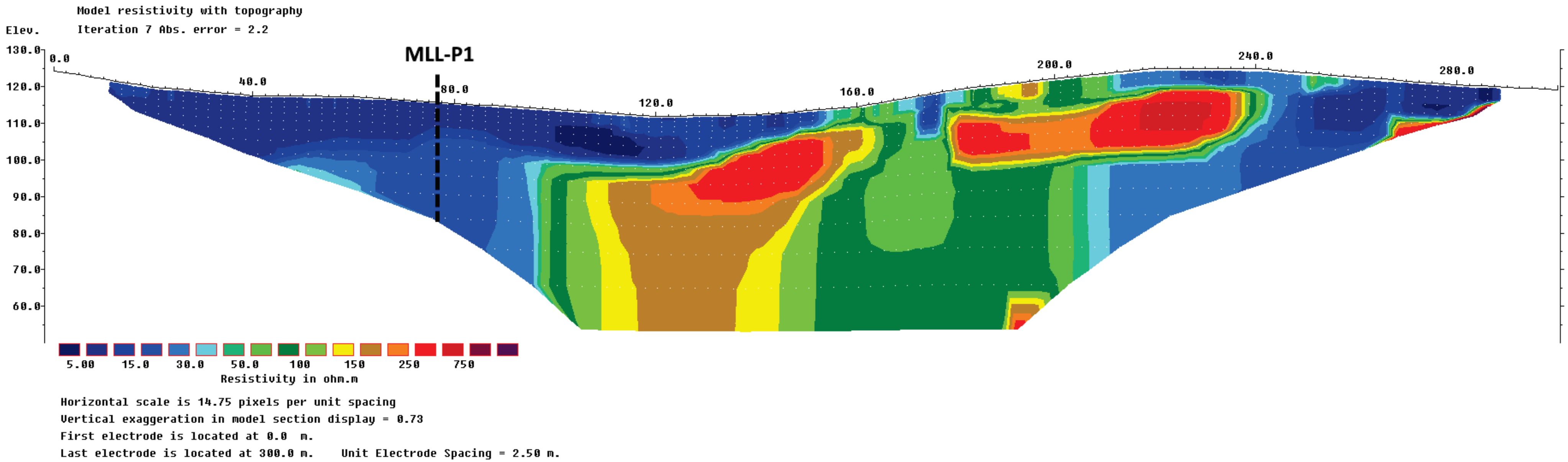


Figure A34 MLL-2

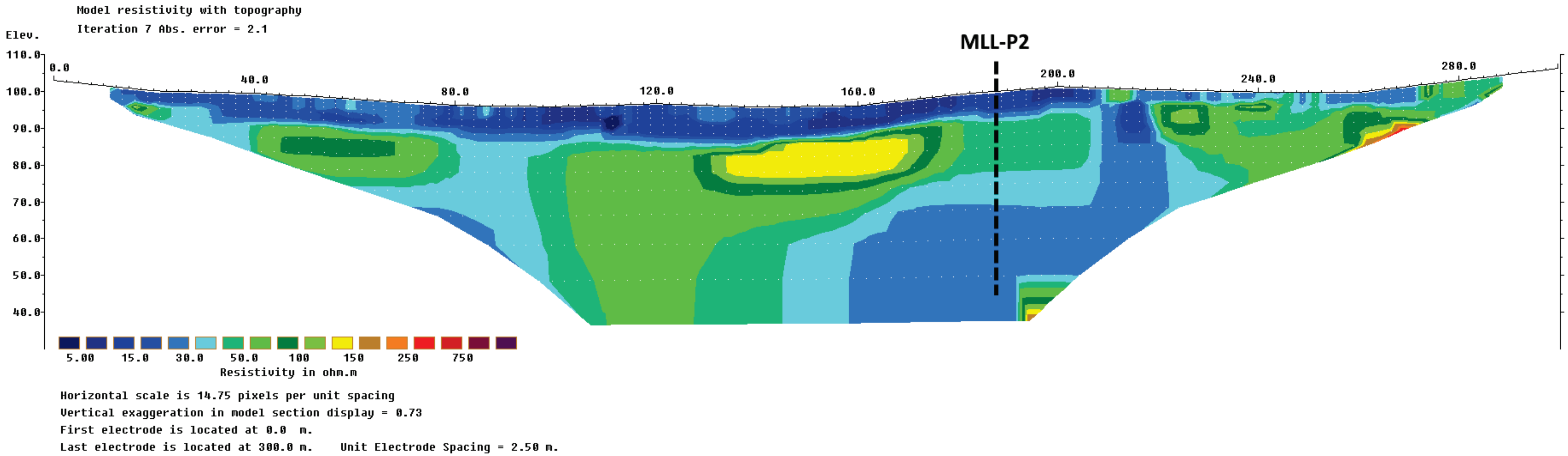


Figure A35 MLL-3

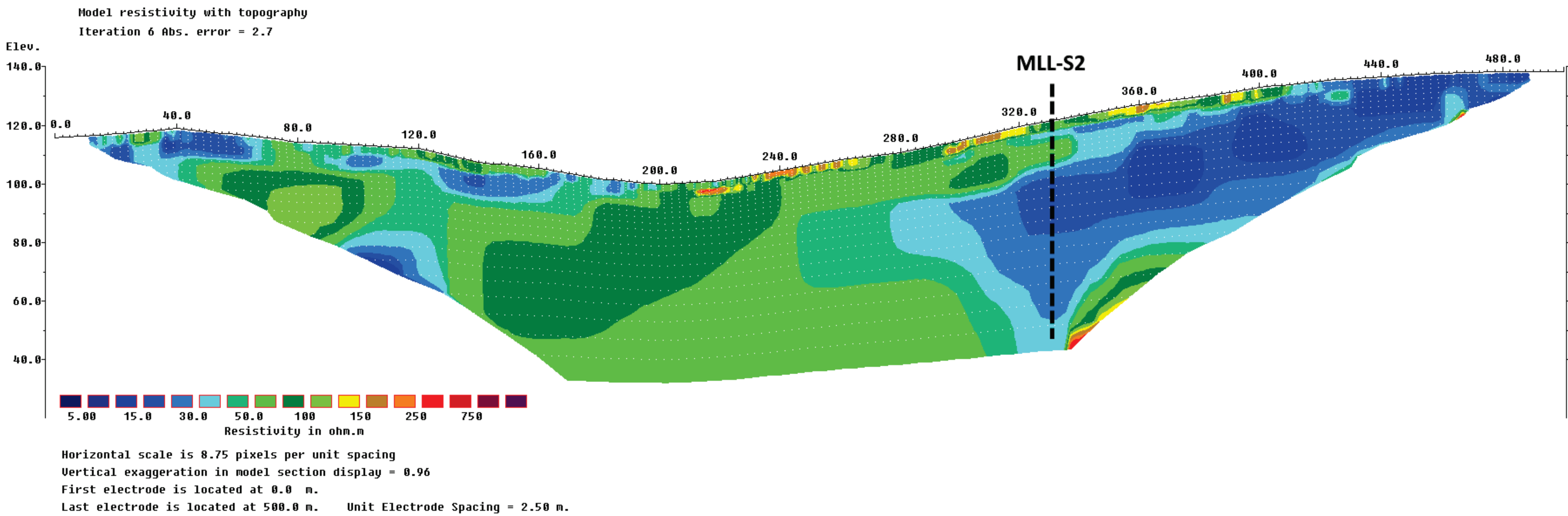


Figure A36 MLL-4

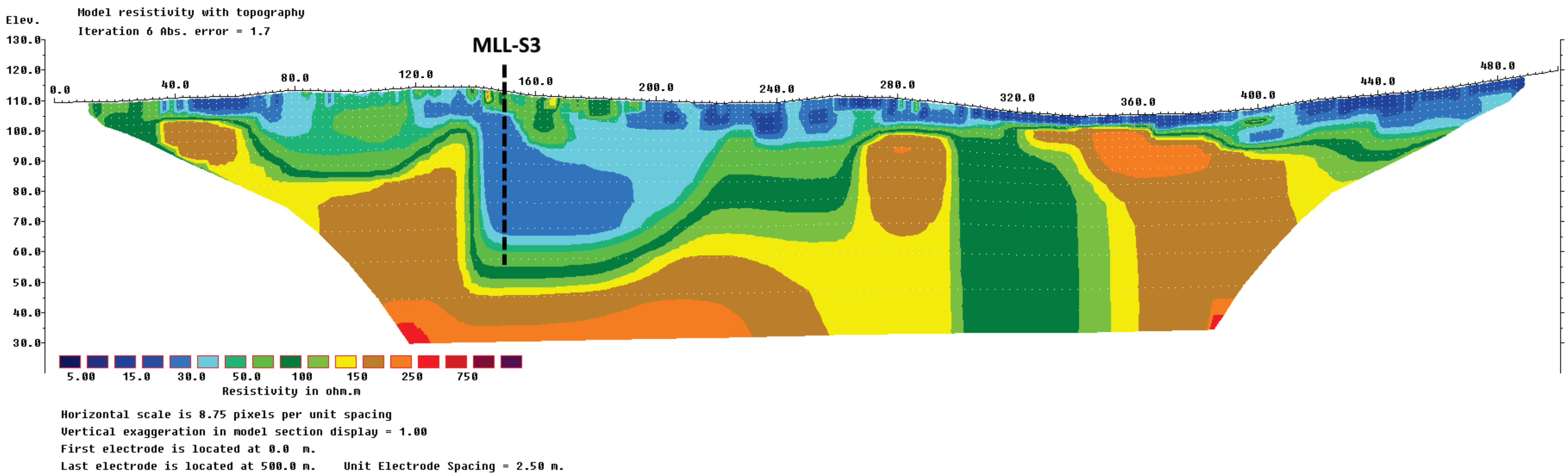


Figure A37 MLL-5

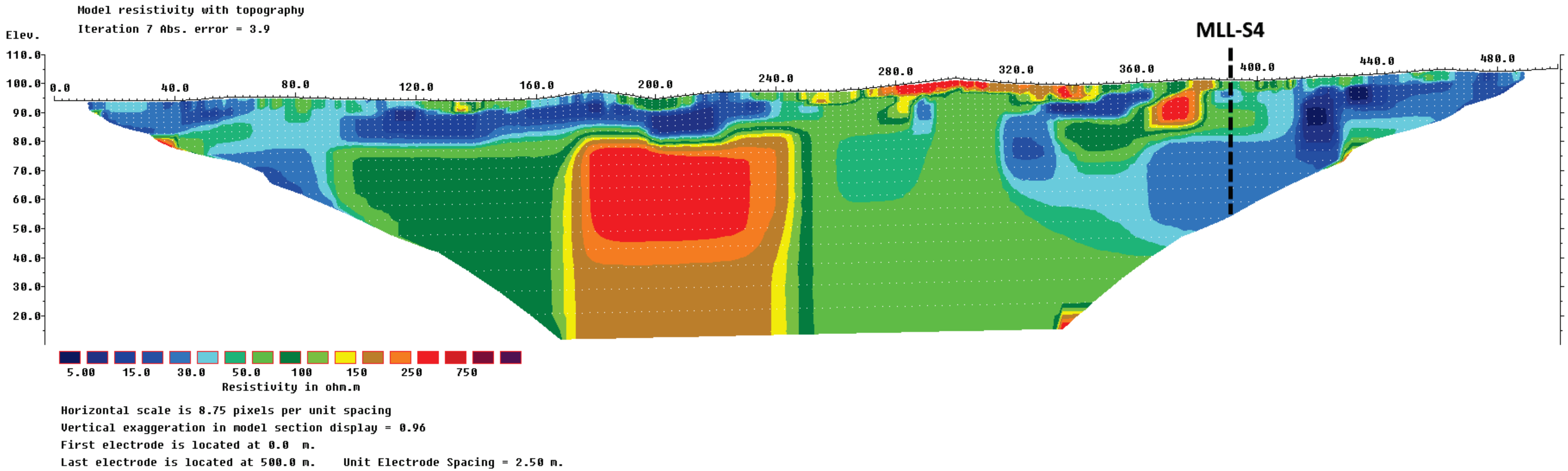
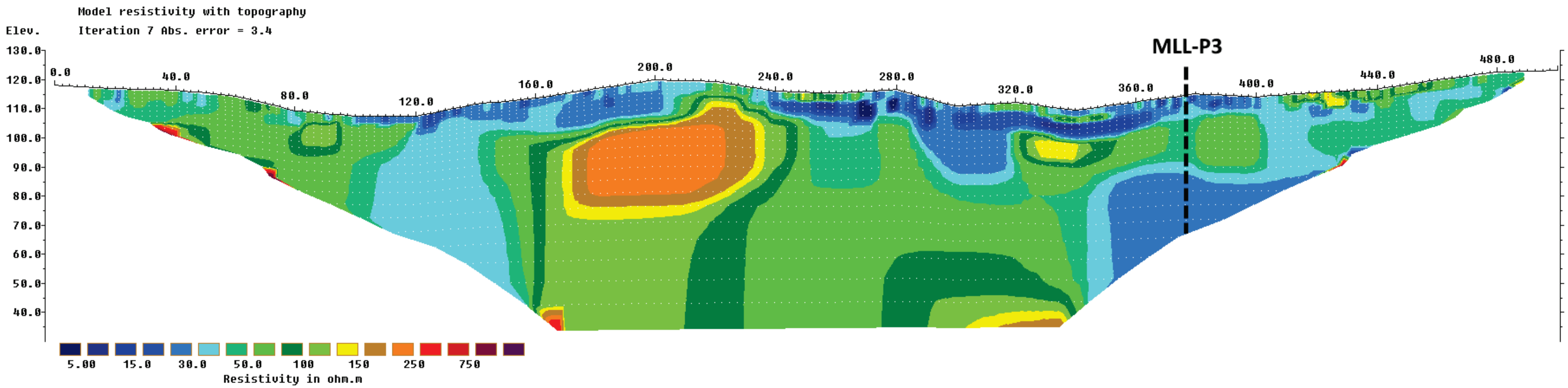
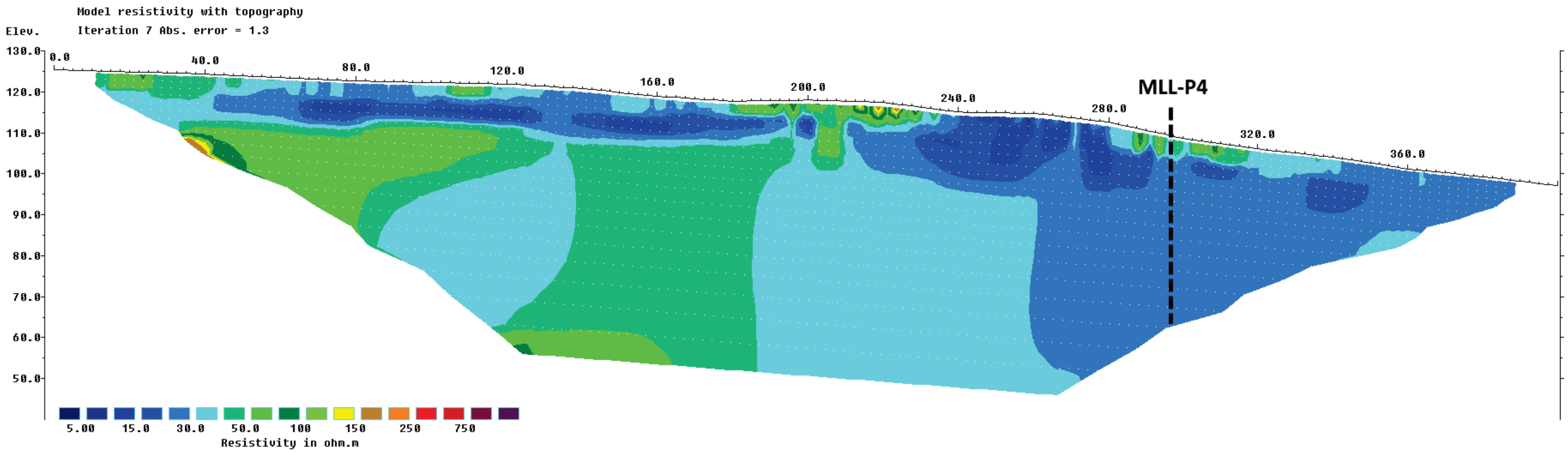


Figure A38 MLL-6



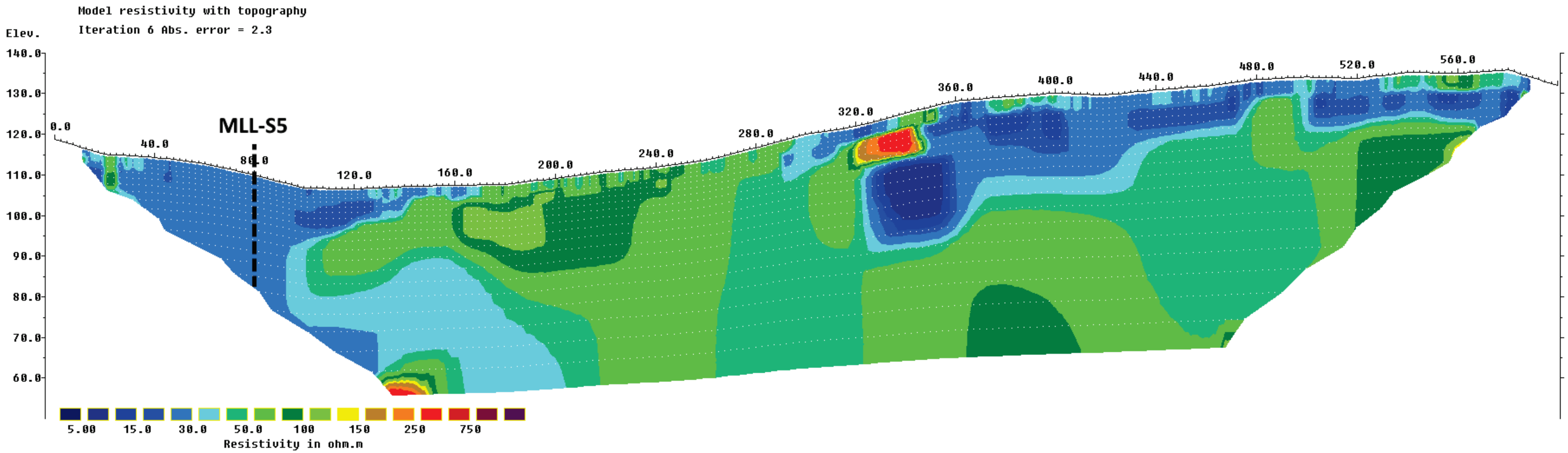
Horizontal scale is 8.75 pixels per unit spacing
Vertical exaggeration in model section display = 0.96
First electrode is located at 0.0 m.
Last electrode is located at 500.0 m. Unit Electrode Spacing = 2.50 m.

Figure A39 MLL-7



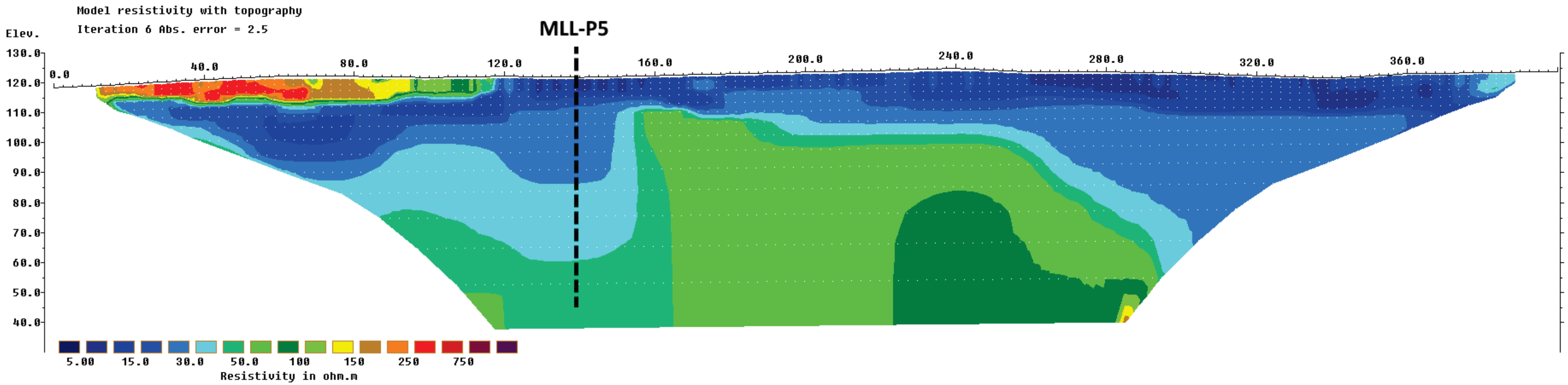
Horizontal scale is 11.00 pixels per unit spacing
Vertical exaggeration in model section display = 1.08
First electrode is located at 0.0 m.
Last electrode is located at 400.0 m. Unit Electrode Spacing = 2.50 m.

Figure A40 MLL-8



Horizontal scale is 7.25 pixels per unit spacing
Vertical exaggeration in model section display = 1.61
First electrode is located at 0.0 m.
Last electrode is located at 600.0 m. Unit Electrode Spacing = 2.50 m.

Figure A41 MLL-9



Horizontal scale is 11.00 pixels per unit spacing
Vertical exaggeration in model section display = 0.80
First electrode is located at 0.0 m.
Last electrode is located at 400.0 m. Unit Electrode Spacing = 2.50 m.

Figure A42 MLL-10

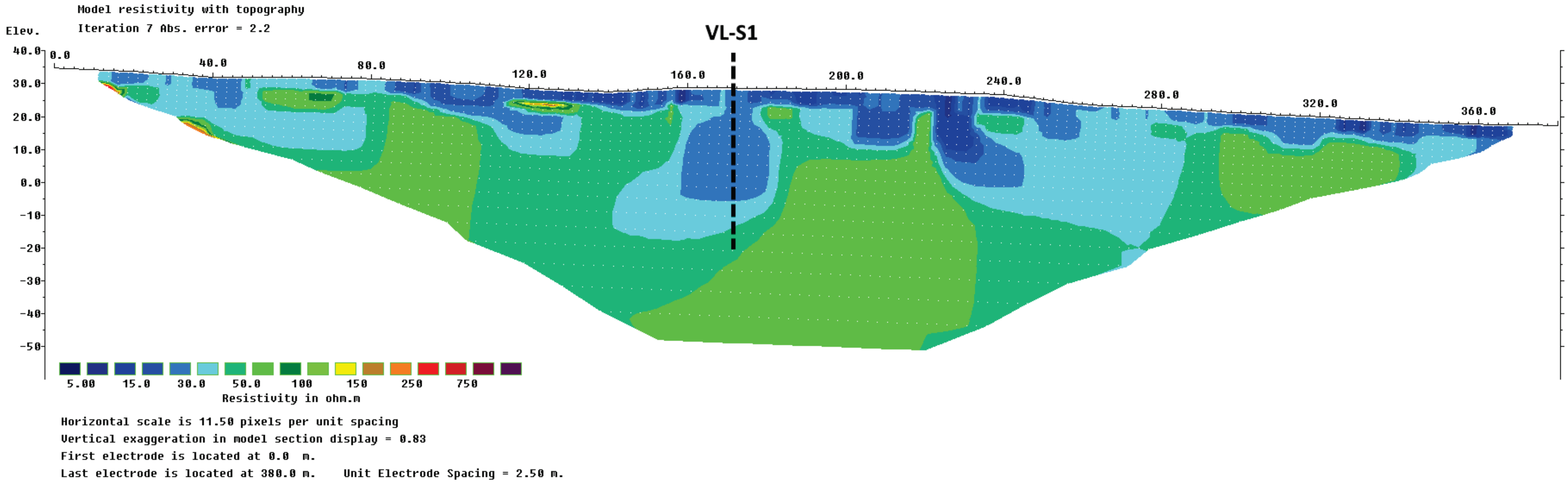


Figure A43 VLV-1

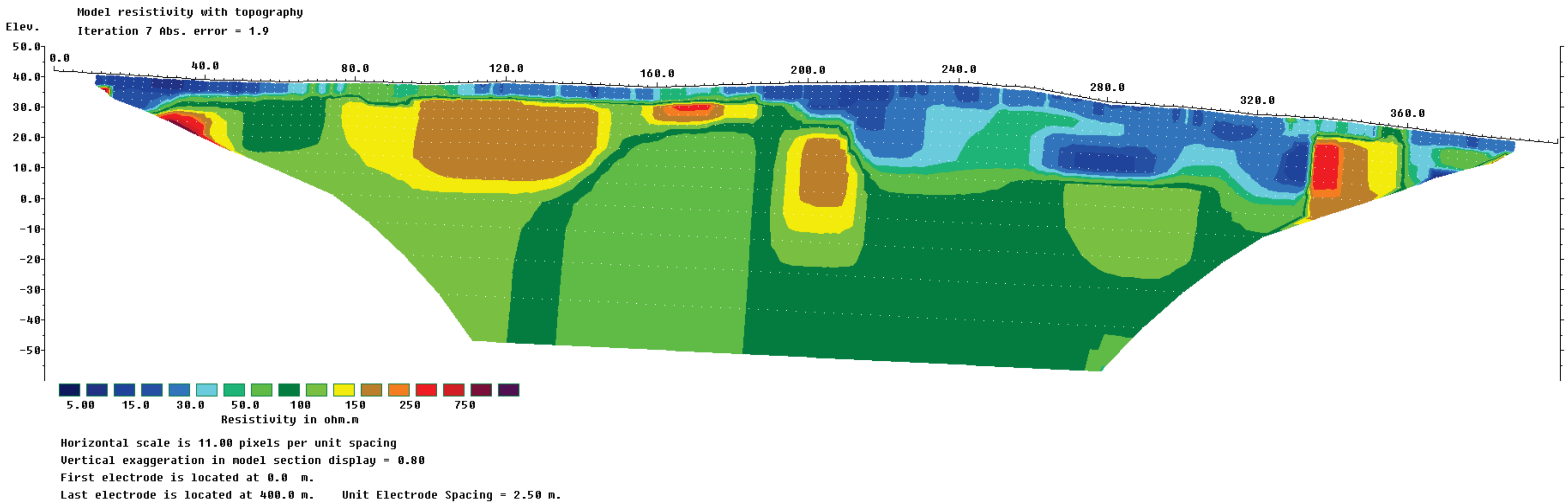


Figure A44 VLV-2

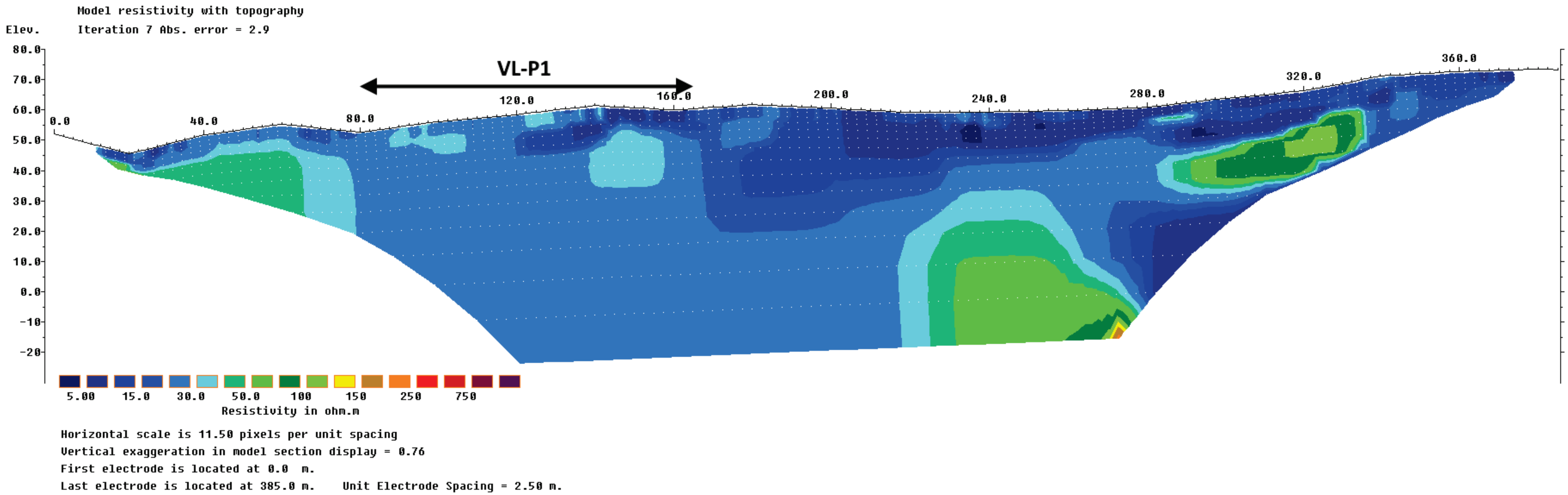


Figure A45 VLV-3

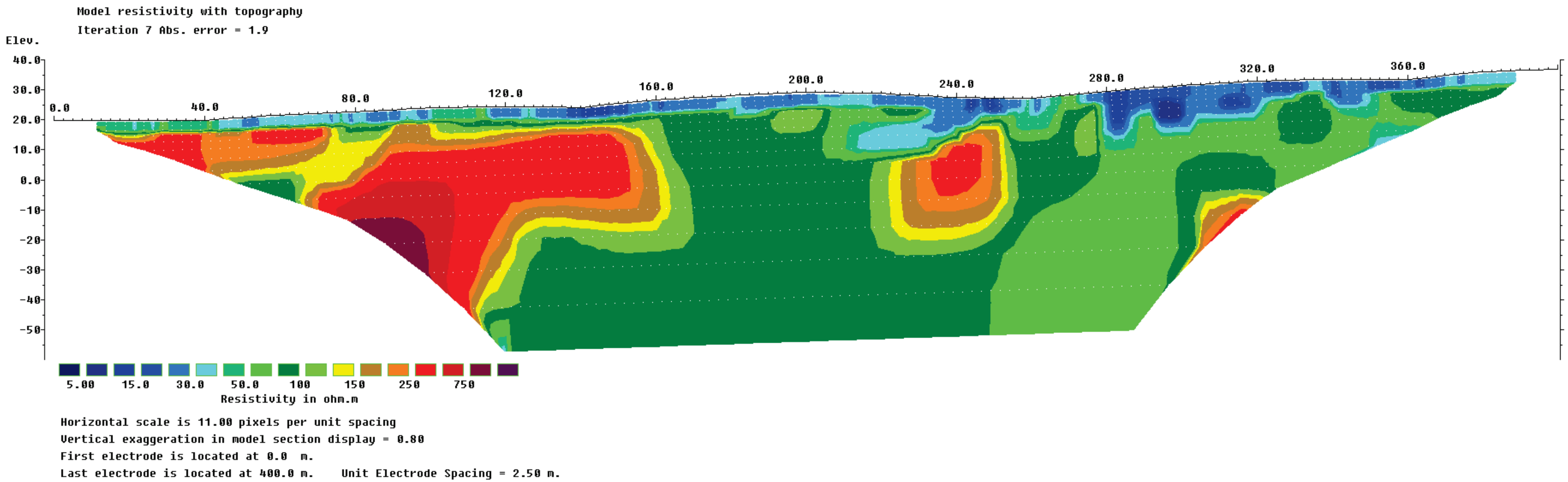
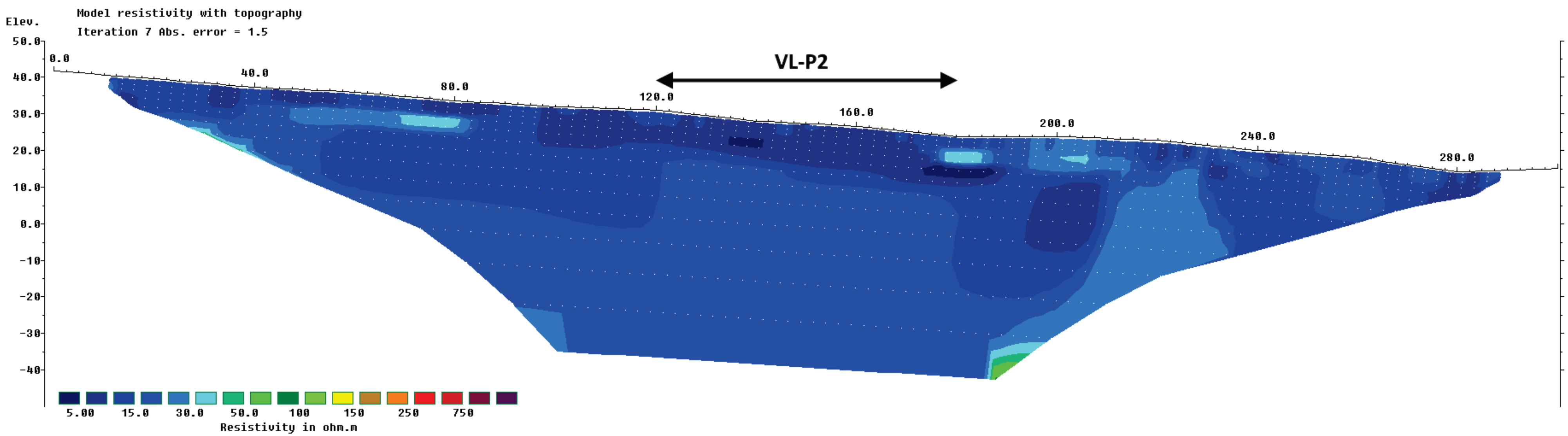
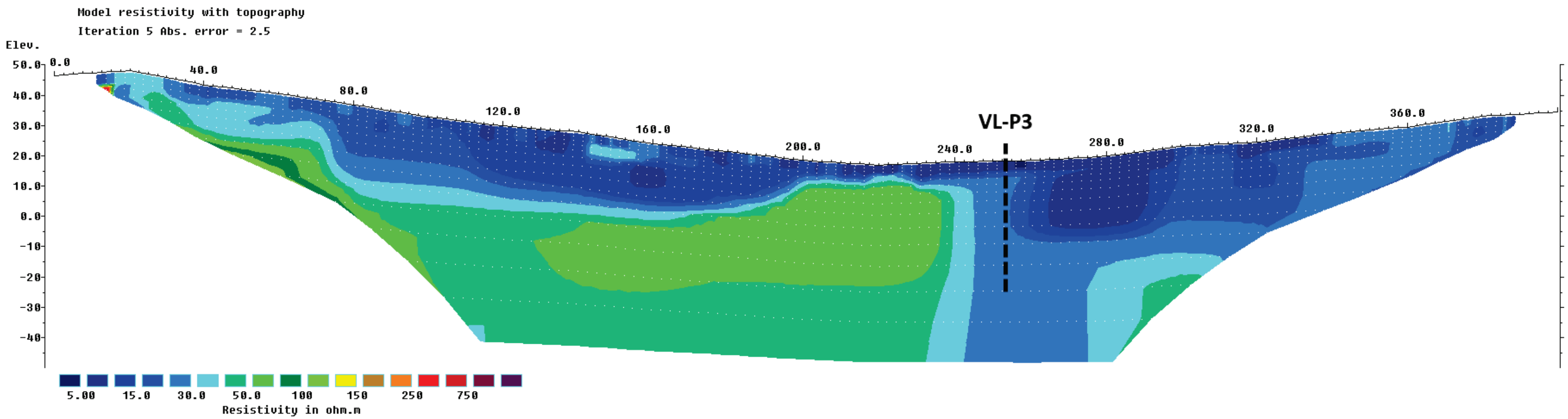


Figure A46 VLV-4



Horizontal scale is 14.75 pixels per unit spacing
Vertical exaggeration in model section display = 0.73
First electrode is located at 0.0 m.
Last electrode is located at 300.0 m. Unit Electrode Spacing = 2.50 m.

Figure A47 VLV-5



Horizontal scale is 11.00 pixels per unit spacing
Vertical exaggeration in model section display = 0.80
First electrode is located at 0.0 m.
Last electrode is located at 400.0 m. Unit Electrode Spacing = 2.50 m.

Figure A48 VLV-6

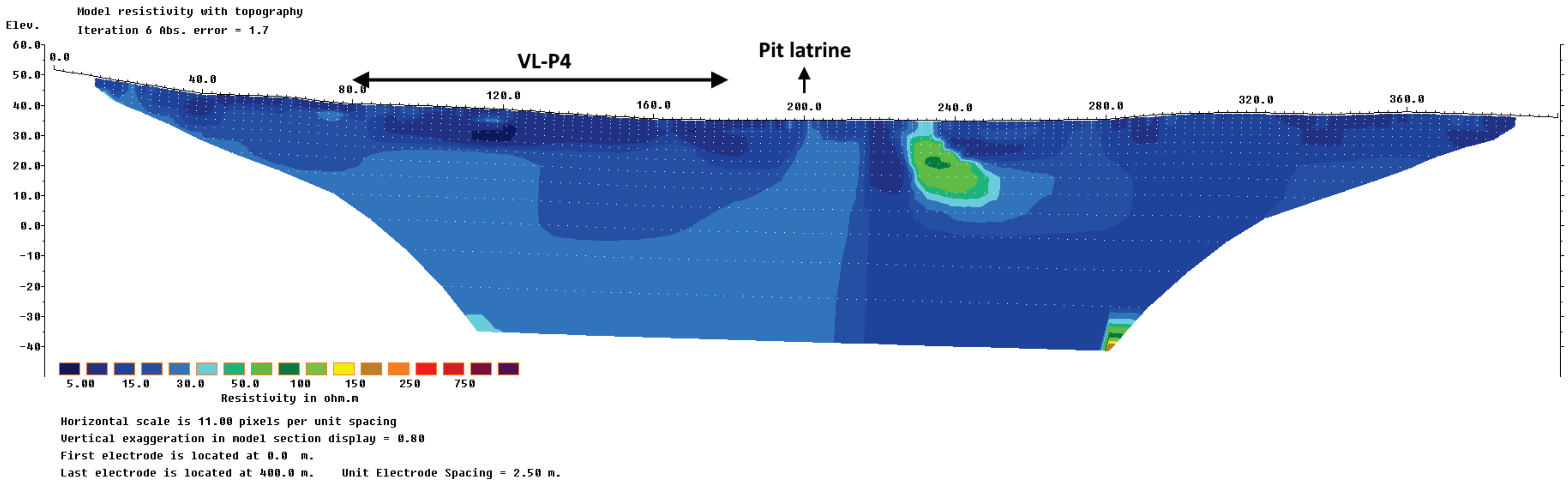


Figure A49 VLV-7

14 Annex 3 – Rainfall data

A3.1 – Rarawai Station in Ba

A3.2 – Tavua Station

A3.3 – Penang Station, Rakiraki

A3.4 – Laucala Sation, Suva

A3.5 – Nadi Airport Station, Nadi

Table A3.1 - Historical monthly rainfall from Rarawai station in Ba from 1942 to August 2017

Rarawai Mill, Ba Latitude: -17.5500, Longitude: 177.6667												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1942	66.4	210.5	252.5	122.2	62.4	150.8	37.7	79	30	81.6	44.8	231.3
1943	335.2	194.3	283.3	241	252.8	30.2	0	24.9	104.9	248.2	157.8	187.3
1944	331.7	288.5	448.7	165.2	52	6.1	3.6	20.9	152.9	58.3	74.1	232.7
1945	333.4	207.8	261.5	196	169.6	109	47.1	10.3	93.4	187.2	80.3	195.7
1946	563.3	614.5	452.1	79.2	72.6	51.8	48.1	36	1.1	39.9	118.1	176.9
1947	222.9	403.9	309.8	118.1	48.7	59.7	79.2	37.1	67.1	55.1	79.3	386
1948	486.7	504.6	118.4	336.8	34	89.6	58.4	42.9	112.7	124.3	370.6	115.7
1949	360.4	224	412.4	366.9	113.8	67.6	24.9	83	128.6	102	149.9	193.6
1950	537.6	402.7	907.3	230.7	72	31.5	7.4	57.2	130.6	173.8	175.9	223.9
1951	255.3	518.4	318.1	213.1	246.5	110	8.9	44.7	85.1	130.8	7.4	62.7
1952	154.6	312.6	295.2	109.1	52.9	96.4	38.6	10.7	77.6	84.9	86.4	457.6
1953	538.5	288.6	603.6	274.1	21.2	131.1	45.9	0	12.9	9.5	25.3	294.4
1954	719	328.9	441.8	283.8	59.1	136.7	101.9	15.2	112.8	27.3	188	176.2
1955	224.6	190.5	856.5	239.6	196.9	130	2	42.9	200.6	29.2	349	191.5
1956	526.3	951.9	986.6	244	135.2	55.1	143.6	22.4	37.9	180.8	237.7	93.2
1957	723	680.9	470.1	101.9	146.6	112.1	1.8	59.7	13.1	25.9	69.9	88.4
1958	35.2	194.2	169.9	327.3	21.6	4.6	27.4	15.5	15.5	106.7	107.7	45.7
1959	508.6	33.3	569.1	166.3	49	50.6	3.8	191.5	81.6	23.6	41.8	226.1
1960	211.4	609.7	600.8	359.5	7.9	139.4	70.2	30	142.3	76.7	238.2	403.2
1961	88.4	705.5	158.9	234	33.6	23.9	52.9	148.4	36.5	34.3	504.2	567.5
1962	522.2	367	383.4	186	86.1	26.5	57.7	4.6	5.3	72.7	266.1	307.3
1963	450.3	131.2	312.6	261.4	275.7	66.6	131.6	96.5	166.9	25.9	115.6	157.3
1964	104.2	589.9	1067.2	78.5	30.1	120.7	27.8	27.1	45.2	73.1	187.2	158
1965	417.8	613.8	412.4	53.8	229.1	10.7	6.4	33.6	104.2	19.9	11.2	30.3
1966	160.4	121.8	358.8	244.5	34.6	23.1	9.4	26.7	13.3	7.7	43.2	190.6

Rarawai Mill, Ba Latitude: -17.5500, Longitude: 177.6667												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	377.9	375	445.4	50.2	23.1	0	9.7	5.6	48	152.6	46.9	93
1968	179.7	284	603.1	114.6	18.5	83	60.8	95.3	74.6	38.1	23.7	168.5
1969	79.8	268.9	179.4	59	0	14.2	32.6	72.4	22.9	6.4	124.4	251.9
1970	213.8	606	289.7	105.4	145.7	118.9	90.2	0	72.2	74.2	189.7	280.1
1971	304.5	356.3	902.2	295.2	113.3	302.1	9.4	58.7	77	217.7	194.5	597.9
1972	475.3	157.5	298.8	79.3	90.8	52.3	12	48.3	16	272.8	103.5	197.4
1973	103.9	292.4	740.5	189.7	35.1	277.4	89.5	68.1	181.6	83.8	255.3	108.6
1974	406.7	680	547.6	552.6	23.9	14.5	30.5	300.9	23.1	284	213.3	432.9
1975	321.3	229.2	190.1	161.3	85.9	17.4	1.3	0	65	374.5	498.5	225.4
1976	342	266.5	363.5	380.5	86.8	44.4	7.8	71.8	312.2	30	59.5	72
1977	597.6	243	467.8	97.7	44.5	11	0	27	35.3	37.1	15.7	64.3
1978	176.1	128	118.5	184.3	106.4	37.3	48.9	19	47	326.2	50.3	111
1979	566.2	210.8	327.6	119.7	157.9	102.9	14.2	24.6	142.2	1.8	108.2	25.9
1980	379.8	419.1	175	121	0	56.4	46.5	40.1	167.3	163.8	161	88.4
1981	566.7	320.4	96.9	255.3	61.2	156.2	9.6	111.9	12	57.4	44.5	195.1
1982	753.1	319	561.4	102.5	48	202.2	69	109.7	37.3	47.2	41.7	49.4
1983	132.8	379.7	61	93	2.5	3.3	33.2	43.7	19.6	113.4	190.3	290.5
1984	216.1	285	579.4	207.6	197.3	115.1	0.7	20.9	28	66.8	113.1	196.9
1985	223.4	352.6	705.7	78.3	62.4	80.7	120.4	18	96.5	98.2	95.3	97.1
1986	203.9	301.6	331.7	777.5	16.8	185.3	0.2	59.9	25.3	23.8	96.3	86.2
1987	113.6	338.5	138.5	42.3	1.6	1.4	7.8	0.8	4.1	15	126	121.3
1988	201.8	405.7	249.8	266.1	47.3	1.6	85.1	2	6.8	104.4	236.8	628.7
1989	340.9	938.1	200	399.2	402.4	19.8	19.7	78.9	113.9	233.4	96.4	171.1
1990	155.3	192.1	565.1	20.6	21.1	245.6	72.7	152.4	109.3	87	206.2	257.2
1991	622.8	337.7	432.7	175.6	41.7	46	35.2	68.3	159.8	27.3	142	108
1992	176.2	296.8	102.6	132	89.3	90.3	6.5	42.5	16.5	28.2	118.3	339.6
1993	251.4	646.8	287.8	85	231.6	0.3	4.6	159.8	13.8	4.8	26.2	276.7

Rarawai Mill, Ba Latitude: -17.5500, Longitude: 177.6667												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	388.6	370.9	357.8	118	47.9	168	7.7	3.9	42.2	7.7	42.7	224.9
1995	434.9	198.8	399.3	311.6	44.5	6.2	26.5	5	119.8	51.4	93.9	121.8
1996	677.7	424	451.1	80.9	346.1	232.6	75.4	24.3	42.6	8.3	109.5	231.2
1997	1028.8	279.7	441.9	311.2	115.9	3.6	26.3	201.4	54.9	81.8	9.1	92.9
1998	138	55.2	47.6	53.9	12.7	3.6	1.4	0	80.7	46.4	490.3	336.4
1999	1044.9	557.5	301.2	363.8	25.3	55.2	94	106.5	67	139.9	226.2	372.9
2000	711.8	324.2	497.3	166	277.6	131.3	211.1	83.6	92.1	169.5	153	646.2
2001	207.6	205.5	212.1	330.3	34.5	25.9	58.4	79.3	22.4	224.1	84.7	636
2002	273.2	347.1	464.4	83	122	45.3	87.1	43	144.6	46.3	37.7	47.1
2003	102.7	204	707.8	218.1	127.5	40.6	6.1	72.3	1.6	62.6	64.1	426
2004	51.6	480.9	426.9	156.8	54.3	98.6	127.7	377.3	62.4	19.7	2	96.5
2005	368.2	66	140.1	385.2	0.6	96.3	53.2	62.7	39.8	71.5	237	228.7
2006	606.6	270.3	213.2	170.9	95.2	52.9	18.7	90.5	57.3	120.4	172.9	325.2
2007	110.3	583	903.8	160.8	13.8	7.1	42.2	14.3	239.2	140	305.4	285.4
2008	826.5	604.6	372.4	270.9	173.2	54.7	52.1	9.2	20.7	80.9	402	184.7
2009	1907.8	357.7	353.3	90.7	149.7	76.5	29.4	27	236.9	56.9	47.7	222.5
2010	122.5	141.4	166.2	166.7	57.0	0.8	53.0	23.5	31.6	141.4	515.2	266.6
2011	760.2	393.2	424.9	255.5	163.7	129.3	106.3	114.3	40.6	268.0	308.6	175.7
2012	932	604.5	767.6	M	63.5	159.7	2.9	46.4	238.1	151.3	99.6	199.7
2013	217.2	415.4	480.5	135.4	157.5	87.7	10.8	29.5	30.7	95.8	277.1	426.4
2014	321.6	260.9	181.6	153.1	144.6	4	5.4	0	5.6	45.8	57.4	138.2
2015	327	241.4	168.7	83.4	3.7	10.4	6.4	28	5.6	4.4	0.8	285.4
2016	214.8	454.3	133.2	430.6	13.6	29.5	11.7	163.9	10.6	129.9	18.5	272.3
2017	415	716	430	62.8	45.9	14.1	3	40				

Table A3.2. Long-term monthly rainfall from Tavua rainfall station from 1942 to August 2017

Tavua - Rainfall Latitude: -17.4500, Longitude: 177.8667												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1942	36	191	144	76	29	163	23	138	44	48	26	209
1943	204	165	242	178	330	18	0	10	74	173	158	64
1944	315	222	468	162	51	20	10	3	117	32	13	203
1945	187	152	276	230	148	88	1	1	106	70	146	148
1946	480	576	612	30	156	22	60	50	3	69	51	63
1947	87	453	227	116	107	53	52	55	71	8	94	330
1948	393	312	91	261	47	55	35	32	97	54	254	206
1949	314	234	597	285	133	12	11	43	93	6	98	166
1950	565	467	989	171	59	14	10	42	146	121	232	108
1951	129	588	380	126	259	93	26	19	73	130	13	23
1952	127	268	336	102	48	63	32	41	23	32	117	318
1953	486	285	543	189	20	141	39	0	23	25	2	288
1954	511	124	329	101	42	86	25	27	124	51	139	171
1955	210	218	925	182	235	105	10	96	268	37	283	177
1956	659	958	1086	326	160	63	104	21	12	152	268	52
1957	715	419	372	58	89	77	0	37	7	39	63	46
1958	38	153	123	165	45	1	23	45	38	66	105	83
1959	417	118	469	126	65	25	11	150	85	6	17	182
1960	148	626	782	257	19	109	45	58	199	187	154	491
1961	186	496	117	206	49	56	23	112	108	18	302	339
1962	495	218	322	195	36	79	65	8	0	32	285	134
1963	294	198	209	237	171	87	88	90	131	40	98	89
1964	42	559	1162	95	22	63	26	36	73	87	98	182
1965	404	695	408	85	99	22	1	55	87	46	23	18
1966	156	55	232	240	17	53		56		7	25	58

Tavua - Rainfall												
Latitude: -17.4500, Longitude: 177.8667												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1967	306	302	358	73	10	1	5	0	87	95	38	25
1968	164	288	531	151	50	42		42	57	58	21	86
1969	41	284	182	49	0	7	37	3	69	14	101	99
1970	130	463	205	133	197	197	22	0	46	39	70	305
1971	181	498	728	106	88	28	3	22	35	178	163	582
1972	391	144	142	83	154	26	17	38	27	176	90	158
1973	80	416	786	107	0	225	162	97	112	50	303	88
1974	558	466	518									
1975	373											
1976	521	171	397	388	72	95	4	66	298	28	109	32
1977	551	0	633	197	25	9	6	52	30	30	20	53
1978	229	131	180	209	85	40	58	51	37	186	64	92
1979					103	87	27	11	117	4	25	23
1980	162	302	133	226	0	57	65	54	171	227	81	69
1981	545	385	168	195	125	94	8	160	20	31	23	126
1982	563	283	406	195	14	208	50	80	13	87	43	71
1983	132	208	125	8	0	1	16	28	15	88	151	372
1984	164	261	454	120	110	169	0	20	0	40	61	96
1985	214	267	553	147	54	49	139	52	28	97	0	84
1986	60	147	254	574	16	101	0	43	6	9	57	52
1987	156	169	240	38	2	2	26	0	7	0	203	145
1988	113	440	221	275	50	0	131	0	45	64	63	518
1989	257	851	174	276	282	16	42	79	73	111	31	97
1990	130	147	459	37	7	234	47	198	184	43	105	138
1991	382	191	435	234	4	18	34	47	142	10	82	21
1992	159	177	103	63	57	93	3	110	19	79	77	321
1993	281	575	146	87	170	12	2	182	14	0	79	134

Tavua - Rainfall Latitude: -17.4500, Longitude: 177.8667												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1994	312	361	275	58	54	169	12	0	20	0	42	45
1995	395	124	365	252	86	13	27	0	74	14	66	33
1996	364	300	320	2	245	185	77	40	77	5	182	192
1997	1109	210	366	248	193	12	31	180	41	66	20	35
1998	94	97	65	26	3	0	1	0	84	10	274	190
1999	841	568	109	295	11	75	79	50	30	147	389	373
2000	453	215	534	181	203	56	193	66	53	89	80	673
2001	243	190	239	293	23	26	60	108	0	206	10	167
2002	497	321	290	86	111	39	208	43	38	39		
2003	100	19	444	209	21	21	0	46	0	58	32	138
2004	31	362	298	349	0	120	95	231	22	0	1	40
2005	191	20	177	421	0	44	33	41	51	34	177	134
2006	437	317	177	136	61	21	14	112	42	81	33	210
2007	45	411	568	125	0	0	40	15	124	61	243	301
2008	892	510	230	347	198	88	21	0		41	271	70
2009	1539	301	370	122	172	47	29	5	220	30	11	145
2010	40	9	149	21	36	5	30	19	25	181	523	74
2011	695	423	122					61				
2013	199	350	552	79	163	102		26	29	57	171	179
2014	143	279	157	186	179	0	0	0			81.5	
2015	168.5	257.5	12	13	9.5	1.5	14	23.5	62.5	24	6	63
2016	210	619	99.5	406	23.5	49.5	5	238.5	2.5	144	67	334
2017	207	747	334	156	53.5	31.5	0	38				

Table A3.3. Long-term monthly rainfall from Penang stations, Rakiraki

Penang Mill, Rakiraki Latitude: -17.3667, Longitude: 178.1667												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	246.2	482	334.6	361.8	49.2	54.6	55.8	61.6	266.6	151	133	86.6
1981	454.1	403.8	132.6	293.4	181.1	57.8	34.8	173.8		122	60.2	338.3
1982	620.6	173.7	456.2	203.2	36.2	278.2	78.5	161.4	20	62.6	213.3	77.7
1983	270.7	718.9	120.2	52.2	12.2	44	52.5	103.6	30.4	223	223.8	251.1
1984	222	397.8	521	213	197.8	256.6	25.9	78.6	19.6	41.4	149	119.8
1985	281.4	225	820.5	212	122.4	58.6	100.4	66	42	138.4	135.8	251.1
1986	381.8	278.6	362.4	790.5	22	148.2	0.8	109.4	4	16	40.4	208.6
1987	9.4	262.4	372.2	84.4	65.2	35.2	22.2	69.6	9.4	25.2	264.8	418.8
1988	205.2	460.4	251		320.8	66.6	94.4	10.8	19.5	98.2	49.6	817.1
1989	300.9	937.1	177	406.5	289	60.4	65	46.2	82	243.4	43.4	99.6
1990	216	185.1	739.1	72.8	16.8	188.8	89.6	96.2	52.8	39.8	290.6	206.6
1991	476	143	421.2	160.4	9.6	14.4	10.8	71.4	163.8	35.2	88	102.2
1992	265.6	194.8	264.2	262.1	85.4	92.9	92.2	20.4	17.4	25	111.6	593
1993	372	376.6	518.3	197.2	260	2.6	18.6	151.4	10.8	10.4	189.8	167.9
1994	565	213.4	363.8	62	162.6	192.2	25.6	8.6	66.4	2.8	217	89.4
1995	517.6	217.6	389	522.8	65.4	34.8	26.6	3.4	93	25.2	38.4	103.3
1996	340.2	343.4	449.6	144.2	224.4	236.6	85	40.4	78	52.8	216.1	193.1
1997	911.1	382.2	695.1	345	440.4	22	36.6	134.7	59.2	71.2	8.8	67.2
1998	178.6	112.4	198.8	120.8	45.6	37.4	12	13	169.9	22.2	124.7	238.7
1999	729.8	409.1	273.6	317.5	436.6	71.6	54.8	102	323.6	379.4	287.4	462.2
2000	446.8	306.7	565.3	302.6	583.6	262.6	147.6	67.3	71.4	203.4	187.3	605.5
2001	315.2	295.2	233.2	182	111	51	81.5	108.9	37.5	323	119.2	256.4
2002	377.8	395.7	301.3	130.4	163.8	17.3	162.7	70.1	123.4	49.8	26.6	
2003	163.2	62.8	535	470.8	128.6	28.6	25	41.3	6.1	45.9	82.4	296.7

Penang Mill, Rakiraki Latitude: -17.3667, Longitude: 178.1667												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	54	371.1	292.3	253.7	11.4	148.9	94.5	196.4	79.3	1.3	29.5	40.7
2005	264.1	77.8	71.9	555.5	7.8	101.2	30.7	36.2	113.9	54.4	95.7	107.7
2006	480.1	404.9	148.6	171.8	65.4	58.8	24.1	83	80.8	107.6	34.4	164.1
2007	64.2	343.1	716	185.7	80.2	25	35.8	29.7	203.4	45.4	329.9	557.8
2008	1240.5	570	200	218.6	271.0	104.4	18.5	74.6	38.3	20.5	381.4	242.3
2009	1261.9	305.0	184.4	188.3	275.9	78.5	38.0	51.6	113.6	22.0	28.2	493.2
2010	59.3	306.8	83.9	153.7	61.8	39.6	22.7	13.9	57.4	249.3	430.2	165.0
2011	659.4	591.8	314.4	277.7	384.6	74.7	38.8	98.5	44.0	184.5	389.1	181.2
2012	990.4	476.9	761.3	575.6	41.3	164.9	18.6	75.3	215.1	147.4	59.6	430.4
2013	311.4	462.4	414.2	289.6	139.5	102.6	61.5	30.9	37.2	124.9	115.1	253.4
2014	353.7	482.6	241.7	123.5	207.1	42.2	23.7	16.2	0.4	98.5	64.8	455.2
2015	136.8	354.1	143.4	101.8	72.2	14.6	3.6	53.0	81.2	34.7	27.7	195.4
2016	84.8	607.6	123.0	552.3	52.8	56.9	13.5	200.8	1.2	72.5	126.0	713.2
2017	170.9	512.7	440.0	32.4	166.7	12.5	1.4	48.7				

Table A3.4. Long-term rainfall from Laucala Station in Suva from 1942 to August 2017

Laucala Bay, Suva - Rainfall Latitude: -18.1333, Longitude: 178.4500												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1942	42.9	225.3	171.0	630.7	234.9	211.4	101.5	140.3	197.1	160.7	45.4	224.0
1943	263.3	197.1	166.5	547.0	158.2	32.5	62.1	52.3	84.8	217.4	324.7	141.4
1944	350.7	381.5	577.1	323.1	110.3	135.2	75.5	127.3	369.4	92.6	61.1	255.2
1945	151.4	289.5	309.9	270.5	234.4	168.8	75.5	142.4	240.0	303.2	355.8	396.1
1946	366.3	408.9	549.6	81.5	155.5	155.5	93.5	120.0	41.4	127.0	220.1	166.9
1947	298.1	373.4	533.4	285.7	345.5	338.9	185.8	77.6	217.2	139.5	124.6	149.2
1948	180.4	832.1	370.9	465.8	201.7	113.5	80.7	149.0	43.7	82.0	139.8	400.2
1949	543.1	183.6	543.0	637.3	917.9	95.2	166.3	196.6	456.6	206.7	234.3	381.1
1950	577.7	210.9	403.3	294.9	231.3	75.8	246.4	65.6	368.7	194.5	368.9	211.8
1951	268.7	328.1	312.3	147.3	135.7	237.9	127.3	70.9	179.6	267.6	24.5	413.6
1952	378.5	398.5	294.6	133.5	188.7	276.9	352.8	50.6	179.6	31.8	245.4	307.2
1953	499.3	384.7	275.8	174.9	184.1	143.3	289.2	36.0	27.7	43.5	55.7	211.9
1954	376.1	324.1	272.7	312.7	78.5	376.8	159.2	306.5	364.4	219.4	752.9	252.5
1955	350.1	234.0	531.8	259.8	430.2	338.2	97.6	229.3	440.2	150.8	162.7	368.3
1956	535.4	337.4	718.9	318.2	175.5	86.9	218.0	83.3	124.0	278.5	246.0	312.7
1957	365.5	143.2	270.5	470.1	165.7	208.3	70.1	88.8	100.0	96.4	194.4	137.6
1958	105.1	338.7	311.9	959.5	143.4	18.6	65.5	69.2	41.8	105.2	509.4	275.9
1959	323.4	280.9	453.4	387.6	185.6	278.8	38.4	396.2	455.7	195.4	210.6	133.6
1960	337.0	311.1	420.4	324.4	161.1	246.9	290.1	55.3	149.5	140.7	456.0	237.2
1961	252.6	231.6	110.0	329.6	156.4	191.5	133.0	126.7	322.9	63.6	652.4	448.9
1962	500.4	491.2	381.4	313.3	185.1	288.8	115.4	82.6	106.9	103.8	202.4	251.3
1963	396.4	163.3	298.9	682.1	249.5	101.3	70.7	522.8	267.0	107.7	204.4	501.4
1964	208.0	530.7	437.0	256.8	210.4	253.4	113.3	201.5	200.6	386.5	194.3	229.1
1965	209.7	498.5	457.0	210.6	453.9	58.9	104.8	143.0	160.9	83.5	99.3	51.9

Laucala Bay, Suva - Rainfall												
Latitude: -18.1333, Longitude: 178.4500												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1966	297.1	96.8	277.1	424.8	199.6	115.2	100.2	98.4	16.7	139.6	143.4	192.5
1967	234.6	246.7	82.8	442.6	200.3	55.5	74.9	48.8	319.2	900.3	45.6	208.4
1968	127.9	239.4	307.7	116.9	260.3	227.5	109.1	54.7	236.2	125.7	130.7	185.6
1969	154.5	360.3	591.8	250.3	73.3	24.0	408.8	93.1	97.1	379.8	247.9	307.3
1970	187.5	241.1	273.0	336.9	150.7	297.5	370.0	52.5	145.0	147.8	773.1	213.7
1971	430.4	386.6	199.7	339.3	317.0	137.6	132.7	88.1	124.9	563.2	248.2	515.5
1972	377.5	395.1	347.0	504.6	384.3	114.3	145.4	137.7	217.3	534.6	379.7	484.9
1973	176.9	348.7	799.2	721.2	194.3	147.8	230.6	125.2	145.0	114.1	202.8	221.8
1974	174.2	94.6	531.3	318.9	477.6	110.8	57.3	268.7	183.7	141.4	252.8	436.2
1975	640.5	254.1	302.2	263.5	496.5	231.0	313.8	49.4	197.4	516.8	548.3	571.2
1976	286.7	345.9	279.8	170.9	510.9	176.2	68.3	313.9	317.8	147.9	340.0	160.0
1977	593.0	425.5	598.2	632.4	61.8	25.6	97.8	115.8	167.7	60.7	57.3	185.2
1978	273.3	207.1	546.7	400.6	285.2	31.3	163.3	163.2	112.5	347.8	205.5	270.6
1979	506.3	256.5	299.7	376.3	536.7	419.3	81.1	125.9	244.7	73.7	205.6	87.7
1980	315.3	244.1	338.2	923.6	49.9	142.9	51.7	180.1	480.5	587.9	500.0	128.0
1981	526.6	295.0	149.6	346.8	273.5	74.8	55.7	227.0	101.6	173.1	790.2	171.5
1982	718.4	169.3	437.2	282.6	177.9	274.9	157.8	282.3	132.4	74.5	221.9	81.4
1983	257.0	392.3	317.4	97.8	124.0	71.4	133.8	231.0	76.7	144.3	205.6	341.3
1984	126.5	169.3	433.3	377.0	266.4	260.1	128.8	156.2	52.6	38.6	200.5	268.3
1985	463.2	293.2	315.8	406.6	480.7	141.1	292.3	134.6	273.3	282.0	94.9	114.3
1986	292.5	260.8	443.1	1116.1	114.6	231.6	24.1	104.1	102.4	70.3	110.1	245.5
1987	146.3	298.2	419.8	101.7	78.5	64.5	24.2	33.1	16.5	110.4	135.0	386.8
1988	236.5	256.7	348.6	456.1	268.2	195.5	182.3	119.7	162.6	173.7	96.9	233.1
1989	143.9	191.2	343.3	371.6	584.3	117.7	65.2	98.7	142.0	236.1	116.0	195.3
1990	200.8	204.5	463.2	149.8	196.8	331.8	244.7	385.6	394.3	198.9	327.8	196.6
1991	649.7	472.2	238.4	239.3	99.3	136.7	188.2	153.8	147.7	275.1	235.0	445.6
1992	254.1	104.8	411.6	246.3	144.8	140.1	164.3	62.3	111.6	372.7	255.7	538.9

Laucala Bay, Suva - Rainfall Latitude: -18.1333, Longitude: 178.4500												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1993	319.9	375.6	682.3	334.9	291.5	71.6	57.6	316.8	130.3	132.1	104.2	173.9
1994	384.6	297.8	492.7	128.9	295.9	167.6	70.9	90.9	105.9	27.3	159.4	288.4
1995	472.5	305.6	297.5	300.0	187.3	48.8	152.2	99.4	132.3	98.5	138.0	129.0
1996	539.1	300.0	214.9	167.8	396.2	367.0	120.7	20.2	122.4	212.8	320.5	198.3
1997	506.3	78.9	249.9	539.6	155.9	35.4	140.1	139.5	144.5	113.3	110.9	160.1
1998	439.4	111.8	147.7	50.5	147.5	56.1	76.2	35.7	103.3	109.1	156.4	147.8
1999	421.0	243.7	384.8	371.8	147.9	125.0	158.8	344.0	326.7	319.9	461.1	559.3
2000	261.7	160.4	194.3	257.5	362.7	441.7	285.5	142.8	328.5	369.2	175.7	375.2
2001	354.3	248.3	362.7	442.8	94.0	110.9	96.2	228.7	78.6	304.2	317.4	296.4
2002	556.8	385.5	435.0	488.2	193.5	98.4	131.9	201.4	326.7	137.9	402.0	229.0
2003	425.3	121.7	461.1	304.6	257.4	84.8	97.8	99.0	43.5	167.8	83.5	330.6
2004	110.2	261.9	239.7	445.4	190.8	325.1	204.7	418.7	77.0	57.4	84.6	363.0
2005	240.7	136.4	382.2	470.1	60.4	243.7	205.4	149.3	415.4	488.2	391.1	173.0
2006	241.5	322.6	196.8	179.7	300.7	118.2	84.1	143.6	448.8	216.6	89.2	454.9
2007	127.3	330.3	566	538.4	191.3	46.7	241.1	78	262.4	389.0	470.7	254.3
2008	428.2	145.4	119.3	350.8	245.3	316.2	73.3	189.5	102.3	203.7	295.8	162.7
2009	731.9	287.7	271.5	182.7	283.1	100.9	55.9	93.2	343.4	55.9	79.7	323.0
2010	72.0	422.3	314.1	397.1	231.0	73.3	67.6	134.1	55.4	708.1	540.3	294.8
2011	170.7	195.6	146.1	313.3	259.4	440.2	192.2	89.1	220.8	199.8	376.3	469.0
2012	376.2	331.2	567.5	347.3	234.5	227.0	140.3	133.0	293.1	182.7	278.9	301.0
2013	188.5	434.5	444.4	240.3	143.7	140.9	238.3	155.4	173.7	248.3	155.3	449.2
2014	404.7	680.8	497.1	186.0	447.1	57.3	115.5	38.1	39.3	218.5	59.5	579.7
2015	292.1	273.1	189.5	82.4	92.9	55.2	53.3	132.5	127.9	98.3	45.2	363.8
2016	177.5	321.3	109.8	351.3	171.3	50.3	78.8	404.8	56.9	310.3	118.0	761.8
2017	305.1	351.3	383.0	317.9	285.2	109.8	85.1	149.8				

Table A3.5. Long term monthly rainfall from the Nadi station from 1942 to August 2017

Nadi Airport, Nadi Latitude: -17.8, Longitude: 177.4												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942	41.4	133.4		144.9	28.2	265.7	44.3	82.4	37.1	85.1		224.9
1943	158.6	71.4	207.3	335.5	177.6	26.1	3.3	21.3	89.6	260.1	152.3	65.5
1944	224.2	317.5	396.1	196.5	83.6	25.9	0	21.4	158.6	19.5	27.9	193.2
1945	484.0	97.4	355.8	146.7	200.2	52.9	11.2	1.8	93.8	193.9	53.9	215.6
1946	426.4					50.6	60.2	33	0	80.3	70.4	59.4
1947	264.8	277.3	416.7	179.7	97.9	88	55.9	65.6	24.2	20	103	119
1948	460.9	326.4	220.8	238	32	31.4	136.3	124.7	21.4	173.4	258.5	65.8
1949	159.4	199.8	295.7	141.4	80.4	4	33.8	112.5	172.2	47.7	118.3	266.8
1950	276.5	310.9	597.9	148.7	67.3	7.1	8.6	76.9	108	158.1	251.6	279.1
1951	244.8	336.6	217	160.1	178.9	137.6	1.3	57.2	49.6	76.6	15.3	171.7
1952	115.8	246.6	296.4	146.2	80.4	146.9	34.8	18.8	164.4	6.1	97.9	398.3
1953	334.8	207.9	366.9	184.1	23	123.7	44.8	30.1	38.1	7	6.6	398.4
1954	511.0	223	421.8	301.1	130.8	114.3	88.8	18.8	134.9	25.2	186.5	210.2
1955	179.1	257.5	621.4	278.3	206.3	247.5	4.4	30.1	245.8	55.7	322.9	328.4
1956	454.1	544.2	639.9	167.2	140.3	69.8	103.2	16.4	31.7	91.6	186.2	50.6
1957	587.5	499.9	464.1	58	132.1	105.1	1.5	136.4	41.5	96.4	50.8	21.6
1958	42.0	153	195	269.4	42.7	3.6	137.2	11.2	2.3	137.8	157.4	42.6
1959	364.4	46	305.1	280.9	72.7	20.3	1.1	286	87.9	39.9	156.9	295.2
1960	227.5	441.0	655.6	382.1	53.5	93.2	114.6	26.7	66.3	61.9	122.9	288.2
1961	143.8	576.0	75.6	250.5	45.0	44.4	35.1	171.0	116.7	42.8	307.4	232.3
1962	373.3	285.9	279.6	149.2	79.8	54.1	84.9	9.6	13.0	46.0	186.5	196.8
1963	563.8	120.9	202.1	125.9	160.4	85.6	189.8	87.0	194.8	11.2	154.0	144.3
1964	89.6	447.3	918.2	96.8	36.6	60.9	18.7	30.7	37.1	113.2	145.7	119.9
1965	467.2	562.6	317.3	78.7	139.9	23.6	21.1	33.1	156.1	35.8	28.1	29.5
1966	307.3	148.9	236.5	239.7	33.3	11.5	5.4	49.6	21.0	10.5	56.0	293.0
1967	301.8	420.2	267.1	211.6	42.5	0.0	11.4	1.5	120.0	155.1	69.6	52.4

Nadi Airport, Nadi Latitude: -17.8, Longitude: 177.4												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1968	211.1	245.4	428.5	118.6	38.1	86.1	70.6	50.8	28.5	95.2	55.6	247.2
1969	121.8	151.7	144.9	83.9	2.3	3.8	42.4	23.8	9.7	30.8	144.9	103.4
1970	146.5	605.9	125.8	174.7	141.5	87.5	99.1	0.0	135.7	51.0	206.0	278.9
1971	255.1	375.4	498.9	109.5	83.7	35.2	20.0	79.9	75.2	245.2	199.5	186.5
1972	424.6	309.2	226.9	86.7	95.2	24.3	8.1	26.7	22.2	341.8	129.6	134.9
1973	41.7	190.6	576.3	115.4	6.0	260.3	166.0	96.8	174.1	117.0	138.0	194.5
1974	478.4	399.9	480.4	405.6	78.4	93.3	40.0	192.7	117.2	277.6	278.1	141.9
1975	295.1	138.3	269.8	101.1	102.7	58.6	29.3	7.0	48.1	268.9	460.6	209.2
1976	308.1	217.3	198.2	255.5	23.3	34.3	6.6	88.2	278.8	38.2	92.4	60.5
1977	597.5	374.5	493.4	95.0	48.0	8.0	12.0	58.9	39.1	15.1	14.2	46.0
1978	220.1	107.8	175.1	68.6	71.8	73.0	54.2	11.3	63.4	182.0	75.6	67.1
1979	580.0	212.1	358.4	145.7	79.7	52.0	14.4	24.6	173.0	18.8	90.1	38.4
1980	302.3	352.0	184.3	122.6	4.1	63.6	72.8	44.3	74.0	107.9	161.0	74.0
1981	594.8	342.8	157.1	345.4	107.0	72.7	5.6	158.6	34.4	81.8	124.7	119.2
1982	544.9	202.9	357.9	92.6	20.7	209.4	127.1	61.2	9.5	56.5	71.3	134.5
1983	104.4	144.1	349.3	21.6	15.9	12.3	22.6	78.6	15.4	131.2	130.2	297.5
1984	322.5	237.1	321.2	213.7	288.0	63.1	0.3	52.1	36.8	34.3	79.6	91.1
1985	251.0	264.5	571.9	92.1	141.8	72.4	112.3	9.0	32.7	140.4	85.2	118.2
1986	170.0	279.0	491.6	580.1	35.3	117.0	0.0	50.9	75.0	29.1	66.5	116.5
1987	12.7	403.3	166.7	25.6	0.8	0.0	4.4	3.4	4.2	1.8	136.9	238.4
1988	311.5	218.8	140.7	159.5	91.1	3.2	87.7	0.3	25.2	236.7	141.9	562.4
1989	281.1	643.6	237.7	293.9	332.1	5.7	10.8	69.4	97.6	141.2	110.9	124.2
1990	152.9	90.1	464.8	29.9	3.1	140.8	17.0	180.8	69.8	25.3	205.1	118.4
1991	368.0	269.6	203.5	242.1	17.7	8.9	35.9	29.6	110.4	36.2	105.7	53.3
1992	97.2	179.1	121.2	67.5	93.7	61.8	4.2	32.5	27.1	86.4	70.7	425.0
1993	148.7	787.9	358.3	121.0	138.8	0.3	1.3	126.2	28.0	16.1	109.5	209.5
1994	323.4	440.0	259.7	37.6	68.3	163.9	30.3	0.0	62.8	18.3	86.1	122.7
1995	216.6	238.1	422.4	154.7	69.1	20.0	85.7	18.1	70.4	10.3	101.4	47.6
1996	329.0	288.1	642.2	46.8	169.3	180.9	84.5	31.2	36.3	52.9	148.2	321.4

Nadi Airport, Nadi Latitude: -17.8, Longitude: 177.4												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	732.8	176.4	417.2	208.3	110.8	31.2	32.2	198.9	50.2	51.7	3.6	60.4
1998	226.0	45.5	130.7	52.1	28.7	7.0	0.9	0.0	29.1	55.4	244.1	176.1
1999	981.1	531.9	337.1	316.4	22.3	51.5	92.6	108.3	114.6	61.3	210.4	301.7
2000	631.9	285.8	607.6	190.9	330.8	23.6	185.8	101.1	98.0	172.7	98.7	561.2
2001	279.9	289.5	296.9	261.0	49.8	17.4	96.6	146.6	31.1	278.2	67.2	151.7
2002	354.7	322.3	266.1	291.6	91.2	53.2	102.8	48.5	142.9	39.5	131.0	25.8
2003	147.9	59.7	411.6	105.9	52.9	29.6	28.8	97.6	2.3	38.6	89.3	210.5
2004	128.1	509.8	245.6	116.6	6.1	69.9	59.2	256.2	72.5	24.8	26.4	31.4
2005	250.8	64.0	200.8	420.4	0.7	80.0	61.0	52.0	35.6	127.4	131.0	263.1
2006	357.4	219.4	175.6	112.9	229.4	39.9	35.6	104.4	88.9	119.4	117.7	88.6
2007	110.1	514.0	670.7	191.2	26.3	1.5	69.3	1.1	217.5	86.0	325.2	310.6
2008	549.2	528.6	258.3	192.7	202.0	50.1	73.2	2.9	54.9	69.2	207.7	270.6
2009	1180.6	237.1	321.3	74.6	163.5	113.5	73.9	55.9	197.3	55.6	41.1	284.6
2010	66.0	112.7	115.4	207.5	42.7	4.6	33.5	22.0	0.9	81.1	260.9	386.9
2011	464.8	385.7	442.4	277.0	217.9	76.4	101.4	80.4	62.5	190.6	187.9	295.6
2012	959.7	574.3	694.3	234.8	37.3	311.9	32.7	66.3	210.8	104.5	122.3	199.0
2013	87.9	464.8	341.7	104.1	116.5	124.9	6.3	10.7	159.3	118.7	239.2	257.6
2014	401.7	243.7	137.0	117.3	133.9	1.3	13.3	0.0	7.6	36.8	89.1	123.9
2015	205.8	346.6	154.0	94.5	2.8	14.8	15.6	49.9	63.0	24.5	28.4	204.6
2016	227.4	424.1	324.0	499.6	21.0	28.0	13.0	197.0	7.3	164.6	123.4	269.9
2017	314.1	786.6	509.8	48.7	55.2	2.4	20.5	60.6				

15 Annex 4 – Selected field investigation photos

4.1 – Field investigation in Qerelevu

4.2 - Field investigation in Wailevu and Nanuku

4.3 – Pre-survey consultation in Benai, Navia and Nadhari, Malele, Volivoli

4.4 - Field investigation in Benai

4.5 - Field investigation in Navia and Nadhari

4.6 - Field investigation in Malele

4.7 - Field investigation in Volivoli

Annex 4.1 – Field investigation in Qerelevu

Figure A4.1.1. Team presenting sevusevu to Tui Ba prior to Qerelevu survey in February 2017.

Figure A4.1.2. Due to unfavourable ground condition from recent heavy rain, the team had to carry survey equipment uphill.

Figure A4.1.3. Dumpy level instrument used to assess relative topographical variation along the survey profile.

Figure A4.1.4. ABEM LS kit operated alongside the elevation survey unit.

Figure A4.1.5. Subsequent to ABEM equipment malfunction, the team undertook an assessment of existing bores around the Nabatolu area within Qerelevu.

Figure A4.1.6. The team visited Wailevu's advisory councillor, Mr Ganesh Rao, to inform him and some community members of the planned survey schedule after Qerelevu.

Figure A4.1.7. The team visited Nanuku's advisory councillor, Mr Darmendra Prasad, to inform him and some community members of the planned survey schedule after Qerelevu.

Figure A4.1.8. Setting up of the Trimble R10 base station prior to field assessment in Qerelevu in May 2017.

Figure A4.1.9. MRD staff enjoying the opportunity to learn how to operate the geophysics equipment.

A4.1.10. Scouting the Qerelevu landscape to determine the presence of interesting structural features and potential survey sites.

Annex 4.2 – Field investigation in Wailevu and Nanuku

Figure A4.2.1. A view of the undulating and highly dissected landscape in Wailevu and Nanuku from a traverse to the nearby hills.

Figure A4.2.2. Highly weathered basalt exposed on the hillside, with dike intrusion marked by vertical structure to the right of the field notebook.

Figure A4.2.3. The team using Trimble R10 GPS during the geophysics survey.

Figure A4.2.4. Using bentonite to improve electrode contact on basal volcanic exposed at a creek bed.

Figure A4.2.5. Survey equipment in operation with profile and cable extending across a creek.

Annex 4.3 – Pre-survey consultation in Benai, Navia and Nadhari, Malele and Volivoli

Figure A4.3.1. Ba District Officer, Mr Alifereti Abenisiga, leading the discussion regarding Benai's water problems.

Figure A4.3.2. Tavua District Officer, Mrs Maria Osborne, and Malele Advisory Councillor, Mr Balbant Singh, ready to lead the consultation meeting.

Figure A4.3.3. Malele advisory councillor explaining the scope of the assessment to community members.

Figure A4.3.4. Navia/Nadhari community members having a discussion with Fiji Sugar Corporation (FSC) field officer, Mr Timoci Sila, on FSC's plan to encourage intercropping and how this might affect current water demand and use.

Figure A4.3.5. Ra Provincial Administrator, Mr Elimi Rokoduru, and Advisory Councillor, Mr Davendra Prasad, presiding over the consultation meeting in Volivoli.

Annex 4.4 – Field investigation in Benai

Figure A4.4. 1. Resistivity data collection conducted alongside topographical survey.

Figure A4.4. 2. ABEM LS equipment in operation along survey line 5 around Benai.

Figure A4.4. 3. Setting up the base station outside the advisory councillor's residence.

Figure A4.4. 4. Initial setup of survey line 6 where a jumper cable is used to connect the electrodes and electrical cable.

Figure A4.4. 5. A de-briefing meeting at the district officer's office in Ba, together with the advisory councillor, permitted the presentation of preliminary results.

Annex 4.5 – Field investigation in Navia and Nadhari

Figure A4.5.1. Setting up a survey profile using a measuring tape to guide the laying of electrical cables.

Figure A4.5.2. Hammering steel electrodes to ensure adequate ground contact.

Figure A4.5.3. Attaching jumper cables to connect the electrodes and the cables.

Figure A4.5.4. Survey equipment operator giving commands on measurement status via a radio.

Figure A4.5.5. Elevation measurements taken along the survey transect using the Trimble R10 series.

Annex 4.6 – Field investigation in Malele

Figure A4.6.1. Setting up a survey profile using a measuring tape.

Figure A4.6.2. Survey equipment in operation.


Figure A4.6.3. Trimble 600 series used to capture location and elevation measurements.


Figure A4.6.4. Survey equipment operated by MRD staff.

Figure A4.6.5. Collecting groundwater samples from one of the private wells with the advisory councillor looking on.

Figure A4.6.6. Presentation of preliminary findings to Tavua district officer and Malele advisory councillor.

Annex 4.7 – Field investigation in Volivoli

Figure A4.7.1. A view of the hilly and undulating landscape of Volivoli, adjacent to the coast.

Figure A4.7.2. Hammering steel electrode into ground as part of survey profile setup.

Figure A4.7.3. Survey protocols and machine operation explained to MRD staff joining the assessment.

Figure A4.7.4. Survey equipment in measurement mode and operators advising team members on the survey progress.

Figure A4.7.5. Electrical cable rolled up after measurement is completed.

Figure A4.7.6. Counting steel pegs as part of the pack-up routine to ensure that nothing is lost or left behind.

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