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Managing Coastal Aquifers in Selected Pacific Small Island Developing States Project (MCAP)

Groundwater Investigation in Jaluit Atoll – Republic of Marshall Islands

Aminisitai Loco, Andreas Antoniou and Carlos Miraldo Ordens

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This work was part of the Managing Coastal Aquifers Project in Selected Pacific SIDS (MCAP). MCAP is executed by the Pacific Community in partnership with the United Nations Development Programme (UNDP). This project is funded by the Global Environment Facility and is being implemented in three countries: Republic of Palau, Republic of the Marshall Islands and Tuvalu. The purpose of the project is to i) understand the potential groundwater development options for communities in three atoll nations of Palau, Marshall Islands and Tuvalu through informed scientific and technical approaches while supporting in-country capacity building to monitor, manage and protect these water sources; ii) support the three countries in better responding to droughts through improved access to groundwater systems; and iii) develop the skills in the outer islands to showcase community-led water management. Supporting this through improved relationships and understanding between national response teams and lead agencies with communities is critical.

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

- Environmental Protection Authority;
- Majuro Water and Sewerage Cooperation;
- Ministry of Culture and Internal Affairs;
- UNDP's Addressing Water and Climate Vulnerability in Atolls project team;
- International Office of Migration;
- Republic of Marshall Islands Red Cross; and
- International Federation of the Red Cross.

The support from community leaders and members of Jabor and Jaluit communities, together with the island mayor and council representatives, played key roles of providing casual staff workers and ensuring strong participation during community meetings, and sharing their views on the assessment work and potential future work.

1. Introduction

1.1 Project background

The Managing Coastal Aquifers in Selected Pacific Small Island Developing States Project (MCAP) is being implemented by the Disaster and Community Resilience Programme within the Geoscience Energy Maritime Division of the Pacific Community in partnership with United Nations Development Programme. The project is funded by the Global Environmental Facility and being implemented in three countries: Republic of the Marshall Islands, Republic of Palau, and Tuvalu. The five-year (2020–2024), USD 5.2 million project is supporting the three countries to build understanding on the use, management and protection of coastal aquifers or usable groundwater to enhance water security in the context of the changing climate. More specifically, the project aims at: 1) identifying the extent, threats and the development potential of groundwater resources; 2) increasing awareness of groundwater as a water security supply source; 3) providing options for improved access to groundwater; and 4) improving aquifer protection and management within Pacific Small Island Developing States.

1.2 Mission objectives and outcomes

The main purpose of this investigation was to identify fresh groundwater resources on the islands of Jabor and Jaluit within Jaluit Atoll in the Republic of the Marshall Islands that could either complement existing water supplies, or serve as a backup during dry periods. Additional objectives included a survey of private wells and an assessment of communal rainwater harvesting (RWH) systems. This resulted in a GIS-based well inventory to gain information on the islands' wells and groundwater characteristics.

The development of new groundwater resources in atoll environments requires: 1) an investigation of groundwater potential and the identification of optimal drilling targets and locations; 2) the placement of horizontal galleries and the assessment of yield and water quality; and 3) equipping galleries with pumps and storage tanks that are compatible with the resource potential, and community's needs and resources.

The work reported on here focuses on the first component, which was achieved through electrical resistivity geophysics, coupled with the assessment of the existing hand-dug wells groundwater salinity and levels, and the rainwater harvesting capacity of communal buildings. This allows us to better understand the local hydrogeology and groundwater storage potential, as well as the role of rainwater collection in the communities' water supplies. Recommendations are given with regards to potential gallery locations, expected yields and expected groundwater quality. Recommendations are also given with regards to the maintenance and use of the existing network of private wells.

2. Background

2.1 Geographical location, population and history

Jaluit is an atoll made up of 91 islets, 7 of which are inhabited. The total land area is 4.38 mi^2 (11.34 km^2). The atoll is oriented in a northeast–southwest direction and is 2.0 mi (3.3 km) long, with a maximum width of 0.68 mi (1.1 km). Jaluit is 132 mi (215 km) southwest of Majuro, and is located between latitudes 5.7765° N and 6.3035° N, and longitudes 169.4045° E and 169.7294° E.

The communities selected for this groundwater investigation were Jabor and Jaluit.[1] These communities are 9.32 mi (15 km) apart and are connected by a very thin beach deposit, allowing the establishment of the airstrip next to Jabor, and an access road. Jabor islet – which is 2790 ft (850 m) long, with a maximum width of 1050 ft (320 m) – is the atoll's administrative center and commercial hub. It is oriented in a northwest–southeast direction and is in the southeastern part of the atoll. Jaluit islet, on the other hand, is oriented west northwest–east southeast, and is 14,760 ft (4500 m) long and 2300 ft (700 m) wide, and is on the atoll's southern end.

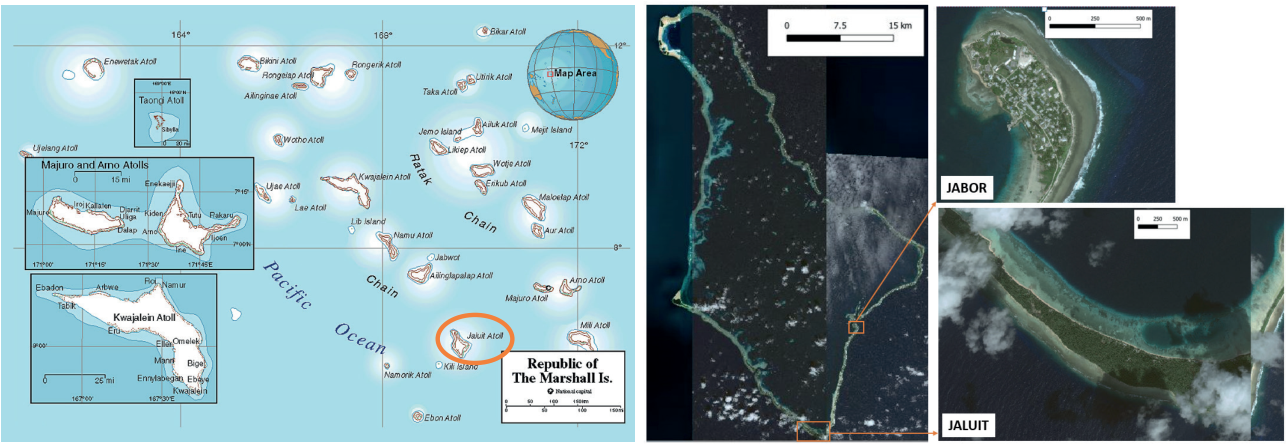

Figure 1. Map of the Marshall Islands. Jabor is in the southeastern part of the atoll, and Jaluit is on the southern end.

Source: https://www.mapsland.com/oceania/marshall-islands/political-map-of-marshall-islands

The last official census in 2011 recorded a population of 1788 inhabitants and 252 households for Jaluit Atoll (SPC 2012). A more recent assessment in 2017 indicated population and household counts of 1533 and 241, respectively (UNDP 2018).

Table 1. 2011 and 2017 population figures for Jaluit Atoll.

	2011	2017
Population	1788	1533
Household	252	241
Average household size	7.1	6.4

Source: SPC (2012); UNDP (2018)

[1] The selection of Jabor and Jaluit islets within Jaluit Atoll was a decision made by the Marshall Islands Government through an objective and multi-criterion ranking, which considers the disaster vulnerability, water security threats, and the presence of important public infrastructure such as the high school.

Jabor's population in 2011 was 714, and the number of households was 108 (SPC 2012). This does not include Jaluit High School's population of 458 students and 50 staff members. The school provides boarding for 358 students, including 180 boys and 178 girls. The high school was set up to provide secondary education for students from the islands of Ailinglaplap, Jabot, Namdrik, Kili, Ebon, Ujae, Lae, Wotho, Namu and Jaluit. Jaluit's population in 2011 was 288, spread across 47 households (SPC 2012).

Table 2. 2017 population and household counts for the seven inhabited islets of Jaluit Atoll.

Community	2017 population	2017 households	Household occupancy
Imiej	131	17	7.7
Imrodj	156	28	5.6
Jabnoren	58	8	7.3
Jabor	714	108	6.6
Jaluit	288	47	6.1
Mejrirok	87	15	5.8
Narmej	99	18	5.5

Source: UNDP 2018

In the 1880s, Jabor was established as the main political municipality, as well as the copra trading and commercial port, of the Marshall Islands. German copra traders successfully persuaded their government to formally annex the island as an Imperial German Protectorate in 1885, resulting in the signing of the German protection treaty by five chiefs in the Ralik Island group. The treaty was the first step of German political intervention, which then led to the full annexation of the Marshall Islands and culminating in the recognition of Jaluit as the capital in 1888 (Deunert et al. 1999).

According to Deunert et al. (1999), at the onset of World War I, Japan seized control of the Marshall Islands from Germany in 1914, following which Jaluit became the Japanese administrative center. An airstrip was constructed on Imiej Island, and tonnes of soil were shipped from Kosrae and Pohnpei (in what is currently the Federated States of Micronesia) to create vegetable gardens on the island. The island was fortified, and Japan started its fishing industry at the same time. In 1917, the British and Japanese agreed to recognize each other's territorial claim after the war. Limited education and medical support became available in Jaluit. The United States captured the atoll during World War II, and mostly ignored it afterward. In the 1950s, Catholic and Protestant missions were set up.

Today, many World War II relics remain on the island, including a large concrete airfield, large concrete storage tanks and coastal artillery. Copra production remains the main land-use activity on the atoll.

2.2 Climate

According to Antoniou (2019), rainfall in the Marshall Islands varies greatly from north to south. The northern atolls receive less than 49.21 in (1250 mm) of rain annually, and experience significant droughts during the dry season. Southern atolls receive more than 98.43 in (2500 mm) of rain annually. Monthly average temperature year-round is 27°C, ranging between 25°C and 30°C. Monthly average precipitation is presented in Figure 2.

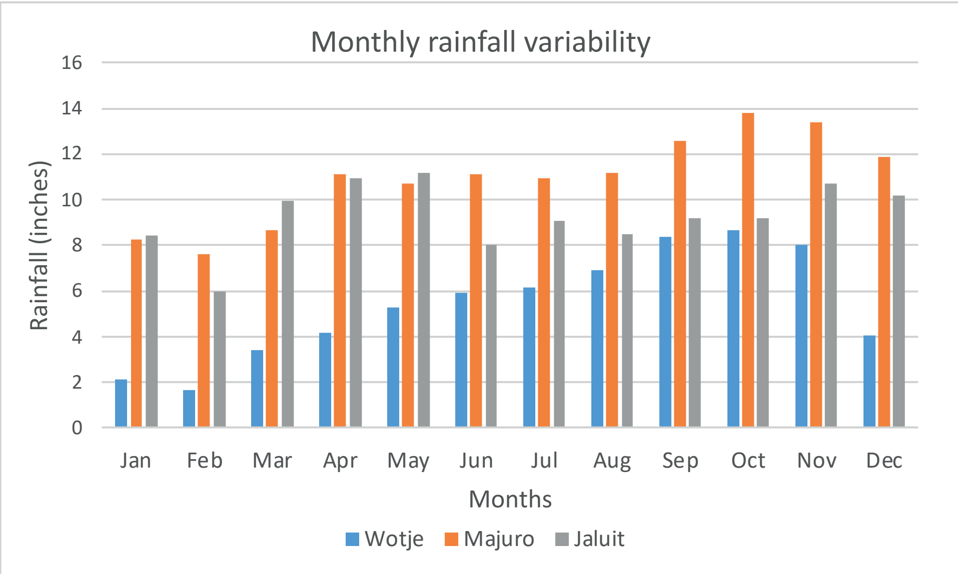

Figure 2. Monthly rainfall records for Wotje (northern island), Majuro and Jaluit (both southern islands), indicating rainfall variability.

Source: Weather Service Office

The Marshall Islands are particularly affected by intense El Niño-induced droughts, and associated depletion of rainwater supplies and thinning of freshwater lenses. Interannual rainfall variability is high, with the wettest years bringing up to twice as much rain as the driest years. Droughts generally occur in the first four to six months of the year following an El Niño (December to June). During severe El Niño events, rainfall can be reduced by as much as 80% (BoM and CSIRO 2011). Groundwater, if available in substantial volume and accessible, is most extensively used during drought due to the depletion of rainwater storages. Otherwise, the temporary installation of reverse osmosis (RO) desalination technologies is utilized to provide drinking water, as experienced in the islands of Wotje and Jaluit, where the big secondary schools and high population centers are located.

Rainfall data for Jaluit Atoll is collected manually on Jabor by the Weather Service Office (WSO). Observed measurements are communicated daily to the WSO's Majuro Office via radio telephone or mobile phone, where data is compiled and analyzed. A summary of monthly rainfall readings from January 1991 to February 2022 for Jaluit is provided in Figure 2 and Table 3. There is a 27% data loss that is attributed to: 1) some months having no data; 2) incomplete daily readings for several months; and 3) a 10-year period of no rainfall measurement between May 2003 and December 2013.

Table 3. Jaluit Atoll annual rainfall and seasonal variations recorded during rainy and dry periods, 1991–2022.

	Yearly in (mm)	Rainy period Jun–Nov in (mm)	Dry period Dec–May in (mm)
Average	109.2 (2774)	58.4 (1483.3)	57.4 (1459.8)
Standard deviation	29.3 (745.4)	4.8 (122.1)	6.3 (160.9)
Coefficient of variation	0.27	0.08	0.11

Source: Weather Service Office

Jaluit Atoll receives 109.2 in (2774 mm) of precipitation annually, while Majuro and Wotje receive 131.3 in (3334 mm) and 64.7 in (1644 mm), respectively, which shows the high variability between the north and south islands. There is little difference between rainy periods and dry periods, which may suggest that the dry months receive relatively high amount of rainfall compared to other islands. However, the slightly higher coefficient of variation observed during the dry period (December–May) suggests a higher rainfall variation on Jaluit during this period, which in turn may result in a slightly reduced reliability of rainfall and its associated harvesting to prevent against droughts. In terms of water resources use and management, the relatively high rainfall pattern indicates the good potential for RWH and rainfall-induced groundwater recharge that will contribute to freshwater availability to support household and community needs.

2.3 Current water supply, drought response

According to the 2011 census, all 252 households on Jaluit Atoll were reported to be dependent on rainwater as their main source of drinking water (SPC 2012), which suggests that all existing wells on the islands are used for secondary purposes such as washing, toilet flushing, gardening and occasional cooking.

An 800-gal/day RO desalination unit has been installed at Jaluit Secondary School to meet daily potable needs within their boarding facilities. Unfortunately, the installation date was not known by the people we spoke to. The RO unit is powered by diesel-powered electricity and is fed by a high-salinity, and well-constructed and protected well with an EC of 20.8 mS/cm. During the 2022 survey conducted as part of this work, this RO was not operational due to a malfunction. The school was expecting a team from the Majuro Water and Sewerage Cooperation (MWSC) to either undertake repair work or replace the unit with a bigger capacity.

Figure 3. Reverse osmosis desalination unit, Aquamiser+ model, installed at Jaluit High School. It was non-operational during our field mission.

During droughts, such as the one in 2016, rainwater supplies diminish substantially, forcing the government, through MWSC, to deploy portable RO units to produce desalinated water and meet the water demand. This process is initiated, through an Initial Situation Overview form, by the focal points of the National Disasters Management Office (NDMO) who are based in the outer islands. The Water, Sanitation and Hygiene (WASH) cluster (including the Environmental Protection Authority, MWSC and the International Organization for Migration), NDMO, and the International Federation for Red Cross verifies the island-specific impacts of the drought impacts. Afterward, it provides a recommendation to NDMO, which subsequently takes that recommendation to the national disaster committee and declares a state of emergency. Jabor and Jaluit community members reported that most of the wells that normally provide fresh groundwater become salty during droughts. During past droughts, due to RO's low flow capacity and the long wait time, families opted for coconut water for drinking purposes.

2.4 Tidal inundation

Tidal inundations associated with typhoons and/or tropical storms have created significant impacts on Jaluit Atoll. Inundation is known to be driven be a combination of oceanographic processes that contribute to sea-level rise at the coastline, and its impact is primarily dependent on how extreme a particular process may be at the time (Smith and Juria 2019). These processes include incoming swells from distant storms and cyclones that can coincide with local high spring tides and/or sea-level anomalies. In the Marshall Islands, Spennemann (2004) documented the known severe typhoons and/or tropical storms between 1840 and 1992 that were associated with inundation and caused widespread damages in the atoll communities (Figure 4), which are known to be strongly affected by El Niño. Figure 4 shows records the number of known typhoons and/or tropical storms that caused major inundation impacts in the Marshall Islands between 1840 and 1992. In the case of Jaluit Atoll, 13 events occurred during the 152-year period. Majuro and Kwajalein atolls, both of which are major population centers, recorded 7 and 10 typhoon events, respectively, while the outer islands of Ujelang and Arno also recorded devastating events.

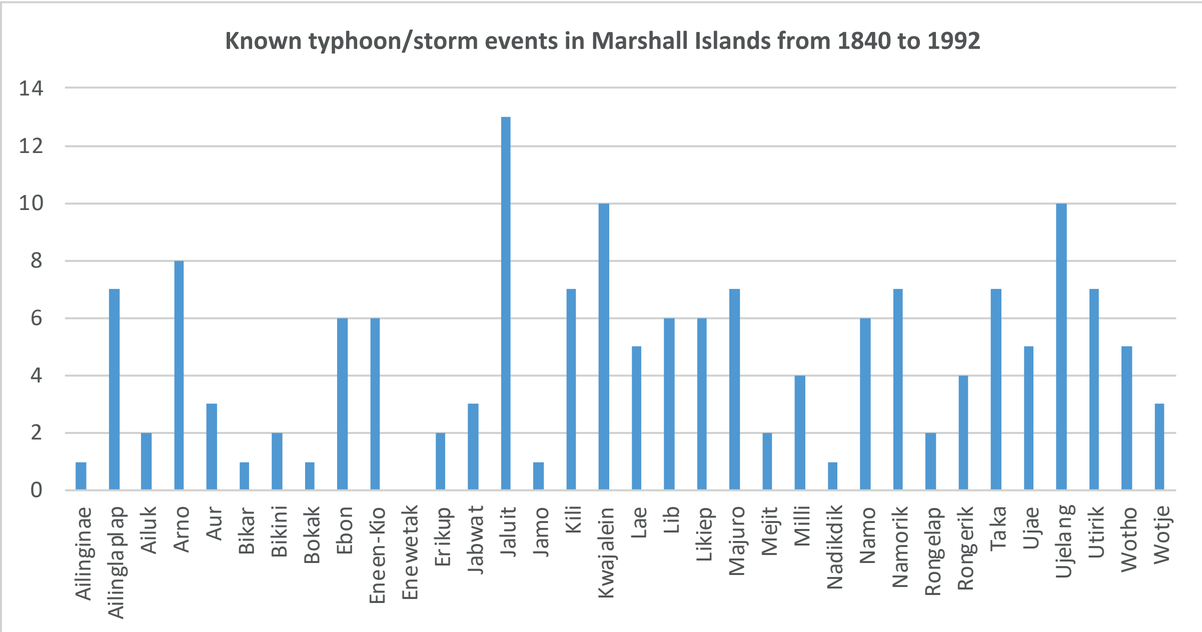

Figure 4. Known typhoons and/or tropical storms that caused major inundation in the Marshall Islands between 1840 and 1992.

Source: Spennemann 2004

Awalkover survey around Jaluit islet during this mission showed signatures of previous inundation events. It was clear from the community engagement, which included a village mapping exercise, that Jabor and Jaluit are vulnerable to tidal inundation. This is shown in Figures 5 and 6, particularly by the red lines on the land, thereby reinforcing the vulnerability of both communities to inundation. These maps were obtained as part of sociocultural survey, which will be the subject of a separate report.

Figure 5. Jabor village map showing the southeastern part being prone to inundation as represented by red lines.

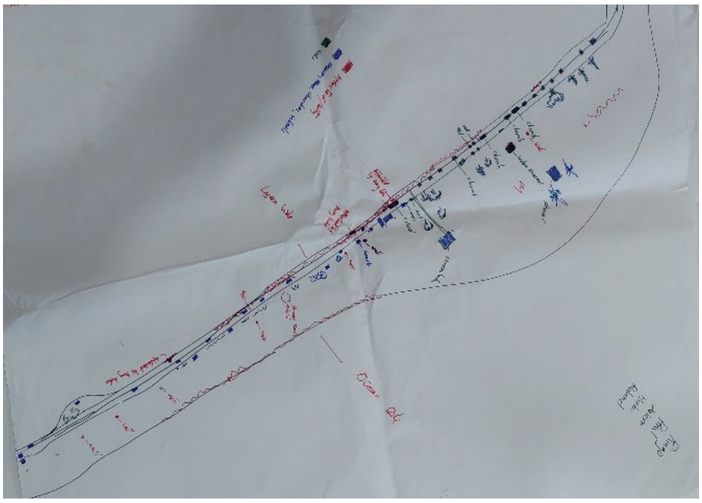

Figure 6. Jaluit Island village map drawn by the youth group, showing areas on the east side that are affected by inundation (red lines).

Smith and Juria (2019) documented 15 more recent events occurring in Majuro and the outer islands between 1994 and 2016. These recent events suggest that the frequency of inundation events is increasing, and indicate the vulnerability of these atolls to oceanic and tidal processes.

The socioeconomic impacts of inundation vary among the atolls and include population relocation, significant clean-up and repair costs, and work disruptions. Further, impacts on food and water can be felt through the salinization of shallow, fresh groundwater systems that support swamp-taro for food as well as hand dug-wells, which can be linked to indirect negative health effects.

2.5 Geology and groundwater occurrence

Atolls are geologic structures that are derived from basaltic volcanoes that have subsided into the ocean. Reef growth results in a cap of calcium carbonate minerals extending from the sea surface to the top of the submerged volcano. The volcanoes that formed the Marshall Islands were active more than 150 million years ago (Schlanger et al. 1987). Chemical alteration and weathering of these carbonate minerals, induced by precipitation and sea-level changes, have governed the shallow subsurface geology, which is generally described by the following three-layer model:

1. Upper sediment unit is composed of unconsolidated and well-sorted coral sand and gravel;
2. Lower sediment unit is composed of unconsolidated lagoonal sands and gravel of Late Pleistocene/Early Holocene age; and
3. Dense and well-consolidated limestone unit of Pleistocene age, which was formed during subaerial exposure and recrystallization to calcite.

The unconformity between the younger sediments and the underlying Pleistocene limestone is called the Thurber Discontinuity, and is typically encountered at depths ranging between 16 ft (5m) and 82 ft (25m).

Fresh groundwater occurs in atolls as a thin lens buoyantly supported by dense underlying saline water. The occurrence of these freshwater lenes is expressed through existing shallow hand-dug wells that atoll communities rely on, either as a primary source for drinking and cooking, or a secondary source for washing, toilets and irrigation, depending on the water quality and salinity. A freshwater lens is formed within the unconsolidated sediments according to suitable hydraulic conditions. On wider islands – those greater than 3280 ft (> 1000 m) – that receive an appreciable amount of rainfall, the base of the freshwater lens can reach the Thurber Discontinuity. The higher permeability of the underlying limestone cannot support the formation of a lens, which is truncated at that point due to immediate mixing with the underlying saltwater (Hamlin and Anthony 1987; Hunt 1997). The thickness of the freshwater lens across the width of the island depends on the recharge rate, the island's width, the thickness and hydraulic conductivity (K) of the upper sediment units, and the depth to the Thurber Discontinuity and the presence or absence of a reef flat (Bailey et al. 2013). A zone of transitional salinity, or transition zone, typically exists between the infiltrated rainwater and underlying saltwater. This zone is formed by the mixing of the two water types promoted by tidal forces and its thickness largely depends on the aquifer's hydraulic properties.

The hydraulic properties of freshwater lens aquifers strongly depend on the orientation and position of the island with respect to the prevailing winds, in addition to the thickness and compositions of the aquifer materials. Islands in the direct path of the prevailing winds and associated high-energy waves tend to have a coarse sediment structure, and therefore higher K, which is less conducive to the formation of thick freshwater lenses. In contrast, aquifers on islands located on the partially protected leeward side of atolls tend to acquire a finer sediment structure and have lower K, which is more conducive to thick freshwater lenses. Considering that the direction of the prevailing trade winds in the Marshall Islands is from the northeast, it is expected that the eastern sides of both Jabor and Jaluit may be exposed to strong tidal influence and, hence, may not offer ideal hydraulic conditions for the development of thick freshwater lenses.

The freshwater lens at Laura on Majuro Atoll was used in this work to calibrate the geophysical results with measured groundwater EC in monitoring wells, and is described as follows. Laura islet is on the western end of Majuro Atoll and has a maximum width of 3940 ft (1.2 km). It holds a known freshwater lens of national significance for meeting both the local community water demands, and the greater Majuro Atoll water demand during drought periods. The Laura lens has been the subject of numerous investigations as documented by United States Geological Survey (Hamlin and Anthony 1987) and SPC (Sinclair et al. 2017). It has been equipped with 10 monitoring sites that allow for multiple-depth investigation points. Seven infiltration galleries have been constructed across the islet. The galleries skim the freshest part of the lens through the placement of horizontal pipes below the water table, and allow groundwater production via pumping and distribution towards a dedicated treatment plant managed by MWSC. After treatment, the water is distributed to households in Laura (on Monday and Friday), and to nearby communities eastward to Ajeltake (from Tuesday to Thursday), during normal conditions. During prolonged drought periods, more demand is placed on the Laura lens, and water is piped to the MWCS airport reservoir to support the main Majuro urban areas of Delap, Uliga and Darrit, as experienced during the 1998 and 2016 drought events.

2.6 Previous investigations

Extensive coastal aquifer assessments and development work in the Marshall Island has been conducted since the 1980s in response to the vulnerability of limited freshwater resources, the increasing demand for drinking water, and chronic water shortages experienced during and after the El-Niño-driven droughts of 1983, 1987, 1992, 1998 and 2015.

The Outer Island Water Resources Planning and Development project conducted water resources assessment of 10 atolls, including Jaluit Atoll (Goodwin et al. 2000). The project aimed at: 1) evaluating the condition of existing water supply infrastructure and facilities, and identifying the necessary improvement works; and 2) assessing the groundwater resources in terms of location and thickness to support water supply needs. The results of the work on Jabor, Jaluit and Imrodj islets are presented in Tables 4 and 5 following.

Table 4. Summary of groundwater survey results for Jabor, Jaluit and Imrodj islets by Goodwin et al. 2000.

Island	Population	No. of households	No. of wells	Percentage of wells with freshwater (%)	Island area mi2 (km2)	Lens area mi2 (km2)	Maximum lens thickness ft (m)	Sustainable yield during drought gpd (lpd)
Jabor	800	54	20	0	0.093 (0.24)	0.0014 (0.0036)	5.1 (1.55)	938 (248)
Jaluit	100	19	5	40	0.626 (1.62)	0.130 (0.337)	8.6 (2.62)	8700 (2299)
Imrodj	150	15	11	12	0.105 (0.272)	0.0045 (0.012)	4.1 (1.25)	3010 (795)

Note: ND means no data collected

Table 5. Summary of rainwater harvesting results for Jabor and Jaluit islets by Goodwin et al. 2000.

Islands	No. of households	No. of household catchments	Average storage capacity gal (l)	Estimated supply per person per day under normal rainfall gal (l)	Estimated supply per person per day during droughts gal (l)	Percentage of tanks that regularly go dry (%)	Percentage of tanks with leaks (%)
Jabor	54	51	4244 (16,063)	8.1 (30.66)	4.7 (17.79)	55	8
Jaluit	19	3	1900 (7191)	5.8 (21.95)	2.5 (9.46)	0	33.3

Note: ND means no data collected

Goodwin (2000) presented the following key findings:

- Assessment on the RWH capacity showed that 94% of the households on Jabor have rainwater tanks, with an estimated supply capacity of 8.1 gal/day (30.6 L/day), while 16% of Jaluit's households have rainwater tanks with an estimated supply capacity of 5.8 gal/day (21.9 L/day).
- A drinking water tank at the Jaluit High School tested positive for bacteriological contamination through a presence/absence test procedure, which was a concern because the tank was providing water to 276 students.
- The assessment of existing hand-dug wells showed that all wells on Jabor exhibit brackish water quality, while Jaluit and Imrodj islets have 40% and 12% brackish wells, respectively.
- The freshwater lenses on Jabor and Imrodj were too small to support any groundwater development, whereas the mapped freshwater lens on Jaluit could be a source of water during droughts.
- The mapped groundwater on Jaluit extends from the central to the western part of the island, while the eastern part, which is also the widest part, appeared to be vulnerable to tidal inundation.

An assessment of the water resources infrastructure, water use and quality by UNDP (2018) captured the following key observations:

- Not all houses have RWH systems, and approximately half of the houses on Jabor and Jaluit do not have RWH, and only half of the houses have wells.
- Large concrete World War II catchment tanks exist on Jabor and remain functional and connected to the RWH system at the High School.
- Gutters were generally in poor condition and there was no first-flush system installed.
- During the dry season, salinity increases in most wells, while some wells maintain their low salinity during dry seasons and when demands are high.

Planned water security activities (UNDP 2018) for Jaluit Atoll included:

- The construction of a 50-Kgal (189-m^3) community storage tank on Jabor and a 25-Kgal (95-m^3) on Jaluit by RMI's Ministry of Public Works.
- An additional concrete tank to be constructed under the European Union-GIZ Climate Change and Sustainable Energy Programme at Jaluit High School.
- A new 792-gal/day (3-m^3/day) RO unit to be delivered and installed by Japan International Cooperation Agency at the high school.

Substantial knowledge and data gaps exist that prevent the holistic, sustainable, and integrated use and management of freshwater resources in RMI. The 2007 hot-spot analysis undertaken by the Environmental Protection Authority identified and evaluated areas of national, regional and global significance within RMI, and where conditions adversely affect human health, ecosystem functioning, biodiversity and/or resources and amenities in a manner that requires priority management attention (EPA et al. 2007). Two main hot-spot areas identified were: 1) education on water and sanitation, highlighting the overall poor awareness and education levels leading to poor water and wastewater management and health problems; and 2) insufficient groundwater assessment, raising the need for a better assessment of groundwater resources, supply and quality, especially during drought periods. These two areas have strong linkages to the objectives of MCAP through: 1) building an understanding of the appropriate usage and management of coastal aquifers; and 2) strengthening community-based governance, through inclusive engagement of communities, focusing on awareness and information exchange in order to improve the development and protection of shallow groundwater systems.

3. Field survey methodology

3.1 Electrical resistivity tomography survey

Electrical resistivity tomography (ERT) geophysics were used to assess, visualize 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 geological medium, hydraulic permeability, electrical conductivity (EC) or salinity of pore fluids, and clay mineralization, 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 because it offers 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 6.6 ft (2 m) was selected to investigate in detail depths up to 98 ft (30 m). The orientation of the survey profiles and distances was guided by the review of satellite photos, an awareness of the freshwater ponds and shallow hand-dug wells to adequately investigate the groundwater potential of the coastal sediments.

Illustrated in Table 6 are the different geological materials that may be encountered in Jabor and Jaluit and the corresponding resistivity range that is likely to be measured.

Table 6. Typical resistivity ranges for the different sediment types typical of atoll environments.

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

Source: Dale 1986; Greggio et al. 2018

3.1.1 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 calculates the apparent resistivity of these blocks using either a finite difference or finite element method and compares 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 color 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, which could 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 underground (e.g. cables or pipes) and aboveground (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 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 more 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, thereby providing improved confidence in the datasets.

3.1.2 Application of ERT

3.1.2.1 ERT survey calibration

Considering the absence of monitoring boreholes on Jaluit Atoll that would have allowed for the *in situ* verification of the recorded resistivity with groundwater EC results, two scoping survey lines were completed on Laura islet within Majuro Atoll. Survey line 1 (Figure A1.1) was completed along the football field on the northern parts of the islet and crossed monitoring bore 1 and gallery 7. Survey line 2 was completed around the central part of the islet and between galleries 1 and 2 (Figure A1.2). Galleries and bore 1 did not show any indication of elevated groundwater salinity (Table 7), although the resistivity profiles showed significant EC changes. This is most likely because bore 1 is not deep enough to reach the transition zone, which the resistivity profiles suggest being at ~ 45 ft (~14 m). Therefore, it was not possible confidently to locate the salt water–freshwater interface, which is essential for mapping the delineation of the freshwater lens. Results of similar scoping work conducted in 2018 (Antoniou et al. 2019) was, therefore, considered because it showed indications of the transition from freshwater towards brackish water, which can be seen for bore 6 in Table 7. This helped the calibration exercise by providing a range of EC measurements and modelled resistivity expected within a freshwater lens zone. Measured EC and modelled resistivity from these sites and locations of these lines are presented in Table 7 and Figure 7.

Table 7. Measured groundwater EC (mS/cm) and modelled resistivity from the calibration exercise on Laura islet, Majuro Atoll combining the 2018 calibration work and the 2022 survey.

Site	Measurement depth ft (m)	EC (mS/cm)	Modelled resistivity (Ohm.m)
Gallery 1	6.6 (2.01)	0.233	80–100
Gallery 2	7 (2.12)	0.242	80–100
Gallery 7	5.8 (1.76) 23 (7)	0.269 0.188	80–100 60–80
Bore 1	33 (10) 43 (13.5)	0.473 0.379	60–80 20–40
Bore 6 (2018)	33 (10) 43 (13.5) 48 (14.6)	0.785 2.43 14.9	20–60 8–10 2–4

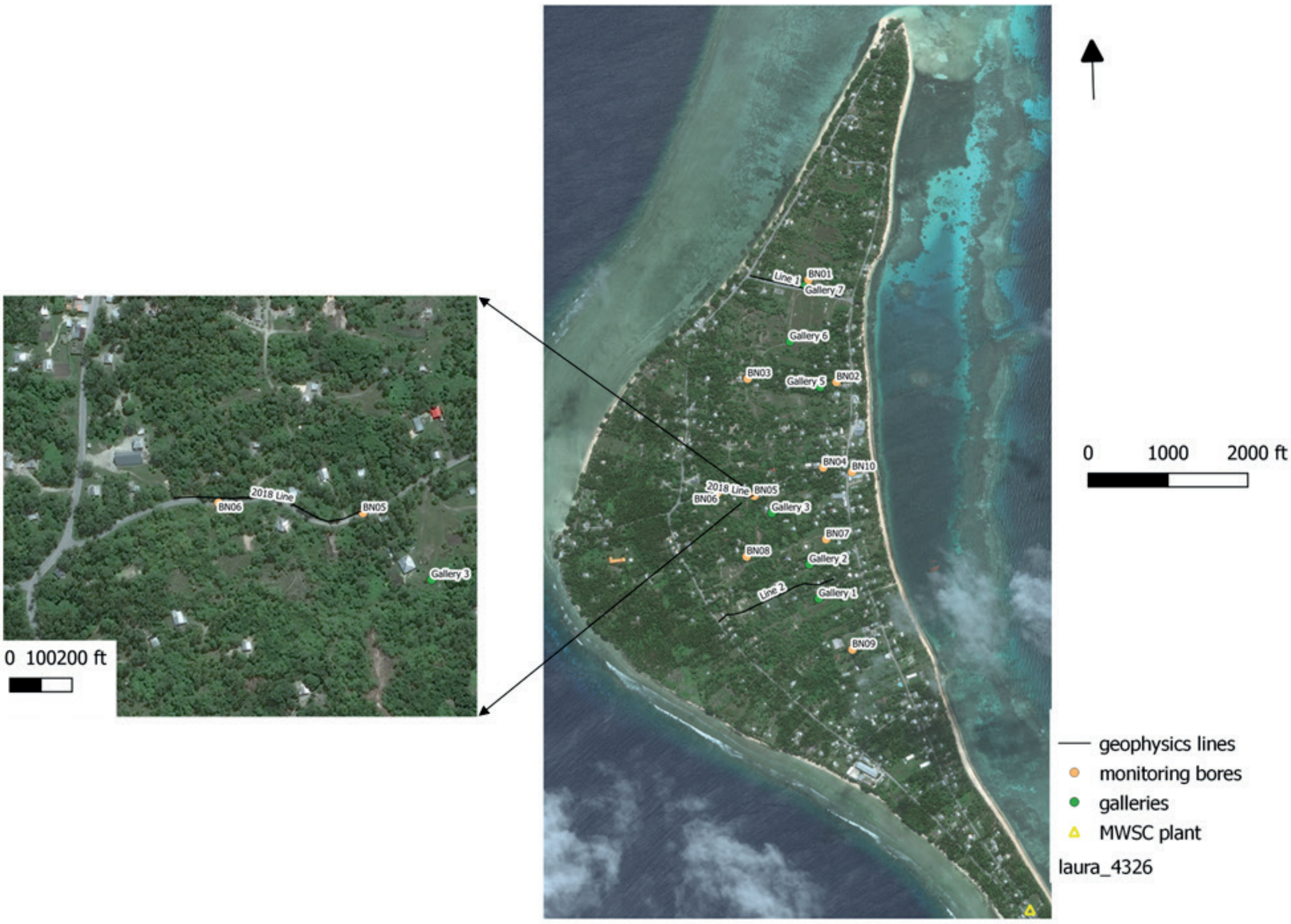

Figure 7. Location of scoping lines in relation to existing monitoring bores and galleries on Laura islet, Majuro Atoll.

Extrapolating the calibrated resistivity values from Laura to Jaluit is done by assuming the same aquifer properties and similar rainfall conditions for the two islets. Although this introduces a degree of uncertainty, it is the best we can do to validate the resistivity results. Because Laura is wider and situated on the leeward (western) side of Majuro Atoll, it is expected that the aquifer is dominated by fine sediments, and that the freshwater lens is thicker, in comparison to the conditions on Jabor and Jaluit islets. These slightly different geological conditions may influence the resistivity responses and, therefore, the accuracy of using the calibration data from Laura in the Jaluit Atoll groundwater assessment. Nevertheless, this calibration exercise was considered suitable in obtaining a general guideline for the vertical and horizontal delineation of the freshwater lens along the survey lines conducted on Jabor and Jaluit. This can be validated through the installation of monitoring bores on both islets.

3.1.2.2 Selection of survey lines

Because Jabor is the main commercial and administration center of Jaluit Atoll, it has multiple access roads, which means that vehicles and motor bikes posed safety risks to the survey team members and equipment as they were working. Support from the island leaders allowed the engagement of two police officers to help control traffic and to ensure work safety.

An extensive part of Jaluit islet is swampy and prone to tidal inundation, which presented an additional risk to groundwater quality. The engagement of a local guide led to the identification of numerous freshwater ponds that are known to have minimal impacts from droughts and are less vulnerable to tidal overtopping. This led to the concentration of survey efforts around the central area, near the Jaluit Primary School, where several nearby ponds neither run dry nor experience elevated salinity during prolonged dry periods.

Figure 8. A pond near Jaluit Primary School with an EC value of 1.02 mS/cm, suggesting the possibility of fresh groundwater, and prompting the resistivity survey to be focused around the area.

Ten ERT survey lines were completed in the two communities using high-resolution imagery to determine existing tracks or roads that have lagoon to ocean trend (Table 8).

Table 8. Summary of survey lines completed during this mission, including the scoping lines on Laura and the investigation lines on Jabor and Jaluit using 2-m separation.

Survey line	Distance ft (m)	Start point	End point
Laura-01	1181 (360)	171.03388°, 7.15586°	171.03686°, 7.15517°
Laura-02	1574 (480)	171.03283°, 7.14389°	171.03672°, 7.14533
Jab-01	590 (180)	169.64179°, 5.92413°	169.64047°, 5.92341°
Jab-02	689 (210)	169.64252°, 5.92374°	169.64124°, 5.92249°
Jab-03	853 (260)	169.64360°, 5.922263°	169.64189°, 5.92135°
Jab-04	394 (120)	169.64352°, 5.92140°	169.64275°, 5.92069°
Jab-05	394 (120)	169.64459°, 5.92000°	169.64350°, 5.91975°
Jal-01	1180 (360)	169.59277°, 5.79503°	169.59082°, 5.79245°
Jal-02	1180 (360)	169.59479°, 5.79426°	169.59322°, 5.79141°
Jal-03	984 (300)	169.59166°, 5.79522°	169.59022°, 5.79333°
Jal-04	984 (300)	169.60119°, 5.79284°	169.60039°, 5.79006°
Jal-05	525 (160)	169.58515°, 5.798887°	169.58429°, 5.79758°

3.2 Survey of private wells and community rainwater systems

A detailed survey of all existing private wells was undertaken on Jabor and Jaluit. This involved capturing the GPS locations of the wells and an assessment of their key attributes, such as the well construction material, presence of a well cover and concrete aprons, existence of protection measures, groundwater level and salinity (as EC), and abstraction technology. The well diameter and depth to groundwater were measured using an 8-m builders' tape, while the groundwater EC was measured using a TPS logger (WP Series). Several wells were dry during low tide and resulted in repeated visits; these highlighted the significant influence that tides have on groundwater level fluctuation. Some of the dry wells did not show any groundwater even during high tides.

Table 9. Summary of the well survey on Jabor and Jaluit islets.

Community	Number of wells surveyed	Average depth to water table ft (m)	Number of wells with concrete and coral casing	Number of wells with proper cover	Number of wells with electric pump	Number of dry wells	Average salinity (mS/cm)	Number of wells having salinity less 2.5 mS/cm
Jabor	30	5.6 (1.71)	24	19	1	9	10.67	8
Jaluit	13	3.9 (1.20)	6	7	0	3	1.97	7

Figure 9. The Jaluit High School well feeds the desalination reverse osmosis unit.

Figure 10. A private well on Jaluit exhibiting the composite casing material of coral and concrete.

Figure 11. A black 200-L plastic drum used as casing material with the rope attached to the bottle for accessing the groundwater.

Community buildings were also assessed for their RWH capacity. These buildings included churches, community halls and the medical center. The building survey entailed the measurement of roof catchment dimensions, the assessment of roofing materials, gutter coverage and condition, and a review of rainwater storage volume and conditions. These were entered into a database for planning and monitoring purposes. Dimensional parameters such as the length and width of roof catchment of the community building were measured using an 8-m builders' tape.

Table 10. Summary of communal rainwater harvesting systems surveyed, focusing on churches, community halls and the medical center.

Community	Number of communal buildings surveyed	Number of buildings with good roofing	Number of buildings with good gutters	Number of buildings with fascia boards	Number of buildings with down pipes	Range of roof catchment area ft^2 (m^2)	Number of buildings with tanks	Total tank volumes gal (L)
Jabor	7	6	4	4	5	598–1740 (55–161)	7	22,457 (85,000)
Jaluit	5	5	5	4	2	1460– 3985 (136–370)	2	3963 (15,000) L

The groundwater wells and RWH information presented here indicate the status of groundwater level and quality. The basic infrastructural levels of the wells and rainwater collection system exhibit the status of freshwater storages during the time of the survey and provides guideline for improvements. MCAP, however, will not support any infrastructural improvements of private wells and rainwater systems mainly because the Addressing Climate Vulnerability in the Water Sector project, currently implemented the United Nations Development Programme (UNDP), supports the infrastructural improvement of all groundwater wells and individual household RWH systems around all the outer islands' communities in the Marshall Islands. Schools are also not covered because the government has routine programs to undertake maintenance work on buildings, including RWH systems.

Figure 12. A church on Jaluit islet with new and good roofing, and fascia board, but with no gutters, downpipe or tank.

Figure 13. A church on Jabor islet with good roofing and fascia board but with no gutters, downpipe or tanks, which are essential for optimal rainwater harvesting.

Figure 14. Jabor water resources assessment map showing the location of hand-dug wells, communal buildings and storage tanks, and resistivity survey lines.

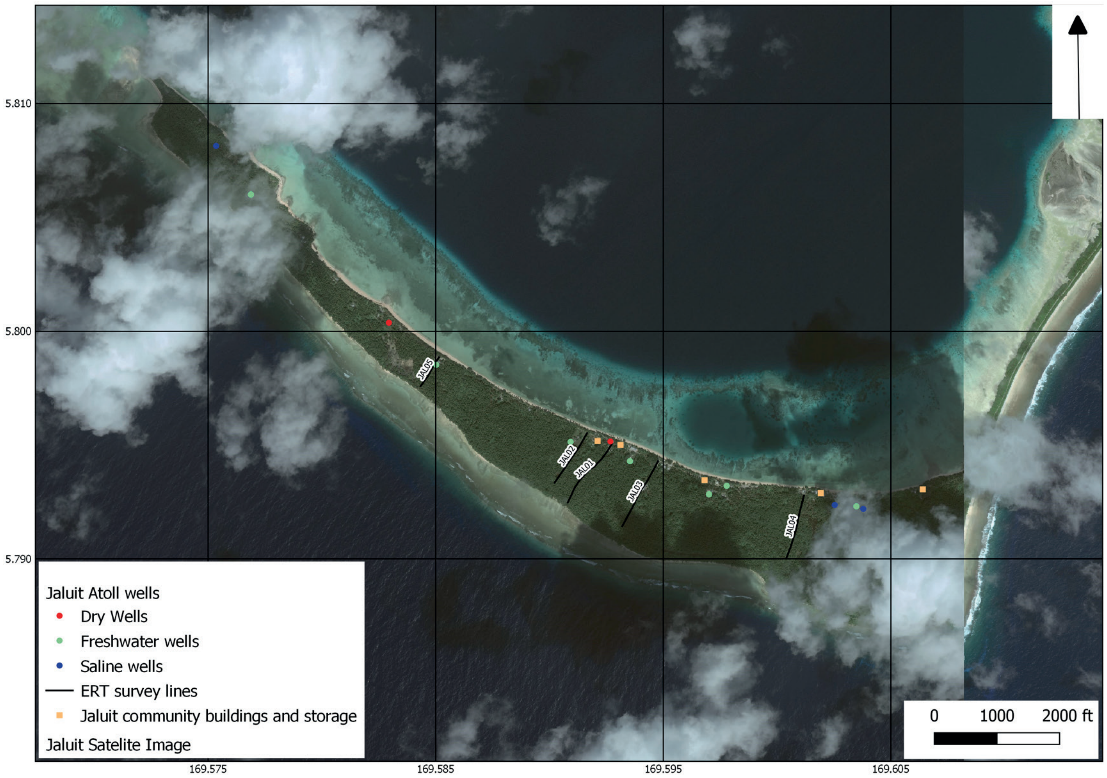

Figure 15. Jaluit water resources assessment map showing the location of hand-dug wells, communal buildings and storage tanks, and resistivity survey lines.

3.3 Community engagement

Multiple community engagement meetings were organized on both Jabor and Jaluit, together with island council representatives and leaders (acting island mayor, councilors, church leaders and senior elders) (Figure 16). A meeting was conducted prior to the investigation, and was designed to:

- introduce the project and the survey approach;
- create awareness of the potential hazard of the survey instrument;
- establish agreement on the proposed workplan; and
- organize logistical requirements.

Figure 16. Meeting with Jabor's leaders prior to the beginning of field work.

At the completion of the survey, preliminary results were again shared in inclusive meetings with men, women and children (Figure 17) to:

- share information based on what the key observations from the wells and RWH survey were, and what geophysical datasets indicated;
- discuss queries and opinions from the communities and leaders arising from the investigation results; and
- collect historical and traditional knowledge essential for the future improvement and governance of water resources.

Figure 17. Community meeting on Jaluit where the groundwater investigation results were presented and discussed.

4. Results and discussion

4.1 Geophysical results and interpretation

From the field results, four resistivity classifications can be deduced:

1. very high resistivity layer (>90 Ohm.m) covering the top 3–15 ft (1–5 m) depth below ground level, which may represent the unsaturated zone, comprising dry sand, beach deposits, and coarse pebbles and gravels;
2. moderate resistivity layer of (14–80 Ohm.m) that may represent the unconsolidated sediments saturated with fresh groundwater;
3. a low resistivity layer (6–13 Ohm.m), which may suggest the mixing zone between fresh groundwater and the increasing influence of basal seawater, resulting in unconsolidated sediments filled with brackish water; and
4. a very low resistivity of (<6 Ohm.m), suggesting that sediments or underlying limestone are saturated with basal seawater.

The thickest part of the freshwater lens in Jaluit was mapped between lines JAL01 and JAL03 (Figures 17 and 19), with thicknesses greater than 10 m identified towards the end of JAL03, which crosses the middle part of the island. Assuming similar aquifer and/or sediment properties between Laura and Jaluit, the freshwater body along profile JAL03 (Figure A1.11) gradually acquires a thickness of up to 39 ft (13 m) at between 902 ft (275 m) and 1082 ft (330 m) along the profile. Survey line JAL01 (Figure A1.9) showed a reduced freshwater body up to 29.5 ft (9 m) thick. Survey line JAL05 (Figure A1.13) showed a reduced thickness of around 10 ft (3 m). Survey line JAL04 (Figure A1.12) showed no indication of freshwater development – the area is known to be vulnerable to tidal inundation and is located towards the eastern end of the island.

On Jabor (Figure 17), the five survey lines (Figures A1.4 to A1.8) show pockets of a thinner freshwater lens compared to Jaluit, of around 3 m thickness, and mainly present between lines JAB01 and JAB03 (Figure 17). The thin lens is likely to support the private wells that exhibit EC less than 2.5 mS/cm, although the fresh groundwater resources would be vulnerable to tidal inundation and drought due to Jabor's relatively small land area. Also, indications of very high resistivities (> 500 Ohm.m) were recorded in the upper layer, suggesting coarser sediments prevalent towards the ocean side – the deposition of these coarse sediments can be attributed to the high-energy waves associated with Jabor's exposure to northeast trade winds and, thus, contributing to highly permeable materials that have low fresh groundwater storage capacity.

The proposed isolines of freshwater lens thickness presented in Figure 18 and Figure 19 are approximate, especially as the distance from the survey lines increases, and should be taken as indicative only. The edge of the 10-ft (3-m) isoline, for example, is approximated to the available resistivity lines and EC information from the private wells.

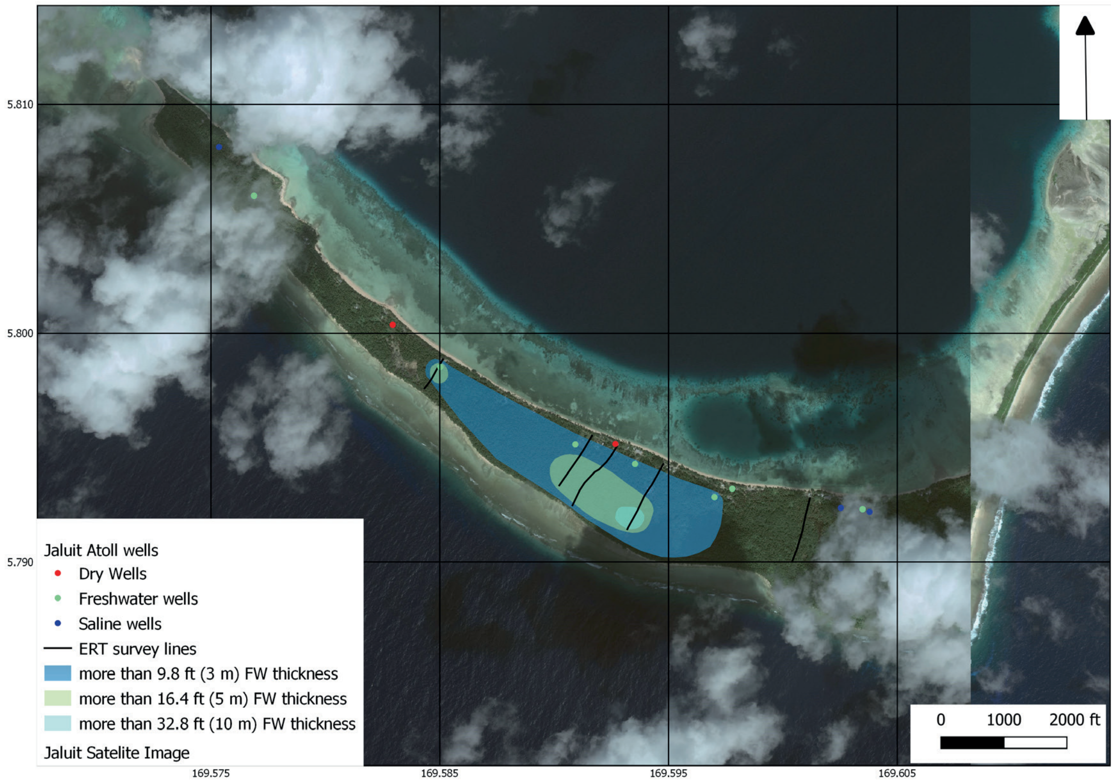

Figure 18. Freshwater lens thickness contours and salinity levels (as EC) in private wells on Jaluit islet.

Figure 19. Freshwater lens thickness contours and salinity levels (as EC) in private wells on Jabor islet.

4.2 Groundwater well assessment

In total, 43 wells were surveyed in the two communities for groundwater salinity, as EC. Out of the 30 wells surveyed on Jabor, 9 (30%) were dry, 8 (27%) showed EC levels below 2.5 mS/cm, and 13 (43%) recorded EC above 2.5 mS/cm. The Jaluit High School well is used to feed water into the school's desalination unit, and recorded an EC of 20.8 mS/cm. For the 13 wells on Jaluit, 3 (23%) were dry, 7 (54%) recorded an EC below 2.5 mS/cm, and 3 (23%) showed EC measurements exceeding 2.5 mS/cm. In terms of groundwater usage, 3 out of 13 wells on Jaluit were used for drinking – the rest were used for secondary purposes. All wells on Jabor were used for secondary purposes, except for the High School well where the desalination unit is installed.

The higher number of saline wells on Jabor than on Jaluit validates the resistivity findings; Jabor has limited groundwater potential, and the relatively thin lens of up to 9.8 ft (3 m) may be responsible for supporting the eight freshwater wells. On the other hand, Jaluit's high number of freshwater wells together with the presence of several freshwater ponds around the central area are likely to be supported by the 16–32 ft (5–10 m)-thick groundwater system described earlier.

In terms of overall well infrastructure, 31 (72%) wells have cement or coral casing, while 12 use materials such as steel or plastic drums to case the wells; 17 (40%) wells were uncovered, while others were covered using wooden board, or a piece of either concrete slab or corrugated iron; 40 (93%) wells use buckets and tins to access well water – 3 wells on Jabor use electrical pumps, 1 for the school desalination unit, while 2 were privately used for washing and toilet purposes. The current infrastructural status of private wells can be attributed to the value currently placed on groundwater as a secondary-only water source. Efforts, however, should be made to protect and improve the access of freshwater (EC < 2.5 mS/cm), which can be done through the installation of concrete casing with a length raised above ground, construction of concrete aprons to prevent any surface ingress, and hand pumps that regulate pumping as practiced in other atoll countries, such as in Kiribati.

No bacteriological sampling was conducted during the survey. It is recommended that *E. coli* testing be done in some of the freshwater wells, as well as in select rainwater tanks, to determine the safety of the water for human consumption. Boiling groundwater prior to use is highly recommended for all households on both Jabor and Jaluit.

4.3 Communal RWH and water security

The assessment of the 12 communal buildings showed that their RWH capacity is relatively poor, which raises a concern, particularly when the UNDP (2018) assessment already reported that more than 90% of the private households on Jabor and Jaluit do not have tanks.

On Jabor, despite having rainwater tanks connected to all seven communal buildings, only 60% of the buildings have good gutters and only 70% have downpipes installed. Considering that all buildings have storage tanks with an aggregated volume of 22,457 gal (85,000 L), it likely to that the roof catchment and their accessories (gutters and downpipes) will not allow optimal rainwater collection and storage. RWH on Jaluit appeared to be poor as expressed by 60% of the surveyed buildings without storage tanks, even though 80% of the buildings have good roofing and fascia board. Only two buildings have tanks with a total volume of ~4000 gal (15,000 L), which is very little storage.

Clearly, rainwater is a very important source of freshwater in RMI, being the primary water source for more 90% of the country's population; harnessing this resource through improved RWH systems will be key. Significant investment and improvements will be required to ensure the optimal use of the communal buildings' large roof catchment on Jaluit and Jabor. These improvements should result in increased rainwater storage, and will in turn act as a buffer for future prolonged dry periods, and strengthen communities' drought resilience, particularly for Jabor where the groundwater potential is limited. Based on information from the survey, the installation of gutters, downpipes and appropriately-sized tanks can be deemed low-cost interventions that will enhance the water security and resilience of the two communities.

4.4 Groundwater resources development

Two freshwater lenses were identified and delineated on both Jabor and Jaluit islets. The central part of Jaluit islet (Figure 19) shows a favorable fresh groundwater thickness of 16 ft (5 m) to slightly above 33 ft (10 m), as recorded towards the end of JAL03 survey line; this area should be prioritized as having good potential for an emergency water supply during droughts. Jabor recorded a thin lens of around 3 m, capable of supporting the shallow wells but will be vulnerable to droughts and, thus, cannot be counted on for community water supply needs.

Developing the mapped Jaluit freshwater lenses should be done by means of horizontal galleries, skimming the fresh groundwater just below the water table to prevent early salinization. Shrinking of the fresh groundwater body occurs by means of the upward movement of the transition zone, especially when vertical wells are used. Galleries in these areas should, therefore, be installed just below the groundwater table, which is stable in atoll environments, and should consider the sensitivity of freshwater lens thickness to tidal processes and rainfall events.

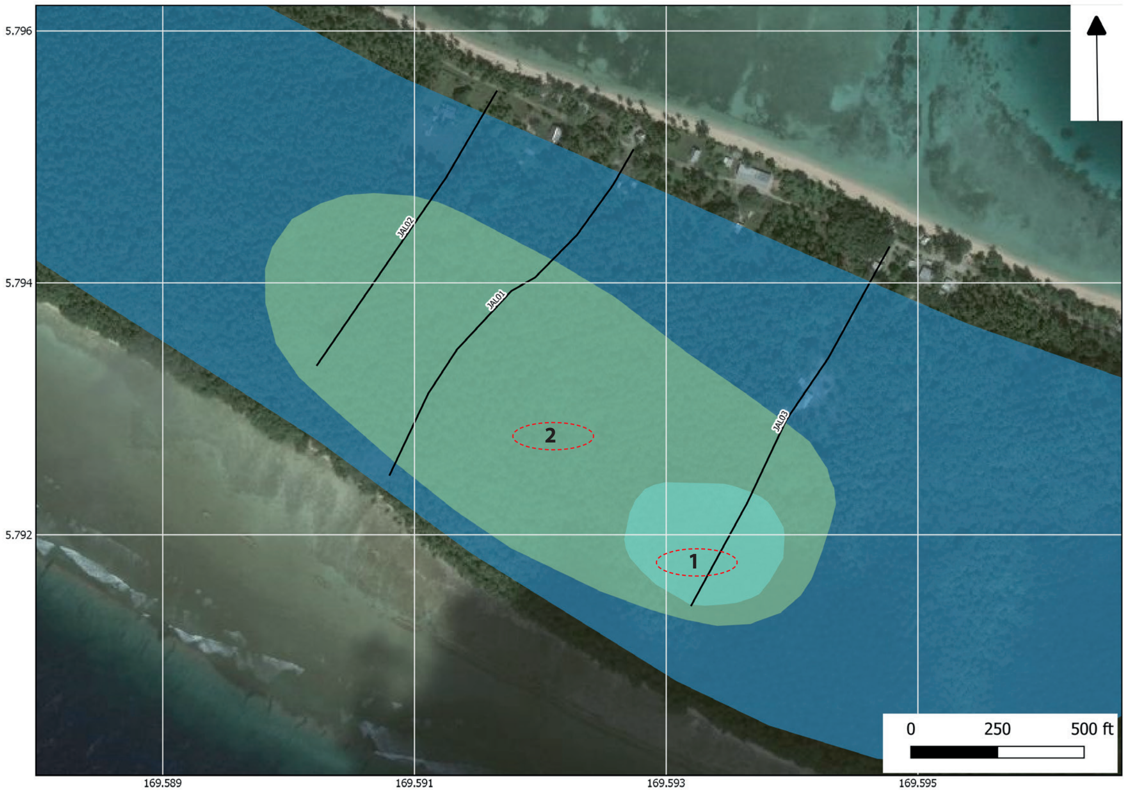

Figure 20. Proposed locations for the installation of a horizontal gallery on Jaluit islet.

Gallery construction in freshwater lenses involves excavating a trench approximately 1 m below the lowest level of the water table from tidal impact and installing horizontal PVC-slotted pipes that drain water towards a central pumping well. The horizontal pipes should be 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 if excavation is relatively easy. If the reef rock is hard or well cemented, or if thick reef rock is intercepted, then trench construction 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.

Considering the risk of tidal inundation to Jaluit, an inundation study should be conducted around the mapped freshwater resources area before starting any infrastructural development. This will provide additional insights on the extent of extreme inundation events, and in turn on how the freshwater lens thickness and salinity may be impacted.

4.5 Water resources protection and management

The integrated and coordinated development, management and protection of freshwater resources on Jaluit will be key to the community's long-term health and security. The following actions are suggested:

1. Improve the groundwater well infrastructures for wells showing EC levels below 2.5 mS/cm in the short to medium term. These improvements should include:
   a. installation of concrete casings and concrete aprons to avoid surface water ingress;
   b. installation of proper cover and fence for protection purpose; and
   c. appropriate abstraction technologies, such as hand pumps or properly designed bailers that are always hanged when unused, to minimize the risk of introducing bacteriological contamination and regulate pumping.

2. Improve the RWH capacity of all communal buildings in the medium term through the:
   a. repair and replacement of roofing materials;
   b. installation of good fascia boards, guttering and downpipes;
   c. installation of first-flush equipment to allow the adequate cleaning of roofs and gutters before rainwater collection;
   d. installation of appropriately sized rainwater tanks with well-secured standpipes; and
   e. proper maintenance and operation of these systems for long-term RWH benefits to be realized.

3. Installation of an infiltration gallery on Jaluit as a long-term emergency drought supply, which will entail the following:
   a. an inclusive community-engagement program to allow the discussion of the i) investigation results, ii) potential gallery location, iii) construction socioenvironmental costs and risks, and iv) gallery long-term water security benefits;
   b. a tidal inundation study to be undertaken prior to the gallery construction to determine the impacts of extreme events, and to establish limits around the freshwater lens extent and pumping constraints;
   c. installation of groundwater monitoring technologies, such as flow, level and EC meters, in future galleries and around the main reservoirs. This will allow for the assessment of groundwater abstraction, water usage and leakage;
   d. installation of a rainfall station near the proposed gallery to allow ongoing rainfall rates monitoring. This will make it possible to determine the temporal variability of rainfall and to estimate the groundwater recharge. This will require the strengthening of the links between the Island Council and the national Weather Service Office on the compilation, archiving and sharing of rainfall data and climate forecast;
   e. identification of appropriate trigger levels for groundwater salinity and rainfall to support water resources management during prolonged dry periods; and
   f. establish and/or strengthen appropriate water restriction actions around the communities during extreme climatic conditions.

4. Develop and continually update an island-wide drought awareness and action plan that considers different climatic conditions, the practical solutions required to protect groundwater resources and reduce drought impacts, and how this might impact the major water users within the community.

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Annex 1 – Inverted resistivity profiles

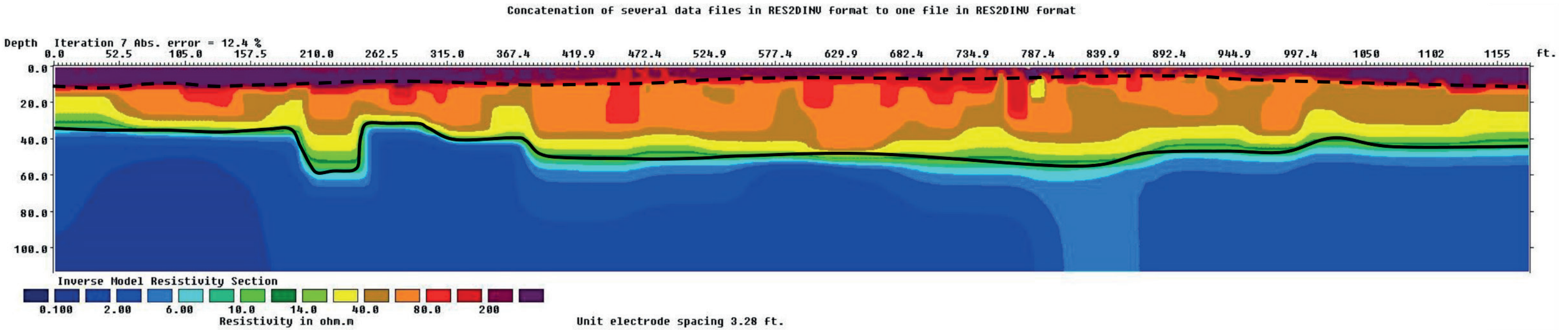

Figure A1.1. Resistivity profile Laura-01 (Majuro Atoll) with depth in feet.

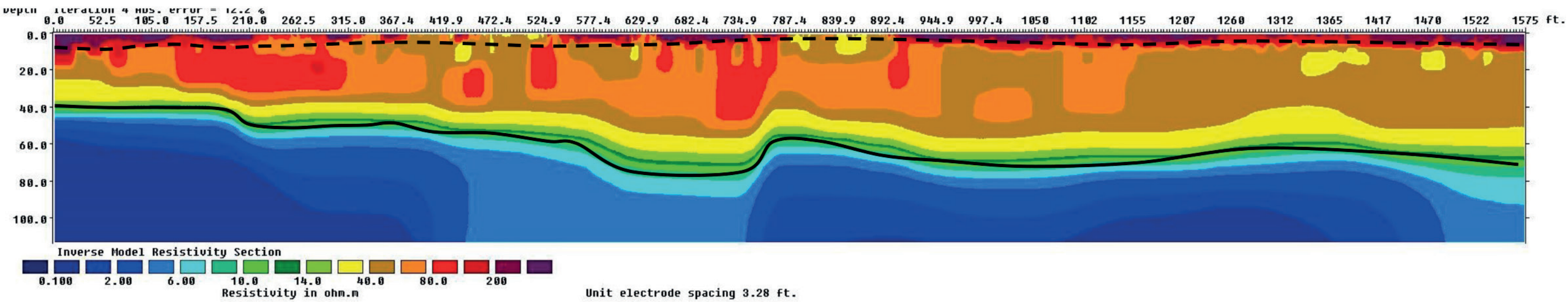

Figure A1.2. Resistivity profile Laura-02 (Majuro Atoll).

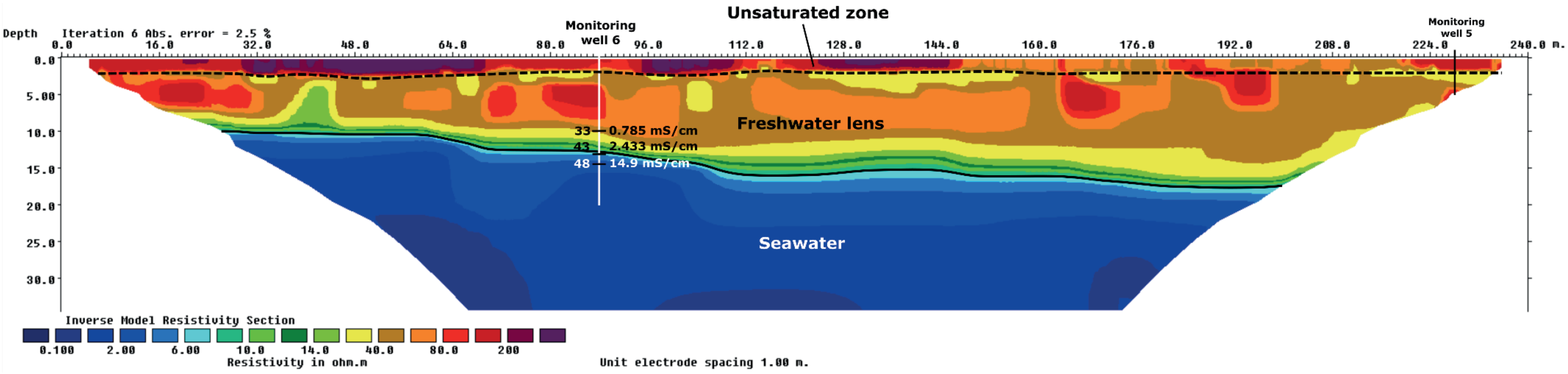

Figure A1.3. Resistivity profile Laura – 2018 line (Majuro Atoll).

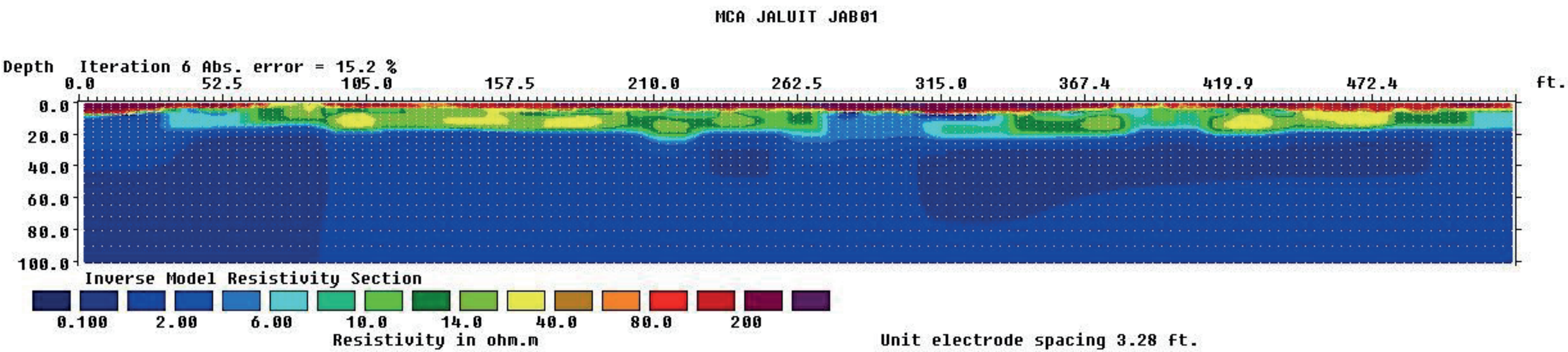

Figure A1.4. Resistivity profile JAB-01 (Jabor).

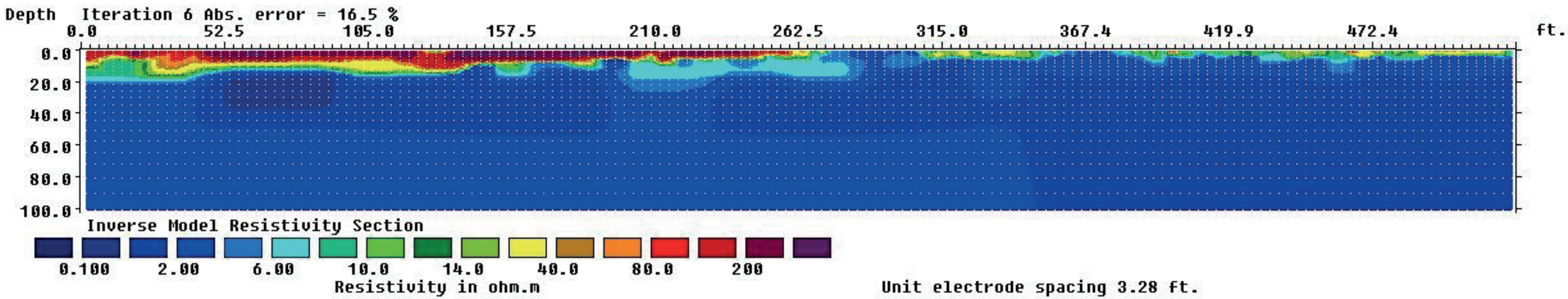

Figure A1.5. Resistivity profile JAB-02 (Jabor).

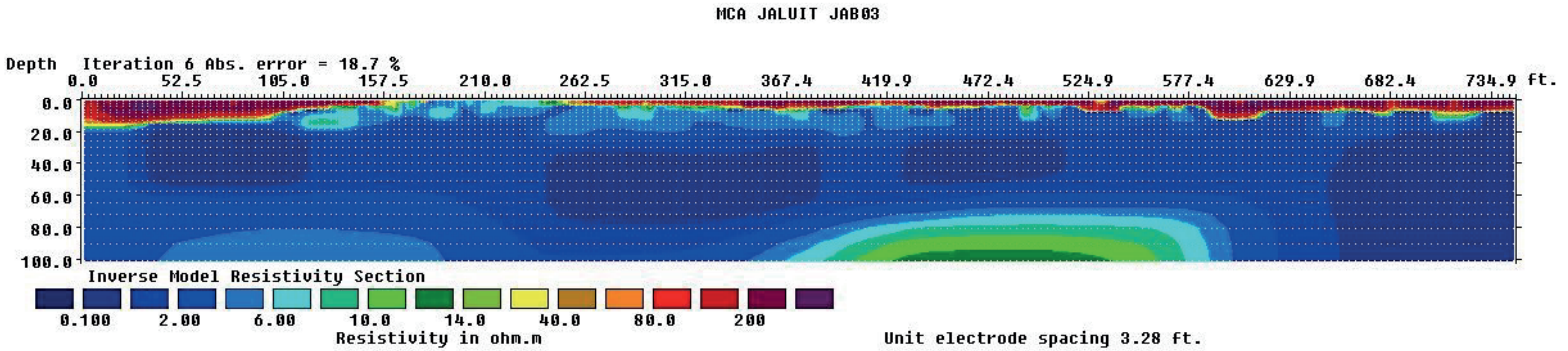

Figure A1.6. Resistivity profile JAB-03 (Jabor).

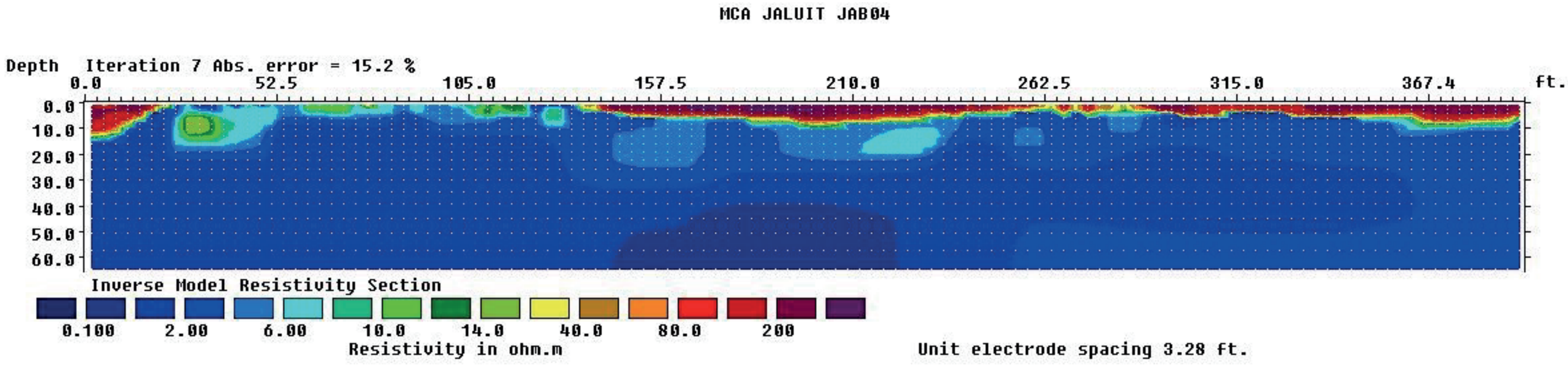

Figure A1.7. Resistivity profile JAB-04 (Jabor).

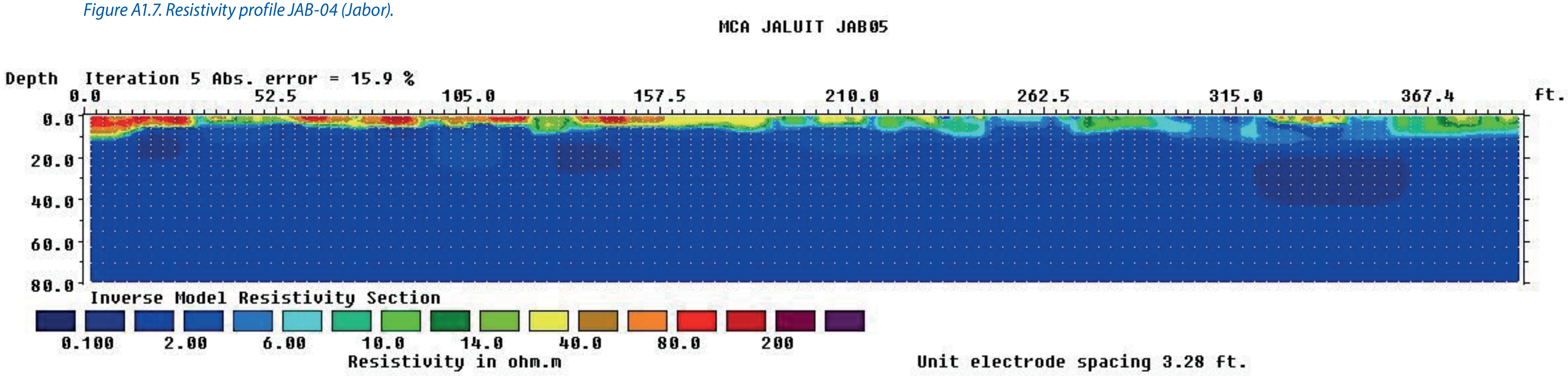

Figure A1.8. Resistivity profile JAB-05 (Jabor).

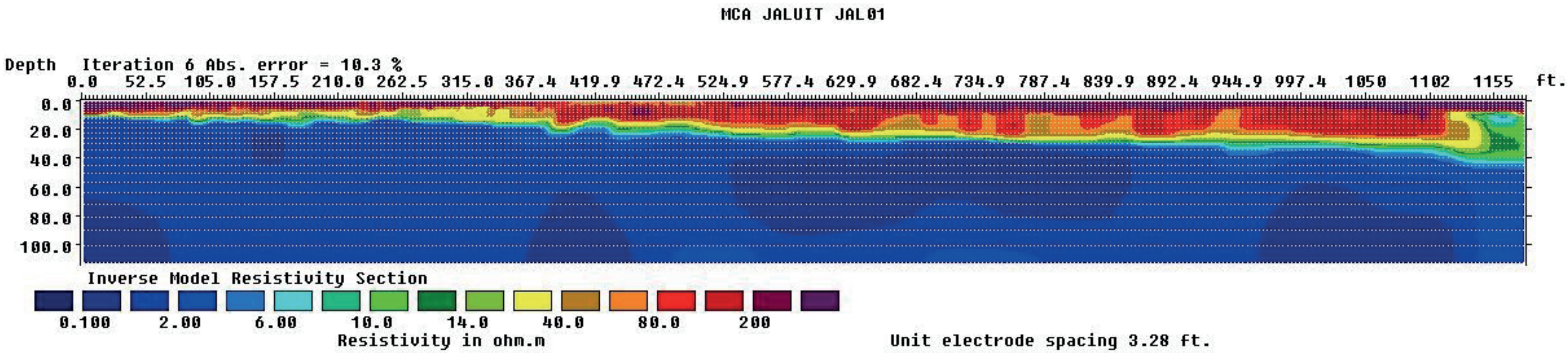

Figure A1.9. Resistivity profile JAL-01 (Jaluit).

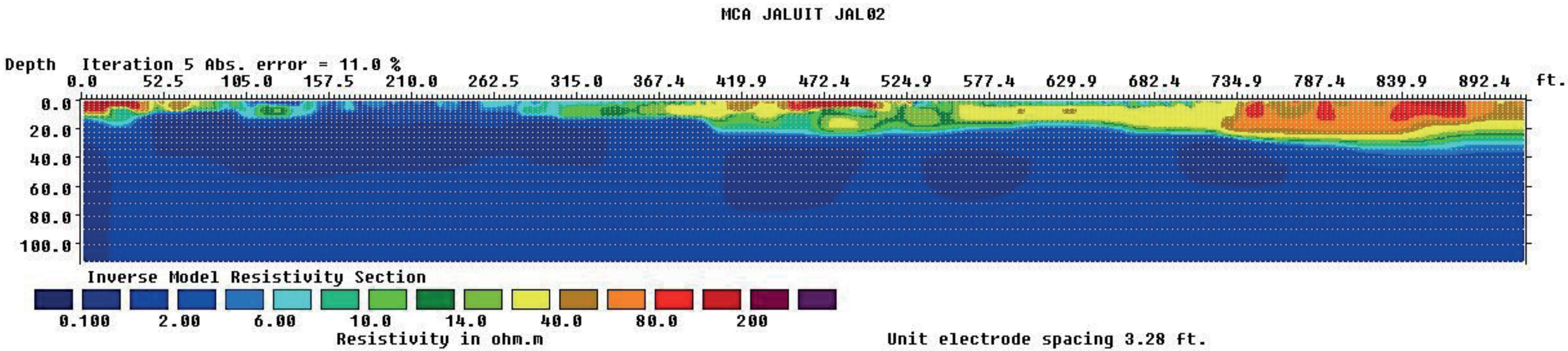

Figure A1.10. Resistivity profile JAL-02 (Jaluit).

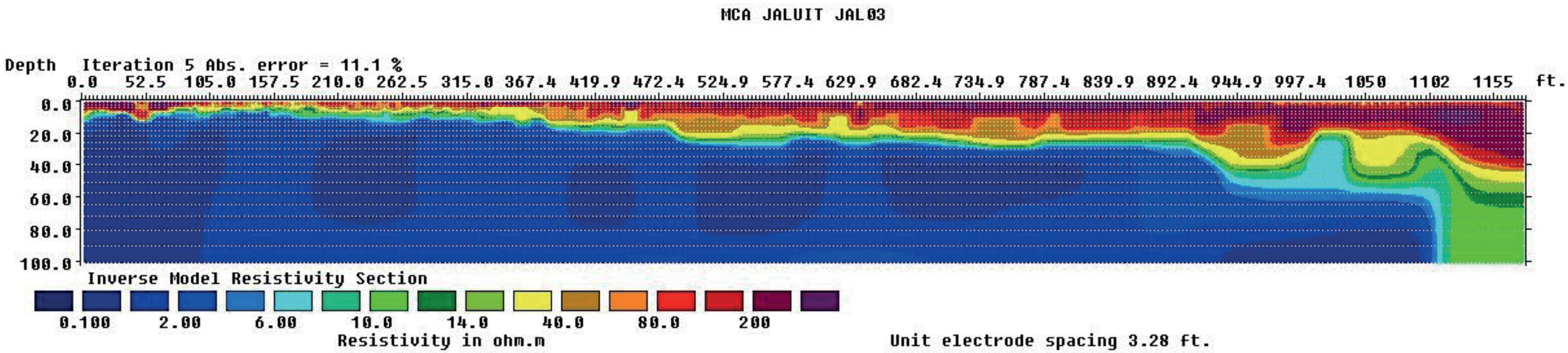

Figure A1.11. Resistivity profile JAL-03 (Jaluit).

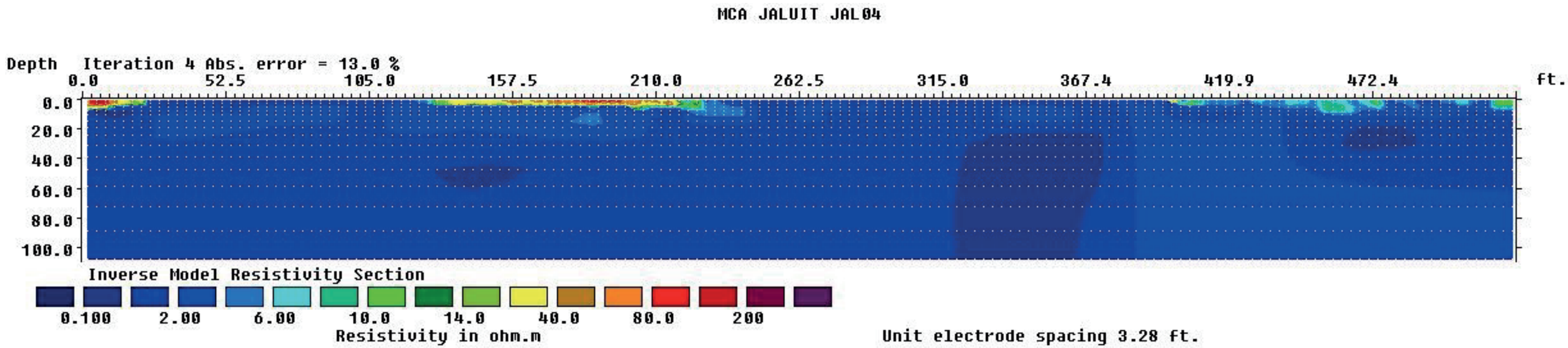

Figure A1.12. Resistivity profile JAL-04 (Jaluit).

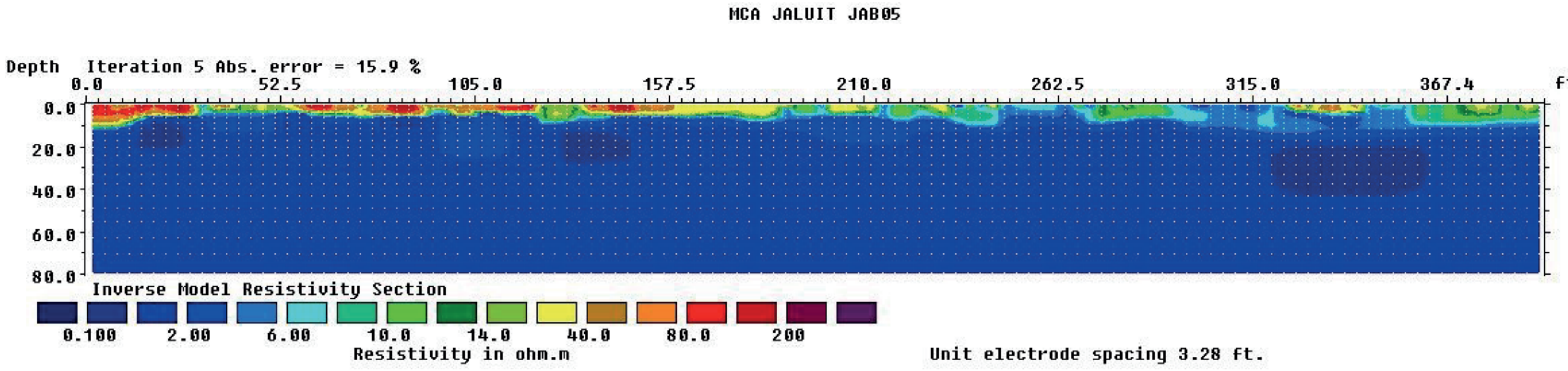

Figure A1.13. Resistivity profile JAL-05 (Jaluit).

Produced by the Pacific Community (SPC)
Pacific Community
Private mail bag, Suva, Fiji

Telephone: +679 337 0733
Email: spc@spc.int
Website: www.spc.int

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