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The Tuvalu Ridge to Reef Project

Groundwater investigations on Nanumea and Nukufetau atolls

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Groundwater investigations on Nanumea and Nukufetau atolls

Andreas Antoniou, Aminisitai Loco, Anesh Kumar, Peter Sinclair

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Key partners and stakeholders that contributed to the implementation of this mission include the:

- Department of Environment,
- Tuvalu Public Works Division,
- Department of Agriculture,
- Department of Lands and Survey,
- Department of Fisheries,
- Tuvalu Meteorological Service,
- Ministry of Home Affairs and Rural Development, and
- Office of the Prime Minister, Climate Change Policy Unit.

The communities and *kaupule* members of Nanumea and Nukufetau, as well as the island mayors, played a key role by participating in community meetings and sharing their views on the proposed work.

Finally, we dedicate this piece of work to the late Kilifi Talakatoa-O'Brien, whose passion and drive for his country and science was instrumental in allowing this investigation to take place.

Executive summary

As part of the Tuvalu Ridge-to-Reef Project funded by the Global Environment Facility, groundwater investigations were conducted on the atolls of Nanumea and Nukufetau to support the delivery of integrated water resource management at the national scale while piloting hands-on approaches at the island scale. The investigations also supported the project through the improvement of knowledge and information to enable evidence-based planning, decision-making, and management of natural resources within Tuvalu.

In total, seven islets in the two atolls were investigated for groundwater potential through the use of geophysics (electrical resistivity tomography). The results revealed a substantial amount of fresh groundwater, in the form of a freshwater lens, on Fale island in Nukufetau Atoll. This freshwater lens, which in places is up to 15 m thick, offers substantial development potential that could supply fresh groundwater to the nearby village of Savave. Considering the absence of fresh groundwater on Savave (apart from a very thin brackish lens), and the high reliance of communities on rainwater, exploiting the fresh groundwater on Fale could substantially increase water security and resilience to droughts for the community.

In Nanumea Atoll, Lakena island offers relatively good groundwater potential with a thicker (on average 5 m) and more consistent freshwater lens in the southeastern part of the islet. Due to its proximity to Nanumea island, Lakena should be considered as a possible groundwater reserve for drinking water carting, which could provide water for Nanumea Village during dry periods. On Nanumea island, the investigations suggest the presence of a freshwater lens (on average 5 m thick) around the Matangi area, however appropriate measures should be taken if this resource is developed due to uncontrolled pig farming.

Finally, a number of WWII drum disposal sites, located in the lagoon of Nanumea were assessed for their potential environmental impacts on the quality of lagoon waters and sediments. Although no multiresidue pesticides or total petroleum hydrocarbons were detected in the soil and seawater samples obtained, the relatively high arsenic concentration measured in one of the soil samples may indicate potential toxicity issues in 25% of the dump sites in Nanumea lagoon. Further investigations would be required to determine to what extent these concentrations are bioavailable and whether they could result in toxic effects on marine biota.

1. Introduction

1.1 Project linkages

This investigation was part of the Tuvalu Ridge-to-Reef Project funded by the Global Environment Facility (GEF). It forms part of GEF's broader Pacific programme on Pacific Islands Ridge-to-Reef National Priorities – Integrated Water, Land, Forest and Coastal Management to Preserve Ecosystem Services, Store Carbon, Improve Climate Resilience and Sustain Livelihoods. More specifically, the present work was aligned with the project's components by supporting the delivery of integrated water resource management at the national scale while piloting hands-on approaches at the island scale (Nanumea and Nukufetau atolls specifically). The investigation also supported the project by improving the level of knowledge and information to enable evidence-based planning, decision-making and management of natural resources in Tuvalu.

This work was additionally supported by the Strengthening Water Security of Vulnerable Island States project, which is funded by the New Zealand Ministry of Foreign Affairs and Trade and is being implemented in Cook Islands, Kiribati, Marshall Islands, Tokelau and Tuvalu by the Disaster and Community Resilience Programme of the Pacific Community's Geoscience Energy Maritime Division. The five-year (2014–2019), NZD 5 million project supports atoll countries in building skills, systems and basic infrastructure to better anticipate, respond to, and withstand the impacts of drought.

The groundwater assessment performed under this project is consistent with the *National Strategy for Sustainable Development 2016 to 2020 (Te Kakeega III)* because it complements:

- Strategic Area 8 – Natural Resources. The key performance indicator "increase in farmer productivity" implies an availability of water, including groundwater;
- Strategic Area 9 – Infrastructure and Support Services. The key performance indicator "enough water in storage to last all the islands through 6 months of drought" is also dependent on groundwater; and
- Strategic Area 10 – Environment. Aims at protecting, restoring and promoting the sustainable use of terrestrial ecosystems, including aquifers.

The need for promoting and enhancing the sustainable use of natural resources, including groundwater, through awareness and conservation was also highlighted in Tuvalu's National Adaptation Programme of Action in 2007.

1.2 Mission objectives and outcomes

The main purpose of this investigation was to identify fresh groundwater resources on the atolls of Nanumea and Nukufetau, which could complement existing water supplies or serve as a backup during dry periods. The assessment of groundwater potential on each of these remote atolls supports communities' desire to manage and develop their water supply needs for domestic use, farming and drought purposes, and strengthens communities' integrated land management practices. A number of islets were investigated on both Nanumea and Nukufetau to allow for more flexibility in terms of groundwater development possibilities, given the relatively short distance between the islets within each atoll. At Nanumea Atoll, the islets of Nanumea, Lakena and Temotufoliki were investigated, especially in light of the existing land-use activities on those islets. At Nukufetau Atoll, the islets of Fale, Savave, Funaota and Motulalo were investigated for groundwater potential.

The development of new groundwater resources in atoll environments requires: 1) an investigation of groundwater resource potential and its location; 2) the construction of horizontal galleries and the assessment of yield and water quality; and 3) equipping galleries with pumps and water storage infrastructure that are aligned with the resource potential, and communities' needs and resources. The current investigation focused on determining the groundwater resource development potential. Investigations to better understand the local hydrogeology and groundwater storage potential was achieved through the use of geophysics, specifically resistivity techniques. Recommendations are given with regards to potential gallery locations, expected yields, and expected groundwater quality.

2. Background

2.1 Geographical location

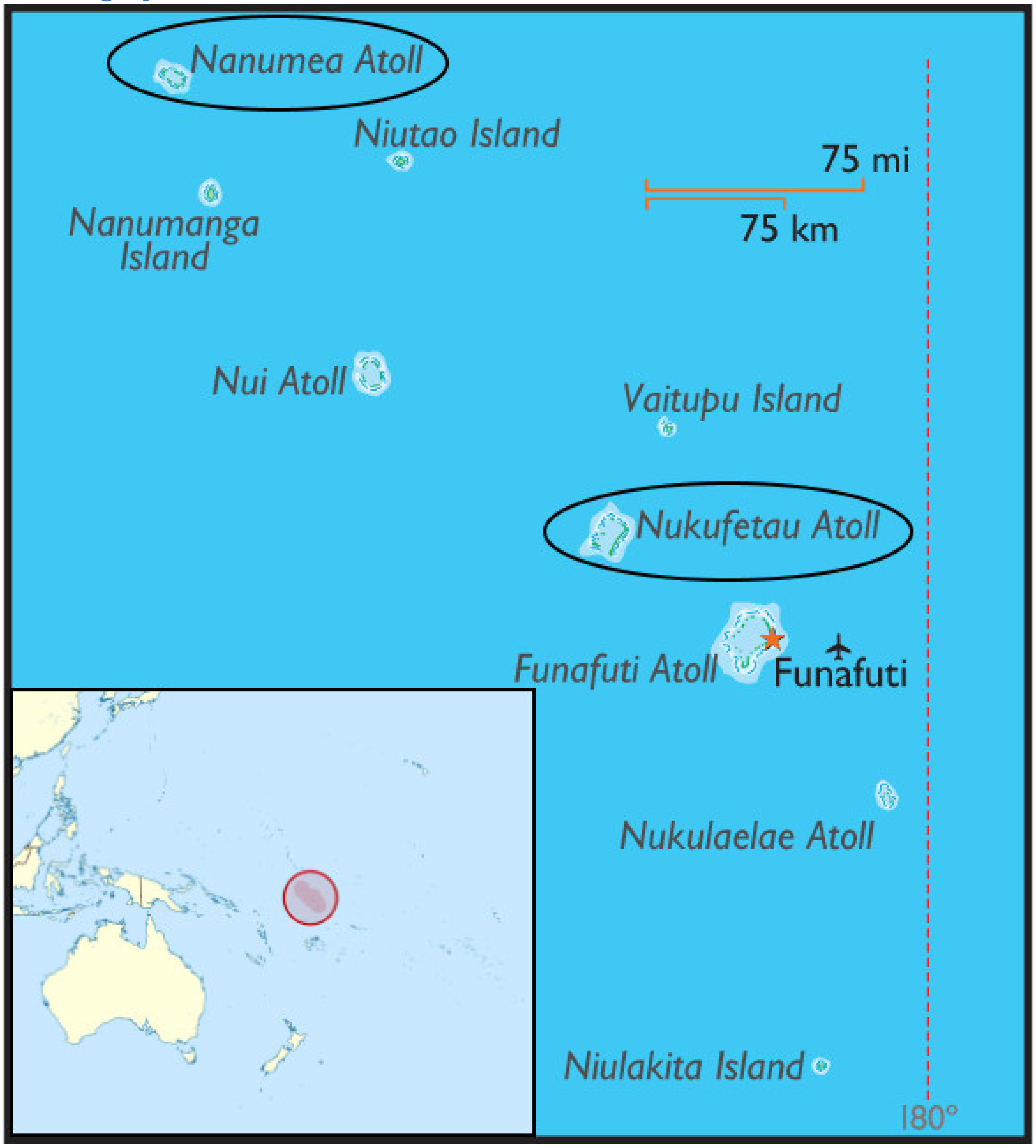

Figure 1. Geographical location of Nanumea and Nukufetau atolls. Source: www.graphicmaps.com

Nukufetau is located at 8°00'S. 178°23'E, 167 km northwest of Funafuti. The atoll consists of 5 major islets and 32 smaller islets, with a total land area of 3.3 km^2 (Fig. 2). The main village is located on Savave islet, while all agricultural activities (piggeries and *pulaka*[1] farms) take place on the neighbouring islet of Fale. *Pulaka* pits are also present on Lafanga and Motulalo islets, while some agriculture also takes place on Funaota islet. Motulalo was used by American forces during World War II (WWII) as an airfield base. After the war, the airfield was dismantled and the land returned to its

[1] Swamp taro (*Cyrtosperma chamissonis*), which is grown in natural depressions and excavated pits is locally known as *pulaka*.

owners; however, because the coral base was compacted to build the runway, the land on which the runway was constructed now provides poor ground for agricultural activities.

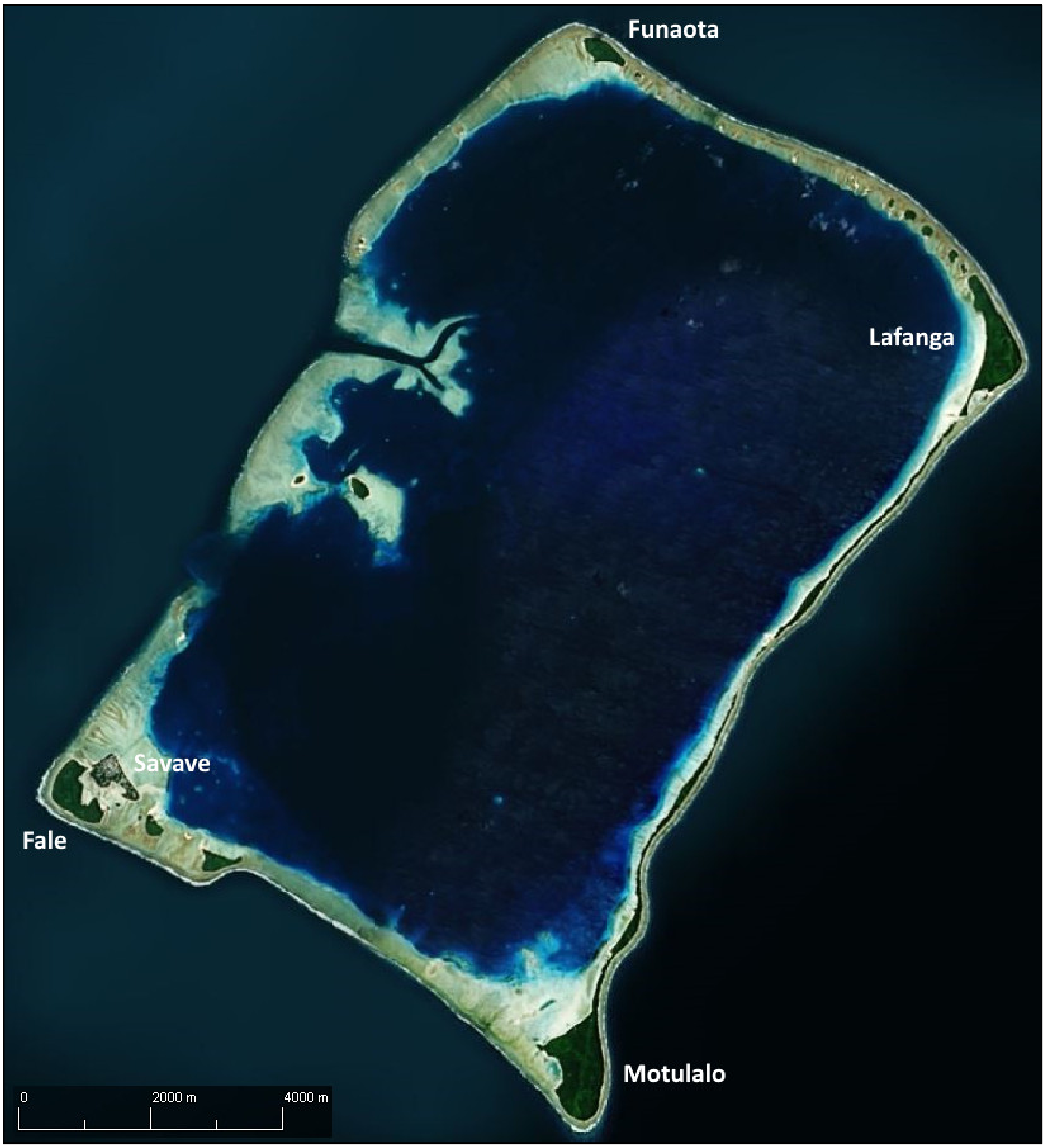

Figure 2. Nukufetau atoll

Nanumea is Tuvalu's northernmost atoll, and is located at 5°40'S, 176°06'E, 470 km northwest from the capital, Funafuti. It consists of two major islets, Nanumea and Lakena, with a narrow lagoon system (2-km wide, lying in a southwest–northeast direction) that connects the two islets (Fig. 3). A third smaller islet, Temotufoliki, forms the extent of the main island from which it is separated by a channel. Nanumea islet has a total length of 4.7 km, extending up to 5.5 km when including Temotufoliki. The widest part of the islet is 890 m. Lakena islet has a length of 2.4 km and a maximum width of 640 m. The lagoon penetrates into the interior of Nanumea creating two peninsulas, with Nanumea village to the south and Matangi area, and Temotufoliki islet to the north. Nanumea Atoll has a land area of 3.66 km^2, making it the second largest atoll in Tuvalu after Vaitupu.

Figure 3. Nanumea atoll (source: Google maps)

2.2 Climate

Tuvalu lies within the southeast tradewind zone but is on the edge of the southwest Pacific equatorial doldrum zone. Prevailing winds are from the easterly quarter and mainly occur between June and August. In most years, between December and March, winds from the northwest usually equal or exceed the easterlies in frequency.

Rainfall in Tuvalu is influenced by the position of the South Pacific Convergence Zone (SPCZ), which is a band of convergence that splits from the Intertropical Convergence Zone (ITCZ) and the Western Pacific Warm Pool, and whose position influences rainfall patterns across the islands of the southwest Pacific Ocean. The SPCZ moves zonally and may be positioned farther east or west as it is influenced by larger-scale climate oscillations, such as the El Niño-Southern Oscillation (ENSO). It is a general observation that La Niña ENSO conditions are likely to result in more reduced rainfall for Tuvalu than Neutral or El Niño ENSO conditions. Monthly rainfall records for Nanumea date back to 1941. Mean annual rainfall is 2,750 mm, with 60% of this falling during the wet period of December to May. The highest annual rainfall was recorded in 1987, with a total of 4,900 mm, while the lowest rainfall recorded was in 2011 with 523 mm. Annual rainfall shows high variation over the years, with a coefficient of variation (CV) of 0.35, indicating that, on average, annual rainfall can have a 35% higher or lower variability than the mean. Rainfall variability is even more pronounced during the dry period (June to November), with a CV of 0.47. Rainfall variation in monthly averages (Fig. 4) is generally high, with greater variability observed towards the end of the dry period.

Table 1. Mean annual rainfall on Nanumea and Nukufetau atolls.

	Nanumea (records available 1941–2018)			**Nukufetau** (records available 1955–1980)		
	Yearly	Dec-May	Jun-Nov	Yearly	Dec-May	Jun-Nov
Mean	2,750	1,648	1,081	2,785	1,595	1,209
Std dev	950	584	507	678	404	394
CV (coeficient of variation)	0.35	0.35	0.47	0.24	0.25	0.33

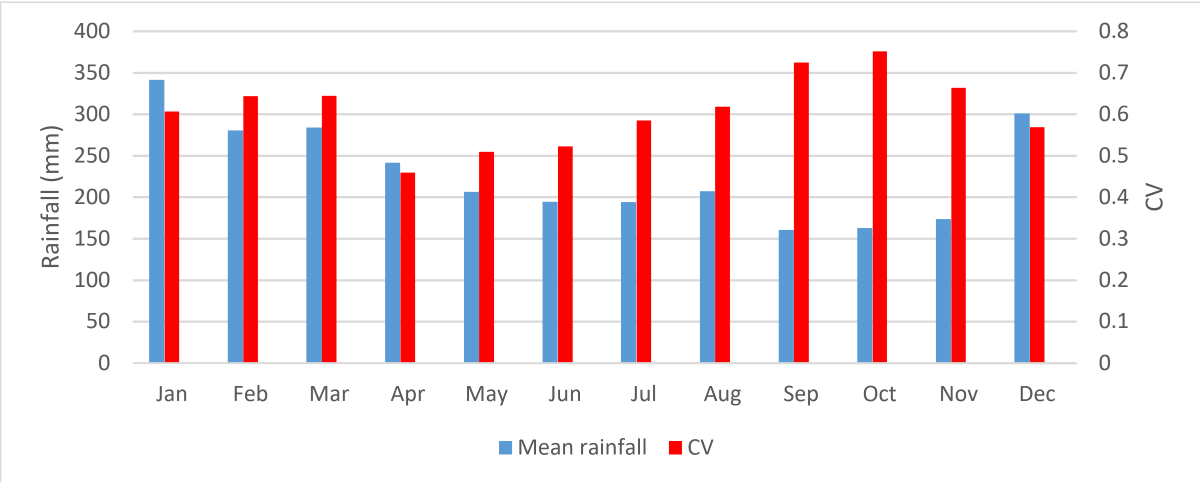

Figure 4. Mean monthly rainfall in Nanumea (78-year record period, 1941–2018). CV= coefficient of variation

For Nukufetau, records were only available for the period 1955–1980, and the statistics are, therefore, less accurate. The mean annual rainfall on Nukufetau is very similar to Nanumea but the difference between the wet and dry period is less pronounced (Fig. 5). In fact, both yearly and seasonal rainfall variability is lower, with a CV of 0.24, indicating that, on average, the annual rainfall is 24% higher or lower than the mean. This suggests that Nukufetau is less likely to experience droughts than Nanumea. Also, the rainfall variability in monthly averages does not suggest any patterns.

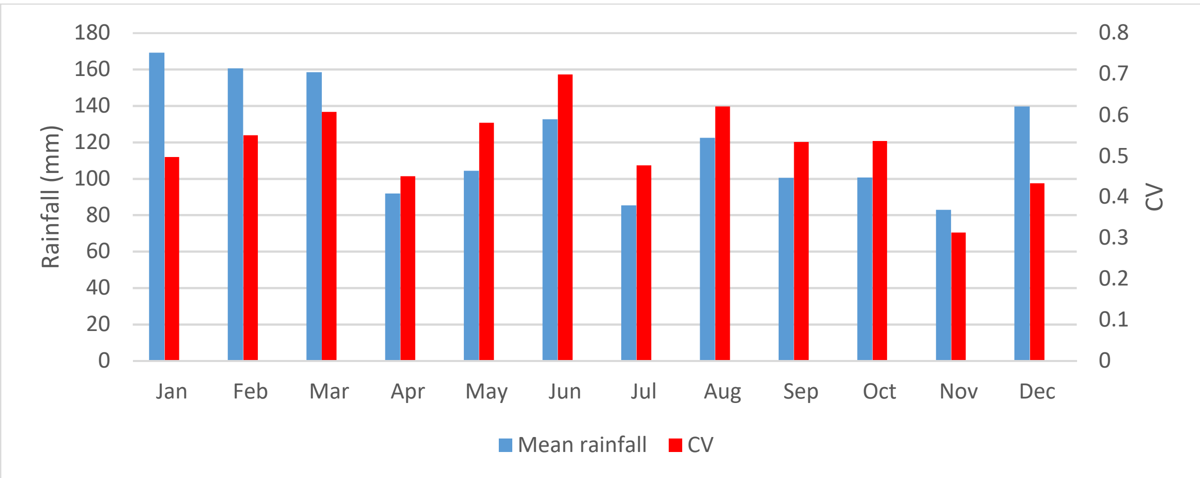

Figure 5. Mean monthly rainfall in Nukufetau (26-year record period, 1995–1980). CV = coefficient of variation

2.2.1 Drought

Drought in Tuvalu can be defined using the percentile method as being a period of rainfall in which the sum of the rainfall for the specified period (e.g. 3, 6, 12 months), is in the lowest 10% of the summed recorded rainfall for that specified period. In other words, the sum of rain recorded over a three-month period, for example September–November in Nanumea, will constitute a drought if it falls in the lowest 10% of the summed recorded rainfall for the same three-month period across the entire rainfall recorded history.

Both Nanumea and Nukufetau currently rely heavily on rainwater harvesting for domestic and drinking water supplies. It is, therefore, appropriate to use a three-month period of rainfall to assess the impact of drought, using the percentile method, due to the smaller storage sizes, and the "residence" time associated with rainwater harvesting. Groundwater systems, which have a larger storage capacity, are more resilient to the impacts of short-term reductions in rainfall, and it is more appropriate to use 6- or 12-month periods when assessing drought impacts on Pacific atolls and islands.

A statistical analysis of the entire rainfall records for Nanumea and Nui[2], using a three-month drought index percentile method, is provided in Table 2 to provide some insight into drought occurrence for both northern and central Tuvalu.

Table 2. Analysis of drought statistics for Nanumea and Nui for available rainfall data, using a three-month drought index percentile method.

	Nanumea (January 1941– April 2018)				**Nui**[1] (January 1946–April 2018)			
	Total	El Niño	La Niña	Neutral	Total	El Niño	La Niña	Neutral
Number of droughts	14	0	10	4	19	2	9	8
Average length of drought (months)	13.6	NA	10.3	21.8	11.2	15.5	8.2	13.5
Average recurrence (months)	46	NA	51.4	33.8	35.6	5.5	41.6	36.6

In summary, Nanumea and the northern Tuvalu group, is more likely to experience drought during La Niña ENSO conditions, which are often shorter in duration (e.g. 10.3 months) and less frequent (approximately once every 4.25 years) than droughts experienced during a Neutral ENSO condition, which have an average duration of 21.8 months and occur approximately once every two to three years. Drought during El Niño conditions were not observed for Nanumea.

On average, the central Tuvalu islands receive more rainfall, and yet statistically they are more likely to experience drought conditions than the northern Tuvalu islands. Drought conditions in central Tuvalu are, however, of shorter duration (up to 10 months shorter on average) compared with Tuvalu's northern islands. Drought can occur during both La Niña and Neutral ENSO conditions, while drought has been experienced during El Niño conditions on only two occasions in central Tuvalu over the 72-year rainfall record.

[2] Synoptic weather stations with extended continuous records are available in Nanumea (northern group), Nui (central group), Funafuti and Nuilakita (southern) island groups. Nukufetau, in the central group, has only 26 years of rainfall records available for statistical analysis, which reduces the confidence of the analysis.

Tables 3 and 4 identify the top five ranked droughts for Nanumea and Nui, respectively, based on both intensity and duration. It is notable that the 2010–2015 drought, a Neutral ENSO event, was the most severe drought on record, being three times longer in duration on Nanumea than previously recorded, and with the lowest average month rainfall record over that period. On Nui, the drought was nearly twice the length than previously recorded, and also with a significantly low average monthly rainfall. It is interesting to note that the 1998–2000 period, a significant El Niño event associated with drought across the Pacific, while impacting Nui and central Tuvalu, did not have as significant an impact on Nanumea. In general, it can be stated that drought is more severe in northern and central Tuvalu than in Funafuti and southern Tuvalu, with regards to both duration and rainfall amount. However, the largest percentage of the country's population resides on Funafuti (57%, Central Statistics Division 2012), meaning that potable water stress and shortages are likely to be more acutely experienced by Funafuti's population than other localities.

Table 3. Historical droughts on Nanumea (three-month percentile index).

Nanumea (January 1941–April 2018)					
Rank	Drought period	Drought length (months)	Drought ENSO state	Total rainfall during drought (mm)	Average monthly rainfall during drought period (mm)
1	May 2010 to April 2015	60	Neutral	5,858.2	97.6
2	March 2008 to October 2009	20	La Niña	2104.1	105.2
3	June 1975 to December 1976	19	La Niña	2,352.0	123.8
4	January 2000 to March 2001	15	La Niña	1,884.4	125.6
5	April 1962 to May 1963	14	Neutral	1,822.8	130.2

Table 4. Historical droughts on Nui (three-month percentile index).

Nui[1] (January 1946–April 2018)					
Rank	Drought period	Drought length (months)	Drought ENSO state	Total rainfall during drought (mm)	Average monthly rainfall during drought period (mm)
1	May 2010 to September 2014	21	Neutral	6658.4	123.7
2	March 1998 to June 2000	28	El Niño	4037.5	144.2
3	March 1962 to July 1963	17	Neutral	2773.8	163.2

4	April 1971 to May 1972	14	La Niña	2202.0	157.3
5	January 2006 to January 2007	13	Neutral	2448.8	188.4

To assess which rainfall stations are more comparable to Nukufetau's, a comparison of rainfall records for Nui, Funafuti and Nukufetau for corresponding periods (1955–1980) was made (Table 5). It is recognised that the available period of rainfall data is only 26 years, and that statistically and climatlogically a longer period (i.e. > 30 years), is recommended. However, the analysis does provide insight into the variabity of rainfall among these islands.

Table 5. Comparison of Nukufetau, Nui and Funafuti drought periods using rainfall records dating from 1955 to 1980 (using a three-month percentile index).

	Nukufetau 8.0⁰ S (January 1955–December 1980)				**Nui[1] 7.2⁰ S** (January 1955–December 1980)				**Funafuti 8.5⁰S** (January 1955–December 1980)			
	Total	El Niño	La Niña	Neutral	Total	El Niño	La Niña	Neutral	Total	El Niño	La Niña	Neutral
Number of droughts	11	1	7	3	9	NA	5	4	12	4	7	1
Average length of drought (months)	7.7	NA	5.6	9.7	9.3	NA	10.4	8	5.9	4.8	7.0	NA
Average recurrence (months)	25.9	NA	12	39.7	22.9	NA	25.2	20.5	17.1	15.5	18.7	NA

As expected, islands separated by large distances can experience significant variation in rainfall as well as variation in drought impact and drought timing. While some broad statements can be made from the rainfall analysis between nearby stations, the variability of rainfall between stations strengthens the case for site-specific rainfall stations on islands, and that prediction of rainfall amounts on one island, based on recorded rainfall on a nearby island can have a high degree of error. Nukufetau is approximately 165 km to the southeast of Nui, in the direction of Funafuti, which in turn is approximately 100 km to the southeast of Nukufetau. It is suggested that Nukufetau demonstrates a progression in the rainfall patterns that can be seen between Nui and Funafuti. That is, moving farther away from the equator, the frequency of drought conditions increases, while in general, the recurrence interval for drought decreases. The data also suggest that the impact of El Niño and drought, increases farther away from the equator. Statistically, it would seem that Nukufetau is likely to experience more frequent drought conditions than Nui, although less frequent drought than Funauti; and that, on average, the length of drought is less in Nukufetau than can be expected in Nui, yet is longer than droughts expected in Funafuti. This type of analysis is useful in understanding the likelihood of drought and an indication of the relative impacts of drought when it is identified.

2.3 Current water supply and drought response

Before the widespread introduction of rainwater tanks, the dominant source of water for potable and domestic use was groundwater abstracted through community wells. Nowadays, with the introduction of rainwater tanks, groundwater from dug communal wells is mostly used for livestock or gardens, with the exception of when rainwater supplies are low.

When household storages run low, water is drawn from government- or community-owned tanks that harvest rain from public buildings. The total water storage capacity for Nanumea in 2012 was 4.2 million litres (L) (Central Statistics Division 2012) of which, at least 1 million L of storage is communal. In Nukufetau, the total water storage capacity in 2012 was 3.5 million L (Central Statistics Division 2012) of which, at least 0.5 million L of storage is communal. Average rainwater storage per person in Nanumea is estimated to be 7,550 L storage/person, while in Nukufetau, where annual rainfall volumes are greater, the estimated rainwater storage is 6,480 L storage/person. With the introduction of new rainwater tanks, these volumes are expected to have increased in the following years by at least 2 million L on each atoll. Consideration of communal storage alone, for Nanuma, indicates that available storage is estimated at 1,800 L communal storage/person, while in Nukufetau available storage is 925 L communal storage/person. Communal water storage infrastructure is managed at the community level by the *kaupule*[3]. However, when there is a declared drought, the government has the legal power to take control of all communal storages and, depending on the situation, may limit water use to 40 L/household/day (Bouchet 2014).

According to a rapid assessment groundwater survey done by Sinclair and others (2012), 95% of households in both Nanumea and Nukufetau had their own water source, which was either a tank or cistern that collected rain water from the roof. During the drought of 2011, 78% of households in Nanumea stated that they had been using wells as a secondary source of water, and 62% stated that they had been using groundwater for secondary purposes (e.g. washing, bathing). In Nukufetau, 42% of households indicated that they had been using wells as a secondary source of water and 41% that they had been using groundwater for secondary purposes. Finally, according to the same survey, 18% of surveyed households in Nanumea experienced at the time, *weekly* water shortages from their main water source, 20% *monthly*, 34% *rarely* and 28% *never*. In Nukufetau, 13% of surveyed households experienced *weekly* water shortage from their main source, 9% *monthly*, 10% *rarely* and 68% *never*. These results suggest that in 2011, Nukufetau suffered fewer water shortages than Nanumea.

2.4 Geology and groundwater occurrence

The geological structure of Nanumea and Nukufetau follows the typical pattern of atolls, in that they originated from basaltic volcanoes that have since submerged with reef growth, resulting in a cap of calcium carbonate minerals. The shallow subsurface geology is influenced by rainfall-induced weathering and sea level changes, and generally follows a three-layer geological model: 1) an upper sediment unit composed of unconsolidated and well-sorted coral sand and gravel; 2) a lower sediment unit composed of unconsolidated lagoonal sands and gravel; and 3) a dense and well-consolidated limestone unit that formed during subaerial exposure and recrystallisation to calcite.

Fresh groundwater normally occurs within the unconsolidated sediments as a lens-shaped body that is buoyantly supported by dense underlying saline water. The higher permeability of the underlying

[3] Community governance and island affairs are led by two bodies within each Tuvalu Island: the *falekaupule* and the *kaupule*. The *falekaupule* functions as an island council, acting as the primary decision-making group on each island. It comprises four people: the chief, a spokesperson, an assistant and the treasurer, each of whom is elected by the community. The *kaupule* is the executive arm of the *falekaupule*, and is in charge of preparing and implementing development plans and other programmes such as transportation services, maintenance of public property and infrastructure, and management of land tenure. The *kaupule* is overseen at the national level by the Tuvalu Ministry of Home Affairs. The *kaupule* is headed by the *pule-kaupule*, the equivalent to the mayor of the island, supported by five helpers with specific roles, or ministries. The *kaupule* is also composed of a planner, secretary, finance, assistant, and the clerk (Sinclair et al. 2017).

limestone (layer 3) does not allow for the formation of a freshwater lens, which is truncated due to mixing with saltwater, at the unconformity between the younger sediments and the older underlying limestone. This geological boundary, called the Thurber Discontinuity, is typically encountered at depths ranging between 5 m and 25 m. The thickness of this freshwater body depends on the recharge rate (rainfall), the width of the island, the hydraulic conductivity of the sediments, the depth of the Thurber Discontinuity, and the presence (or absence) of a reef flat plate (Bailey and Jenson 2012).

Mixing between the fresh groundwater and underlying salt water, promoted by tidal forces, is responsible for the presence of a zone of transitional salinity. Its thickness largely depends on the hydraulic properties of the aquifer sediments.

The hydraulic properties of freshwater lens aquifers can be strongly influenced by the position of the island with respect to the direction of the prevailing winds. Low carbonate islands tend to acquire a coarse sediment structure when they are located in the direct path of the prevailing winds and associated high-energy waves. In contrast, islands located on the partially protected leeward side of atolls tend to acquire a finer sediment structure. Considering that northwestern and southeastern winds are equally frequent throughout the year in Tuvalu, it is expected that islands located on the northwest and southeast sides of atolls might offer better hydraulic conditions for the development of freshwater lenses.

Nanumea

McLean and others (1986a) conducted a land resources survey of Tuvalu for land-use planning purposes. Among other things, the survey consisted of landform and soil surveys and preliminary groundwater quality investigations to identify the land suitability for agricultural purposes. According to the researchers (McLean 1986a), the landform units – that are distinguishable in the three islets of Nanumea – include oceanside ridge complex, lagoon margin, interior depression, and enclosed basin.

The oceanside ridge complex forms the outer borders of the main islets, and its width can range between 200 m and 300 m. It comprises a single ridge or a ridge-and-swale complex with a steep seaward-facing foreslope and a smoother inland-facing backslope, which gradually converts into the internal depression. Along the eastern ridge complex, the crest typically reaches 2.0–2.5 m above the level of the reef flat, whereas along the western ridge crest, elevations reach 4.0–5.0 m above reef flat level. In Lakena, the ridge substrate is mainly composed of sand with occasional coral fragments, while in Temotufoliki it is composed of coarse coral rubble. On Nanumea islet, the dominant substrate material is sand with a veneer of coral gravel on the surface, which is only present along the eastern side (Matangi). Here, the ridge complex is rather flat due to the construction of a, now absent, WWII airfield.

The lagoon margins are lower than the oceanside ridge complex, and consist of coarse sandy beach materials that have been deposited on a reef rock platform. These deposits are particularly thick in Temotufoliki where a 2-m berm has developed due to the islet's exposure to waves.

The interior flat depressions are generally present in-between the oceanside ridge complexes and the lagoon margins, and their elevation does not exceed 2 m above reef flat level. These areas are predominantly composed of sands. Three enclosed basins are present in the interior depressions, two in Lakena (Te Tongo at the western and Te Koko at the eastern end) and one on the main islet (Te Milo). Te Tongo and Te Milo share similar characteristics as they are surrounded by steep conglomerate and coarse coral gravel slopes and high saline water. Te Tongo on the other hand, has fresher water and features a riparian zone of grassy banks and unconsolidated sands where small *pulaka* pits have been dug.

Nukufetau

According to McLean and others (1986b), the landform units that can be distinguished in Nukufetau's islets include the oceanside ridge complex, lagoonside ridge complex, interior depression and the saline and *pulaka* basins.

The oceanside ridge complex is made up of coarse coral rubble and consists of a single ridge (Motulalo islet) or a ridge-and-swale complex (Fale, Lafanga, Funaota islets). The ridge crest rises 2–4 m above reef flat level and usually located along the vegetation edge.

The lagoonside ridge complex presents a fairly different morphology with a lower ridge (up to 2 m above reef flat level), a flatter and wider crest and a broader and more gentle backslope. This complex is usually composed of a sandy single ridge. The underlying beachrock occasionally becomes exposed due to shoreline erosion (Lafanga and Motumua islets), causing a steeper beachslope and a broader berm.

The interior depressions occupy the low-lying areas between the oceanside and lagoonside ridge complexes. On Fale islet, this landform is not well developed and is characterised by irregular topography with a substrate consisting of coarse coral rubble packed with large coral boulders. Parts of the interior depressions (Motulalo and Lafanga islets) are regularly indundated at high tide through subsurface saline water intrusion. *Pulaka* pits are only found on Fale, Motulalo and Lafanga islets.

Extended areas of Motulalo were altered for the construction of the airfield during WWII. This included vegetation clearance, land levelling, excavation of borrow-pits and basins, and of road construction.

2.5 Previous investigations

Nanumea

In 1976, Flynn and Makin tested the groundwater salinity at a number of wells and found high electrical conductivity (EC) values in Matangi and in Nanumea village, and found fresh groundwater in Lakena, close to the eastern end of the islet.

As part of the land resources survey conducted at Nanumea (McLean 1986a), water in *pulaka* pits, pools and wells was tested for salinity using a portable conductivity meter. These results provide a snapshot of groundwater salinity at shallow depths and can be used to approximate the presence of a freshwater lens. Figure 6 shows that fresh groundwater is present in the central and southeastern areas of Lakena and Temotufoliki islets as well as in the central depression along the Matangi peninsula. Variable groundwater salinities were measured in wells in Nanumea village, and these indicate less favourable conditions. Fresh water (1,070 µS/cm) was measured in the Te Koko pond while the water measured from Te Tongo and Te Milo ponds was saline (> 20,000 µS/cm).

Van Putten (1988) conducted a hydrogeophysical assessment of groundwater resources in Tuvalu, including Nanumea. Vertical electrical soundings were conducted in the Matangi area and in the Tefanga and Lataki areas. The results suggested the presence of a 3 m- to 5- m-thick freshwater lens in Matangi, and a 2 m- to 4- m-thick lens in Tefanga and Lataki. Groundwater salinity was tested in a well in the southern Matangi area and was found to have an EC of 600 µS/cm.

Webb (2007) measured the salinity in *pulaka* pits on all islands in Tuvalu, including Nanumea. Measurements in each pit were taken at the surface (~5 cm), midway down (~15 cm) and at the bottom (~30 cm). Considering the shallow sampling depth, the measurements give a conservative indication of the overall fresh groundwater potential. On the other hand, the absolute measurements

Figure 6. Mapped landforms, groundwater salinity, electrical resistivity tomography survey lines, and WWII dump sites (with sample names) on Nanumea (inset: Lakena islet).

should be treated with caution as measurement sites within *pulaka* pits may demonstrate increased evaporation, or even pooled fresher rainfall, which would influence individual salinity readings. The average EC of all pits (37 total) was 745 µS/cm, with a standard deviation of 421.

Finally, Sinclair and others (2012) surveyed nine private and communal wells around Nanumea Village and tested their salinity during drought periods. The recorded EC values ranged between 4,000 µS/cm and 14,500 µS/cm, indicating the general absence of freshwater in this part of the island.

Nukufetau

Flynn and Makin (1976) tested groundwater salinity at a number of wells and *pulaka* pits on the islets of Fale, Savave and Motulalo. Fresh groundwater (EC: 600–650 µS/cm) was recorded in wells located 100 m from the sea channel between the islets of Fale and Savave, whereas saline groundwater (EC: 14,000 µS/cm) was recorded in the only village well that they tested, located in the middle of Savave islet (Flynn and Makin 1976).

As part of the land resources survey of Nukufetau (Mc Lean 1986b), additional water samples were collected from *pulaka* pits, pools and wells, and were tested for salinity using a portable conductivity meter. Ther results suggested the presence of a fresh groundwater lens (EC: 360–810 µS/cm) in the northern and central areas of Fale, and in the northwestern part of Motulalo (EC: 480 µS/cm).

Hydrogeophysical assessments conducted by Van Putten (1988) in Nukufetau suggested the presence of negligible fresh groundwater on the islet of Savave, and the presence of a significant fresh groundwater body (4–12 m thick) on Fale islet.

Water salinity was measured in 19 *pulaka* pits on Fale islet, and the average EC was found to be 161 µS/cm, with a standard deviation of 90 (Webb 2007). These results support the findings of previous authors (Mc Lean 1986b; Van Putten 1988) on the presence of significant fresh groundwater on Fale.

Finally, five wells were surveyed by Sinclair and others (2012 on Savave islet, three on Fale and one on Motulalo. Groundwater salinity on Savave ranged between 2,200 µS/cm and 6,500 µS/cm, while fresh groundwater was recorded in two wells on Fale (450–812 µS/cm) and brackish to saline water on Motulalo (6,430 µS/cm). It is noted that Sinclair undertook the salinity survey of wells during an extended dry period.

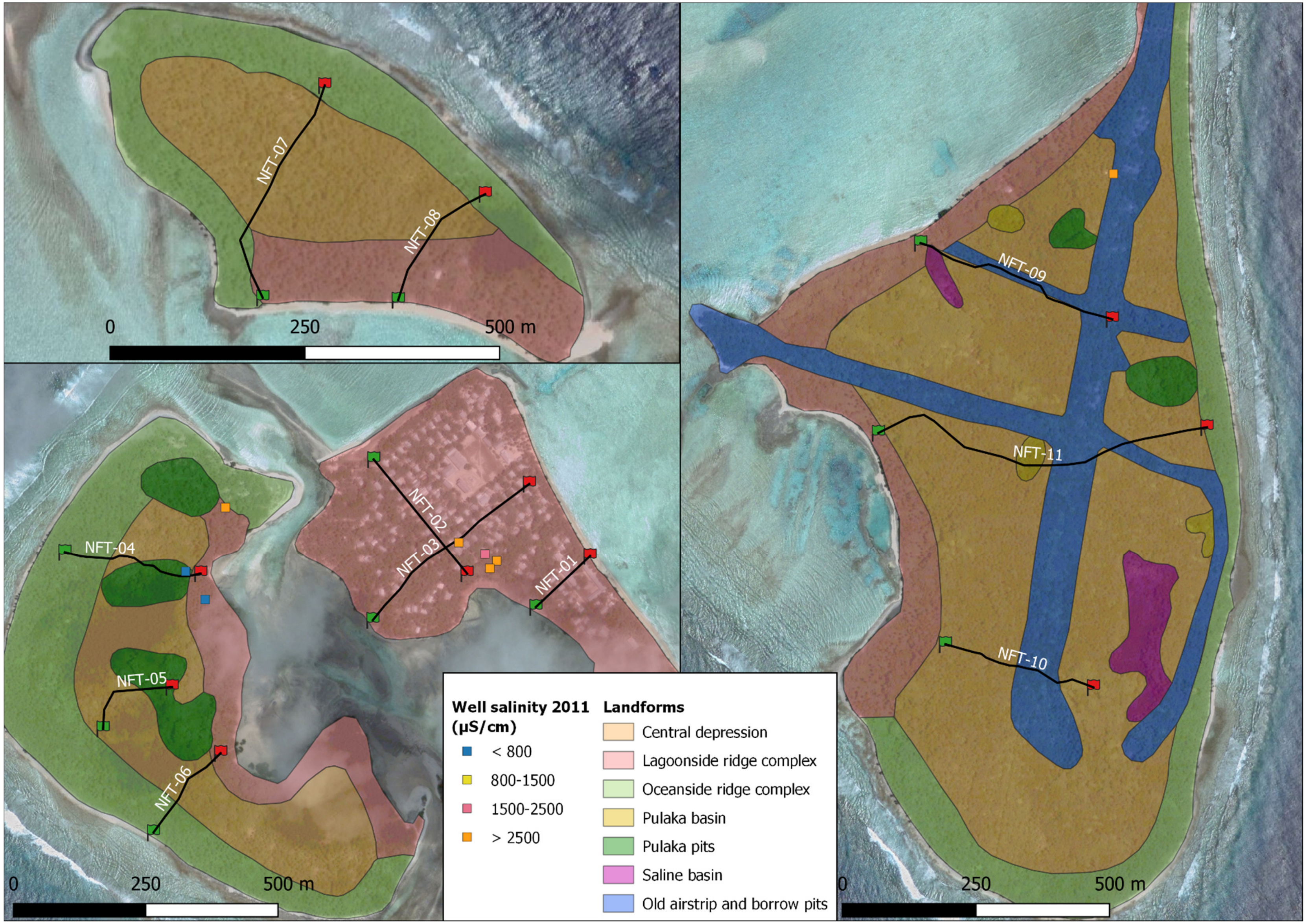

Figure 7. Mapped landforms, groundwater salinity and electrical resistivity tomography survey lines on Nukufetau (top left: Funaota islet, bottom left: Fale and Savave islets, right: Motulalo islet).

3. Field survey methodology

3.1 Electrical resistivity tomography survey

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

The ABEM Terrameter LS2 from GuidelineGeo Inc. was used in combination with the multiple gradient array as the preferred survey protocol, thus providing high horizontal and vertical data resolution (Dahlin and Zhou 2006). The depth of investigation is a function of the electrode spacing and the Earth's resistance; in general, the greater the electrode spacing, the deeper the investigation. An electrode separation length of 2 m was selected to investigate in detail depths up to 30 m. The orientation of the survey profiles and the traverse distance was guided by a review of satellite photos and existing shallow wells so as to adequately investigate the groundwater potential of the shallow coastal sediments.

Table 6 illustrates the different geological materials that are encountered on the two atolls and the corresponding resistivity range that is likely to be measured. The absence of monitoring boreholes did not allow for in situ verification of the recorded resistivity results and empirical resistivity values from similar environments (Antoniou et al. 2019) were used to interpret the vertical extent of the fresh groundwater bodies. Even if the exact depth cannot be accurately determined, it is the lateral variation along the survey transects that provides insights on locations offering the greatest potential for groundwater development.

Table 6. Typical resistivity ranges for different sediment types (based on Dale 1986; Greggio et al. 2018).

Rock and sediment type	Resistivity (Ohm.m)
Dry coral sediments	500–3000
Coral sediments saturated with freshwater	30–300
Hard coral saturated with sea water	5–15
Coral sand saturated with sea water	2–10

3.2 Model inversion methodology

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

Prior to running the model inversions, the raw exported database was first treated to remove any ‘negative resistivity’ readings that might affect the accuracy and reliability of the inversion. These erroneous readings indicate the electrode’s inability to read a realistic difference in electrode potential and contribute substantially to the total absolute error. This is usually related to poor electrode contact, misplaced electrodes, the presence of human-made objects in the ground (e.g. cables or pipes) and above the ground (e.g. metal fences), and noise from electrical fences or power lines. Other reasons are related to incorrect transmitter and/or receiver settings with respect to field conditions, and finally to highly variable geological conditions in two or three dimensions, forcing the electrical current to travel in unexpected ways and cause negative readings (Fredrik Nyqvist, Product manager, Guideline Geo Group MALÅ/ABEM, 2017, pers. comm.). The presence of seawater with very low resistivity along the coastal survey lines is another factor that can contribute to noisy datasets. After removing the negative values, a preliminary inversion was carried out using all of the remaining data points. Then, using the ‘RMS error statistics’ option that displays the distribution of the percentage difference between the logarithms of the measured and calculated apparent resistivity values, bad data points having an error of 100% and above were further removed. A final inversion was then carried out using the new filtered dataset, allowing for a much lower absolute error compared to the first run, and providing improved confidence in the datasets.

Elevation data along the ERT survey lines were not obtained during this study. As a consequence, the modelled resistivity profiles were not corrected for surface morphology. The resistivity distribution along the modelled profiles is only expected to be slightly influenced by the absence of such correction, due to the small changes in elevation along the survey lines.

3.3 Selection of ERT survey locations

A total of 13 ERT survey lines were undertaken in Nanumea, ten of which were undertaken on the main island, two on Lakena and one on Temotufoliki islet. In Nukufetau, 11 ERT survey lines were carried out: 3 lines were undertaken on the main islet of Savave, 3 on the nearby islet of Fale, 2 on the islet of Funaota and 3 on Motulalo. The survey lines were selected in such a way as to cover as much representative area as possible, and to investigate the different landforms and their boundaries. This in turn allowed for a more accurate assessment of the lateral and vertical extent of the fresh groundwater bodies.

Table 7. Electrical resistivity tomography survey lines undertaken on Nanumea and Nukufetau.

Survey line	Location	Distance (m)	Start point	End point
NFT-01	Savave, Nukufetau	144	8° 1'45.59"S 178°18'54.50"E	8° 1'42.43"S 178°18'57.85"E
NFT-02	Savave, Nukufetau	280	8° 1'36.45"S 178°18'44.49"E	8° 1'43.51"S 178°18'50.25"E
NFT-03	Savave, Nukufetau	400	8° 1'46.39"S 178°18'44.44"E	8° 1'37.96"S 178°18'54.09"E
NFT-04	Fale, Nukufetau	280	8° 1'42.18"S 178°18'25.42"E	8° 1'43.51"S 178°18'33.80"E
NFT-05	Fale, Nukufetau	200	8° 1'53.09"S 178°18'27.78"E	8° 1'50.52"S 178°18'32.04"E
NFT-06	Fale, Nukufetau	200	8° 1'59.48"S 178°18'30.89"E	8° 1'54.62"S 178°18'35.04"E
NFT-07	Funaota, Nukufetau	320	7°55'57.42"S 178°22'47.08"E	7°55'48.51"S 178°22'49.69"E
NFT-08	Funaota, Nukufetau	186	7°55'57.51"S 178°22'52.76"E	7°55'53.08"S 178°22'56.41"E
NFT-09	Motulalo, Nukufetau	400	8° 3'45.90"S 178°22'30.93"E	8° 3'50.56"S 178°22'42.65"E

NFT-10	Motulalo, Nukufetau	320	8° 4'10.48"S 178°22'32.44"E	8° 4'13.12"S 178°22'41.50"E
NFT-11	Motulalo, Nukufetau	720	8° 3'57.54"S 178°22'28.34"E	8° 3'57.19"S 178°22'48.44"E
NMA-01	Nanumea village	120	5°40'20.92"S 176° 6'49.39"E	5°40'19.76"S 176° 6'53.13"E
NMA-02	Matangi, Nanumea	200	5°40'9.32"S 176° 7'20.44"E	5°40'5.87"S 176° 7'25.74"E
NMA-03	Matangi, Nanumea	280	5°40'21.83"S 176° 7'24.57"E	5°40'17.52"S 176° 7'32.67"E
NMA-04	Matangi, Nanumea	160	5°40'29.06"S 176° 7'31.67"E	5°40'27.27"S 176° 7'36.53"E
NMA-05	Matangi, Nanumea	280	5°40'48.46"S 176° 7'35.17"E	5°40'42.10"S 176° 7'41.81"E
NMA-06	Nanumea south	200	5°40'56.80"S 176° 7'37.17"E	5°40'51.93"S 176° 7'40.46"E
NMA-07	Nanumea south	320	5°41'6.59"S 176° 7'29.42"E	5°40'58.95"S 176° 7'35.54"E
NMA-08	Nanumea south	480	5°40'59.14"S 176° 7'32.52"E	5°40'54.14"S 176° 7'46.47"E
NMA-09	Nanumea south	320	5°41'23.95"S 176° 7'44.18"E	5°41'19.91"S 176° 7'53.59"E
NMA-10	Nanumea village	138	5°40'17.63"S 176° 6'45.42"E	5°40'14.24"S 176° 6'47.98"E
NMA-11	Lakena, Nanumea	520	5°39'5.75"S 176° 4'20.98"E	5°38'50.47"S 176° 4'24.01"E
NMA-12	Lakena, Nanumea	680	5°38'52.92"S 176° 3'47.48"E	5°38'38.90"S 176° 4'2.29"E
NMA-13	Temotufoliki, Nanumea	280	5°39'40.09"S 176° 6'45.44"E	5°39'32.57"S 176° 6'50.52"E
Total distance of profiles (m)		Nanumea	3,978 m	
		Nukufetau	3,450 m	

3.4 Assessment of World War II sites

A number of WWII drum disposal sites in Nanumea Lagoon were assessed for their potential environmental impacts on the quality of the lagoon’s waters and sediments. The sites are close to the lagoon’s shoreline in shallow water (2–3 m depth), and consist of steel drums, completely corroded and flooded with seawater. The sites were located using visual survey techniques from a small boat, with their locations recorded using GPS. Seawater and sediment samples were collected at depth from from four representative dump sites (Fig. 6) and were analysed for heavy metals (sediments only), multiresidue pesticides and total petroleum hydrocarbons. The analyses were performed at Hill Laboratories in New Zealand. The results of the analysis are discussed in section 4.3.

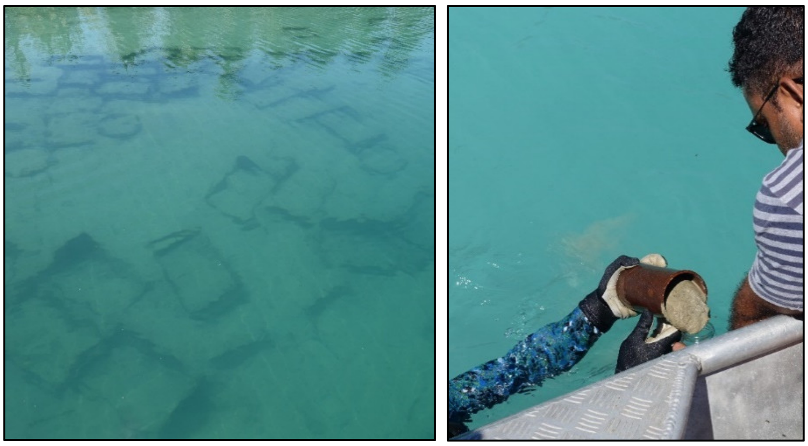

Figure 8. Corroded steel drums from WWII in Nanumea lagoon (left) and sampling of lagoonal sediments from WWII drum disposal sites (right).

4. Results and discussion

4.1 Geophysical results and interpretation

The extent and depth of the freshwater lens was described by means of isolines indicating the depth to the interface between potable groundwater (defined as EC < 2,500 µS/cm) and brackish groundwater, as inferred by the ERT profiles (Fig. 9 and Fig. 10). As mentioned earlier, due to the absence of monitoring bores, calibrated values from Majuro Atoll (Republic of the Marshall Islands) were used to match derived resistivity values to groundwater salinity, on the assumption that the geologies were similar. The isolines are based on the results of the ERT surveys, and their location is fairly accurate along the survey lines but become uncertain as the distance from the survey lines increases, particularly when there was no other neighbouring survey line, which would have allowed interpolation of the results. The results should, therefore, be treated with caution. It should also be noted that the interpretation provides a snapshot related to the current rainfall conditions, and hence, areas identified as having good groundwater potential may reveal a lower potential during periods of prolonged rainfall deficiency.

Nanumea

In total, 13 ERT profiles were completed on Nanumea Atoll (Fig. 6): 2 profiles around the village, 4 around the Matangi area, 4 in the southeastern part of the island, 2 on Lakena islet, and 1 on Temotufoliki islet.

The four profiles completed in Matangi revealed contrasting resistivity responses, which are probably controlled by the presence, composition, variable thickness and permeability of the eastern ridge deposits across which all the profiles extended. All profiles revealed a three-layer resistivity model with the top, high-resistivity layer (> 500 Ohm.m) representing unsaturated marine sediments (predominantly sands), the middle, moderate resistivity layer (20–200 Ohm.m) representing marine sediments saturated with fresh groundwater, and the third, very low-resistivity layer (< 15 Ohm.m) suggesting saltwater-bearing sediments and basal limestone. Where present, layer 2 has an average thickness of 5 m extending up to 7 m occasionally. Pockets of high-resistivity materials observed within the potential freshwater lens zone may represent areas of reduced permeability, possibly due to compaction of the surrounding sediments. The last 40 m of profile NMA-03 revealed a high-resistivity zone that extended at depth and appeared to have scoured the basement. This appears to be material derived from high-energy waves, likely porous and dominated by gravels and pebbles, with high permeability and, thus, poor groundwater potential. Finally, the higher resistivities observed along NMA-05 may be attributed to the intensely compacted materials as a result of the construction of an airstrip during WWII.

The two profiles conducted on Lakena islet exhibited contrasting resistivity responses. The eastern part of the island exhibited a relatively thicker zone of moderate resistivity (30–80 0hm.m) extending up to 8 m in depth. This area coincides with the mapped zone of depression where sediments are expected to be saturated with fresh groundwater and conducive to *pulaka* plantation, as extensively mapped. This groundwater potential was well supported by the numerous wells exhibiting freshwater quality in the 2011 sampling (Fig. 7). Hence, it may be fair to assume that the extent of the *pulaka* pits, as previously mapped, is a good representation of fresher groundwater potential, although the thickness would vary over space. In the western part of the island the potential fresh groundwater zone becomes very thin, possibly due to a reduction in the thickness of sediments comprising the depression zone. Remarkably, both profiles showed an increased thickness (up to 20 m) of high resistivity materials towards the southern coast. This may suggest accreting high wave-energy materials, likely too porous and unable to store and transmit fresh groundwater.

The other survey profiles generally revealed a two-layer resistivity model with the absence of a moderate resistivity layer, suggesting very limited to negligible fresh groundwater potential. Survey lines NMA-01 and NMA-10 around the village area revealed the absence of moderate resistivity layers, suggesting negligible fresh groundwater potential. The same holds for the western part of Temotufoliki islet and the southern part of Nanumea. The identification of a number of low-salinity wells by previous researchers (e.g. Mc Lean 1986b) on the eastern end of Temotufoliki suggests fresh groundwater potential in this portion of the island. Unfortunately, because the area is inaccessible due to thick vegetation, time permitted only one survey line to be completed on Temotufoliki.

Nukufetau

In total, 11 ERT profiles were completed on Nukufetau Atoll (Fig. 7), which included 3 profiles on Savave islet, 3 on Fale islet, 2 on Funaota and 3 on Motulalo.

On Savave, all three profiles revealed a two-layer resistivity model comprising a thin zone of high resistivity materials (> 200 Ohm.m) on top, underlain by a low-resistivity zone. The capping layer represents unsaturated marine sediments, possibly comprising lagoon ridge complex materials dominated by sand and fine deposits. Layer 2, again, indicated basal saline water filling the marine sediments and the underlying limestone. All profiles showed a very thin layer of moderate resistivity response (20–40 Ohm.m), representing the thin transition zone of fresh to brackish groundwater derived from infiltrating rainfall. The overall resistivity response on Savave suggests that the freshwater lens is negligible and is, therefore, inadequate for supporting water supply needs. Two remaining wells within the village of Savave confirm the geophysical interpretation, one well was observed dry, while the other showed scant but brackish water.

On Fale, all three profiles revealed promising resistivity responses, with a reasonably thick (5–10 m) layer of moderate resistivity (20–100 Ohm.m), suggesting sediments saturated with fresh groundwater. Also, moderate-resistivity responses were captured around the *pulaka* pits in the central part of the islet, which suggests good groundwater potential. The presence of four hand-dug wells, all exhibiting fresh groundwater (< 800 µS/cm), confirmed that good groundwater potential exists on Fale.

On Funaota, the presence of government investments and infrastructure such as vegetable farms and piggeries reinforced the need for investing in supplementary water sources in order to support the caretakers as well as the livestock and agriculture. A three-layer resistivity model was revealed in the western part of the islet and towards the ocean side, suggesting some limited groundwater potential with a thickness of up to 5 m. This electrical response is interpreted as increasing thickness and coarseness of the sediments towards the ocean side. A low-resistivity layer seems to overlie the moderate resistivity layer along the eastern part of the islet, potentially suggesting inundation at high tide through subsurface saline water intrusion.

The survey conducted on Motulalo was aligned with the ongoing interest from the government to revive the old airstrip. The three survey lines revealed contrasting resistivity results, which were mainly influenced by either the presence of highly compacted filling materials from the old airstrip, sediments comprising the central depression, or *pulaka* pit landforms. A three-layer resistivity model was only encountered in the central part of the island where there was a 5–7 m thick and 300 m long moderate resistivity layer (20–100 Ohm.m) that extended along the central-eastern half of the island. The presence of low permeability compacted materials derived from the old airstrip may have contributed to favourable conditions for groundwater to accumulate in this area.

A number of high-resistivity features were encountered at depth, within the saltwater-saturated zone on Savave, Funaota and Motulalo islets. These are difficult to interpret but may suggest the presence of consolidated geological features with negligible permeability, such as buried limestone, coral boulders or concrete blocks. Alternatively, these readings could also be related to instrument malfunction related to a possible electrode disconnection during the survey.

4.2 Groundwater resources development

As inferred by the ERT survey lines, the only promising option for developing fresh groundwater on Nanumea island is in the Matangi area where, assuming an average groundwater table of 1.5 m below ground, the existing freshwater lens attains an estimated thickness of at least 5 m (Fig. 9). Based on the inverted resistivity profiles, it is recommended that future fresh groundwater development focus on the area around survey line NMA-04, as the resistivity distribution indicates better conditions for groundwater accumulation and development. In terms of groundwater contamination, the widespread and uncontrolled pig farming around the entire Nanumea island, including Matangi, may have some implications to the quality of groundwater. It is recommended that if groundwater is developed on Matangi, appropriate measures (such as groundwater protection zones) should be taken to exclude pigs and other livestock, or inappropriate land-use activities, from the water production infrastructure area.

Lakena seems to offer better conditions as there is a thicker and more consistent freshwater lens in the southeastern part of the islet (Fig. 9). This could be related to the more suitable hydraulic conditions (finer sediment structure), which may have developed due to the southeastern half of the islet being on the leeward side and, thus, being protected from high-energy waves. It is recommended that any groundwater development activities be focused along survey line NMA-11 where a 5-m-thick freshwater lens seems to be present. Due to its proximity to Nanumea islet, Lakena should be considered as a possible groundwater reserve for drinking water carting, which could provide for the needs of Nanumea Village during dry periods. The presence of *pulaka* pits is not expected to cause any significant groundwater contamination provided the development of the groundwater is located at a minimum of 50-m distance from the pits.

The only survey line conducted on Temotufoliki islet did not suggest any major fresh groundwater supply available. Local knowledge, however, in combination with well and *pulaka* pit salinity data from 1976 (Flynn and Makin 1976) suggest that there may be a thicker freshwater lens in the eastern half of the islet, something that would match with the pattern observed on Lakena islet. The presence of WWII drum disposal sites (at least one identified) on the islet is of concern to the underlying groundwater quality. The site consisted of cemented Union Carbide steel drums, the contents of which is unknown, although they appear to now contain cement. It is possible that such onshore dump sites have, in the past, acted as point sources of groundwater pollution. Further investigation as to the content of these drums, and possibly water quality sampling of the groundwater, is recommended prior to development and use of the fresh groundwater.

From the survey conducted on Nanumea, it becomes clear that the Te Vai communal well, constructed in 2009 as an emergency water source for use during droughts, and located at the end of survey line NMA-07, does not intersect with any significant thickness of fresh groundwater-bearing sediments. This limited thickness of freshwater, coupled with the well design (single well) and abstraction technology (solar pump) will result in saline intrusion, rendering the availbale water unsuitable for its intended purpose. In contrast, it is advisable that if groundwater in the Matangi area is to be developed, horizontal infiltration galleries should be utilised to skim fresh groundwater through larger surface areas and prevent saltwater intrusion due to upconing.

On Nukufetau Atoll (Fig. 10), Fale islet seems to be holding a surprisingly thick (in places up to 15 m thick) and extended freshwater lens with substantial development potential that could supply fresh groundwater to the nearby village of Savave. This could be related to the more suitable hydraulic conditions on Fale and its finer sediment structure, developed as a result of the island's location on the partially protected leeward side of the atoll. Considering the absence of fresh groundwater on Savave (apart from a very thin brackish lens) and the high reliance of communities on rainwater, exploiting the fresh groundwater on Fale could substantially increase water security and resilience to droughts for the community of Savave. The absence of households on Fale reduces the threat of anthropogenic contamination to groundwater, and with careful construction with regard to the existing *pulaka* pits, concerns over water quality impacts can be reduced. While Fale has historically been used as a site for burials, the majority of the cemeteries are located closer to the lagoon while the thicker part of the freshwater lens aquifer is found farther inland. The complex relief of the islet, however, and the presence of many *pulaka* pits may complicate the installation of groundwater production infrastructure, and thus, careful planning and management would be required.

Finally, Funaota and Motulalo islets have the possibility of limited groundwater development along survey lines NFT-07 and NFT-11, respectively (Fig. 10). These islets could serve the needs for farming activities on Funaota and of the single household on Motulalo. On both islands, however, there are indications of inundation at high tide through subsurface saline water intrusion. Groundwater development should take this into consideration and avoid these areas.

Figure 9. Isolines showing the depth to the freshwater–saltwater interface, as inferred by the electrical resistivity tomography survey lines (inset: Lakena islet).

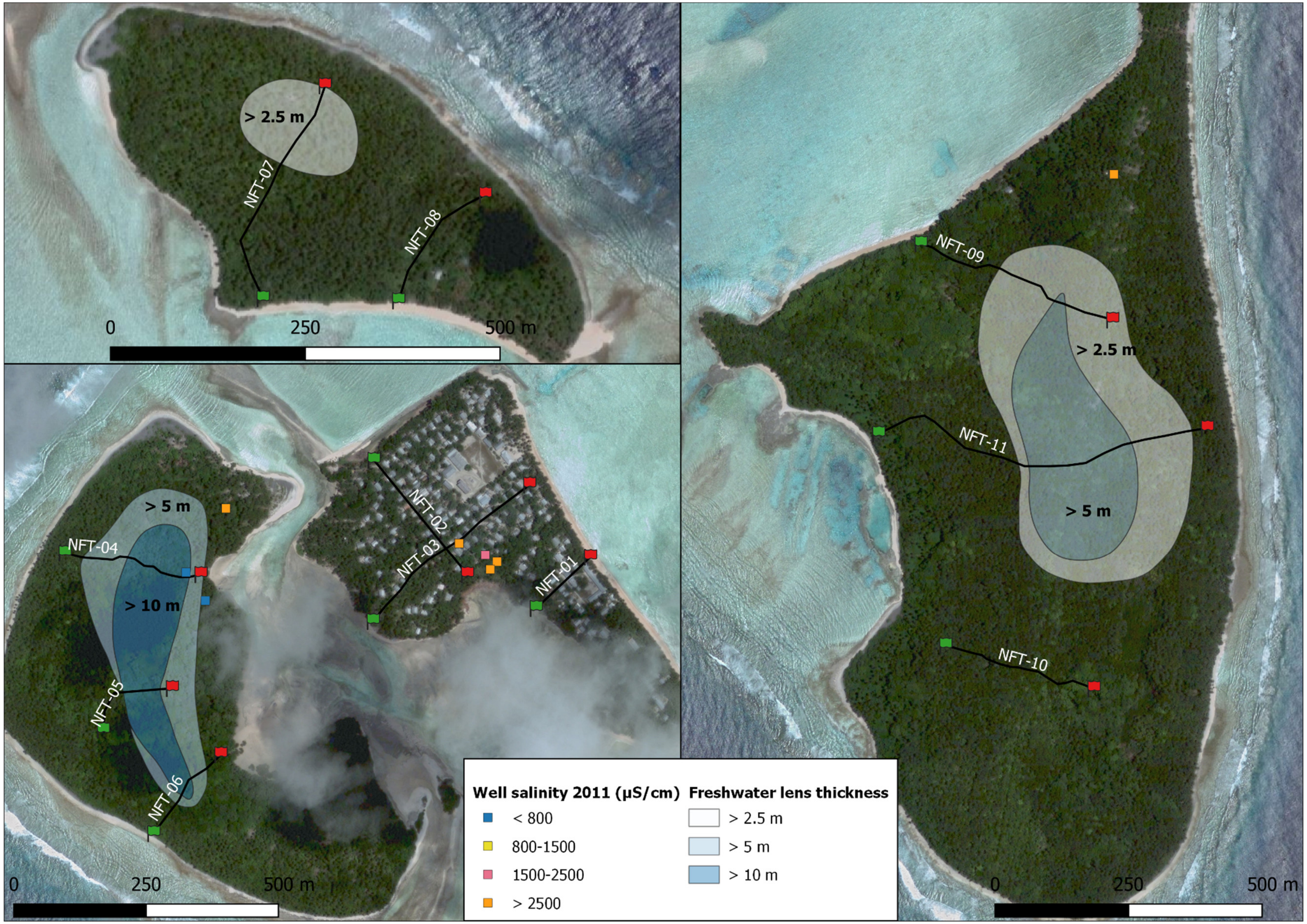

Figure 10. Isolines showing the depth to the freshwater–saltwater interface, as inferred by the electrical resistivity tomography survey lines (top left: Funaota islet, bottom left: Fale and Savave islets, right: Motulalo islet).

4.3 Lagoon water and sediment samples

The seawater samples that were analysed for potential contamination deriving from the WWII drum disposal sites in Nanumea Lagoon were found to be devoid of any pesticide traces and petroleum hydrocarbons. The sediment samples collected near the sites were also found devoid of pesticide traces and petroleum hydrocarbons but with slightly elevated heavy metal concentrations (Table 8). With the exception of the arsenic concentration in sediment sample NMA-1, all other concentrations were below the default guideline values (DGVs), which characterise sediment quality (ANZECC and ARMCANZ 2000). ANZECC and ARMCANZ derived DGVs using a ranking of both field ecological and laboratory ecotoxicity effects data from North America (Long et al. 1995), with the DGV representing the 10th percentile value of the data distribution, and using the median value as an additional upper guideline value (GV-high). It is recommended to only use the GV-high as an indicator of potential toxicity problems. The relatively high arsenic concentration measured in sample NMA-1 (89 mg/kg) may, therefore, indicate potential toxicity issues in 25% of the dump sites in Nanumea Lagoon. Further investigations would be required to determine to what extent these concentrations are bioavailable and whether they could result in toxic effects on marine biota.

Table 8. Heavy metal concentrations in sediment samples obtained next to World War II dump sites in Nanumea Lagoon. Default guideline values (DGV) and upper guideline values (GV) serve as indicators for sediment quality.

Heavy metals (mg/kg dry wt)	DGV	GV-high	NMA-1	NMA-2	NMA-3	NMA-4
Total recoverable arsenic	20	70	89	< 8	13	< 4
Total recoverable cadmium	1.5	10	< 0.4	< 0.4	< 0.5	< 0.19
Total recoverable chromium	80	370	16	< 8	10	< 4
Total recoverable copper	65	270	23	< 8	13	< 4
Total recoverable lead	50	220	5.1	13.2	5.5	< 0.8
Total recoverable nickel	21	52	8	< 8	< 9	< 4
Total recoverable zinc	200	410	17	< 16	25	< 8

These sites are not posing any threat to groundwater. However, at least one WWII drum disposal site was identified on Temotufoliki islet along the survey line. The site consisted of what appeared to be a cemented steel drum with Union Carbide markings on the drums. It is not known what the drums previously contained prior to being filled by cement at the end of WWII. It is possible that such onshore drum disposal sites could act as point sources of groundwater pollution, either historically or current, and if development and use of the groundwater at these locations is undertaken, it is recommended that further investigation as to the possible contents of the drums and the sampling of groundwater is undertaken prior to its use.

5. Conclusions and recommendations

5.1. Groundwater development

A number of areas were identified and delineated as having good potential for groundwater development. These areas are located on Matangi and Lakena islets on Nanumea Atoll, and on Fale islet on Nukufetau Atoll. It is suggested that existing rainwater resources on Nanumea and Nukufetau could be complemented by fresh groundwater developed from the identified areas. This would allow for better resilience of the communities against climate variability and natural disasters such as droughts.

Horizontal infiltration galleries are generally considered the most effective mean of abstracting groundwater from freshwater lenses (Falkland 2003). Groundwater abstraction through horizontal galleries ensures freshwater quality over a longer time as compared with abstraction through conventionally drilled vertical wells. Gallery construction in freshwater lenses involves excavating a trench approximately 1 m below the lowest level of the water table (to accommodate any tidal influence), and installing horizontal PVC-slotted pipes that lead to a central pumping station. The horizontal wells are backfilled with suitably sized rounded gravel to help develop a gravel pack before being backfilled with the excavated sand. It is suggested that during the excavation of the trench for the gallery, if reef rock is encountered and remains weathered to moderately weathered, trench construction should continue. A practical approach during construction may be that if the trench excavation can continue relatively easily through the reef rock, then trench construction should continue. If the reef rock is hard or well cemented or thick reef rock is intercepted, then the continued construction of the trench should be assessed. In the areas where thick and unweathered reef rock is encountered, it is expected that the recharge may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery.

It is recommended that protection zones be established around the groundwater abstraction infrastructure to reduce the risk of contamination. This is particularly relevant for Nanumea, where free-range pig farming is practiced. It is suggested that a 50-m buffer zone be established around installed infiltration galleries to reduce vulnerability of abstracted groundwater to contamination. Within the exclusion zone, land-use activities should be restricted and fencing installed to keep pigs out.

5.2. Groundwater monitoring

If groundwater is to be developed, monitoring systems should be put in place to allow future management of the supply and to determine climate impacts. Long-term monitoring of groundwater quality (salinity) can help guide abstraction rates and improve future management of the supply by ensuring that long-term water needs are met and that water quality is maintained for its intended purpose. A properly designed monitoring network would support and promote early warning and proactive management of the resource for long-term sustainability.

Additionally, periodical sampling of groundwater for bacteriological analyses would give further insight on the suitability of water for human consumption. *Escherichia coli* (*E. coli*) is generally a good indicator of potential contamination from pathogens. If groundwater is developed, it is recommended that water be analysed for *E. coli* bacteria on a monthly basis.

5.3. Integrated water resources management

The integrated and coordinated development and local management of freshwater resources on Nanumea and Nukufetau atolls will be key to the communities' long-term health and water security. Thus, it is critical to:

1. Undertake an audit of existing and predicted water demand and water supply infrastructure to provide an insight into how much water is required by the local communities under normal and extreme climatic conditions.
2. Undertake regular analysis of the existing rainfall stations to determine the temporal and spatial variability of rainfall and better understand groundwater recharge. This will require strengthening the links between the island government and the national weather office on the compilation, archiving and sharing of rainfall data and climate forecast.
3. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management during prolonged dry periods.
4. Establish appropriate water restriction actions during extreme climatic conditions.
5. Develop a drought awareness and action plan that offers practical and effective local guidance for water conservation and water security management under different climatic conditions.
6. Ridge to Reef Project to initiate dialogue with respective government departments and *kaupules* aimed at implementing recommendation #5, and planning for the other four recommendations, which may require long-term commitment. Discussions on recommendation #5 to be aligned with annual plans arising from current island strategic plans and any future reviews.

In view of the sensitive nature of these groundwater systems, sound management strategies, including the installation of appropriate technologies and subsequent monitoring of groundwater level and salinity, should be considered and adopted to ensure the safety and availability of freshwater resources at all times. Appropriate protection measures against improper land-use activities are equally important and will be required to safeguard groundwater bodies for water supply purposes.

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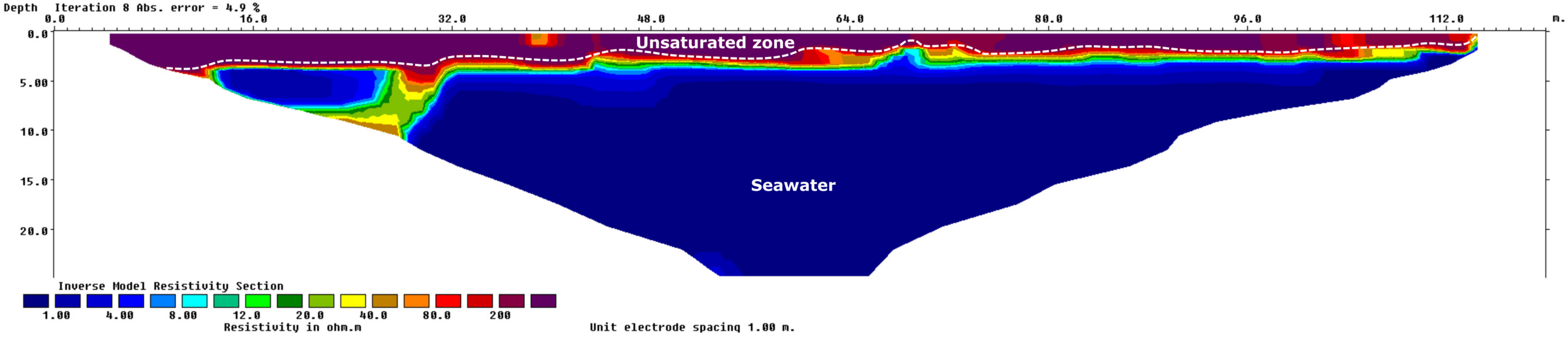
Annex 1 – Inverted resistivity profiles



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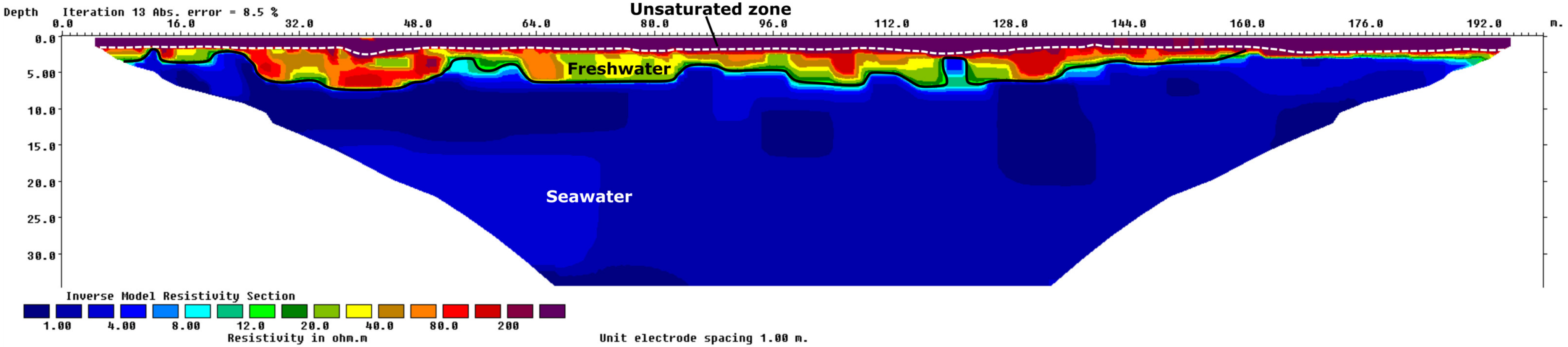

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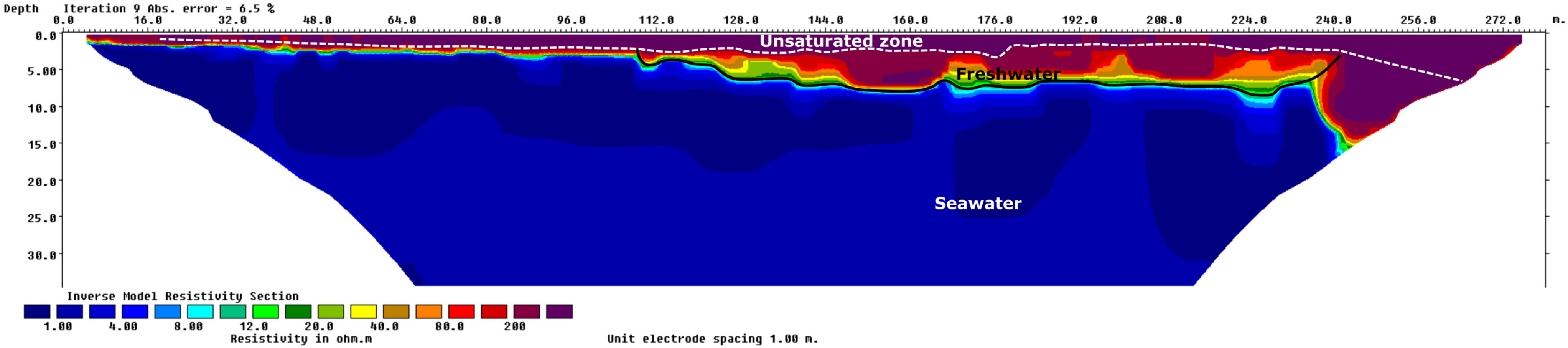

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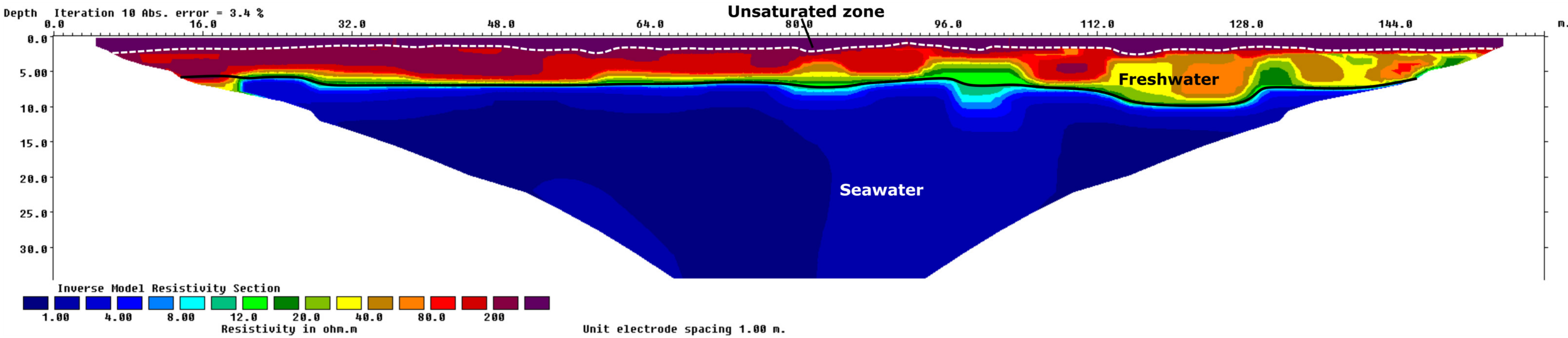

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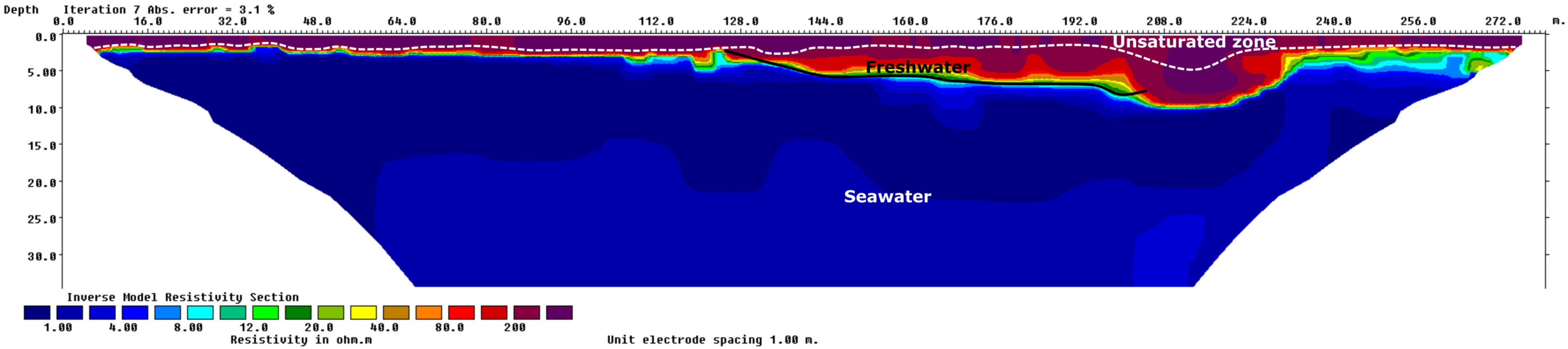

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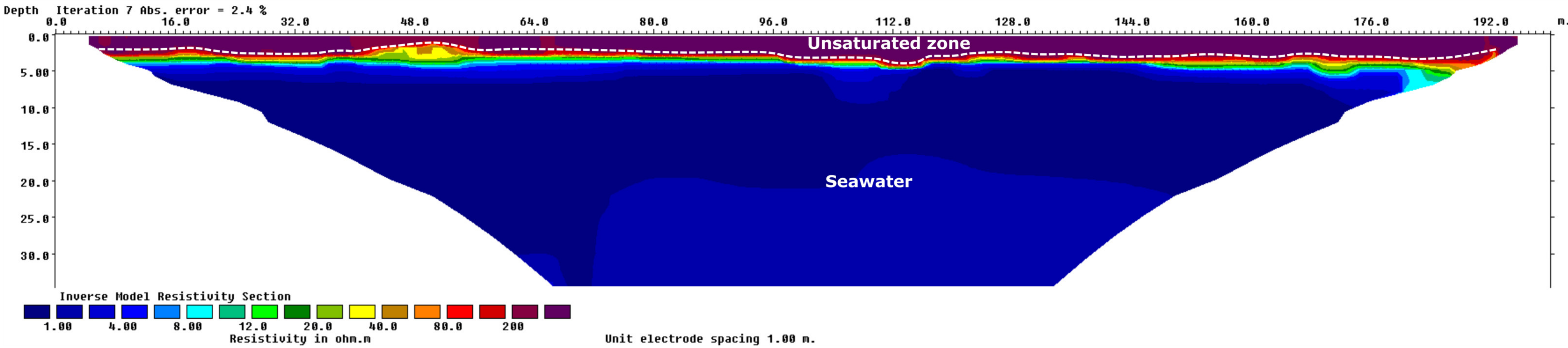

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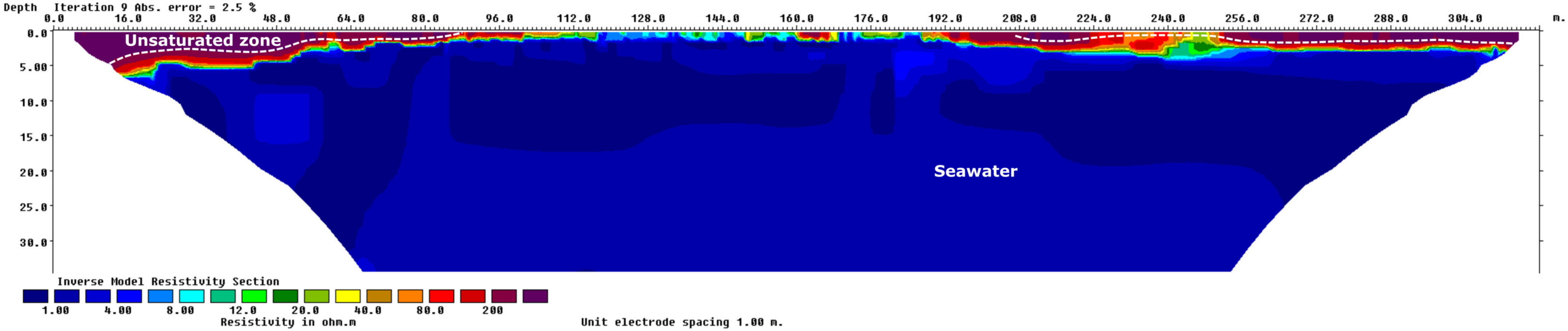

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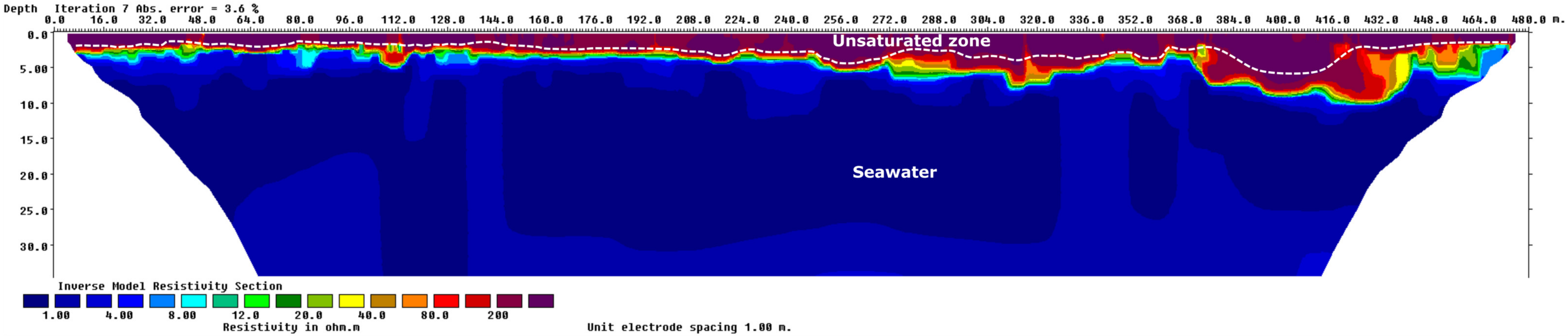

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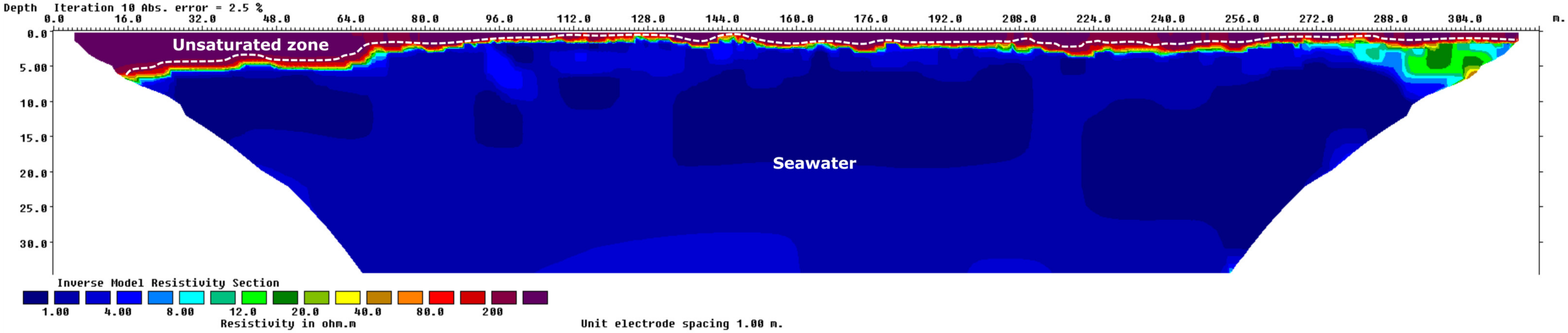

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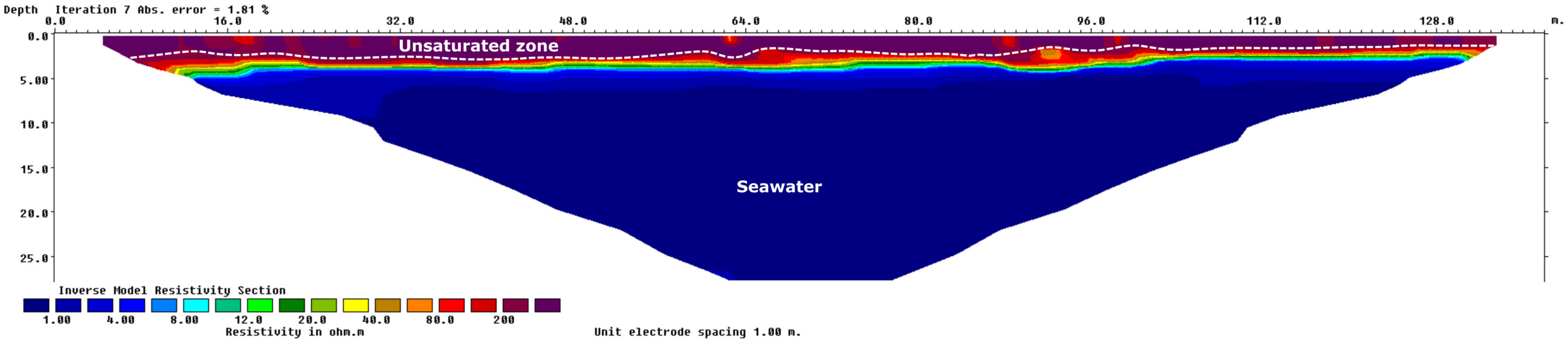

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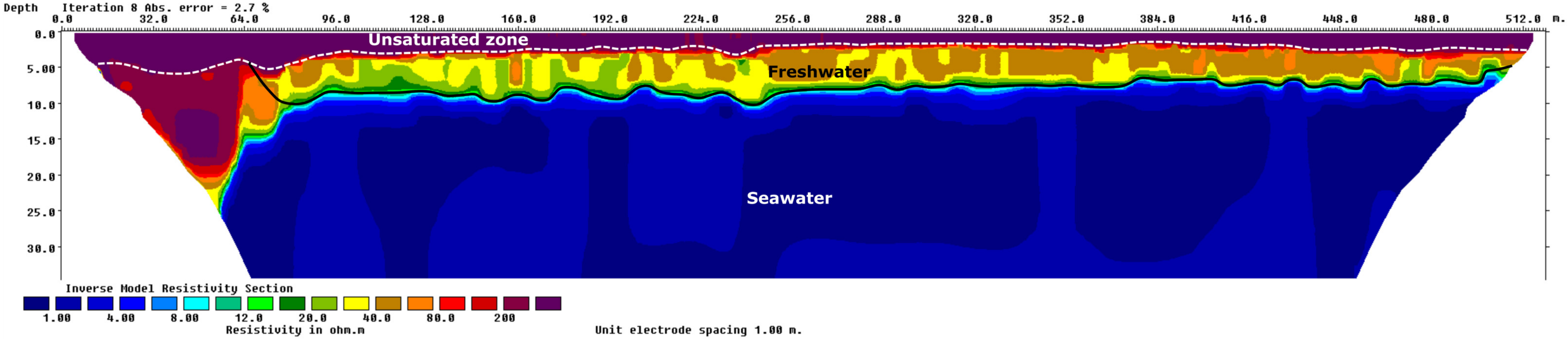

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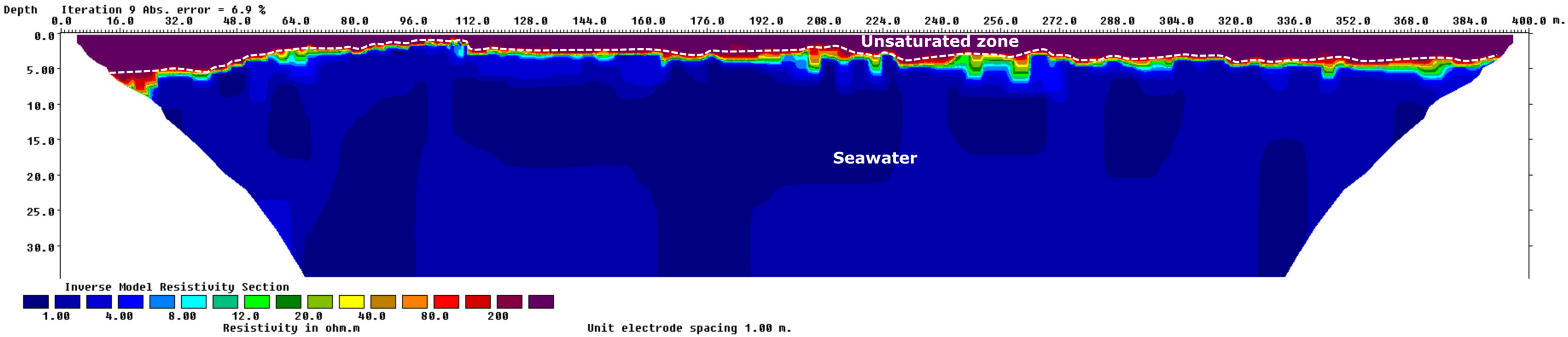

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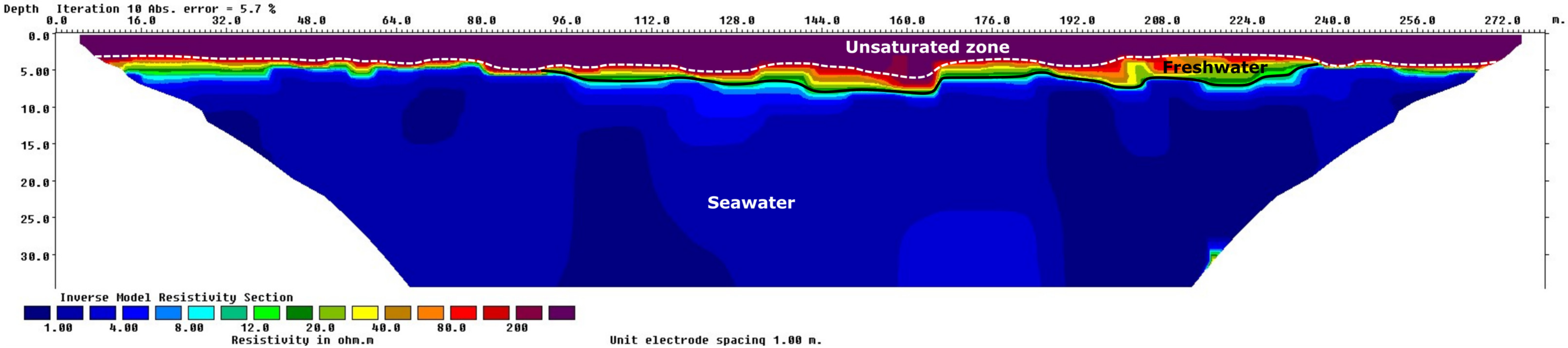

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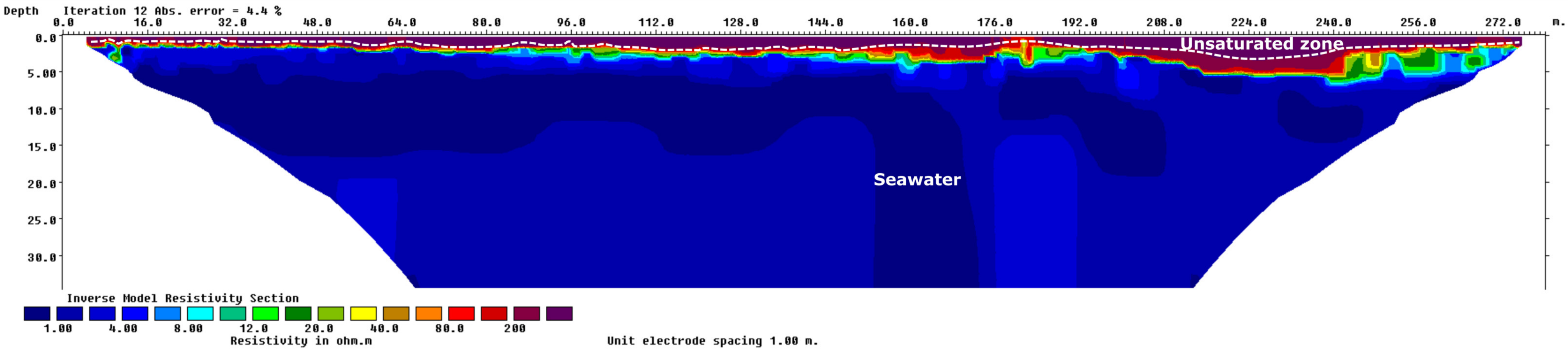

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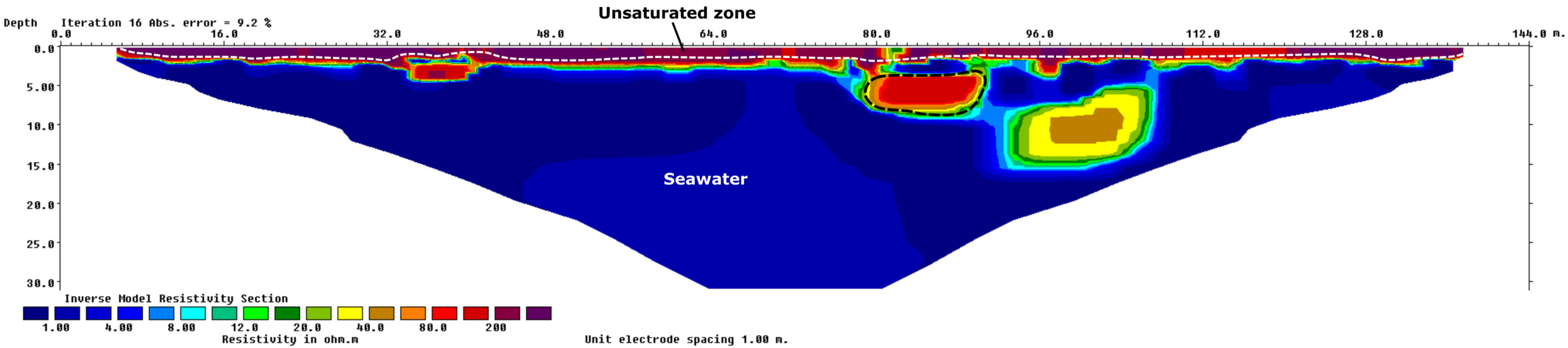

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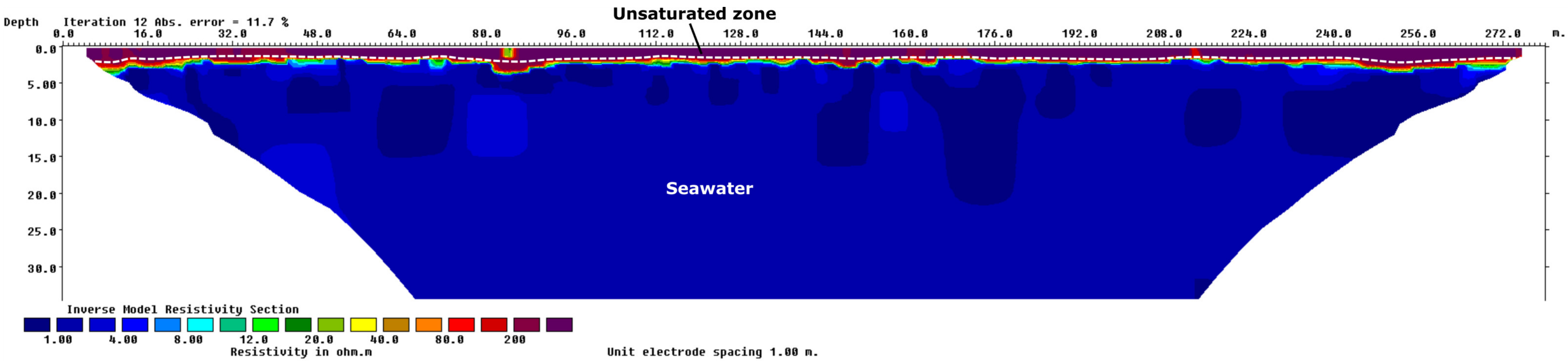

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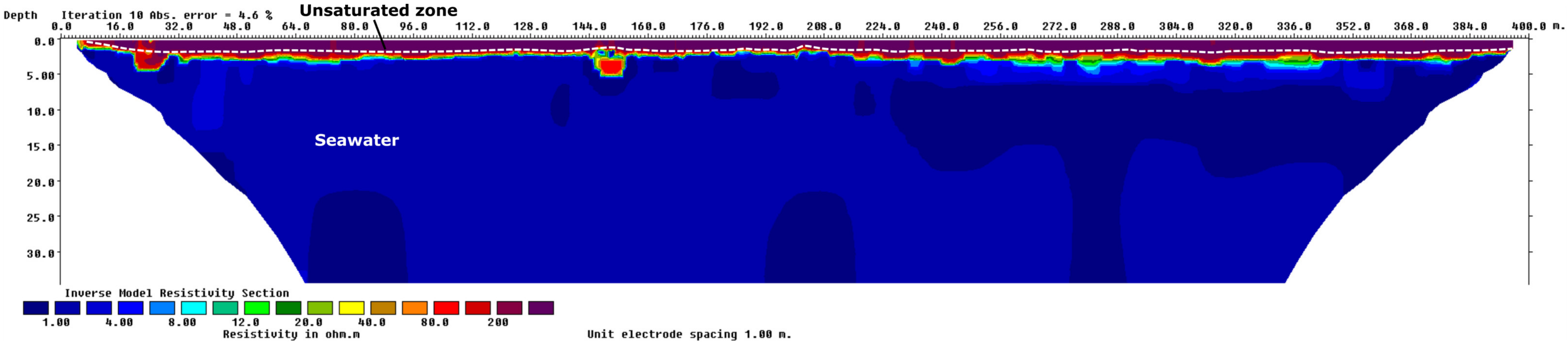

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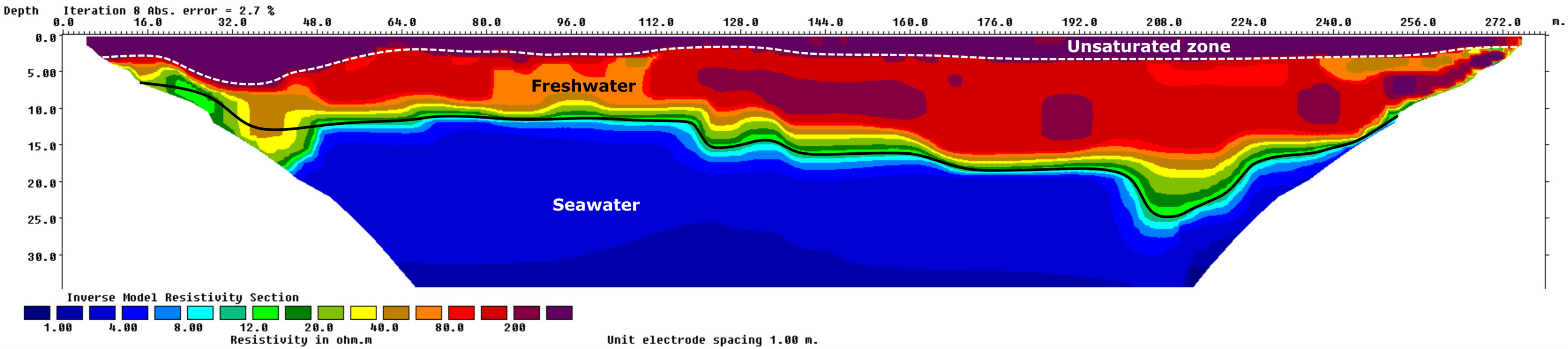

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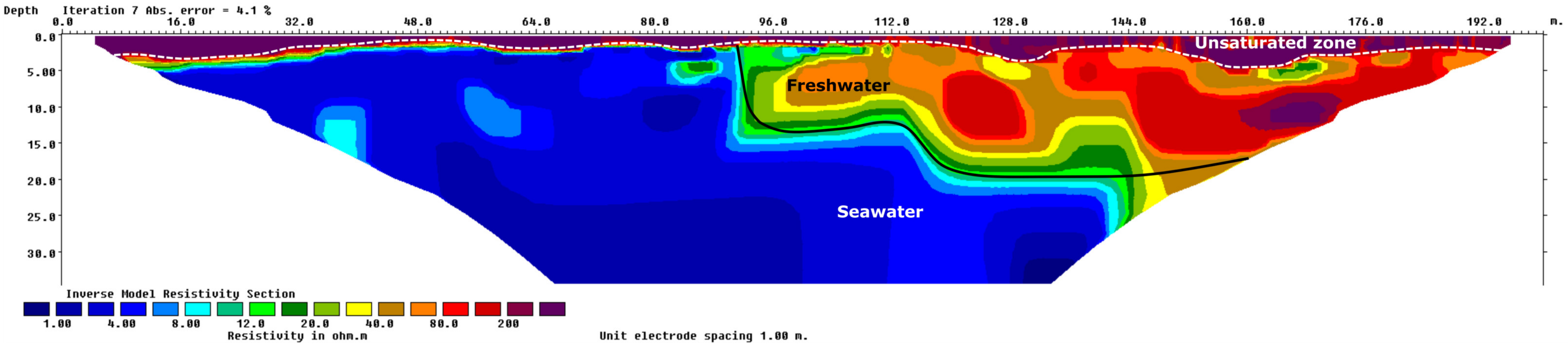

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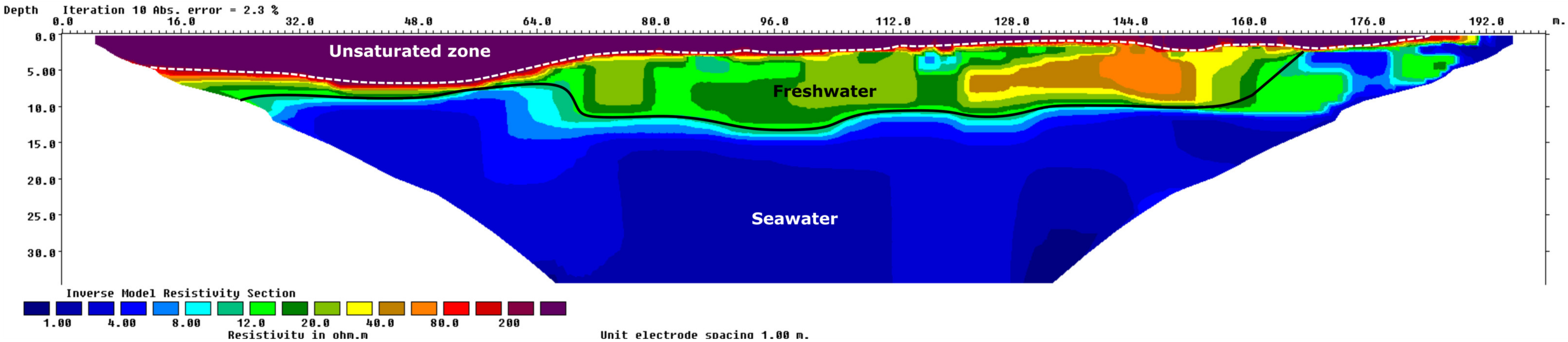

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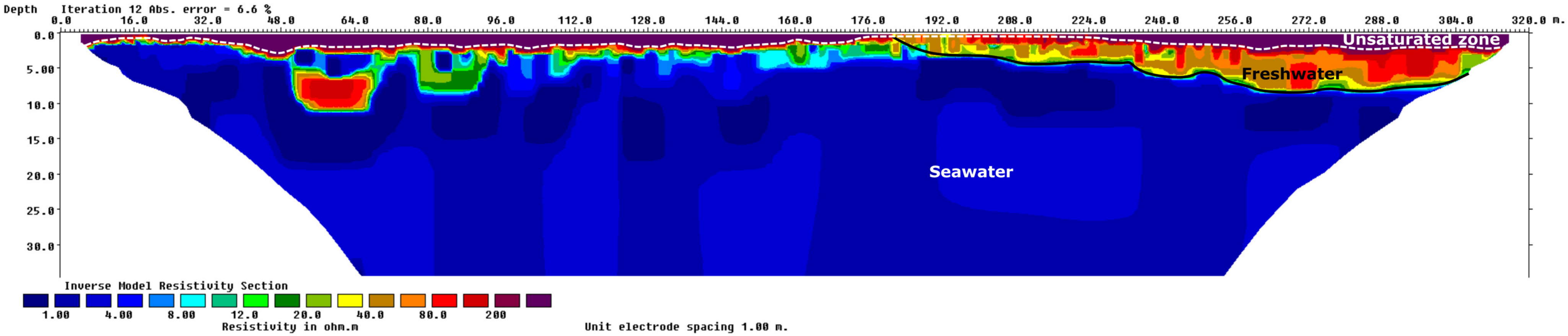

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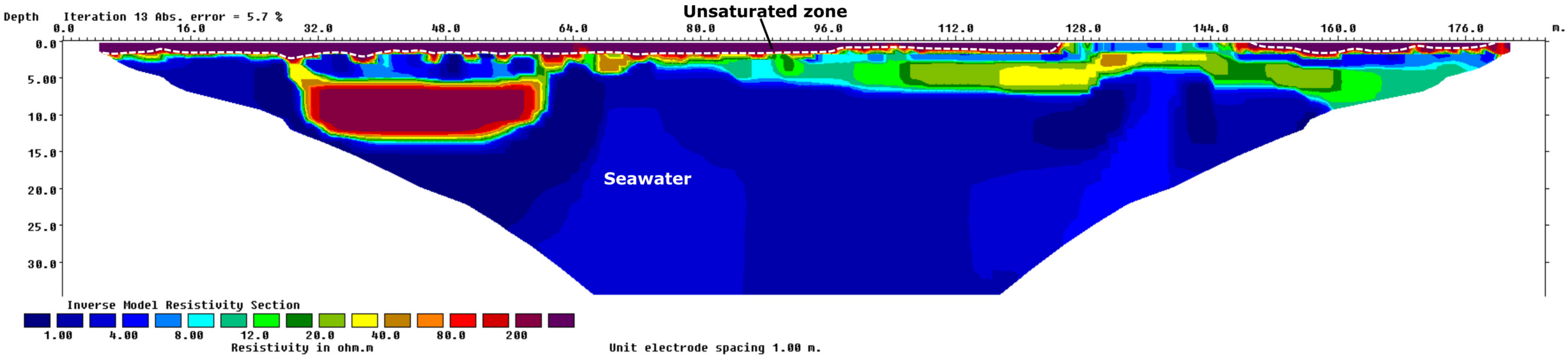

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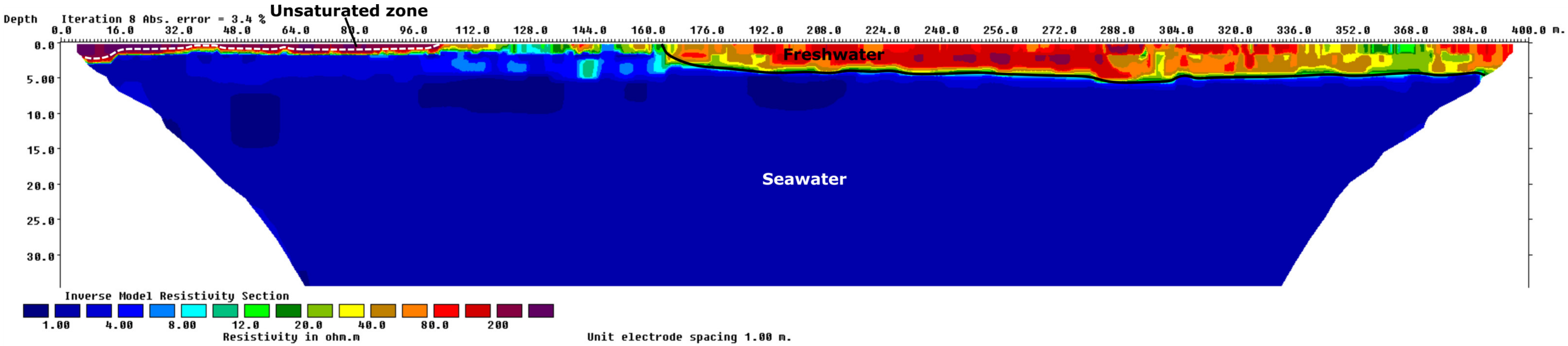

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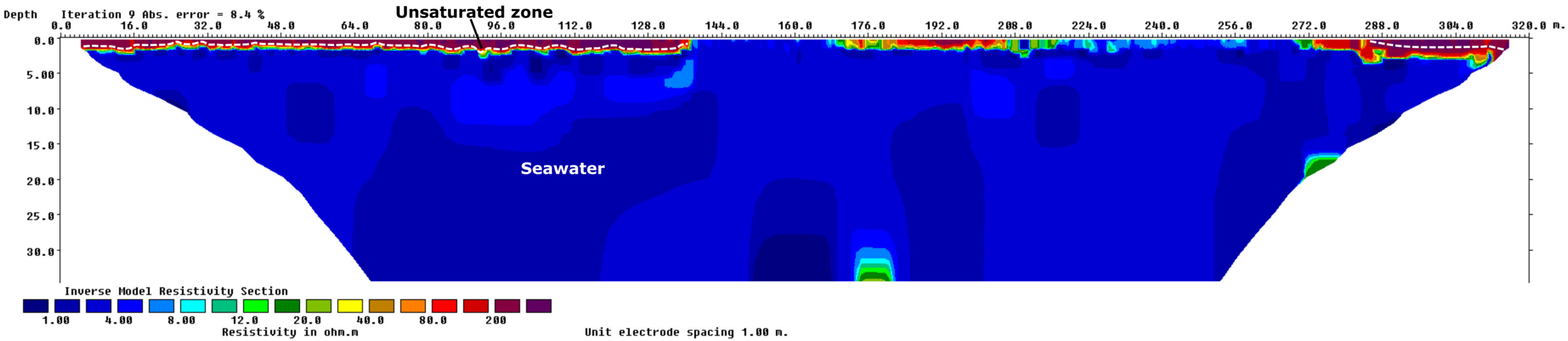

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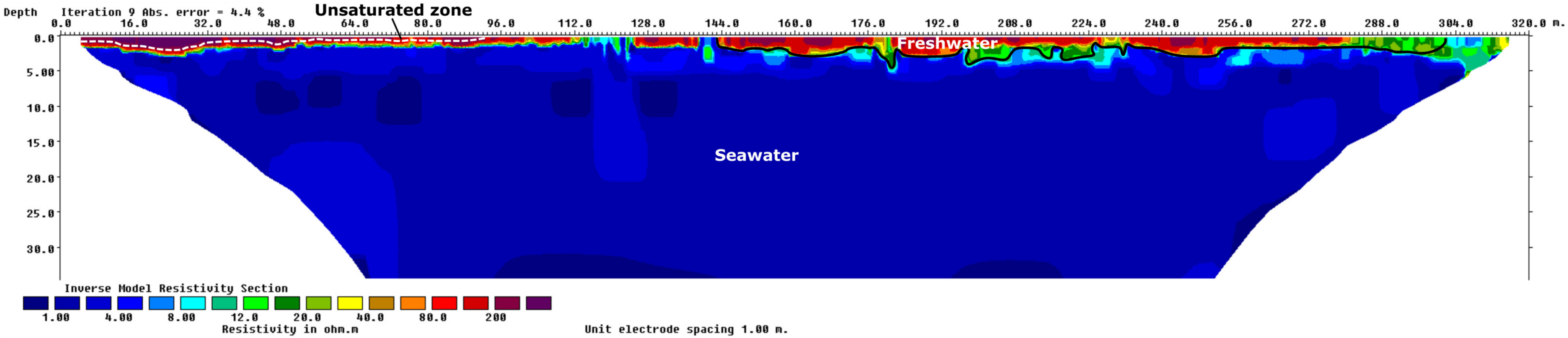

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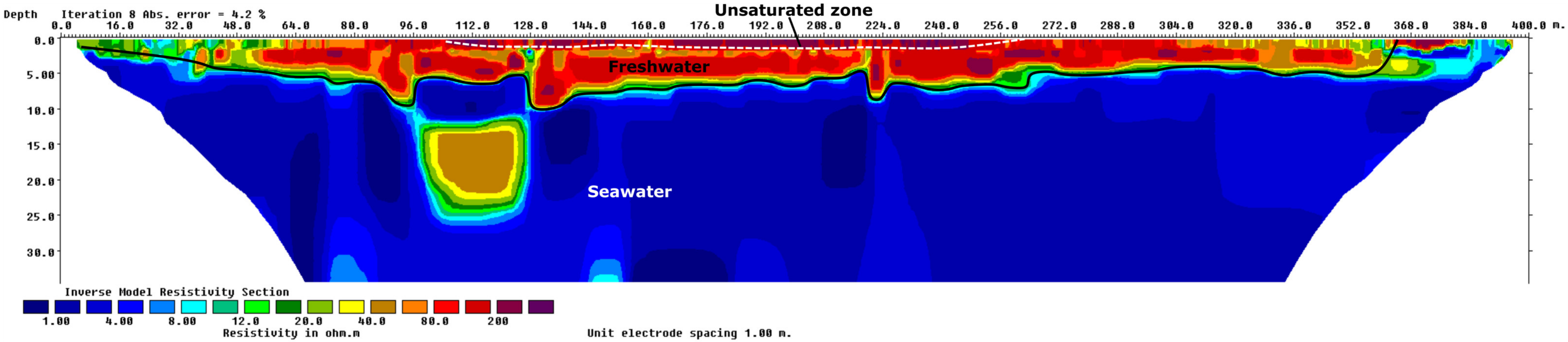

Figure A26. NFT-11b

Pacific Community
spc@spc.int | www.spc.int
Headquarters: Noumea, New Caledonia