Pacific Community
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Pacific Community Recovery Support for Tropical Cyclone Pam

Groundwater Investigation
West Ambae, Vanuatu

Aminisitai Loco, Andreas Antoniou, Anesh Kumar and Peter Sinclair

Geoscience Division, Pacific Community

EUROPEAN UNION

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- The Department of Water Resources, Vanuatu Ministry of Lands and Natural Resources
- United Nations Children's Fund
- World Health Organization
- The Australian Department of Foreign Affairs and Trade
- The New Zealand Ministry of Foreign Affairs and Trade

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1. Introduction

1.1 Project background

In March 2015, one of the southern hemisphere's most intense tropical cyclones ever recorded in history caused widespread damage and loss of life across four countries: Kiribati, Solomon Islands, Tuvalu and Vanuatu. Some of the greatest impacts were felt in Vanuatu, which suffered a direct hit from the category 5 cyclone. Significant damage to a range of services occurred in Vanuatu's eastern islands and provinces. Following on from the immediate humanitarian disaster response needs of the countries, which were supported by a range of regional and international organisations and governments, ongoing recovery efforts to the many services that were impacted was required.

In February 2016 the Pacific Community, in collaboration with the German banking group KfW, developed a suite of multisectoral activities under the 'SPC Recovery Support for Tropical Cyclone Pam' to support the recovery needs of Kiribati, Solomon Islands, Tuvalu and Vanuatu, which were the Pacific Island countries most impacted by Tropical Cyclone Pam.

1.2 Project objectives and outcomes

The SPC Recovery Support for Tropical Cyclone Pam project, with funding support by KfW, aimed at contributing to the socioeconomic rehabilitation and enhancement of living conditions, and the resilience of the population in the affected areas. This work is part of recovery activities implemented in Vanuatu. Activities developed in collaboration between SPC and the Vanuatu government took place over a 24-month period and included;

- maritime and aids to navigation;
- support to the Department of Geology, Mines and Water Resources as they coordinate the recovery efforts of multiple partners and continue to restore safe drinking water systems across affected communities;
- strengthening emergency communications;
- support for health services;
- multihazard mapping to inform strategies for improved resilience of coastal communities; and
- food supply for food security, by helping with improving fisheries and replanting crops.

This report is an outcome from the coordination of the domestic water supply recovery component of the project.

Groundwater has the potential to provide an alternate source of freshwater in certain locations of Vanuatu, and a significant factor in the decision to investigate its potential is the fact that groundwater is resilient to droughts and cyclones. To date, however, this potential has yet to be fully investigated. A direct request for a hydrogeological assessment of west Ambae was made by the Government of Vanuatu, due to long-standing and ongoing freshwater supply issues in certain localities of the country. This report summarises the findings from the investigation on the potential of fresh groundwater in west Ambae to support the domestic water supply needs of the more than 1,500 residents in the districts of Ndui Ndui and Walaha on Ambae's southwest coast.

1.3 Project linkages

A hydrogeological investigation to identify fresh groundwater potential and to locate drill targets for further investigation is considered to be the first phase in locating sustainable and resilient freshwater supplies for local communities on Ambae. Other phases in the sustainable development of a groundwater resource as a freshwater supply include drilling and pumping tests to assess the quantity, quality and potential application of the groundwater; and developing a community-operated water supply that is safe, affordable and socially acceptable to meet the needs of the community.

The KfW project component, 'Support for domestic water supply rehabilitation', undertook the first phase of developing sustainable and resilient water supply systems in selected locations. Hydrogeological investigations, including geophysical surveys and the identification of specific drilling targets, were undertaken in these selected localities by SPC, in collaboration with the Government of Vanuatu.

The second phase for improved water supply systems involves proving the potential of the groundwater resource. This requires drilling and undertaking a pumping test to help determine the volume of water that is accessible for abstraction and its sustainability, and the options for the development of the groundwater resource.

In collaboration with the European Union under the EDF10 Building Safety and Resilience in the Pacific project, the KfW's Recovery Support for Tropical Cyclone Pam project has purchased a suitable drilling rig capable of drilling and constructing water supply wells to required depths in expected geology for communities on West Ambae. In addition, KfW's Recovery Support for Tropical Cyclone Pam project will assist with the cost associated with getting the drill rig to the outer islands, for four villages on two islands. The costs for the drilling will be borne by the Government of Vanuatu, and include fuel, drilling fluids and casing, drilling consumables for construction, and staff salaries. Advice on borehole completion, pumping tests and options for groundwater development will be supported by SPC through the KfW's Recovery Support for Tropical Cyclone Pam project for the selected sites.

The third phase of the project includes equipping the water wells with pumps and storage tanks designing and installing appropriate access points, including any reticulation and additional storage needs; and ensuring the sustainability of the water supply through ongoing operation and maintenance. This work is currently outside the project brief and does not have committed funding by KfW or Government of Vanuatu. Other actors in the water sector, including the United Nations Children's Fund, Australian Department of Foreign Affairs and Trade, New Zealand Ministry of Foreign Affairs and Trade, and nongovernmental organisations (NGOs) have indicated their support for the identification and proving of the potential groundwater supplies, and have indicated their interest in exploring the third phase of the project, which would entail working closely with the communities to identify the location of tanks and access points, and assisting with the funding of village or district water supply systems.

1.4 Report structure

This report has seven sections:

- 'Project overview' summarises the SPC Recovery Support for Tropical Cyclone Pam project and its objectives, outcomes and scope of the Coordination of Domestic Water Supply Recovery component.
- 'Contextual information' provided for west Ambae and on the communities of Ndui Ndui and Walaha.
- 'Methodology', which discusses the approaches used to undertake the assessment.

- 'Key results' and interpretations are presented with a discussion on the potential development options for the available fresh groundwater, and resource development considerations.
- 'Recommendations' from the hydrogeological and geophysical investigation.
- 'References', which include the reports used for this investigation.

1.5 Purpose of report

This report summarises and synthesises the hydrogeological activities and results of this project for the purposes of:

- improving the understanding of the geology and hydrogeology of the selected sites;
- assessing the fresh groundwater potential of the selected sites for domestic water supply purposes;
- identifying drilling targets for development as water supply wells, including expected site conditions, depths to water-bearing formations, and anticipated water quality and yields; and
- Collating geological, hydrogeological and other relevant information to assist with future investigations and water supply development.

2. Background

2.1 Geographical location and social structure

Ambae (also known as Aoba) is a northeast-southwest (NE-SW) trending volcanic island located within Penama Province (Fig. 1) in the north-central part of Vanuatu Island (Nemeth and Cronin 2008). The island is 50 km east of Santo and 20 km west of Maewo and is located between longitudes 167.6°E and 168.0°E, and between latitudes 15.2°S and 15.5°S, with an estimated land area of 405 km^2 (Terry 2008). The island is steep and rugged and, as a result, the 276 extended family settlements and villages are dispersed and restricted to the lower slopes within 4 km of the coast (Cronin et.al 2004).

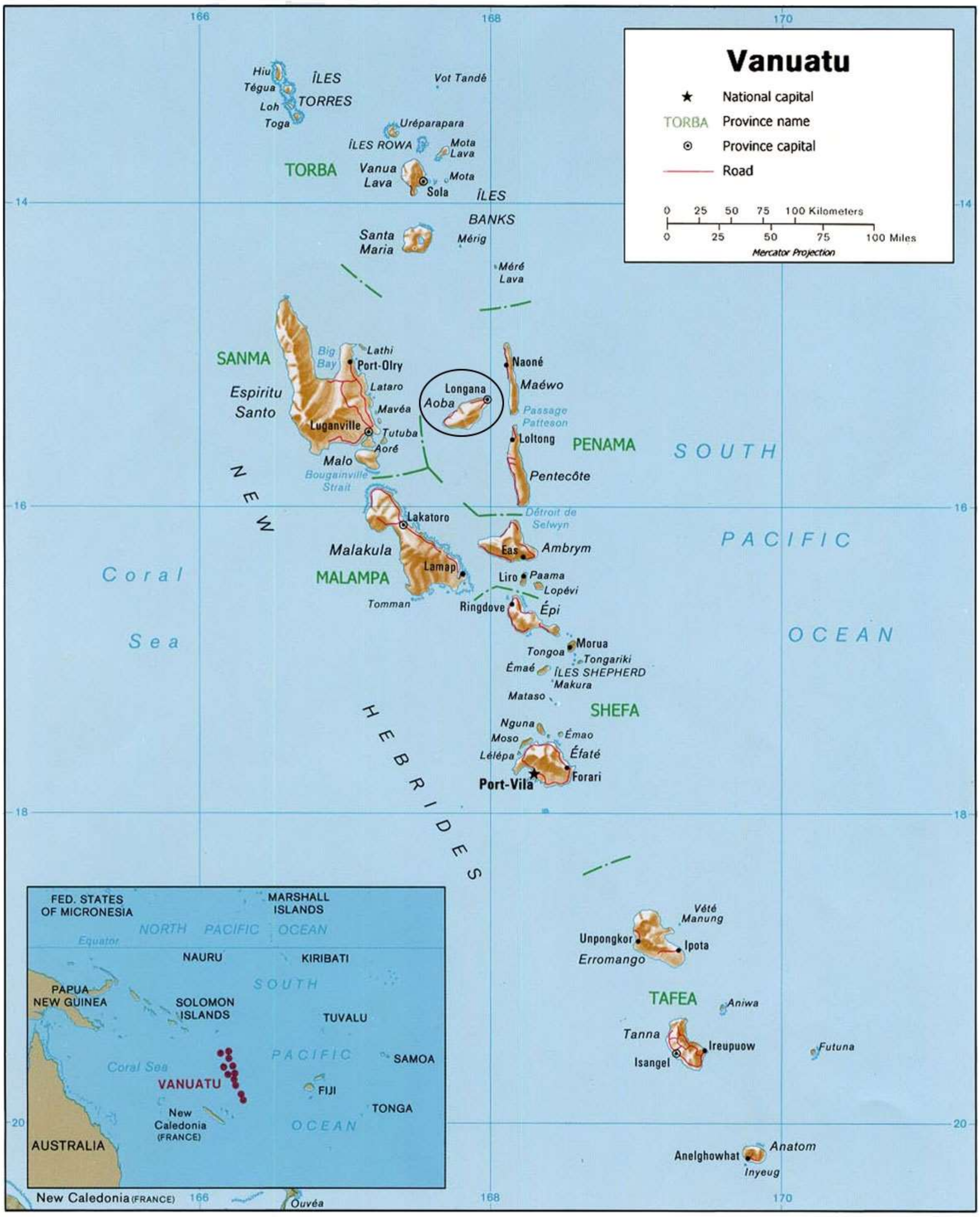

Figure 1. Administrative map of the Republic of Vanuatu (from: www.nationsonline.org).

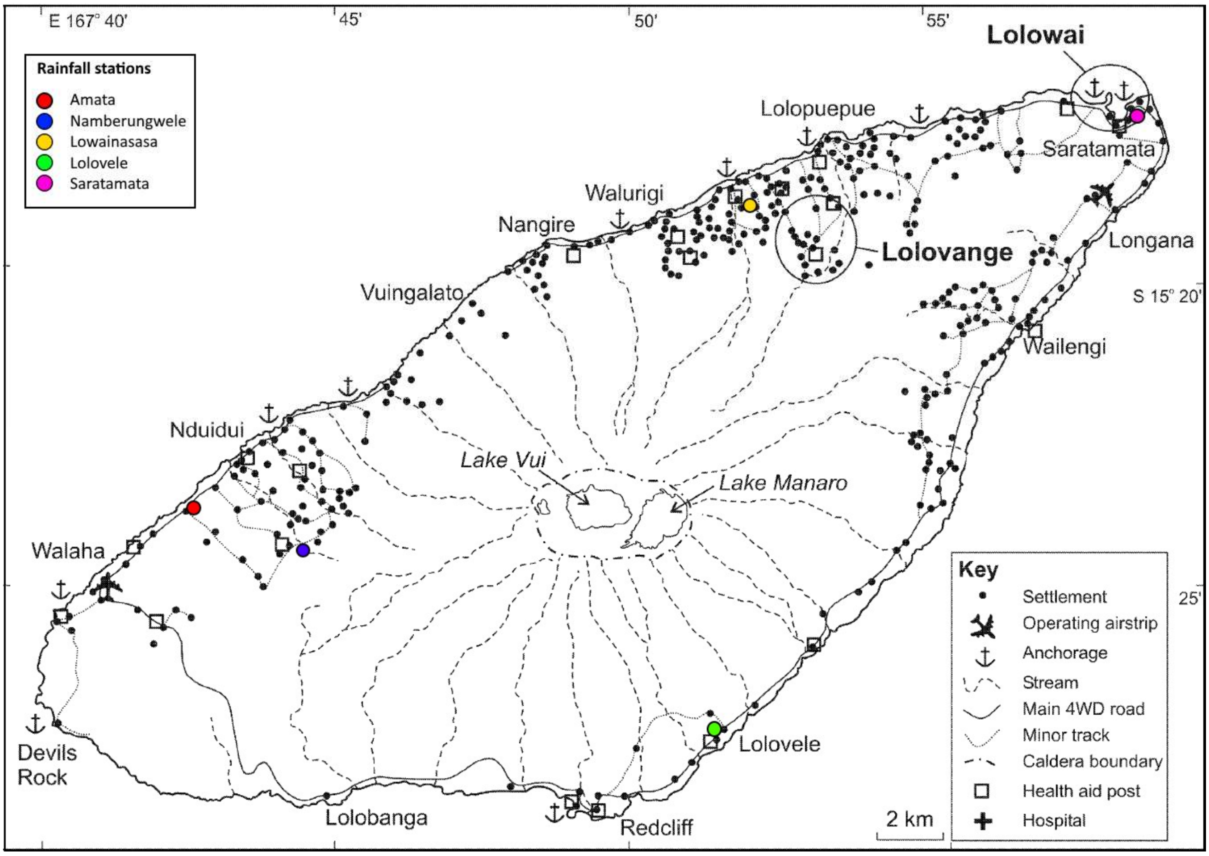

Figure 2. Ambae Island showing the location of settlements, rainfall stations and major stream channels (Cronin et.al, 2004).

This field groundwater assessment was conducted within the districts of Ndui Ndui and Walaha in southwest Ambae. The choice of these districts was the result of an objective selection process undertaken by the Vanuatu government, which rated these districts as highly populated outer island communities that are adversely impacted by ongoing water supply issues during extended dry conditions, as exemplified during the recent 2015– 016 El Niño drought.

Ambae has four council areas: North, South, East and West. Each council area has three to four wards, with each ward comprising two to four custom institutions, or *nakamal*. A *nakamal* consists of two to four family groups or settlements (Cronin et.al. 2004). Land on Ambae, as with most outer islands in Vanuatu, is owned by a custom owner,[1] and decisions on land access and use are made by custom owners and chiefs or the custom land tribunal[2] (Republic of Vanuatu 2013).

Island-wide administration is achieved through an established hierarchical structure where the Penama Provincial Council oversees the administration of Pentecost, Maewo and Ambae Islands. The council is composed of elected representatives from the islands, plus representatives of women's and

[1] Custom or *kastom* owners refers to any lineage, family, clan, tribe or other group who are regarded by the rules of custom, following the custom of the area in which the land is situated (Republic of Vanuatu 2013)

[2] Custom area land tribunal means a customary institution consisting of chiefs and other persons knowledgeable in custom who will apply the rules of custom of the custom area to determine the custom owners of a land area. This tribunal can also be established as a joint custom area land tribunal where the land concerned lies within two or more custom areas (Republic of Vanuatu 2013)

youth groups, chiefs and churches. A provincial administration centre is located in Saratamata, northeast of Longana (Fig. 2), where other government offices such as the police, health, education and women's affairs, are also present (Cronin et. al. 2004). An Area Council Administrator or Secretary is appointed for each of the four council areas to assist with the administration of the wards (more commonly known as Districts on Ambae). There are separate villages within each district, which administratively are referred to as *nakamal*s, representing the traditional use and ownership of land and rules of custom in which family groups reside.

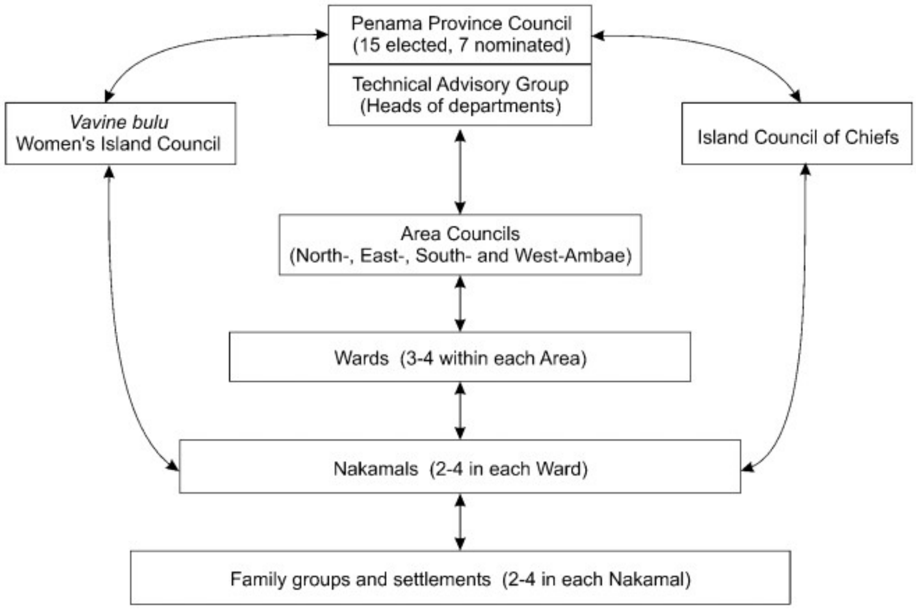

Figure 3. Generalised social structure of Ambae Island communities (Cronin et.al. 2004).

2.2 Population and land use with a focus on households, land use and water use

The population on Ambae is approximately 10,407 based on the 2009 national census (Government of Vanuatu, 2009), and is 33.7% of the total population for Penama Province, and 4.5% of Vanuatu's entire population. The island population recorded in 1999 was 9400.

Land use in most communities on Ambae is focused on subsistence agriculture, with observations from the team that the main cash crops include kava, copra and cocoa. Future cash crops may include sandalwood. These activities are concentrated around the lower parts of Ambae's slopes towards the coast. Some crops of kava are grown on the hilly and steeper terrain where rainfall and more temperate climate is more favourable for kava farming. During dry periods, the population has limited alternative water sources; there are no flowing streams and very few springs, and these are located at a significant distance from settlements. The population is reliant on accessing the brackish water found on the coast during low tide. This lack of an alternative water source and reliance on rainwater places great social and economic stress on the communities, with regard to both potable water needs and food security.

2.3 Climate and rainfall analysis

Ambae, and all of Vanuatu, has a tropical wet/dry maritime climate moderated by the southeast trade winds. The hot and wet season is from November to April, when most severe tropical cyclones occur. A drier warm season extends from May to October when droughts are more likely to be expected

(Terry 2008; White 2016a). Ambae's NE-SW orientation, together with the island's steep high topography in the central section, creates a boundary to the southeast, moisture-laden air masses. Consequently, most of the precipitation occurs on the windward side, between the south and northeastern side of the island, as well as on the summit. West Ambae, on the island's other end, experiences leeward conditions, creating a rain shadow effect where dry and hot weather is common.

There are seven long-term rainfall stations across Vanuatu, with the closest climate station to West Ambae being at Pekoa Airport on the southeast tip of Santo Island (Fig. 2). Pekoa station has nearly 45 years of monthly rainfall readings (White 2016a). However, caution is required when attempting to transpose the rainfall data from Pekoa to West Ambae due to the distance between the islands, the known rain shadow effect on west Ambae, and orographic impacts due to the Ambae's steepness. Pekoa is directly exposed to the moisture-laden southeast trade winds and experiences more rainfall than West Ambae. Location details and statistical rainfall data from the long-term stations are summarised by White (2016b) and are illustrated in the tables below.

Pekoa station has an annual rainfall of 2,423 mm with a distinct wet season (November to April), and dry season (May to October). The monthly averages of 415 and 387 mm (Table 1) were recorded for the wet and dry season, respectively. The calculated coefficient of variation (Table 1) for Pekoa's annual and seasonal values confirms the area as having highly variable rainfall. This high coefficient of variation impacts on the reliability of rainwater harvesting and rainfall-dependent springs.

Table 1. Rainfall summary from the seven long-term stations around Vanuatu.

Station Name		Port Patterson	Sola	Port Patterson – Sola*	Pekoa Airport	Lamap	Bauerfield	Port Vila (Nambatu)	Whitegrass	Aneityum
Location Details & Data Quality	Province	Torba	Torba	Torba	Samna	Malampa	Shefa	Shefa	Tafea	Tafea
	Island	Vanua Lava	Vanua Lava	Vanua Lava	Santo	Malekula	Efate	Efate	Tanna	Aneityum
	Elevation (m ASL#)	42	18	30	45	24	21	20	7.8	7
	Latitude	13° 52'S	13° 54'S	13° 53'S	15°31'S	16°26'S	17°42'S	17° 45'S	19° 27' S	20° 14'S
	Longitude	167° 33'E	167° 29'E	167° 31'E	167°13'E	167°48'E	168°18'E	168° 18'E	169° 13' E	169° 46'E
	Years	1954-1972	1971-2016	1954-2016	1971-2016	1961-2016	1972-2016	1953-2016	1972-2016	1952-2016
	Missing monthly data	1/228	60/542	58/746	5/542	4/662	12/530	4/658	9/530	0/770
Annual Rainfall Summary	Mean (mm)	4067	4080	4092	2423	2018	2259	2165	1255	2314
	STD (mm)	762	915	853	694	534	550	542	362	515
	CV*	0.187	0.224	0.209	0.287	0.265	0.244	0.25	0.289	0.222
	Maximum (mm)	5641	5588	5,641	3480	3700	4104	3,603	2,026	3779
	Minimum (mm)	2818	2437	2,437	685	1299	1097	1,091	607	1294
May–October summary	Mean (mm)	1839	1766	1790	873	735	733	717	411	811
	STD (mm)	529	612	588	387	290	308	291	198	257
	CV	0.287	0.347	0.329	0.443	0.395	0.421	0.405	0.482	0.316
	Maximum (mm)	2800	3093	3093	1530	1414	1596	1534	1011	1498
	Minimum (mm)	695	930	695	153	215	185	134	86	385
November–April Summary	Mean (mm)	2310	2249	2307	1547	1268	1490	1444	830	1501
	STD (mm)	393	580	490	415	349	394	376	282	472
	CV	0.17	0.258	0.212	0.268	0.275	0.264	0.26	0.34	0.314
	Maximum (mm)	3096	3911	3911	2537	2280	2436	2439	1538	2642
	Minimum (mm)	1597	1323	1323	405	791	746	766	345	540

m ASL = metres above sea level

* CV refers to the coefficient of variation, which equals the standard deviation divided by the mean and is a measure of how much the monthly records deviate from the long-term mean.

In addition, there are five stations in Ambae that have been recording daily rainfall during the last three to eight years, although there are frequent gaps in their records (Table 2). Nevertheless, some interesting conclusions could be drawn by studying these short-term records.

As observed in Figure 4, the rainfall stations of Amata and Namberungwele are located within Ndui Ndui District and clearly show the differences in rainfall between the coastal and lower-slope areas, respectively. The coastal areas receive half of the annual mean rain that falls on the lower slopes of Ndui Ndui District, with this ratio decreasing to 44% during the dry season. The lower coefficient of variation in Namberungwele indicates lower rainfall fluctuation throughout the year, suggesting a somewhat higher resilience against droughts as compared with low-elevation coastal areas, which show a very high variation, especially during the dry season. The highest mean annual rainfall is recorded in the highest-altitude station (Lowainasasa), reflecting again the influence of altitude. Lolovele station, albeit at low elevation, shows a high mean annual rainfall, supporting the implication of South Ambae generally receiving more rain.

Table 2 Rainfall summary from the five short-term stations in Ambae.

Station name	Altitude (m)	Years	Mean rainfall (mm)			Standard deviation			Coefficient of variation		
			Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr
Lowainasasa	322	2009-2016	4114	1411	2703	1667	697	1231	0.41	0.49	0.46
Lolovele	36	2013-2016	3307	1210	2097						
Namberungwele	227	2010-2017	2961	720	2241	736	272	571	0.25	0.38	0.25
Saratamata	27	2008-2015	2325	839	1486						
Amata	17	2012-2017	1467	315	1153	707	339	510	0.48	1.08	0.44

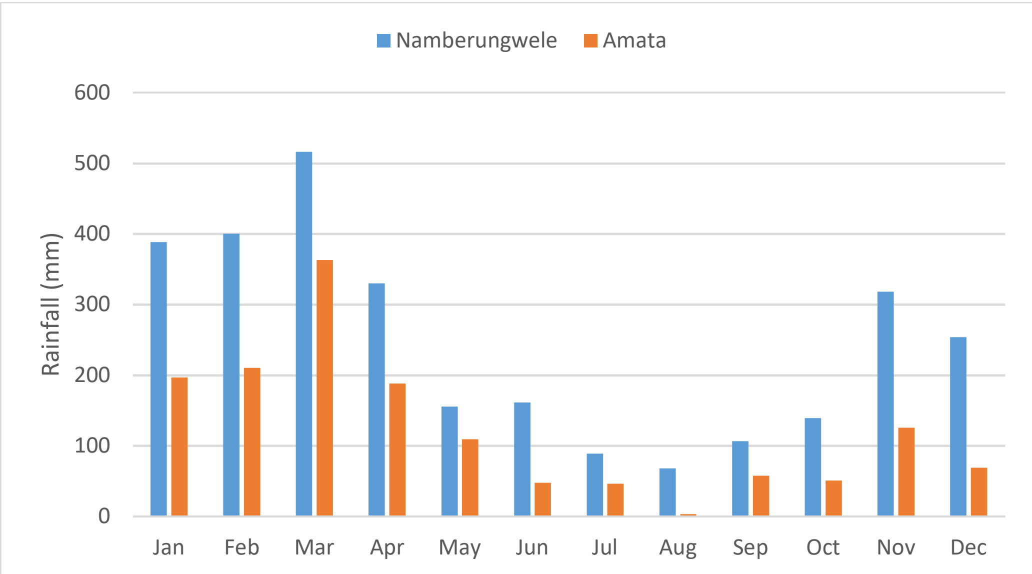

Figure 4 Comparison of monthly rainfall between a low-elevation (Amata) station and a high-elevation (Namberungwele) rain station in the study area.

The country-wide drought vulnerability assessment by White (2016a) and the subsequent identified hot spot analysis based on historical rainfall data (White 2016b) provided valuable insights into the long-term variability, particularly periodical and prolonged low measurements, in rainfall and the factors considered for drought vulnerability.

The rainfall study looked at several analyses, including the assessment of lowest recorded annual and seasonal rainfalls in Vanuatu and the intensity of the corresponding El Niño-Southern Oscillation event. Table 3 shows that the 1982–1983 drought event was controlled by a strong El Niño. As communicated by the people of Ambae, the 1982–1983 drought was experienced as one of the most severe droughts in memory. Interestingly, this event was ranked higher than the 1997–1998 low rainfall period, which was commonly known to be the worst drought event in many parts of the Pacific. While the 1997–1998 event was strong, it had a marginal effect on water resources. This was attributed to the occurrence of Tropical Cyclone Dani during this drought period, which provided episodic high rainfall and brought much-needed water to the islands that were facing a water shortage.

Table 3. Assessment of historical drought events around Vanuatu and their connection to El Niño (White 2016b).

Rainfall Station	Annual	May–October	November–April
Port Patterson - Sola*	1993 unknown El Niño intensity	1966 Strong El Niño	1992–1993 unknown El Niño intensity
Pekoa Airport	1983 very strong El Niño	1983 very strong El Niño	1982–1983 very strong El Niño
Lamap	1995 weak El Niño	1994 weak El Niño	1982–1983 very strong El Niño
Bauerfield*	1983 very strong El Niño	1987 moderate El Niño	1982–1983 very strong El Niño
Port Vila (Nambatu)	1978 weak El Niño	1987 moderate El Niño	1982–1983 very strong El Niño
Whitegrass	1993 unknown El Niño intensity	1983 very strong El Niño	2009–2010 moderate El Niño
Aneityum	1983 very strong El Niño	1995 weak El Niño	1972–1973 strong El Niño

The hot spot assessment also looked into the reliability of rainwater tanks and the probability of water shortage during low rainfall periods. It was clear that rainwater-harvesting systems will not provide the continual supply of potable water necessary, thereby indicating that most islands are vulnerable to freshwater shortages. Therefore, rainwater harvesting should not be relied on as the main source of water supply in rural, remote and peri-urban communities in Vanuatu, and where it exists, alternative sources of water should be explored, with groundwater being the most attractive option, provided it can be protected, regulated and well managed.

The drought vulnerability assessment was undertaken to assist the Vanuatu government towards the development of a National Water and Sanitation Strategy for Response, Recovery and Resilience following Tropical Cyclone Pam and the recent El Niño drought. Part of this work included the assessment of the drought monitoring index, which considers five key indicators: water quantity, water quality, water access, water-related health, and reports on social conflicts arising from water

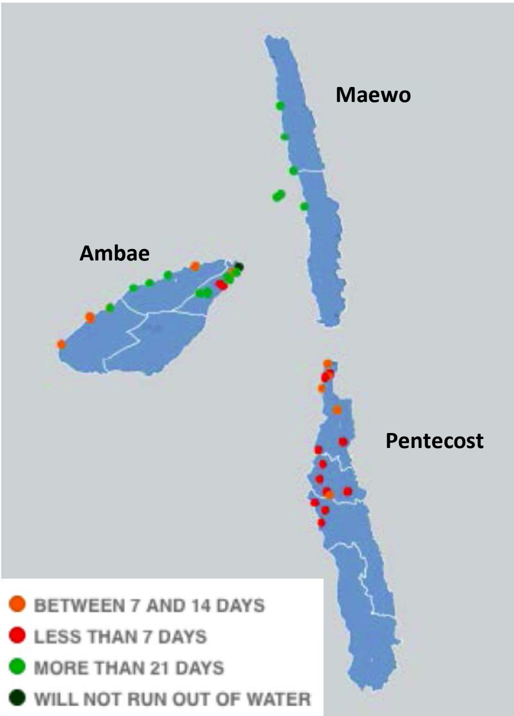

Figure 5. Drought monitoring index of Penama Province (White 2016a)

shortages. This assessment was conducted around the 29 islands in Vanuatu, with priorities given to areas where 75% or more of the communities are dependent on rainwater harvesting, based on the 2009 census. Community groups, representing leaders, gender groups, youth groups and health workers in selected areas were engaged. For instance, in Penama Province, a number of communities were visited and assessed on Ambae, Maewo and Pentecost, including West Ambae by White (2016a). Figure 5 shows Pentecost, West and North Ambae to be more vulnerable based on the limited water supplied by rainwater harvesting, which can be exhausted within 14 days. The high dependency on rainwater harvesting contributes to the vulnerability of these communities, and which either the usage of unsafe water sources or relocation towards a safer water source will be expected (White 2016a).

In general, the climate information and drought monitoring index identifies the north central area of Vanuatu as being susceptible to drought. Alternate water sources such as groundwater should be investigated to build resilience.

2.4 Geology, geomorphology and hydrogeology

Ambae is part of the Vanuatu active volcanic arc and is regarded as the most voluminous active volcanic island in the country, with its summit standing at 3,900 m above the sea floor and emerging up to 1,496 m above sea level (Nemeth and Cronin 2008). Its elongated shape and orientation has the characteristics of a rift zone with an en-echelon offset structure on each side of the central vent system. The rift system forms an incipient graben structure with scoria cones, lava spatter cones and multiple lava flows concentrated along its margin (Warden 1970). Plateaus of lava have been observed around the south while multiple layers of tuffs and interbedded tuffs and lavas have been found adjacent to the central volcanoes (Warden 1970).

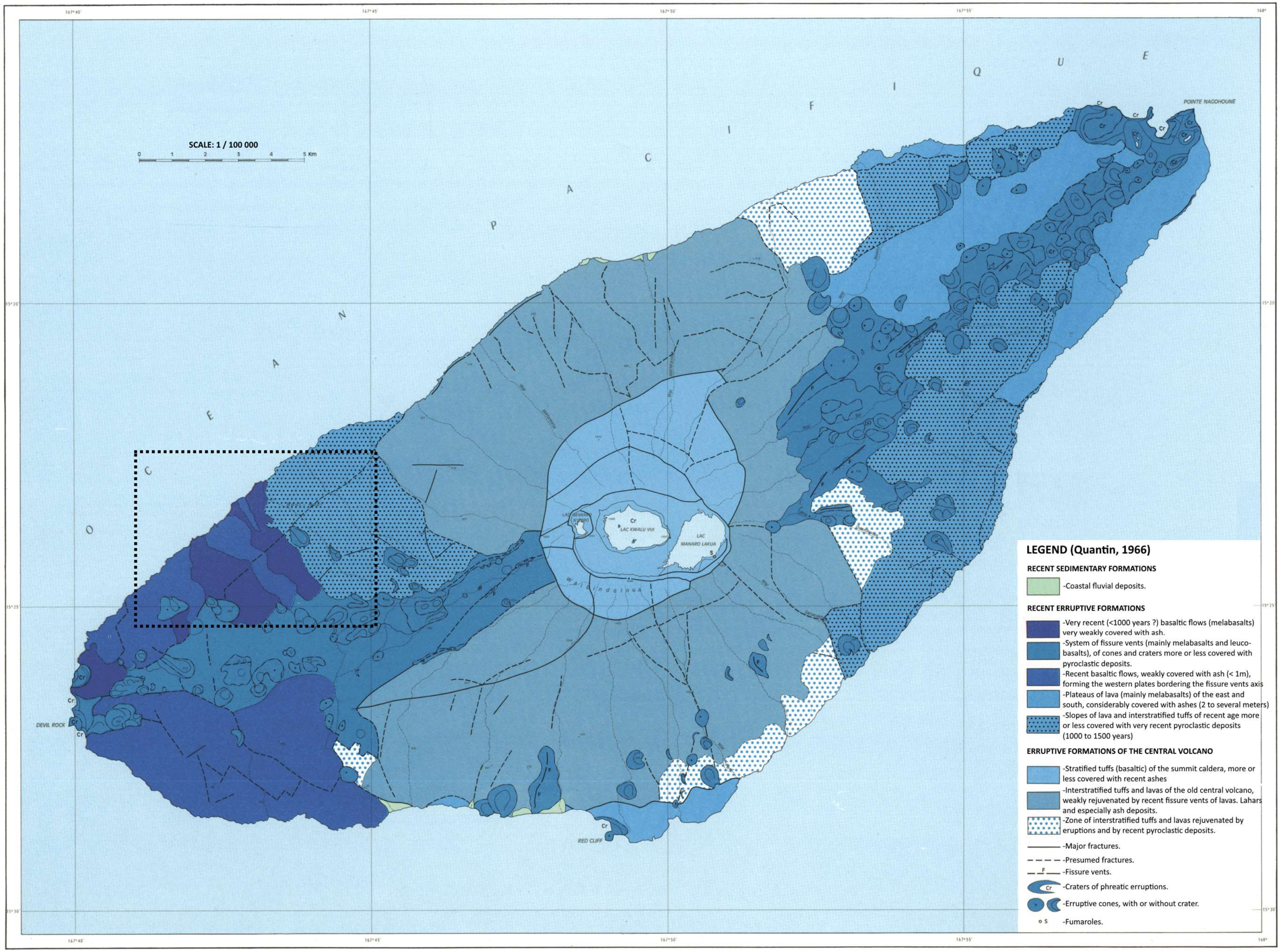

Figure 6. Geological map of the study area (Quantin 1966).

West Ambae, including Ndui Ndui and Walaha, is covered by four major units mapped by Warden (1970) and summarised below with the youngest unit on top:

a. **Recent materials.** This refers to very recent (< 1,000 years) basaltic flows (melabasalts) that are weakly covered with ash.
b. **System of fissured vents**. This includes mainly melabasalts and leucobasalts, and cones and craters more or less covered with pyroclastic deposits.
c. **Recent basaltic short flows of viscous lava (coulees)**. These includes coulees that are weakly covered with ash (< 1 m), forming the western plates bordering the fissure vents axis.
d. **Slopes of lava**. These are lava flows and interstratified tuffs of recent age (forms of melabasalts in Lolosori or leucobasalts in Ambore), more or less covered with very recent pyroclastic deposits (estimated age of 1000–1500 years).

The geomorphology of Ambae is characterised by a dominant steep and rugged terrain concomitant to the summit and concentrated around the island's central section. Adjacent to the higher slopes of the NE–SW rift axis are swarms of dome-like landforms and gullies which grade into gently-dipping slopes and coastal planes fringed by narrow beaches comprising mixed terrigenous and marine sediments (Terry 2008). Drainage consists of well-defined, intermittent streams that exhibit a radial flow pattern from the summit's lake storage (Fig. 2). These landforms and drainage features indicate the strong interaction between plate tectonics, wave action and hydrogeological processes that helped shape Ambae over time.

Although limited hydrogeological information was available, the presence of 60 million m^3 of lake water perched in the summit caldera, together with observed springs discharging around the high land and along the shorelines where coral growth is inhibited in some areas by freshwater intrusion (Cronin et. al. 2004; Terry 2008), indicate groundwater potential in this volcanic framework. These expressions of water suggest that the occurrence of groundwater would likely be through perched aquifers, localised fracture zones, and freshwater-lenses, suggesting a variety of storage and discharge settings, be it impoundment, preferential or density controlled. The spatter cones along the rift axis around West Ambae also suggest a high density of localised fractures zones and/or fissures that would enable groundwater storage. These hydrogeological settings will be investigated in detail in later sections.

2.5 Current water supply situation

The main sources of water around West Ambae, as in most outer islands, are rainwater harvesting, groundwater springs, and boreholes (White 2016a). Rainwater was observed to be either privately or communally owned. Figure 7 shows a church, an example of a communal system, having a rainwater tank that is connected to a few gutters and a transmission pipe. The capacity and reliability of this system could be easily improved if the entire roof catchment was utilised. This includes installing proper fascia boards and a guttering system to cover the entire roof, and adequately sized downpipes and transmission pipes to the storage tank.

Figure 7. A church with a storage tank attached to inadequate gutters and transmission pipes.

Figure 8. Privately owned catchment system comprising a constructed well raised above ground and two sheets of roofing iron inclined towards the centre of the well.

Figure 8 shows a privately owned rainwater collection system where a well is constructed mostly above the ground and sheets of roofing iron are placed atop the well and inclined inwards the centre to allow water to flow into the well. This system is used to collect freshwater for potable purposes. It is clear that the capacity of privately owned rainwater harvesting systems around Ambae may be limited due to high installation costs, including tanks, fascia boards, gutters, transmission pipes and downpipes, and due to many houses having unsuitable roofing materials (i.e. thatched materials) that do not allow the adequate collection of rainwater.

Figure 9. Borehole drilled by a private contractor along the coast. Several boreholes exhibited strong tidal influence in water level and quality.

A number of boreholes were recently drilled on Ambae, mostly around the coast, but with only moderate success. The drilling explored the freshwater lens potential underlying the coastal plains. The freshwater lens that is believed to exist under the island is thought to control the numerous groundwater springs observed along the coast. Figure 9 shows one of the constructed boreholes. Some of these boreholes indicate brackish water and exhibit strong tidal influence. These wells are susceptible to becoming brackish either when over pumped or during prolonged dry periods. The drilled wells, however, are relied on for potable needs and the communities are willing to accept the brackish taste during dry periods (this is based on field observations and anecdotal information provided by the Area Administrator, with no source document). Observations during the field study indicated that one of these boreholes drilled at Loone (on 25 March 2015) indicated a standing water level of 2.71 m, with a total depth of 4.7 m from ground level and an electrical conductivity (EC) of 5,471 µS/cm.

These existing water sources, however, have limited storage capacity and are prone to deteriorating water quality during prolonged dry conditions, which threatens the livelihood and security of West Ambae communities. As a consequence, remote islands such as Ambae incur high costs for transporting water when emergency interventions are undertaken (White 2016a).

3. Field Survey Methodology

3.1 Geological settings for groundwater occurrence

The only direct observation of groundwater in West Ambae is through the existing boreholes in Loone that target the shallow freshwater lens near the coast, and the presence of subsurface coastal springs that discharge freshwater into the sea. The coastal spring discharge supports the concept of the existence of an extended freshwater lens system that is fed by infiltrating rainwater at higher elevations. The high susceptibility of these coastal bores to saltwater intrusion confirms the thin and sensitive nature of the freshwater lens system, which makes it unsuitable for a reliable water supply.

In the absence of drilling and subsurface information at higher elevations, two types of probable, documented geological settings, offering suitable conditions for groundwater occurrence, are recognised. The first geological setting involves the occurrence of perched groundwater in between the various lava flows, which are often interbedded with weathered and pyroclastic materials. The greater the age difference between two lava flows, the higher the probability of weathering by the underlying flow and the higher the chance for groundwater occurrence near the contact. This is due to the impervious character volcanic rocks acquire when they become weathered. Weathering tends to reduce the permeability of volcanic rocks due to the presence of clayey secondary minerals such as montmorillonite, a product of weathered basalt. In places, the flows are interbedded with ash beds, “baked soils” and tuff that also form confining layers subparallel to the topography.

The second geological setting involves the potential groundwater impoundment between intrusive dikes. According to Pryet et al (2012), surficial expressions such as eruptive fissures and cones may indicate the position of subsurface dikes. Moreover, when cones are elongated or aligned, as observed in the study area, they are likely to reveal the presence of dike swarms (Acocella and Neri 2009). Rising magma that does not erupt at the land surface cools within fissures and forms thin, near-vertical sheets of massive rock that intrude existing permeable lava flows. Moreover, eruptive fissures and cones may have resulted in some fracturing along their edges, which may allow groundwater to occur at shallow depths.

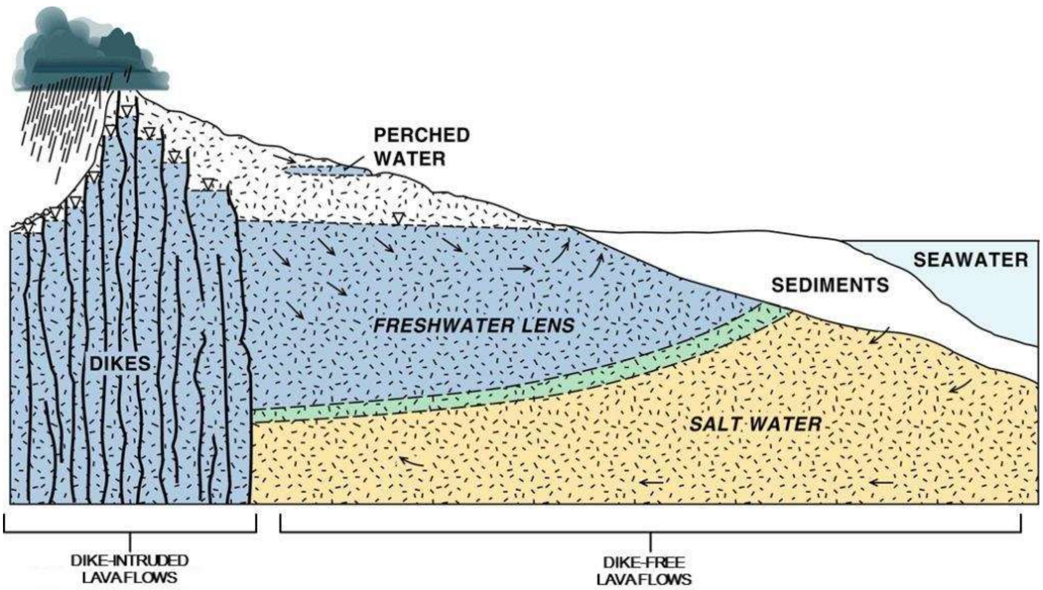

Figure 10. Schematic cross section showing groundwater occurrence in the dike-impounded and freshwater lens systems (Oki 2002).

3.2 Resistivity survey

The basic principle of operation in electrical resistivity methods is the injection of 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. This value can provide a range of information regarding the survey site. Different types of soil and geological formations have different resistivity responses as a function of the soil and rock depth, porosity, permeability, ionic content of pore fluids, and clay mineralisation. Resistivity is useful in determining the depth, thickness and extent of groundwater bearing zone(s). 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.

To get as much ground information as possible, resistivity should be measured in many positions. By using several multi-electrode cables, it becomes possible to measure the resistivity variation along a survey line. The ABEM Terrameter LS was used with four electrical cables, each with 21 electrode take-outs. The 'roll-along' technique was employed to create seamless profiles longer than the four-cable spread along the survey lines. The multiple gradient array was chosen as the electrode configuration protocol because it offers good signal-to-noise ratio and good resolution to horizontal and vertical structures.

Because basaltic rocks and pyroclastic deposits are the main geological formations present in the area, resistivity is expected to be high. Expected resistivity ranges for groundwater-bearing formations were based on literature-documented values. Marzan (2005) proposed a resistivity range of 400–550 Ohm.m for weathered basalts potentially holding groundwater in the Afar Region in Ethiopia. For the Deccan traps in the Chandrabhaga River Basin in India, Rai et al. (2013) proposed a much lower range of 20–70 Ohm.m for saturated weathered and fractured basalt whereas anything above 70 Ohm.m reflects massive basalt. Gupta et al. (2016) interpreted a resistivity range of 30–110 Ohm.m in the Raigad District of India, as saturated fractured basalt. Kebede (2001), however indicated a range of 100–300 Ohm.m for saturated, rather dense basalts, encountered in the Krísuvík geothermal area of Reykjanes Peninsula in Iceland. D'Ozouville et al. (2008) identified the resistivity range of 50–200 Ohm.m as hydrogeologically interesting in the Galapagos Islands. Based on these references, resistivity values of up to 250 Ohm.m were treated with confidence with respect to groundwater development potential whereas anything between 250 Ohm.m and 500 Ohm.m are considered of secondary importance. The identification of potential groundwater was also determined from the relative values of the resistivity compared with the geological background. For hard rock geologies such as the ones found in West Ambae with generally high resistivities, zones of lower resistivities are targeted as having higher groundwater potential.

3.3 Selection of survey locations

In order to determine suitable locations for the geophysical surveys, we considered the following parameters: potential groundwater occurrence, water demand, elevation and accessibility.

3.3.1 Groundwater occurrence

After identifying possible geological models supporting groundwater occurrence, the locations of survey survey lines were selected based on existing geological maps, Google Earth and field observations of topographical and geological features. Surficial geology was generally difficult to assess due to dense vegetation (e.g. rainforest and coconut plantations) obscuring outcrops. Geological maps were used to identify locations where recent lava flows overlay older flows with the intention to investigate the groundwater potential at contacts between the flows. Geological maps and Google Earth were also used to identify the location of small eruptive cones, fissure vents, and lineaments. Field observations around these surficial features supported the identification of exact locations based on site accessibility.

3.3.2 Water demand

Ndui Ndui and Walaha districts were identified by the government as top-priority areas in need of additional water supplies besides existing rainwater harvesting systems. The highest demand is concentrated in the populated area around the Ndui Ndui health centre due to a combination of greater population density and reduced rainfall on the lower slopes and coastal fringes. However, communities in need of additional water supplies extend uphill up to an elevation of 400 m.

3.3.3 Elevation

Elevation was another parameter playing a key role in the selection of survey sites. The intention is to eventually supply the developed groundwater source to as many communities as possible using gravity-fed water supply systems. We, therefore, gave preference to areas located close to the highland communities. Moreover, drilling at lower elevations into the coastal freshwater lens system had already proved to be ineffective due to the susceptibility of boreholes to saltwater intrusion. The thin freshwater lens located close to the shore is unable to sustain the required pumping rates without causing saltwater intrusion toexisting boreholes. It became clear that any groundwater development activities in West Ambae should preferably be established at higher elevations. We generally tried to stay above 100 m in elevation to prevent underlying seawater to be picked up by the resistivity survey.

3.3.4 Accessibility

Drilling site suitability also depends on accessibility and road network conditions. Consideration was given to undertaking geophysical surveys in areas that could be accessible by a drilling rig. Even performing the geophysical survey requires a certain level of accessibility and suitable conditions such as the ability to maintain a relatively straight survey line. Other factors complicating the survey execution includes steep topography and dense vegetation limiting the elevation survey using GPS techniques.

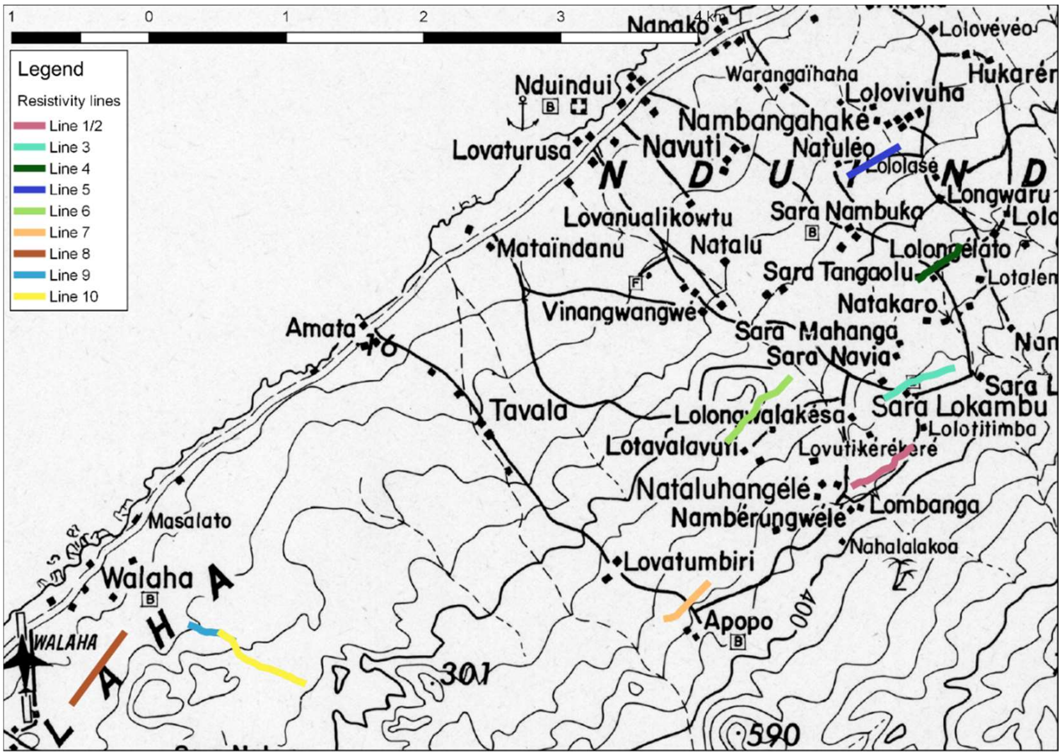

Figure 11. Topographical map of study area (base map after Royal Australian Survey Corps 1982)

Nine locations were selected that fulfilled the various requirements. Four locations were based on the conceptual model of possible groundwater occurrence in-between lava flows and five locations were based on the conceptual model associated with surficial geological features. As indicated in Figure 12, survey lines were performed in most cases along existing roads. We performed 10 survey lines, two of which (lines 1 and 2) were performed along the same survey line using different electrode separation lengths (2.5 m and 5 m). This was done in order to assess survey capabilities in terms of penetration depth and level of detail, and to be able to better determine suitable separation lengths during the subsequent survey lines.

Table 4. Summary of resistivity lines.

Line	Line code	District	Location	Direction	Length (m)	Electrode spacing (m)
1	WA-ND-L1	Ndui Ndui	Nambérungwélé - Lolotitimba	SW-NE	500	2.5
2	WA-ND-L2	Ndui Ndui	Nambérungwélé - Lolotitimba	SW-NE	500	5
3	WA-ND-L3	Ndui Ndui	Sara Lokambu - Sara Longwandu	SW-NE	500	5
4	WA-ND-L4	Ndui Ndui	Lolongélato	SW-NE	400	5
5	WA-ND-L5	Ndui Ndui	Natuléo - Lololasé	SW-NE	400	5
6	WA-ND-L6	Ndui Ndui	Lotavalavuti - Lolongwalakésa	SW-NE	640	4
7	WA-ND-L7	Ndui Ndui	Apopo	SW-NE	400	5
8	WA-WH-L1	Walaha		SW-NE	600	5
9	WA-WH-L2	Walaha		NW-SE	320	4
10	WA-WH-L3	Walaha		NW-SE	700	5

All lines were performed along eruptive formations of recent age (1000–1500 years). Lines 1–6 were performed along lava flows and tuff beds interstratified with each other and, in places, heavily covered with pyroclastic deposits. Lines 7–10 were carried out along basaltic flows (melabasalts) weakly covered with ash layers (< 1 m thick). A number of survey lines were deliberately performed along the edges of spatter cones with the intention of targetting potential fracturing associated with the system of fissure vents responsible for cone formation.

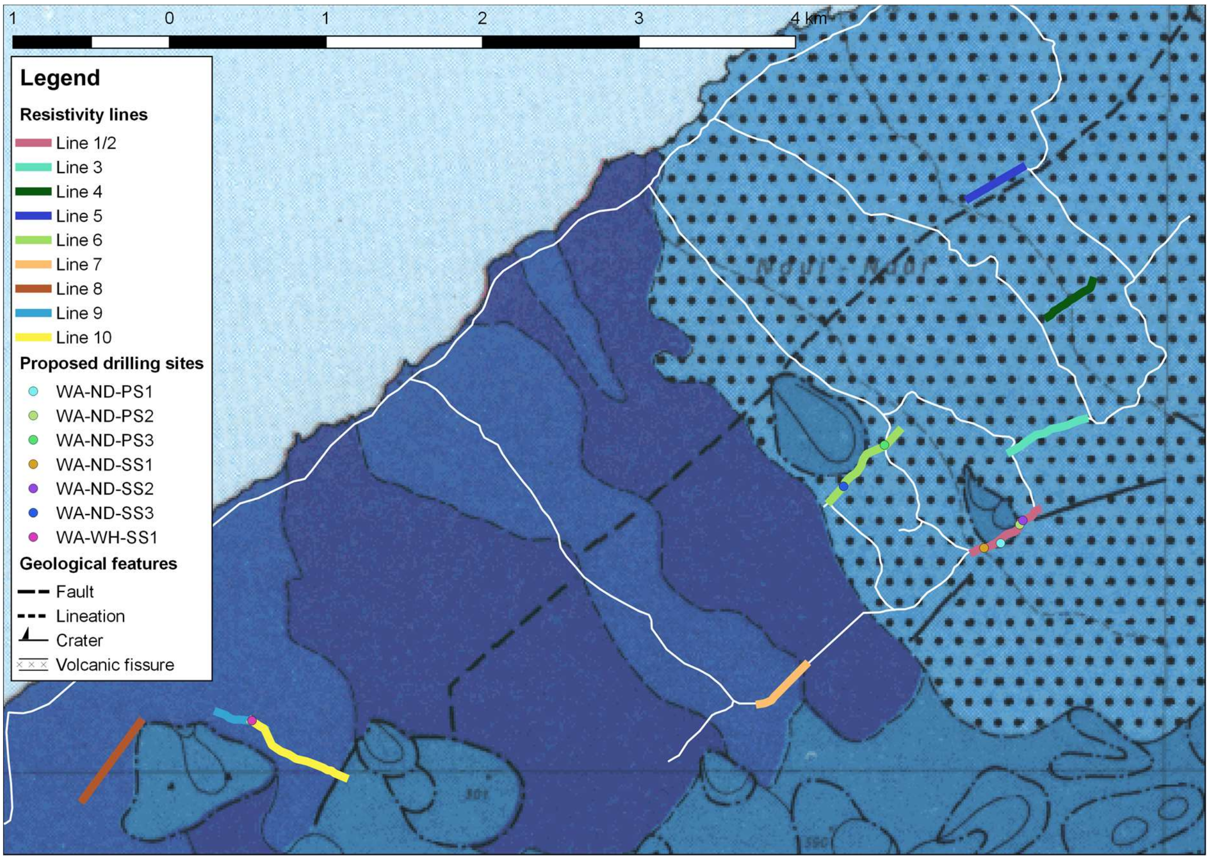

Figure 12. Resistivity lines and proposed sites (base map after Quantin 1966). For geological map legend, refer to Figure 6.

4. Results and discussion

4.1 Geophysical results and interpretation

The model inversions for the 10 survey lines are presented in Annex 3.

Line 1/2: Namberungwele – Lolotitimba

Lines 1 and 2 were performed along the same survey line so their inversions represent the same resistivity distribution as recorded using different electrode separation lengths. A 2.5 m spacing (line 1) allowed for a penetration depth of ~45 m whereas a 5 m spacing (line 2) allowed for a penetration depth of ~85 m. Line 1 allowed for a detailed representation of the shallow subsurface, although the resolution – and, therefore, level of accuracy – decreases with depth.

Line 1 suggests a general occurrence of fresh groundwater along the entire survey line length. Geophysics suggest that water infiltrates in three different areas located at 70–105 m, 155–180 m and 310–325 m along the survey line, whereas the remaining sections are covered with high-resistivity pyroclastic deposits (12–18 m thick). The second infiltration area coincided with a dry stream crossing the road along which the survey line was performed. Three high-resistivity subsurface features appear at 65 m, 150 m and 320 m, and seem to be acting as barriers to groundwater flow. These subvertical features appear to be associated with the nearby spatter cone and are interpreted as probable dikes that have formed by lava intrusion in vent zones in lava flows and tephra deposits. The dikes act as barriers against lateral groundwater flow, compartmentalising it at different heights.

From line 1 it is not clear how deep the groundwater-bearing formation extends. Line 2, having a larger electrode spacing and, therefore, a greater depth of investigation, allowed for a better and more reliable evaluation of the aquifer's vertical extent. The shape of resistivity distribution suggests a perched groundwater body that is impounded between two intrusive dikes. The perched situation is likely due to low-permeability layers encountered at 55 m depth. These low-permeability layers could either be weathered or massive basalts. The vertical and steeply inclined character of dikes seems to be poorly defined in line 2 probably due to the coarser resolution associated with the larger electrode spacing. Three different groundwater compartments are clearly distinguished and offer the potential for groundwater development.

Line 3: Sara Lokambu – Sara Longwandu

Line 3 was carried out along the road between the villages of Sara Lokambu and Sara Longwandu in a SW-NE direction. A total distance of 500 m was surveyed, and an electrode separation length of 5 m was used with the intention of investigating as deep as possible considering the absence of surficial features suggestive of the presence of dikes and fissure vents. In addition, the close comparison between lines 1 and 2 gave us confidence that the type of shallow groundwater targets we were after would still be observed, despite the lower resolution of the 5-m spacing. The 5-m spacing was thus preferred because it also allowed greater coverage in the same amount of time.

The resistivity distribution is generally high along the entire section, suggesting the absence of any promising drilling targets. A high-resistivity, 10–20 m thick formation (> 1000 Ohm.m) overlies a lower resistivity (500–1000 Ohm.m) formation, probably representing two different lava flows. No groundwater seems to occur along the contact, suggesting either the impermeable character of the upper lava flow not allowing any infiltration, or more likely, the highly porous character of both formations, which allows groundwater to percolate deep into the basal aquifer and eventually discharge through coastal springs into the sea.

Line 4: Lolongelato

Line 4 was carried out in a SW-NE direction at Lolongelato with a 5-m electrode spacing. Despite the site's difficult access, the location was chosen for the presence of a creek and observed lineament at 100 m distance along the line, which may possibly be acting as a feeding point of perched groundwater, similarly to line 1/2. The high resistivity under the creek and along the entire survey line indicates the absence of perched or impounded groundwater settings. The absence of eruptive fissures and cones suggests, consequently, the probable absence of subsurface dikes able to confine groundwater at higher elevations. A thin, shallow and unconfined groundwater body was interpreted to exist, and is believed to be a localised perched aquifer over low-permeability weathered lava flows. This thin body, 5–10 m thick, extends between 125 m and 350 m along the survey line length.

Line 5: Natuleo – Lololase

Line 5 survey was located between Natuleo and Lololase in a SW-NE direction and with a 5-m electrode separation length. The line was run along a road parallel to line 4 at 900 m distance downhill, with the intention of capturing the lateral extent of any interesting resistivity features identified along line 4 (interpretation of line 4 had not been conducted yet). No interesting geophysical features appear along line 5 besides an interpreted very thin (2–5 m), shallow groundwater table perched on low permeability soil and weathered volcanic formations.

Line 6: Lotavalavuti – Lolongwalakésa

Line 6 survey was conducted along the road between Lotavalavuti and Lolongwalakésa using a 4-m electrode spacing. The location was selected on the upslope side of an eruptive cone, a promising setting that gave good results along line 1/2. Particularly interesting resistivity patterns were observed along line 6. A massive dome-shaped feature of very high resistivity (> 5000 Ohm.m) was observed in the central part of the section. This feature is believed to represent the subsurface representation of the eruptive cone, which outcrops 150 m downslope towards to the northwest. A thin (5–10 m thick), unconfined groundwater body is interpreted to be perched on top of the low-permeability massive basalt of the eruptive cone.

An interesting, low-resistivity feature is observed at 500–525 m distance along the line, suggesting the presence of useable groundwater. This vertically shaped feature suggests either groundwater impoundment due to the presence of an intrusive dike or, most probably, fractured basalt sandwiched between massive units (Singhal 1973). Fracturing of the country rock can be caused by dike intrusion due to thermal effects and differences in mechanical properties (Gudmundsson et al. 2003). In fact, a very high-resistivity (> 5000 Ohm.m) vertical feature is present right next to the fracture, and is probably an intrusive dike. The vertical extent of the groundwater body could not be deduced as it extends past the current depth of penetration (~60 m).

Based on the geophysical interpretation, this semi-confined groundwater body seems to be fed by rainwater infiltrating the ground along an area that extends from 445 m to 470 m along the survey line. The identified resistivity pattern suggests a relatively slow recharge rate that may not be able to sustain high abstraction rates. Drilling and a pumping test would be required to further assess groundwater potential. The zone of slightly higher resistivity (300–350 Ohm.m) observed between the groundwater body and the probable infiltration area suggests a slower recharge rate, as opposed to what is observed along survey line 1 for example.

Another interesting feature is observed in the southwest side of the cone at 190 m distance along the survey line. Groundwater seems to infiltrate through a more permeable conduit, although no signs of groundwater accumulation are observed. This location, however, could warrant additional exploration with drilling if an additional groundwater target is required and the location for a groundwater supply, near Lotavalavuti village, warrants further investigation.

Line 7: Apopo

Line 7 was carried out near Apopo Village along a 400-m-long stretch of road. A 5-m electrode separation length was applied with the intention of exploring potential contacts between the recent lava flows prevailing in the area. The resistivity distribution does not suggest any interesting geophysical groundwater potential targets. Resistivities were generally above 1000 Ohm.m.

The penetration depth of investigation, 70–90 m, suggests contacts between the lava flows that generally are no greater than 6-m thick (Warden 1970), were encountered but not distinguished. The absence of low resistivity layers and of distinct resistivity patterns suggests either the impermeable character of the volcanic formation or, more likely, its highly porous character, a similar situation as the one observed along line 3.

Line 8: Walaha

Line 8 was carried out along a low-elevation, 600-m stretch using a 5-m electrode spacing. The location was selected on the downslope side of a volcanic fissure that has caused two eruptive cones. A high resistivity (> 1000 Ohm.m) vertical feature is observed in the central part of the section (270– 20 m distance), probably reflecting another fissure that has developed off the main SW-NE axis. A low resistivity area is observed between 220 m and 270 m distance, indicating groundwater, probably brackish, due to absolute elevation below sea level. Fracturing of the country rock occurring on either side of the fissure may have allowed the seawater to penetrate higher.

Line 9: Walaha

Line 9 was carried out along an uphill NW-SE trending road with the intention of targeting the previous eruptive features from a different angle. The entire survey line is characterised by high-resistivity (> 1000 Ohm.m) lava formations that are partly covered with pyroclastic deposits of very high resistivity (> 5000 Ohm.m). A small and relatively low-resistivity (250–500 Ohm.m) subsurface anomaly appears at 206–230 m distance along the survey line, possibly reflecting a lava tube or tunnel containing groundwater. According to Singhal and Gupta (2010), these features are formed when the surface of lava flows cool and harden but the interior remains fluid and happens to drain out, leaving behind a tunnel-like void. This feature is possibly associated with the mapped fissure vent that extends in a SW-NE direction vertically to the survey line. This feature could also be interpreted as a confined and low-yielding aquifer of limited width.

Line 10: Walaha

Line 10 was carried out as a continuation of line 9 but with a 5-m spacing as opposed to 4-m, to cover as much ground as possible in order to target identified lineament (NW-SE striking). The entire section is characterised by high-resistivity (> 1000 Ohm.m) lava formations that are partly covered with pyroclastic deposits and subsurface dike-like features of very high resistivity (> 5000 Ohm.m). No groundwater bearing formations or targets were indicated from the geophysics.

4.2 Hydrogeological conceptual model

Based on geophysical interpretations and field observations it is concluded that groundwater in West Ambae occurs in four different hydrogeological settings.

- The main basal aquifer, being a freshwater lens floating on denser seawater. The presence of subsurface coastal springs discharging freshwater into the sea supports the existence of a freshwater lens system, fed by infiltrating rainwater at higher elevations. The high susceptibility of the Lone boreholes to saltwater intrusion confirms the thin and sensitive nature of the freshwater lens system, making it unsuitable to provide a reliable water supply.
- Small perched, dike-impounded systems encountered at higher elevations and expected to hold limited amounts of fresh groundwater. Low-permeability layers (weathered or massive basalts) allow groundwater to be held between the dikes. These systems seem to offer the best option for small, but reliable, groundwater development. Additionally, the presence of these geological settings can be tentatively inferred from surficial features and geological maps, allowing for a pre-selection of areas for resistivity survey or even for 'wildcat' drilling.
- Basalts fractured by intrusive dikes, resulting in the formation of conduits allowing for groundwater flow. These fractures are of limited width and appear to be associated with dikes causing the fracturing of the country rock they intrude. The lateral and vertical extent of these features could not be evaluated during this survey. Groundwater potential is considered to be relatively low but could prove valuable at the household level.
- Shallow unconfined aquifers perched on top of massive or weathered, low-permeability volcanic rocks. These aquifers have a thickness of < 10 m and may provide limited potential for groundwater development at the household level.

Extended perched systems — where groundwater occurs near the contact between recent volcanic deposits and older, low-permeability (weathered or massive) deposits — were not observed in this study. These systems are, however, not to be excluded for West Ambae as they have been identified in other islands with similar geological conditions (e.g. Hawaii, San Cristobal, Reunion, Cape Verde).

The presence of eruptive domes, identified on the geological maps as spatter cones, indicates some alignment perpendicular to the main rift zone and suggests the occurrence of dikes intruding weaknesses in the overlying lava and welded pyroclastic flows. It is very probable that a large number of subsurface swarm dikes are present, especially in areas around and between eruptive domes. These subsurface dikes are thought to be able to compartmentalise and store groundwater, particularly when additional fracturing of the country rock was caused during their upward intrusion. As indicated by Underwood et al. (1995), the seaward extent of volcanic vents, represented by lava domes, corresponds to the general boundary between dike-impounded groundwater systems and the freshwater lens system. Line 6 was performed within the dike-impounded system, just before its boundary with the lens system. Beyond that, no impounded groundwater occurrences are expected.

No springs exist in the areas where the survey was performed. At higher altitudes, spring discharges are reported. The presence of springs at these higher altitudes suggests discharge of dike-impounded groundwater where dike compartments have been exposed by erosion and where rainfall is high (Oki 2002).

Streams are generally dry except during strong rainfall events and the unconsolidated colluvial deposits lying in streambeds act as infiltration areas for rainwater. Unless dikes and impermeable layers are present (as it happens in line 1/2), water percolates down to the main basal lens system and flows outwards towards the sea.

4.3 Groundwater resources development options

4.3.1 Expected water quality

Groundwater samples were not obtained during this survey. Bani et al. (2009) conducted analysis of groundwater samples obtained in 2005 a few months before the volcanic eruption that took place in late November (Table 5). Samples were obtained from two springs, one coastal (Vandue) and one at a higher elevation (Ambanga), possibly associated with an existing fault in the area.

Groundwater sampled in the coastal spring of Vandue was relatively acidic with a measured pH below the Australian Drinking Water Guideline of 6.5. This is, however, only an aesthetic guideline as health-related concerns only appear at pH values below 4. It should be noted that clean rainwater is always slightly acidic (pH = 5–5.5) because moisture in the air absorbs carbon dioxide (CO_2) producing carbonic acid (H_2CO_3). The low pH of discharged groundwater indicates the inability of volcanic rocks to effectively buffer the acidity in combination with a low residence time (minimum interaction with the soil). The sample probably reflects rainwater that percolates quickly through highly porous volcanic rocks into the main basal aquifer and discharges into the sea. On the other hand, groundwater sampled in the Ambanga spring is neutral (pH = 7), indicating a different, probably slower and shallower flow path, involving the interaction with soils and alluvial deposits, which are more effective in neutralising rainwater acidity. This is probably associated with dike-impounded or perched groundwater exfiltrating through a contact or breakslope spring. These types of springs are, therefore, good indications of groundwater bodies with high potential for development.

Both samples are characterised by a relatively high silica content, probably released by weathering of silicate minerals such as pyroxenes and feldspars. These values, however, do not pose any concerns with regards to potability, and are considered to likely improve the aesthetic potability of the groundwater. The conductivity or salinity of the groundwater samples suggest low salinity, which further suggests that the water is acceptable to all for drinking purposes.

Table 5. Composition of groundwater samples obtained by Bani et al., 2009. All concentrations in mg/L. Conductivity in µS/cm

Site	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	SiO_2
Vandue	June 2005	5.6	149	14.68	4.23	6.23	3.72	7.31	6.26	1.47	21.06
Ambanga	July 2005	7	260	9.6	4.23	7.75	46.88	6.62	2.82	0.06	22.92

Although these preliminary observations suggest suitable water quality for domestic purposes, potability will be fully determined after analysing groundwater samples obtained during the drilling phase.

4.3.2 Expected yield

Porosity and permeability in basaltic rocks is due to openings related to scoria deposits, breccia zones and cavities between flows, lava tubes, fractures and lineaments (Singhal and Gupta 2010). Porosity and hydraulic conductivity tend to decrease with increasing age and degree of weathering of volcanic rocks due to the filling of fractures by secondary minerals. Increasing age, however, can also lead to additional fracturing and increase permeability.

Aquifer properties are difficult to estimate as they depend on the connectivity between fractures, vesicles and lava tubes. 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 pumping test data. Table 6 presents the range for porosity and hydraulic conductivity in volcanic rocks.

Table 6. 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

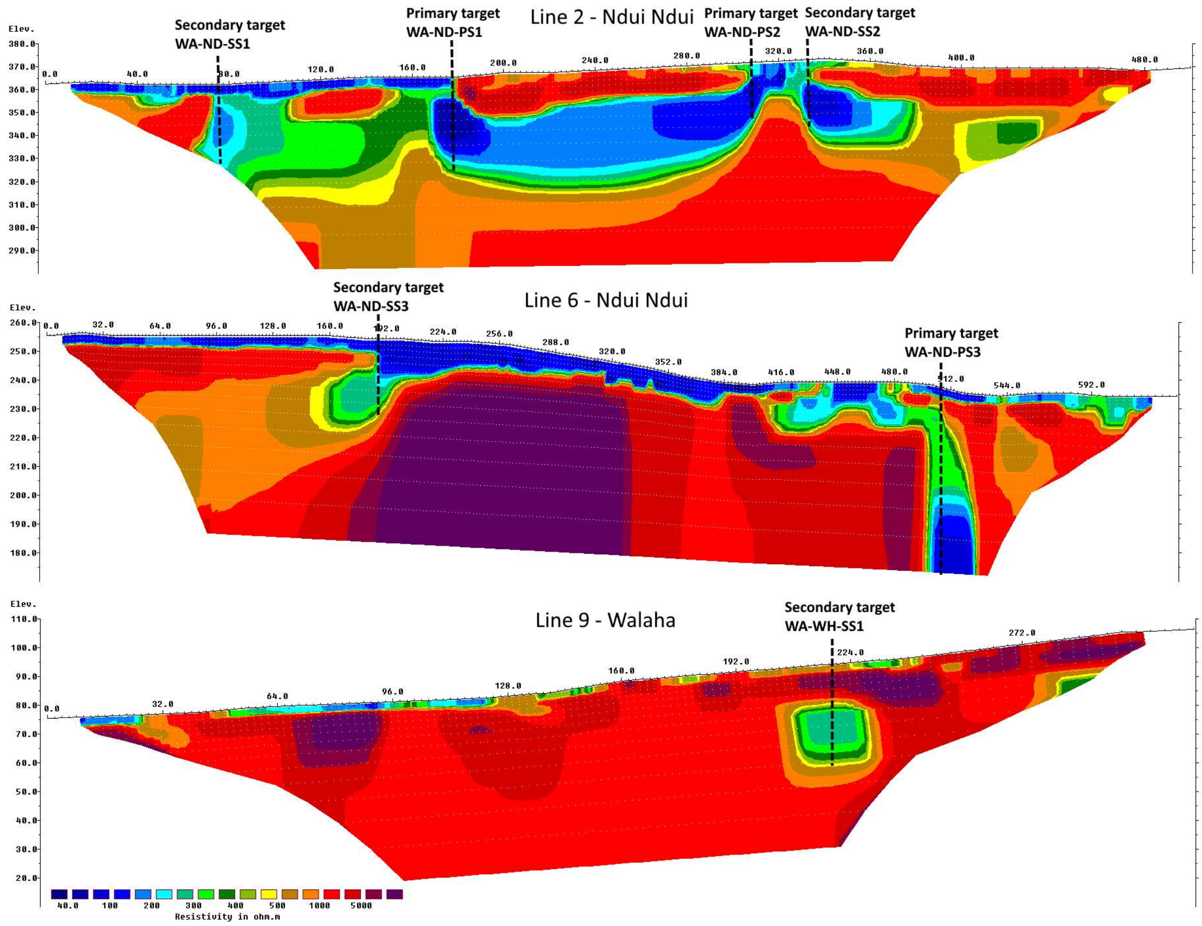

Figure 13. Primary and secondary drilling targets identified along survey lines 2, 6 and 9.

In total, seven potential drilling sites were identified and classified into primary and secondary targets based on development potential, location and expected productivity. Two primary and two secondary targets were identified along survey line 1/2. The two primary targets tap the same resource and are proposed as two alternative options. Primary site WA-ND-PS1 should be given priority, and if the drilling proves unsuccessful, then WA-ND-PS2 should be considered. Installing an observation borehole at the primary site that will not be selected for groundwater development is strongly recommended. This will allow performing a more accurate pumping test and better monitoring of groundwater connectivity and drawdown once the site becomes operational. The low-permeability formation causing the perched aquifer is expected to be encountered at 45 m and 25 m depth at sites PS1 and PS2, respectively.

Due to the difficulty in identifying exploitable groundwater supplies and the small number of primary targets identified during the overall survey, two additional targets are proposed along line 1/2. Pumping from these two secondary targets is not expected to influence the primary targets because intrusive dikes obstruct hydraulic connectivity. Drilling a secondary site (SS1) down to at least 35 m depth is suggested, acknowledging that the water-bearing formation may extend farther. Drilling in secondary site SS2 is expected to terminate at 30 m depth.

Drilling in all proposed targets along survey line 1/2 is not expected to be difficult due to the absence of high-resistivity pyroclastic deposits (scoria) and the expectation that hammer drilling will be suitable. Carefully pushing the drilling past the indicated depths is encouraged because the resistivity interpretations become less reliable with depth and aquifers may extend deeper than what is depicted in the profiles. Massive or weathered basalts will eventually be encountered and drilling should be terminated at that point. There is a possibility that confining layers creating perched aquifer conditions are breached during the drilling, resulting in the sudden loss of groundwater into the main basal aquifer system. In such cases, it is recommended to terminate the drilling and use cement to grout the hole past the depth of the water-bearing zone and, if need be, redrill the hole to the desired depth.

Along survey line 6, one primary and one secondary target was identified. The width of the primary water-bearing feature (WA-ND-PS3) is limited, although site productivity will depend on the vertical and lateral extent of the feature. A pumping test is crucial to determine the yield and recharge rate, which seems to be limited in this specific location. Drilling this primary target may intercept a shallow and relatively thin (~5 m) scoria layer. This scoria material is likely to present some challenges for drilling, where the scoria may break up into ball-shaped pieces, requiring casing to prevent blowouts with excessive air. Past that layer, drilling is expected to improve. Groundwater is expected to be encountered below the scoria layer with the most productive water-bearing zone expected to start at 35 m depth. Because the vertical extent of the groundwater-bearing feature is unknown, we recommend drilling to 50 m minimum (70 m maximum). Drilling should continue to the maximum depth while the hole continues to produce water.

A secondary target (WA-ND-SS3) is proposed in the shallow, unconfined aquifer along line 6, by constructing a bore with limited productivity but providing a useable supply that may help to alleviate water demand during drought periods at the household level in the specific village. A target depth of 20–25 m is proposed for this location to assess groundwater potential.

The three survey lines performed in Walaha District did not reveal any drilling targets that would indicate promising groundwater potential. One anomalous feature of relatively low resistivity was encountered along line 9 and potentially could be interpreted as a saturated lava tube or a confined aquifer of limited width, although there is low confidence that this could constitute a viable groundwater target. Due to its limited two-dimensional extent, the anomaly was considered of secondary importance for targeting as a potential groundwater supply. However, in the absence of other targets in Walaha, and the unknown extent in the third dimension, it is recommended that drilling to a depth of 40–45 m would be useful for investigating the groundwater potential for this survey line. The resistivity indicates that the low resistivity feature should be encountered at 10–15 m depth. The vertical extent of a low-yielding section, if encountered, is expected to be less than 30 m. It is highly recommended that additional investigations are performed in Walaha District, for further exploring the groundwater potential of this area.

Table 7. Proposed drilling targets

Site	Priority	Longitude	Latitude	Elevation (m)	Expected depth to water-bearing zone (m)	Expected drill depth range (m)
WA-ND-PS1	Primary	167.7478061	-15.39913662	366	10–15	40–50

WA-ND-PS2	Primary	167.7485774	-15.39826337	372	10–15	25–30
WA-ND-PS3	Primary	167.741205	-15.39391853	237	30–35	50–70
WA-ND-SS1	Secondary	167.7469443	-15.39964054	362	10–15	35–45
WA-ND-SS2	Secondary	167.748794	-15.39814467	374	15–20	30–35
WA-ND-SS3	Secondary	167.7391967	-15.39579354	255	15–20	20–25
WA-WH-SS1	Secondary	167.7048922	-15.40908123	95	15–20	40–45

4.4 Groundwater resource development considerations

4.4.1 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 the land usage and long-term accessibility as a water supply. The land in Vanuatu, including Ambae, is owned by custom owners and administered by the owners or a land tribunal. It is imperative that the custom owner(s) who will forfeit their customary land right in the long term as a result of the installation of community water supply system components are adequately informed about this. These components will include but not be limited to:

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

Considering the potential costs of installing these components and the associated land area required, a pragmatic and inclusive approach will be essential from the onset of a water supply development project to adequately inform and engage the affected custom owners in order to solicit their immediate and long-term support, and to ensure the system's minimal or negligible disruption and/or damage. The approach should include (but not be limited to):

- a consent letter to be signed by all affected custom owners to allow 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 custom owners for relinquishing their customary right to the land; and
- consideration to introduce a law limiting the type of land-use activities that are allowed in and around the borehole site and expected recharge areas.

During the fieldwork, early discussions with landowners and chiefs of the respective villages were undertaken, in order to gain input on the proposed locations and obtain an initial agreement on the proposed drilling sites. In each case, the landowners and chiefs pledged their support to the construction of a water supply bore.

4.4.2 Land accessibility for drilling rig

Accessibility to the selected drill sites is important, especially given the island's steep and rugged terrain and limited road network, and should take into consideration that the truck-mounted drilling machine, its compressor, drill rods and accessories, and support truck must be able to reach the selected drill target locations with minimal concern or damage. Given these factors, the communities and the Government of Vanuatu should be prepared to allocate adequate resources towards improving site accessibility through road clearing and track improvement. Given the localised nature of the productive groundwater, drilling must take place at the selected and prioritised targets. This drilling will also help in validating geophysical results and conceptual groundwater model to assist with future hydrogeological assessments.

A scoping mission was undertaken to assess possible access points for the drilling rig on the island. Devil's Rock beach appears to be a good, and possibly the only, option where the drive-on barge could unload safely.

4.4.3 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 the chiefs, to allow the consistent access and usage of a community water supply system to benefit all users. This includes making sure the groundwater quantity and quality is usable and safe, and establishing rules and mechanisms to warrant 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).

4.4.4 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 possible replacement of submersible pumps; and
- repairing and replacing leaking distribution pipes and any extension of the system.

The above needs highlight the major responsibilities and associated costs inherent to operation and maintenance components. In a disadvantageous and isolated community such as West Ambae, a pragmatic, cost-recovery mechanism should be designed to ensure that all beneficiaries understand these obligations, and to get their support towards the collection, management and disbursement of funds when needed.

Preliminary survey results were presented to the communities of Ndui Ndui and Walaha who appreciated the importance of adopting a community-based approach with regards to site operation and maintenance. Landowners expressed their support and willingness to secure and maintain the sites once they become available.

4.4.5 Hazards

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

The swarms of earthquakes and small phreatic volcanic explosions in Lake Vui in 1995 and 2005 (Cronin et. al. 2004; Nemeth and Cronin 2008) suggest the vulnerability of settlements and infrastructure on Ambae. Mercer et al. (2007) also highlighted that pervasive gas smells, trees dying and rapid rotting of taro roots in the ground were observed prior to these recent explosions. A volcanic hazard map generated by Nemeth and Cronin (2008) indicates the vulnerability of the surrounding communities and the level of awareness raising and steps needed to minimise damages. This hazard map should be considered when the target drill sites are selected.

The increasing frequency and intensity of tropical cyclones and droughts has created widespread and massive damages to buildings, infrastructure and communities around Vanuatu. The 2015 category 5 Tropical Cyclone Pam, destroyed water and sanitation facilities and crops, compromising the livelihoods of at least 80% of Vanuatu's rural population with an aggregate cost of USD445 million (White 2016a). Damages to the water and sanitation infrastructure from the cyclone affected 68% of rainwater harvesting infrastructures, destroyed 70% of above-ground sanitation infrastructures, and resulted in the contamination of 70% of the mostly shallow and poorly constructed wells. The 2015–2016 severe drought, caused by ENSO, recorded to be nearly as intense as the 1997–1998 event, brought severe water shortages and major challenges to raising and livestock in many areas in Vanuatu, especially in the northern provinces, including Ambae (White 2016a).

The considerations of these hazards and their potential impact and financial costs necessitate thorough planning in the design and construction of water supply systems and facilities. This is to ensure that the 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.

5. Recommendations and conclusions

5.1 Resistivity survey

This study highlights the value of employing high-resolution resistivity surveys to assist in identifying potential drilling targets for groundwater development. The complex geology of West Ambae does not favour groundwater occurrence at higher elevations except in small perched aquifers impounded between intrusive dikes or formed within fractures. The identification of drilling locations associated with these potentially exploitable localised aquifers would not have been possible without knowledge of the spatial distribution of subsurface resistivity. Additional resistivity surveys are, therefore, recommended if additional targets need to be identified in West Ambae.

It became apparent that an *a priori* study of geological maps and satellite imagery, in combination with field observations, could effectively guide the selection of areas offering suitable conditions for small aquifers to occur. A well-developed complex of fissures along the main rift axis is generally expected. The presence of parasitic cinder cones at lower elevations, especially when aligned, suggests the existence of subsurface fissures and dikes developed off the main rift axis, indicates the (possibly) suitable conditions for groundwater to occur. It is, therefore, recommended that resistivity surveys between and around these features to increase the chances of groundwater detection should be planned.

Choosing between short (2.5 m) and long (5 m) electrode spacing depends on the level of detail required and the distance that needs to be covered. In the case of West Ambae, due to the difficulty of identifying exploitable groundwater targets, covering as much ground (and depth) as possible became the main priority. The reduced resolution did not mask any groundwater targets, as shown by survey line 1/2. However, the increased resolution of line 1 helped identify geological structures (dikes) and helped developing the conceptual hydrogeological model of groundwater occurrence in West Ambae.

5.2 Drilling

It is recommended that priority be given to the primary drilling targets identified in Ndui Ndui District and described in Table 7. Pumping tests will be required to fully assess groundwater potential and estimate borehole yields. This information will subsequently be used to strategically plan emergency water supply mechanisms. Secondary targets should be drilled in case the primary targets do not prove effective or sufficient in covering the existing water demand, or additional water sources are required at specific locations. Secondary targets are expected to yield lower groundwater volumes compared with primary ones, although in the absence of alternatives and demonstrated need, it is recommended to drill these targets, especially in Walaha where no primary targets were identified. Although groundwater quality is expected to be good, it is recommended to fully determine potability after analysing groundwater samples obtained during the drilling phase.

It is also recommended that prior to drill mobilisation, site accessibility through road clearing and track improvement is undertaken. This will be important to ensure that drill sites will be accessible and the risk of delays or damage to the drill rig will be reduced. With regards to access of the drilling rig to the island, Devil's Rock beach appears to be a good, and possibly the only, option where the drive on-barge could unload safely.

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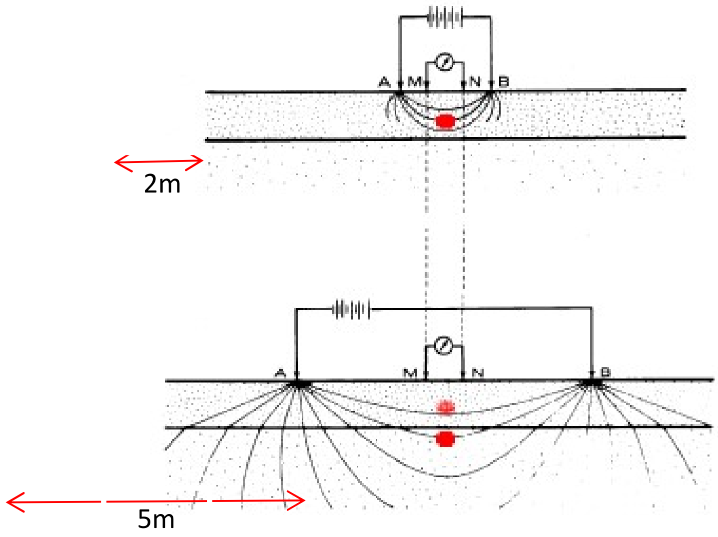
Annex 1 – Resistivity survey notes

For the purpose of obtaining information on subsurface geological and hydrogeological structures, geophysical methods are relatively inexpensive when considering survey cost compared to the relatively large areas over which detailed information can be obtained. Geophysical techniques are generally noninvasive and, thus, offer significant benefits in cases where conventional drilling, testing and sampling are difficult, or where potentially contaminated soils may occur in the subsurface (Loke 2001[3]). Electrical resistivity is a common method used for geophysical surveys.

The basic principle of operation in electrical resistivity methods is the injection of 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 specific survey parameters (e.g. electrode spacing), be converted into an apparent resistivity value. This value can provide a range of subsurface information regarding the survey site. Different types of soil and geological formations have different resistivity responses as a function of the soil and rock depth, porosity, permeability, ionic content of pore fluids, and clay mineralisation.

Resistivity is particularly useful in determining the depth, thickness and extent of the groundwater-bearing zone(s). The depth of investigation is a function of the electrode spacing and earth resistivity; in general the greater the spacing, the deeper the investigation (Reynolds, 1998[4]).



Measuring depths at different electrode spacing (A and B: current electrodes. M and N = potential electrodes.

To get as much ground information as possible, measuring the resistivity in as many locations as possible is required. A way of improving the number of data points and, thus, obtain more information is to perform 'imaging', also called tomography or CVES (continuous vertical electrical sounding). To collect an imaging dataset, a multi-electrode cable and an electrode selector are needed.

[3] Loke M.H. 2001. Tutorial: 2D and 3D electrical imaging surveys

[4] Reynolds J. 1998. An Introduction to Applied and Environment Geophysics. Wiley.

ABEM Terrameter LS equipment was used for this research. It offers 4 measurement channels for increased efficiency while the built-in electrode selector allows for connection of up to 81 unique electrodes, providing high resolution and adequate depth capabilities (ABEM 2016[5]).

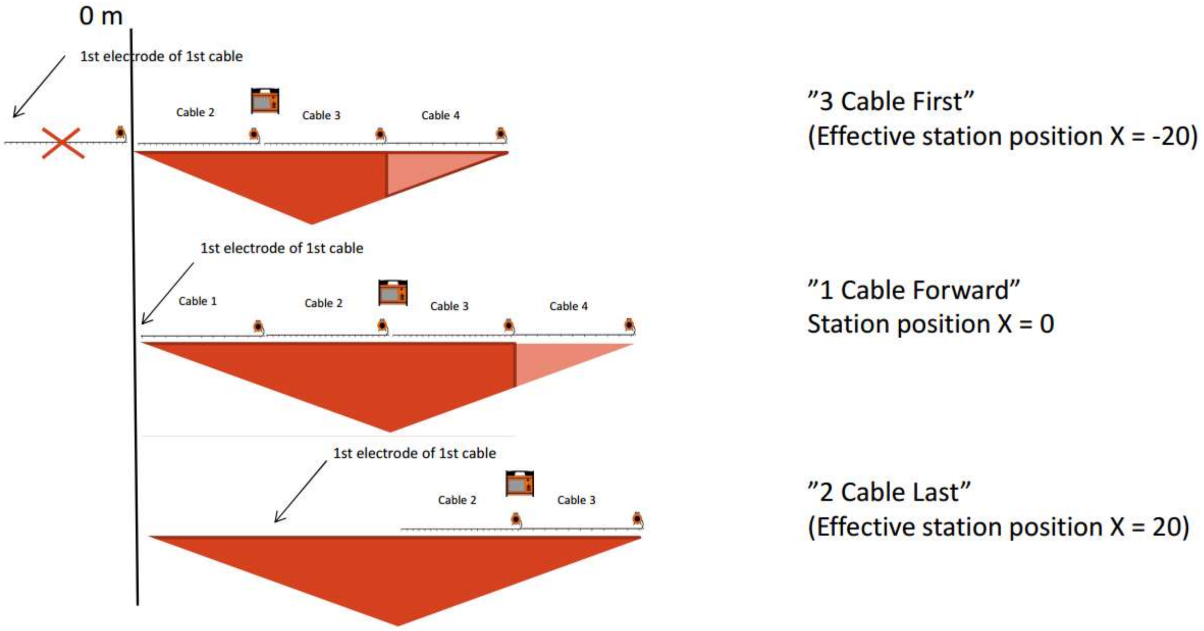
The equipment uses 4 electrical cables, each with 21 take-out cables allowing for 81 readings at a maximum spacing of 5 m between take-outs. This allows flexibility using spacing less than 5 m dependent on the target depth as well as the resolution required. Longer profiles are undertaken employing roll-along surveys, which involve leap frogging of the electrodes and cabling to provide greater coverage of the survey area and improved interpretation.

The inbuilt multiple gradient array was chosen as a suitable electrode arrangement offering good resolution to horizontal as well as vertical structures in the ground. Moreover, a good signal-to-noise ratio was established.

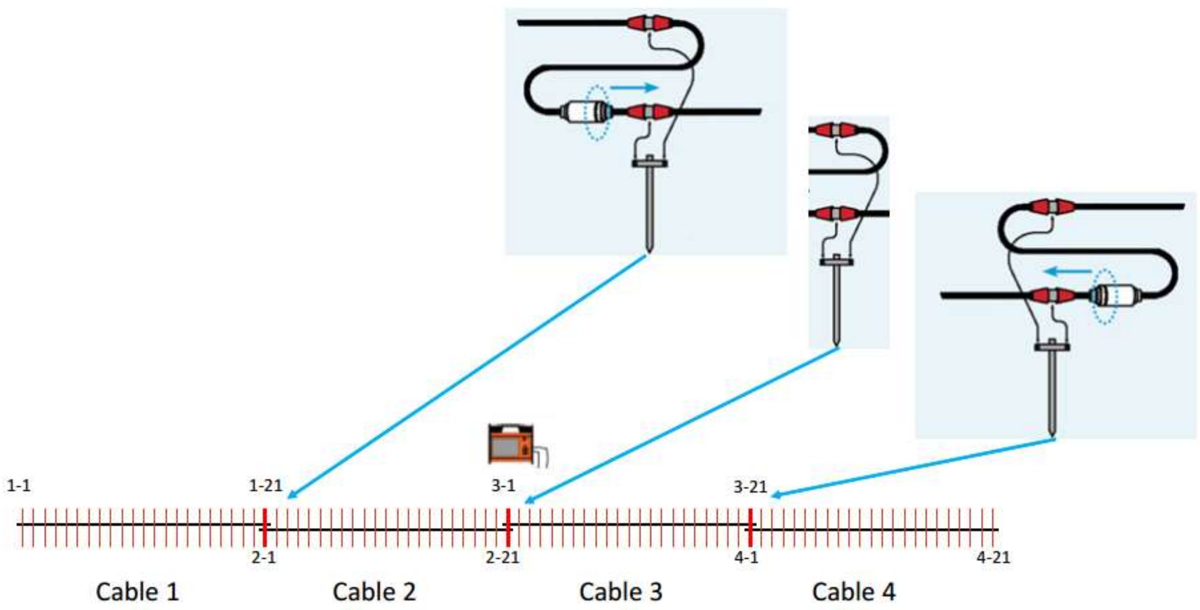
Steps for setting up a Terrameter LS Resistivity Survey

1. 100 m measuring tapes are laid out to mark the survey line.
2. Steel electrodes are hammered into the ground according to the desired spacing (2.5 m, 4 m and 5 m in this instance). Ensure that there is adequate contact.
3. Electric cables are rolled out.
4. Jumper cables are used to connect the electric cables to the steel electrodes.
   Note: Take-out #21 of each cable should overlap take-out #1 of the next cable at the cable joints and in the layout centre (instrument position). Overlapping take-outs connect to the same electrode.
5. At the first measurement station, start laying out and connecting three cables only, and connect the instrument between the first two cables. In the data acquisition software these cables are designated as Cable 2, Cable 3 and Cable 4, where the instrument is connected between Cable 2 and Cable 3, and Cable 1 is excluded at the first station.
6. Link together the inner and outer electrode cables (Cable 3 and Cable 4 only at this stage) with a cable joint called “groove” (cylindrical connecting device). The cable joints have two groove joiners for 4x21 cable sets. The groove(s) on the cable joints should point towards the instrument in the layout centre.
7. Connect the external battery to the Terrameter LS. The instrument should turn on and measurement preparation is done.
8. At the second measurement station, and all the following stations as long as the line is being extended, connect all four cables. Cable 1 is connected to Cable 2 with a groove as well, where again the groove must face the cable closest to the instrument. Cable 1 to Cable 2 and Cable 3 to Cable 4 are connected via grooves.
9. When finishing the measurement profile, and no additional electrode cables and electrodes are put out, the instrument should still be moved one step in order to get all of the near surface information. The active electrode cables will be Cable 2 and Cable 3.

[5] ABEM 2016. Terrameter LS Instruction Manual



Cable arrangements during a roll-along survey (ABEM, 2016).



Cable connections using groove (ABEM 2016).

A measuring tape is laid out to mark the survey line.

A hammer is used to ensure adequate ground contact of steel electrodes.

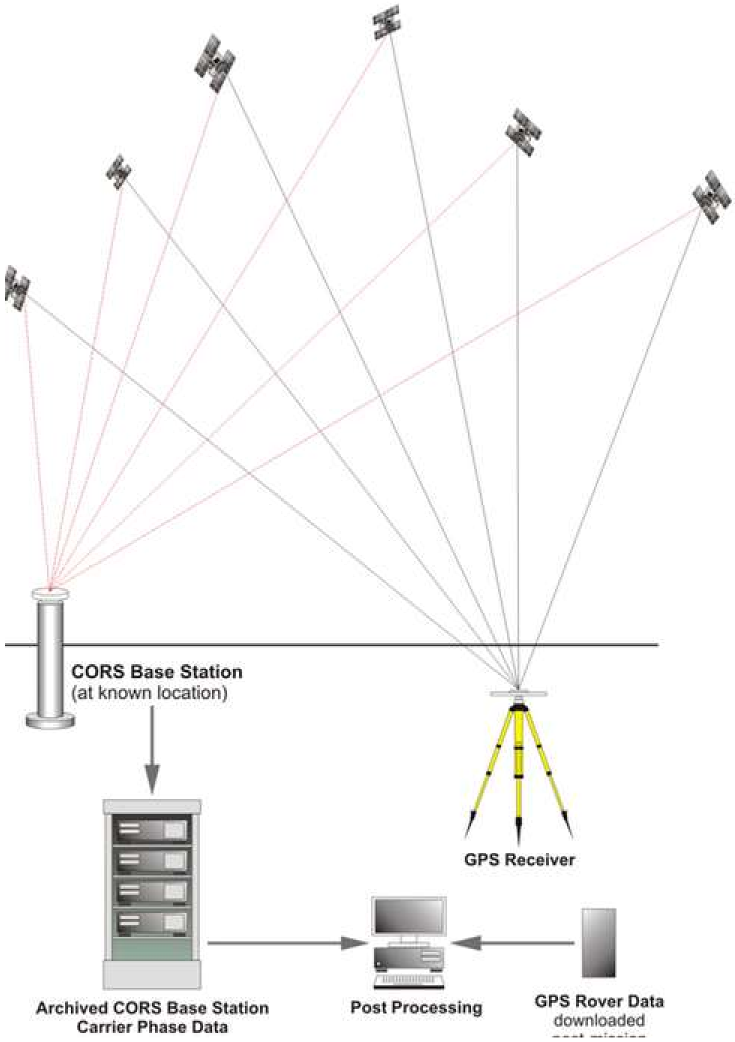
Securing electric cables to steel electrodes using connector cables.

Electric cables connected using a groove.

Annex 2 – Elevation survey notes

An important component of geophysical surveys for groundwater exploration is the elevation survey along the survey line. A fast, yet relatively accurate (+/- 0.01 m), method for determining elevation is needed. The use of GPS in conjunction with other technologies assists with increasing the accuracy of elevation measurements. There are many techniques available for topographic and elevation surveys.

A post-processed kinematic (PPK) survey style is used when no radio is available. PPK system surveys are generally used for mapping or for surveying points where only several centimetres of precision are needed. Occupation times for survey points are in the order of seconds. PPK surveys require data from at least two receivers: a base (reference) receiver and a rover (moving) receiver.



Post-processed kinematic GPS survey principle.

A survey controller is recommended for running the rover receiver. The survey controller gives control over the survey and records metadata, which facilitates data organisation. A Trimble Survey Controller and a Trimble R8 GNSS GPS were used for the elevation survey. The rover was programmed to continuous survey mode, which allows ongoing data collection at a specified logging interval (e.g. every second). The rover was mounted on a 2-m pole so that all points collected were automatically adjusted to the ground level.

Preparation

Create a New Job

1. Turn on the survey controller by pushing the green power button.
2. If needed, enter the 'Survey Controller' program by double-clicking the corresponding icon.
3. The main menu consists of six options on the screen. Select 'Files' in the top left, then select 'New Job'.
4. Give the job a name (using the letter and number keys) and hit 'Enter'. Select a memory location for the job; suggested setting is Main memory.
5. Select 'Coordinate System'. The local coordinate system was established for the survey in Ambae as follows:

   - Map projection: UTM Zone 59 South
   - Horizontal datum: WGS84

Set the Survey Style

1. From the main menu, select 'Configuration' in the top right.
2. Select 'Survey Styles'-->'PP Kinematic' or 'PPK' -->'Rover options'.
3. Select "Base options".
   - Survey type: PP Kinematic
   - Logging device: [Receiver]
   - Logging interval: [1 second]
   - Antenna height: [2 m]

Setting up the rover (Satellite Receiver)

The suggested setup includes an antenna mounted a range pole (higher precision) and the steps to be taken include the following.

1. Connect the GPS antenna to the antenna mount.
2. Put the internal batteries in the receiver.
3. Connect the straight end of the GPS antenna cable to the antenna port on the receiver.
4. The controller is connected via a bluetooth to the receiver.
5. Turn on the survey controller and the receiver if they are not on already. Receiver, antenna and satellite icons should be seen on the controller's screen. Select 'Survey' in the lower left. Select chosen survey style (e.g. PP Kinematic).
6. Select 'Start Survey'. At the bottom of the screen, the controller will display survey messages. Possible messages include 'Searching for satellites', 'Poor PDOP', and 'Initializing'. If there is a positioning problem ('Searching for satellites' or 'Poor PDOP'), move into a clearer area to increase the rover antenna's sky view. As stated before, at least five satellites in common should be tracked with the base receiver. 'Initialization' refers to collecting enough data (at least 8 minutes of continuous satellite tracking with 6 or more satellites) to be able to calculate high-precision solutions in the data processing. If 'lock' or tracking of satellites is lost, then reinitialize again; that is, at least another 8 minutes or more of data without another interruption. Start surveying points or mapping immediately upon starting the survey, but if lock is lost before initialization is gained, it may have low-precision ('Float' as opposed to 'Fixed') solutions. Be wary of 'Initialization lost' messages.

Running the survey with rover

1. Points every 20 m were marked using a survey spray paints including the start and end of the line prior to the elevation survey.
2. The elevation survey was carried out by two people at every line. One carried the rover while the other recorded the waypoint location every 20 m. A handheld Oregon 650 GPS was used in conjunction with the rover. This was done to match the time reading that was taken at every 20 m, as well as for comparison purposes.
3. The rover took readings every 1 second but for accuracy purposes at marked points (20 m) the rover was stationary for 30 seconds.
4. After taking the last readings at the end of the line, the Trimble controller was used to stop the measurements and also downloading the data from rover to the controller as a raw file.

Ending the survey using the Controller

1. Select 'End Survey'. If downloading the data to the controller is not intended, 'Power Down Receiver?', select 'Yes'.
2. Downloading the data. 'Data Files', download to controller. Data from controller can be downloaded to a personal computer using a data cable.
3. Power down the survey controller by pressing and holding the green power key for 2 seconds.
4. If the rover receiver is not powered down already, do so by pressing and holding the green power button for 2 seconds (Trimble 2010[6]).

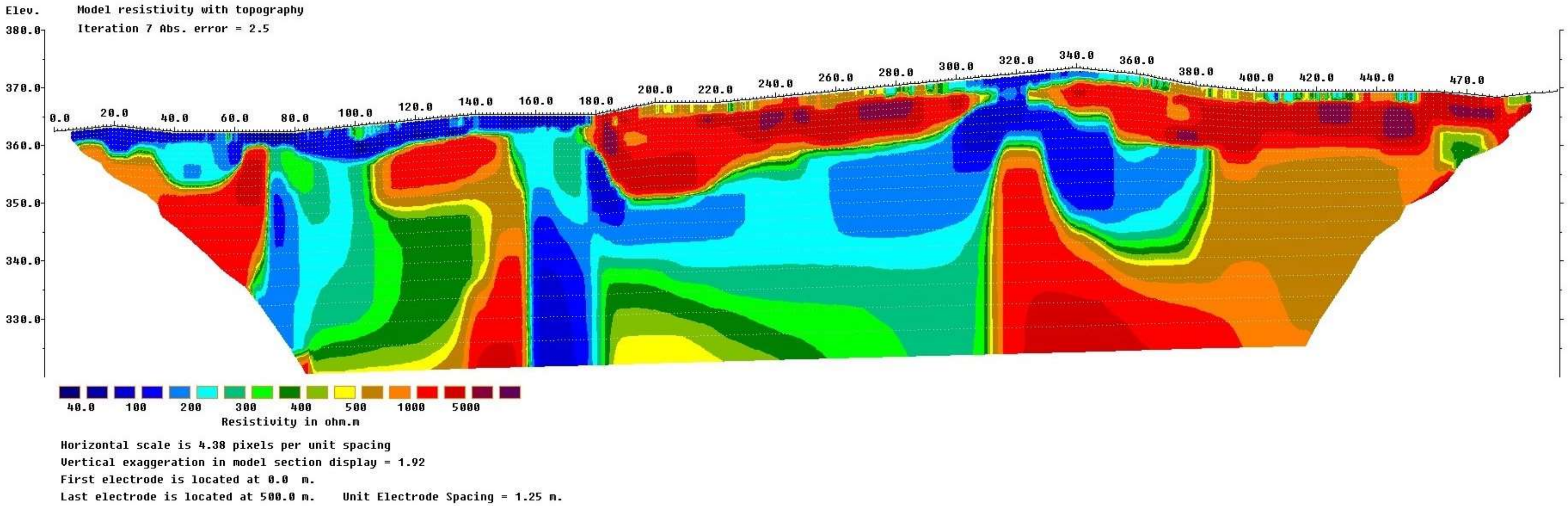
[6] Trimble. 2010. How to execute a post-processing kinematic (PPK) survey from start to finish. Trimble 4700/5700/R7. Manual.

Marking survey points every 20 m.

Recording measurements at one of the survey points.

The Trimble R8 Rover unit mounted on a 2-m pole (Satellite Receiver).

Annex 3 – Resistivity profiles



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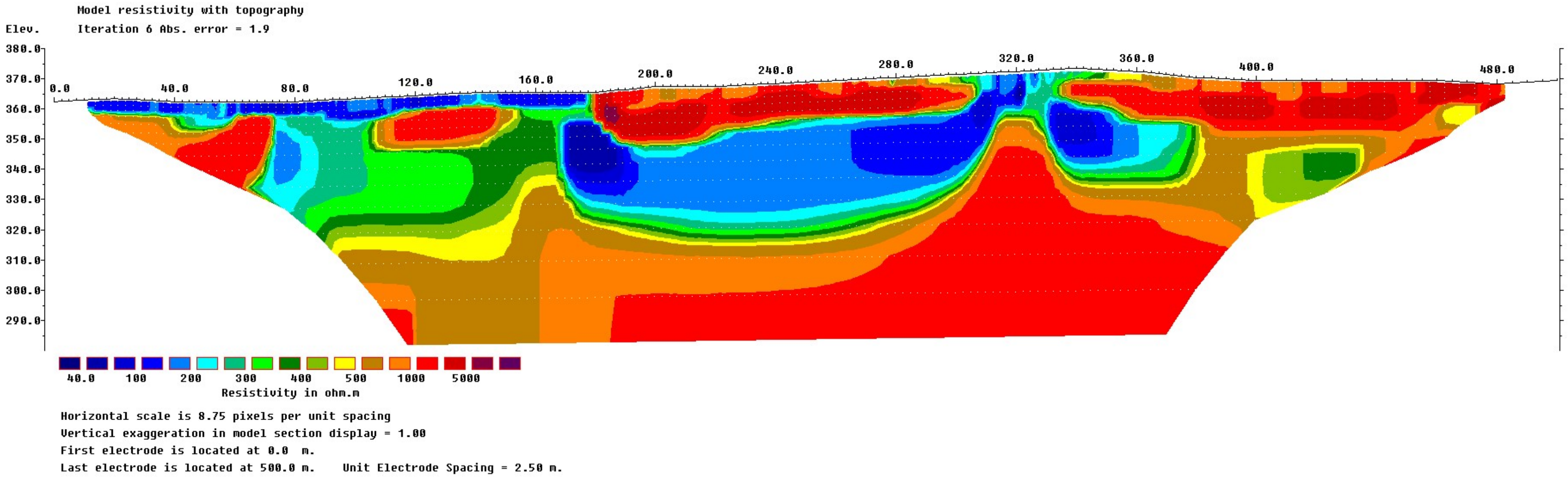

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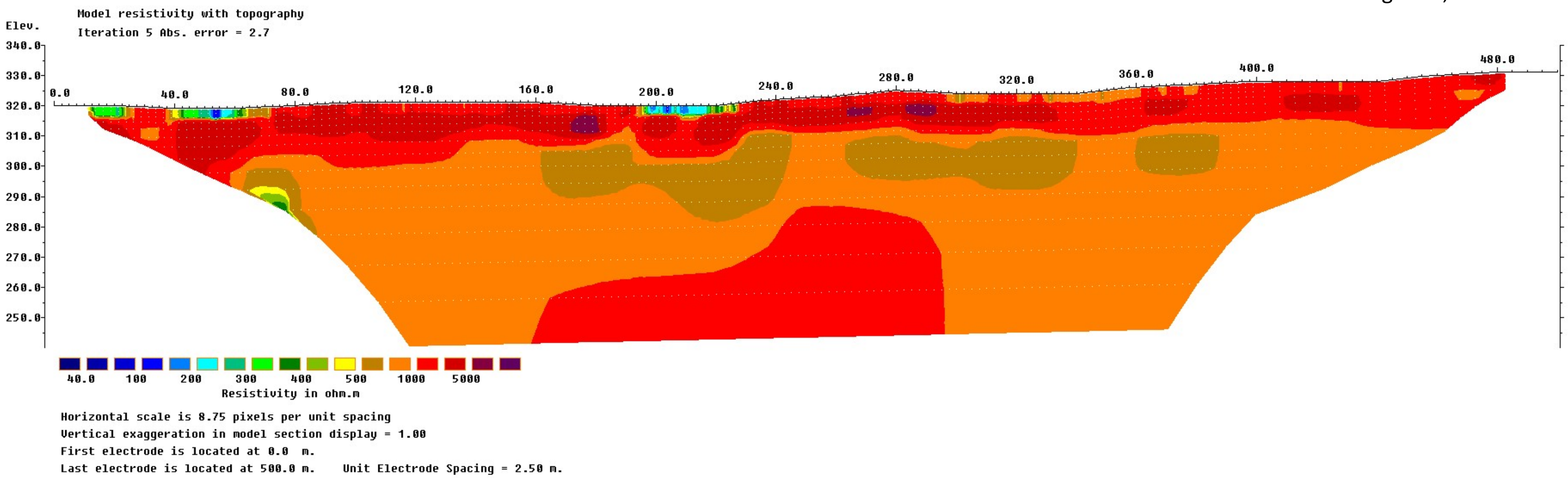

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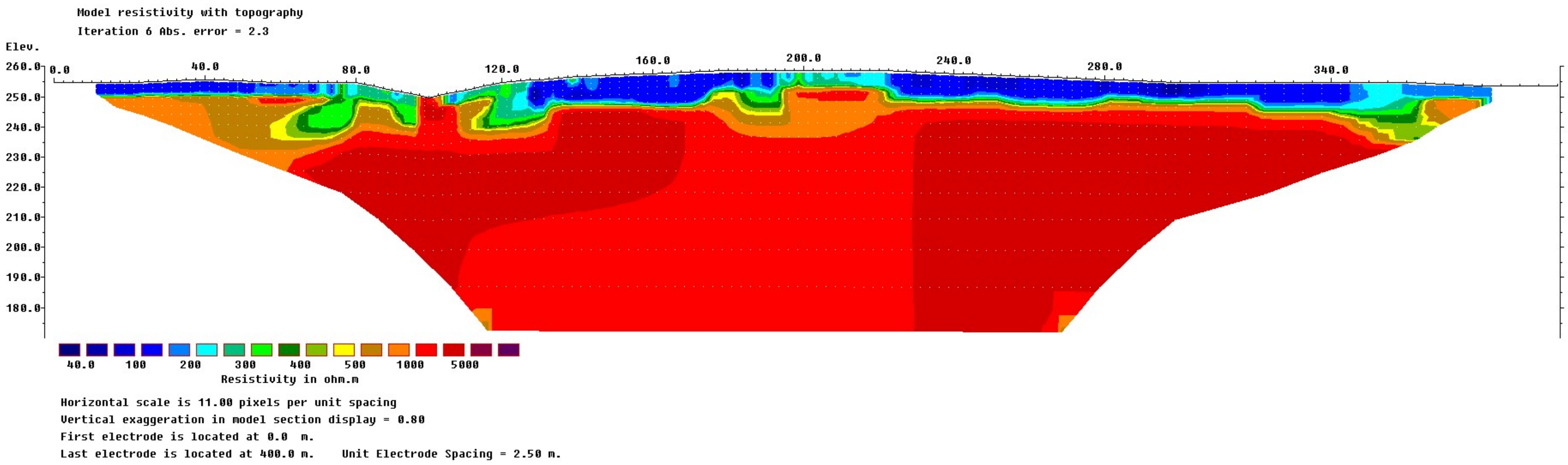

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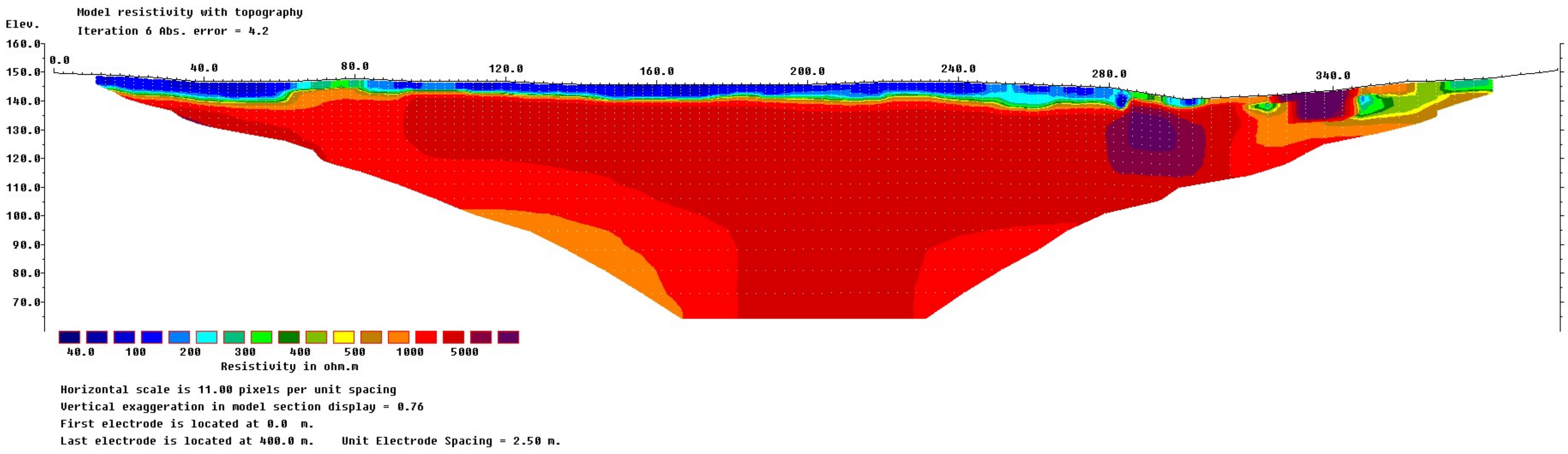

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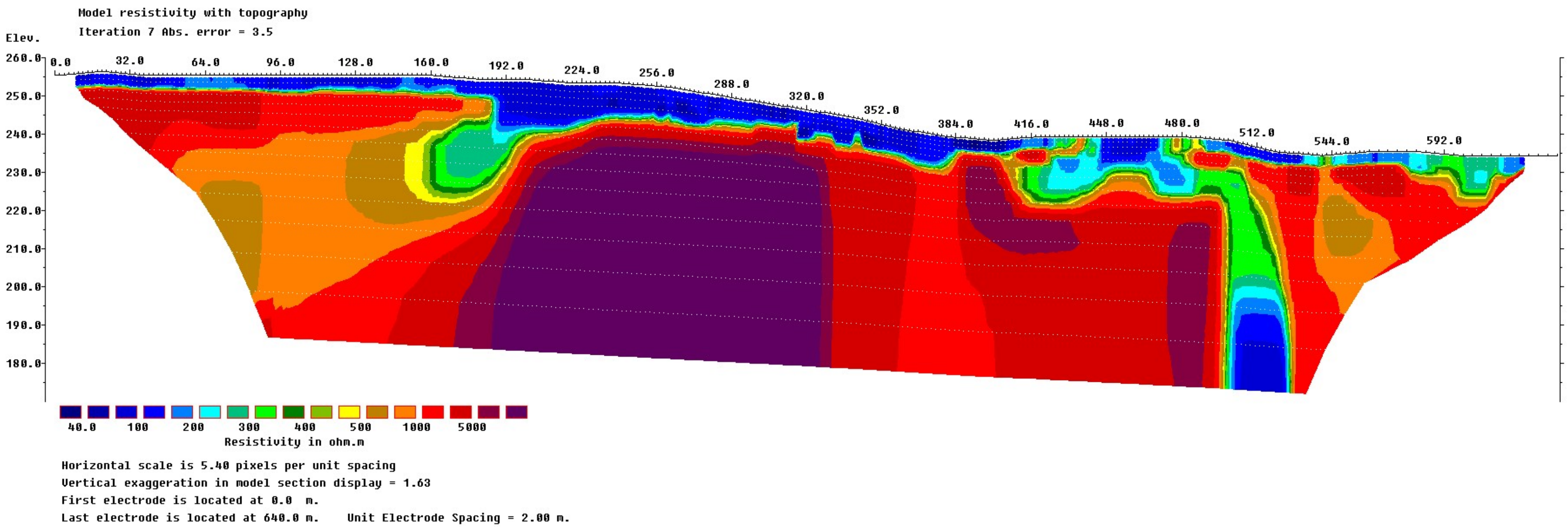

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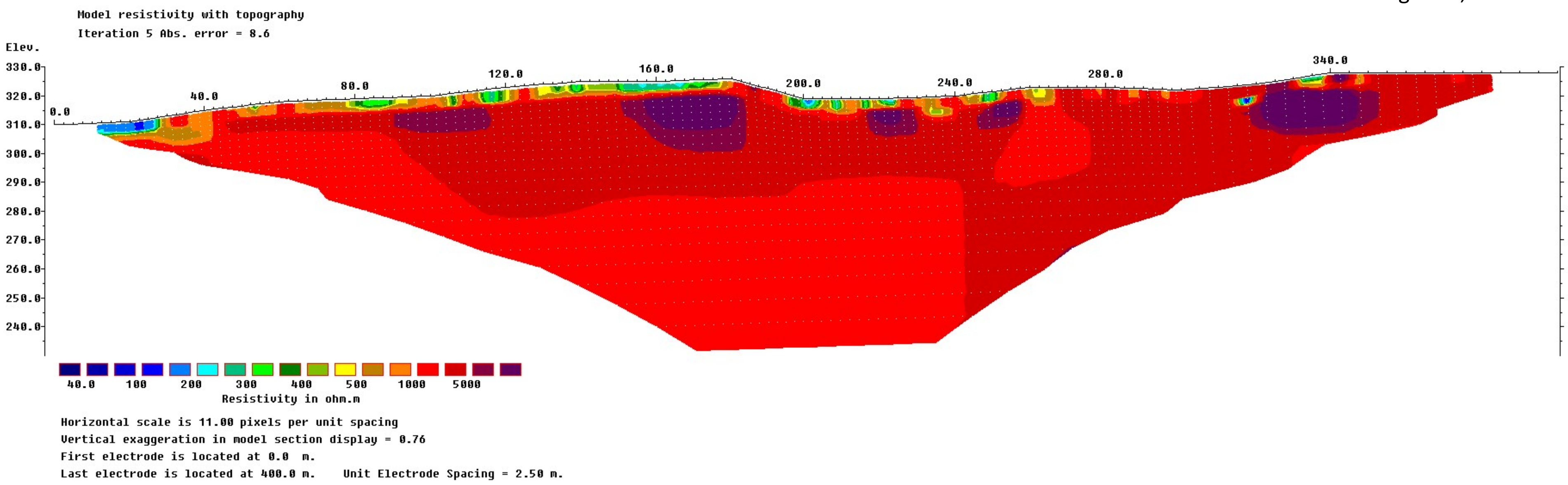

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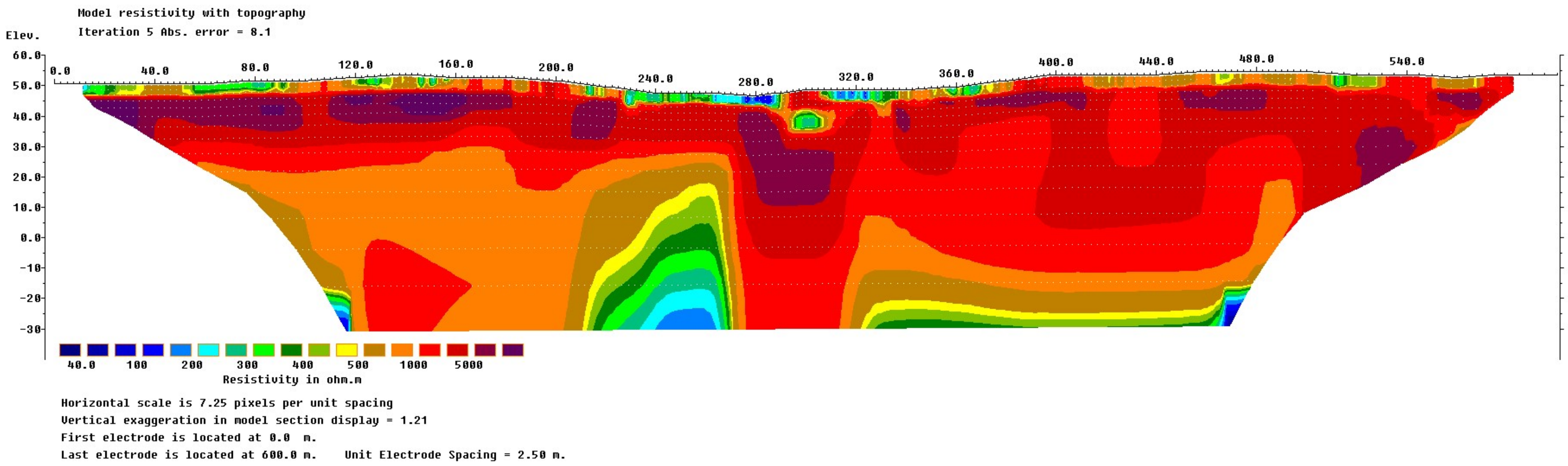
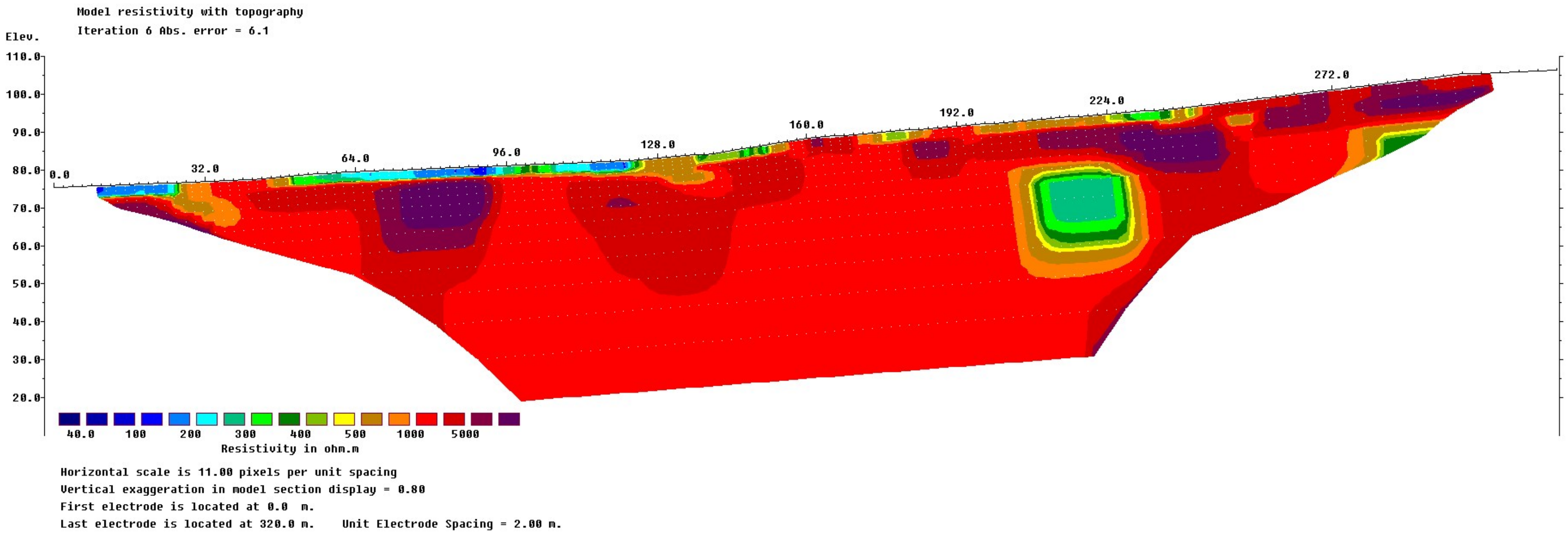
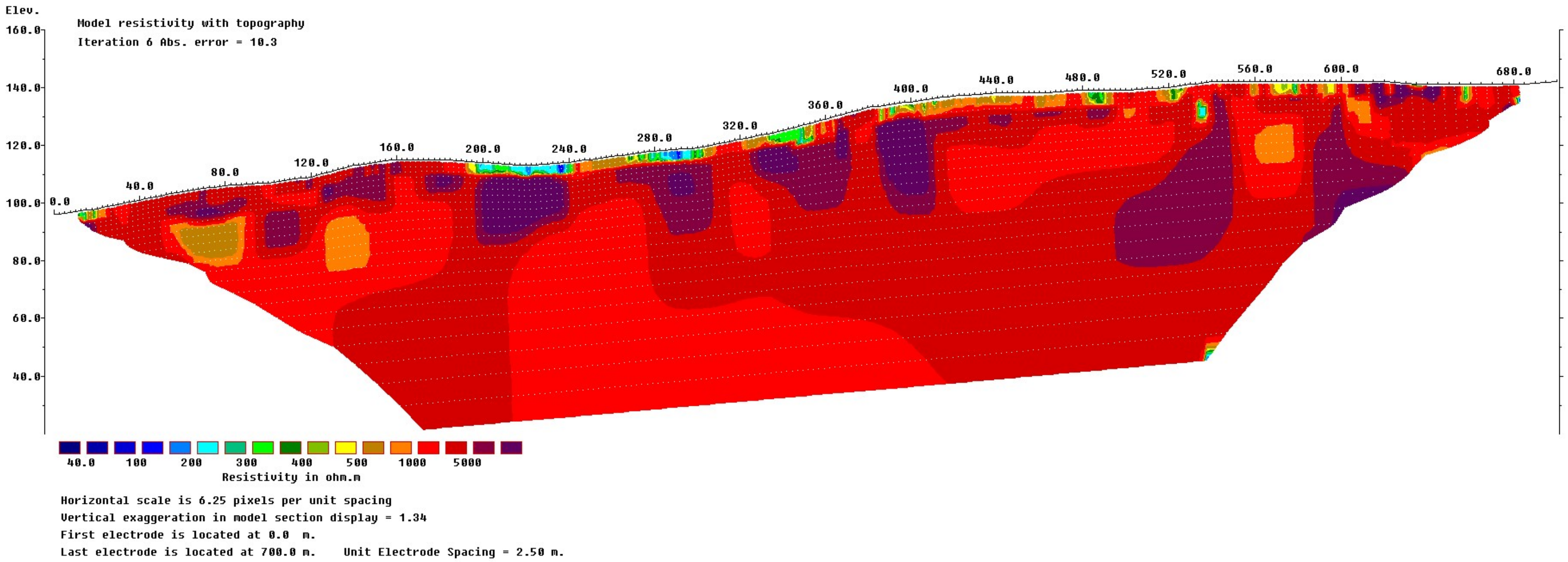


Line 8, WA-WH-L1



Line 9, WA-WH-L2



Line 10, WA-WH-L3

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