Strengthening Water Security of Vulnerable Island States

Groundwater investigations on Wotje Atoll, Republic of the Marshall Islands

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Andreas Antoniou, Aminisitai Loco, Anesh Kumar and Peter Sinclair

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- Republic of the Marshall Islands National Disaster Management Office,
- Office of Environmental Policy and Planning Coordination,
- Environmental Protection Authority,
- Majuro Water and Sewerage Cooperation, and
- International Office of Migration.

Community members of the Wotje Island Council, and the island mayor and deputy mayor played a key role by participating in community meetings and sharing their views on the proposed work.

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1. Introduction

1.1 Project background

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

1.2 Mission objectives and outcomes

The main purpose of this investigation was to identify fresh groundwater resources on the islands of Wotje and Wormej within Wotje Atoll that could complement existing water supplies or serve as a backup during dry periods. Additional objectives included a survey of private wells and the sampling of groundwater from some of those wells for bacteriological analysis. This resulted in a geographic information system (GIS)-based well inventory that included information on well location, construction and groundwater.

The development of new groundwater resources in atoll environments requires: 1) an investigation of groundwater resource potential and optimal drilling targets and locations; 2) the construction of horizontal galleries and an assessment of yield and water quality; 3) equipping galleries with pumps and storage tanks that are in line with the resource potential and the community's needs and resources; and 4) the formulation of operational, maintenance and management guidelines – in conjunction with the community – that promote ongoing operation and sustainability. The current work focused on the first component, which was achieved through the use of geophysics to better understand the local hydrogeology and groundwater storage potential. Recommendations are given with regards to potential gallery locations, expected yields and expected groundwater quality. Recommendations are also given on the maintenance and use of the existing network of private wells.

2. Background

2.1 Geographical location and history

Wotje is a coral atoll composed of 75 islets with a total land area of 8.2 km^2, and is one of the largest atolls in the Republic of the Marshall Islands (RMI). Wotje lies in RMI's northern group of atolls within the Ratak Chain. Wotje island (within Wotje Atoll) is oriented in a north–south direction and is 3.3 km long and 1.1 km wide. The atoll's population in 2017 was estimated to be 751, with a total of 114 households. The population figure also includes 150 high school students living on Wotje island. Wormej, the other inhabited islet within the atoll, is 12.5 km northwest of Wotje and has a population of 137 with 22 households. Wormej is 1.8 km long (lying in an east–west orientation) and 720 m wide.

Figure 1. The islands comprising the Republic of the Marshall Islands. Source: www.graphicmaps.com

After World War I, the Marshall Islands came under the South Pacific Mandate of the Empire of Japan. At the end of the 1930s, Wotje was developed into a major military base consisting of an airfield and numerous military buildings. Following the end of World War II, the islands came under the control of the United States as part of the Trust Territory of the Pacific Islands until the Republic of the Marshall Islands gained independence in 1986.

Today, many World War II relics remain on the island, including a large concrete airfield, bunkers and coastal artillery. The current village is established around the existing concrete surfaces. Copra production is the main land-use activity on the island.

2.2 Climate

Rainfall varies greatly from north to south in RMI. The northern atolls receive less than 1250 mm of rain annually, and experience significant droughts during the dry season. The southern atolls receive more than 2500 mm of rain annually. The difference between the wet and dry season is more pronounced in the northern atolls. The monthly average temperature on Wotje is 27°C year round, ranging between 25°C and 30°C. The monthly average precipitation is presented in Figure 2.

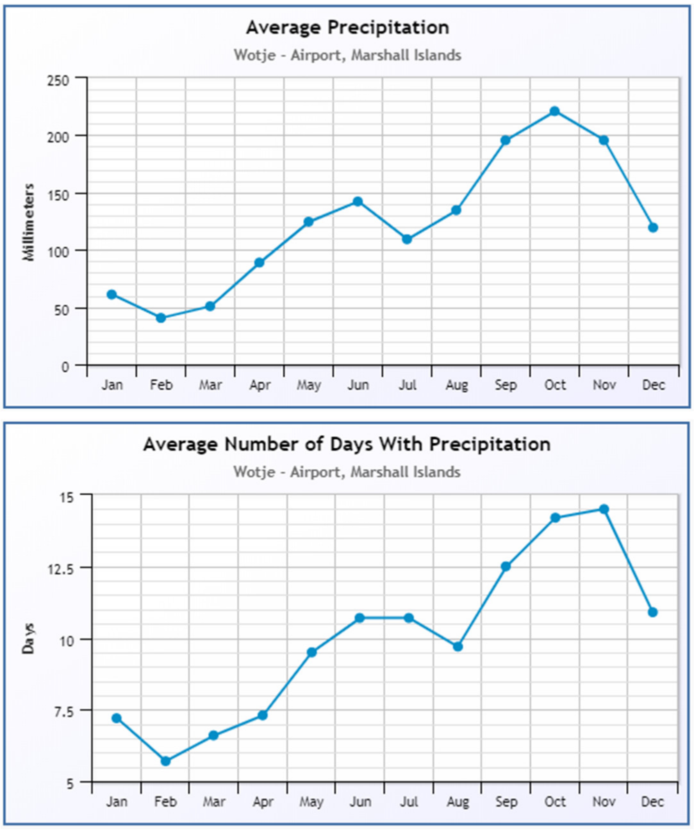

Figure 2. Monthly average precipitation (years on record: 30) and number of days with precipitation. (www.weatherbase.com)

RMI is particularly affected by intense El Niño-induced droughts and the associated depletion of rainwater storage and the thinning of freshwater lenses. Rainfall variability throughout the years 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 event. During severe El Niño events, rainfall can be suppressed by as much as 80% (ABM and CSIRO 2011). Groundwater is most extensively used during drought due to depletion of rainwater storage.

Table 1. Rainfall statistics for Wotje Atoll from available rainfall data.

	Yearly (mm)	Rainy period Jun–Nov	Dry period Dec–May
Average	1594	1081	522
St dev	505.4	164.4	279.6
CV	0.32	0.15	0.54

Compared with RMI's atolls in the south, Wotje Atoll receives 1594 mm, a lower amount of average rainfall on a yearly basis. The high coefficient of variation (CV) observed during the dry period (December–May) indicates higher rainfall fluctuation, which suggests greater vulnerability and risk of water shortages during this period.

Drought in RMI's Islands can be defined, using the percentile method, as being a period 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 February–April in Wotje, 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.

Wotje relies heavily on rainwater harvesting for domestic use and drinking water, therefore, it is 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 that 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 islands that depend on groundwater. A statistical analysis of the entire rainfall record for Wotje (January 1986 to September 2018), using a three-month drought index percentile method, is shown in Table 1 to provide some insight into drought occurrence for atolls in the central part of RMI.

Table 2. Analysis of drought statistics for Wotje Atoll from available rainfall data, using a three-month drought index percentile.

	Total	El Niño	La Niña	Neutral
Number of droughts	16	7	2	7
Average length of drought (months)	4.7	3	7.5	5.5
Average recurrence (months)	20	23	17	17

Wotje is likely to experience short drought events during El Niño conditions, which occur, on average, about every two years. In the last 30 years, only two droughts were experienced during La Niña conditions; however, these were longer and more intensive than droughts experienced during El Niño conditions. Table 2 identifies the top five droughts on Wotje in terms of intensity and duration. It is notable that the 1998 drought that strongly affected Majuro Atoll, did not greatly affect Wotje.

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

Wotje Atoll (January 1986–September 2018)					
Rank	**Drought period**	**Drought length (months)**	**Drought ENSO state**	**Total rainfall during drought (mm)**	**Average monthly rainfall during drought period (mm)**
1	Oct 2012 to Jul 2013	10	Neutral	688	69
2	Apr 2001 to Mar 2002	12	Neutral	950	79
3	Jan 2012 to Jul 2012	7	La Niña	424	60.5
4	Oct 2005 to Mar 2006	6	Neutral	405	67.5
5	Sep 2008 to Apr 2009	8	La Niña	702	87.8

2.3 Current water supply and drought response

During the 2011 census, all households reported rainwater as their main source of drinking water(SPC 2012). In 2017, RMI's Ministry of Public Works constructed a 189 m^3 storage tank on Wotje and a 95

m^3 tank on Wormej. Additional tanks were installed by the EU-GIZ 'Adapting to Climate Change and Sustainable Energy' (ACSE) programme in 2018, and additional community rainwater harvesting improvements are planned for the upcoming Green Climate Fund (GCF) project 'Addressing Climate Vulnerability in the Water Sector (ACWA) in the Marshall Islands' (2019–2026). A permanent reverse osmosis desalination unit is planned for Northern Islands High School, with a production capacity of 3 m^3/day (UNDP 2018).

During a survey conducted in 2016 (UNDP 2018), the total rainwater tank volume needed for Wotje was estimated at 970 m^3 (1290 L/person), and the tank volume needed for Wormej was estimated at 314 m^3 (2290 L/pers). The total communal rain-water tank capacity was estimated at 323 m^3 (430 L/pers) and 189 m^3 (1380 L/pers), repectively for the two islands. Groundwater is also extracted from private wells, which are widespread around the island; however, groundwater is only used for secondary purposes such as washing, toilet flushing, gardening and occasionally cooking. A few well owners mentioned during this survey that they also use their groundwater for drinking purposes, after adequate boiling.

During droughts (e.g. 2013), rainwater supplies can diminish substantially, and the government response is to deploy portable reverse osmosis units to produce desalinated water for basic water needs. This process is initiated through an Initial Situation Overview form by the focal points of the National Disasters Management Office (NDMO), which are based in the outer islands. Then, the Water Sanitation and Hygiene (WASH) cluster[1] is activated to undertake an assessment and analysis to confirm the drought conditions and provide recommendations to NDMO, which is responsible for coordinating the national disaster committee, and any subsequent declaration of drought and response.

2.4 Geology and groundwater occurrence

Atolls are geologic structures derived from basaltic volcanoes that have subsided. 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 composed of unconsolidated and well-sorted coral sand and gravel; 2) lower sediment unit 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 formed during subaerial exposure and recrystallisation 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 5 m and 25 m.

Fresh groundwater occurs in an atoll as a thin lens, buoyantly supported by dense underlying saline water. A freshwater lens is formed within the unconsolidated sediments due to suitable hydraulic conditions. On wider islands (> 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 that 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,

[1] The WASH cluster consists of the following members: RMI Environmental Protection Agency, Majuro Water and Sewer Company, International Organization of Migration, National Disaster Management Office, and the International Federation of Red Cross.

hydraulic conductivity (K) of the upper sediment units, depth to the Thurber Discontinuity, and the presence or absence of a reef flat plate (Bailey and Jenson 2012). A zone of transitional salinity typically exists between the infiltrated rainwater and the underlying saltwater. This zone is formed by the mixing of the two water types, which is promoted by tidal forces; the thickness of this transitional zone largely depends on the hydraulic properties of the aquifer sediments.

The hydraulic properties of freshwater lens aquifers strongly depend on the island's position with respect to the prevailing winds. Freshwater lens aquifers tend to acquire a coarse sediment structure on islands that are in the direct path of the prevailing winds and their associated high-energy waves. In contrast, aquifers on the partially protected leeward side of atolls tend to acquire a finer sediment structure. Considering that the prevailing direction of the tradewinds in the Marshall Islands is from the northeast, it is expected that both Wotje and Wormej do not offer ideal hydraulic conditions for the development of thick freshwater lenses.

2.5 Previous investigations

Extensive coastal aquifer assessment and development work in the Marshall Islands has been done since the 1980s in response to the vulnerability of limited freshwater resources, increasing drinking water demand, 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 focused on the water resources assessment of 10 atolls, including Wotje (Goodwin et al. 2000). This work aimed at: 1) evaluating the condition of existing water supply infrastructure and facilities and identifying the necessary improvement works necessary; and 2) assessing groundwater resources in terms of location and thickness to support water supply needs. The results for Wotje and Wormej islands are presented in Table 4.

Table 4. Summary of survey results for Wotje and Wormej islands.

Island	Groundwater and rainwater catchment information				Groundwater potential				
	No. of houses	No. of household catchments	No. of wells	Percentage wells with freshwater (%)	Island area (km^2)	Lens area (km^2)	Maximum lens thickness (m)	Safe yield under average rainfall (m^3/day)	Safe yield under drought (m^3/day)
Wotje	64	37	5 6	90	2.76	1.71	2.56	2068.34	541.88
Wormej	17	3	1 5	50	0.97	0.32	2.62	387.22	101.46

Source: Goodwin et al. 2000

The 2007 hot spot analysis, undertaken by RMI's Environmental Protection Authority, identified and evaluated 'hot spot areas' of national, regional and global significance within RMI, and where conditions adversely affect human health, threaten ecosystem functioning, reduce biodiversity and/or compromise resources and amenities in a manner that requires priority management attention (Graham 2007). Two main hot spot areas identified were: 1) education on water and sanitation, highlighting the poor overall awareness and education levels leading to poor water and wastewater management and health problems; and 2) 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 this project: strengthening community-based governance through the inclusive engagement of communities, and focusing on awareness and information exchange. This in turn is expected to improve understanding of development and use of fresh 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 the geological medium, hydraulic permeability, electrical conductivity 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 offering a high horizontal and vertical data resolution (Darlin 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 depths up to 30 m. The orientation of the survey profiles and surveyed distance was guided by the review of satellite photos and existing shallow wells so as to adequately investigate the groundwater potential of shallow coastal sediments.

Table 5 illustrates the different geological materials that may be encountered on Wotje and the corresponding resistivity range that is likely to be measured.

Table 5. Typical resistivity ranges for different sediment types.

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

Source: Dale 1986; Greggio et al. 2018

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 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 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 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, thus contributing 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 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.

3.3 Selection of ERT survey locations

Considering the absence of monitoring boreholes on Wotje that would have allowed for the in situ verification of the recorded resistivity results, a scoping survey line was conducted in Laura, Majuro Atoll (Fig. A1.5). The survey line was conducted along monitoring wells 5 and 6, in which groundwater salinity could be measured at various depths. This allowed calibrating the recorded resistivity results at the borehole location with real groundwater salinity measurements. As mentioned earlier, the recorded resistivity value is a combination of pore-water salinity and matrix properties. Extrapolating the calibrated resistivity values in Laura to Wotje is done by assuming the same aquifer properties for the two islands, which introduces a certain degree of uncertainty.

As Laura is situated on the leeward side of Majuro Atoll, it is expected that the freshwater lens aquifer has acquired a finer sediment structure, as compared to the aquifers existing in Wotje and Wormej. The lower permeability in Laura, therefore, is expected to contribute to decreasing the overall recorded resistivity, possibly resulting in overestimation of the freshwater thickness in Wotje when using the same 'recorded resistivity to groundwater salinity' ratio. Nevertheless, this calibration exercise was considered suitable for obtaining a general guideline for the vertical delineation of the freshwater lens along the survey lines conducted on Wotje and Wormej.

Table 6. Summary of survey lines.

Survey line	Distance (m)	Electrode spacing (m)	Start point	End point
Laura-01	240	2	7°8'54.23"N 171°1'56.58"E	7°8'53.99"N 171°2'2.88"E
Wot-01	520	2	9°27'41.69"N 170°14'0.17"E	9°27'49.69"N 170°14'14.82"E
Wot-02	240	2	9°26'47.31"N 170°14'13.11"E	9°26'45.49"N 170°14'21.96"E
Wot-03	320	2	9°27'8.50"N 170°14'13.37"E	9°27'9.84"N 170°14'23.65"E
Wot-04	560	2	9°27'28.29"N 170°14'13.75"E	9°27'37.90"N 170°14'28.38"E
Wot-05	200	2	9°27'10.11"N 170°14'25.96"E	9°27'15.26"N 170°14'29.95"E
Wor-01	480	2	9°33'2.99"N 170°9'2.64"E	9°33'16.86"N 170°9'9.85"E
Wor-02	400	2	9°33'1.54"N 170°8'56.74"E	9°33'13.60"N 170°8'56.88"E

3.4 Survey of private wells

A detailed survey was undertaken of all private wells on Wotje and Wormej. GPS locations and key information from wells was collected to create a database for planning and monitoring purposes. Information captured included well construction and condition, groundwater levels and groundwater quality (electrical conductivity and coliform bacteria). Additionally, potential sources of pollution for each well were captured to complement the results of the bacteriological tests. Electrical conductivity was measured using a TPS logger (WP Series) while total coliform bacteria and *E. coli* were estimated for a representative number of wells using 3M™ Petrifilm™ E. coli/coliform count plates.

Groundwater was monitored through the entire study period by installing automatic loggers (Eijkelkamp divers) at a number of representative private wells, allowing for continuous electrical conductivitiy (EC) and water level measurements during the study period. Two loggers were installed on Wotje and two on Wormej. The loggers were suspended on stainless steel wire at a depth that ensured they were submerged below the water table at all times. A barometric logger was installed to compensate for barometric influences. The loggers were set up to record data every six minutes. Manual water level and EC readings were taken at the beginning and at the end of the monitoring period in order to validate the readings recorded by the loggers. Also, a logger was installed on the seabed by the wharf on Wotje (on the lagoon side) to measure the time and amplitude of sea tides to allow the estimation of tidal damping and tidal lag through the aquifer material.

Groundwater levels and, in certain situations, groundwater salinity are affected by sea tides. Generally, sea tides induce fluctuations of the groundwater table. These tidal effects decay inland exponentially and diminish over a certain distance, depending on the amplitude of a given sea tide and on the aquifer's properties (hydraulic conductivity and effective porosity) (Li et al. 1999). The tidal effect at a specific location also decays upward as the distance to the transition zone increases. Tidal effects can, thus, also cause some fluctuations in groundwater salinity, particularly at close distance to the freshwater–saltwater interface. During the well survey, groundwater levels and salinity were recorded at different moments in time because they were partly influenced by the tides. It is not an easy task to normalize groundwater level data against tidal influence, considering the horizontal and vertical propagation of the tidal signal. Consequently, it is not recommended to use measured hydraulic heads to estimate groundwater flow patterns. It is, however, strongly recommended to take note of the exact time the measurements were obtained in order to be able to, at a later stage, compare with tide tables and draw conclusions on the response of different wells to different tidal conditions.

4. Results and discussion

4.1 Geophysical results and interpretation

The survey line performed in Laura, allowed the calibration of the obtained resistivity results with real salinity observations from the monitoring bore existing along the profile. The tested groundwater revealed an EC of 0.785 mS/cm in bore 6-33 (10.0 m), 2.433 mS/cm in bore 6-43 (13.1 m) and 14.900 mS/cm in bore 6-48 (14.6 m), suggesting the presence of a relatively sharp interface between fresh groundwater and seawater. According to the inverted resistivity profile (Fig. A2.1), modeled resistivities for these depths were 40–60 Ohm.m, 8–10 Ohm.m and 2–4 Ohm.m, respectively. In interpreting the resistivity profiles and freshwater lens extent, an EC of 2.5 mS/cm was chosen as the higher limit for freshwater occurrence, corresponding to a modeled resistivity of 8–10 Ohm.m for the specific matrix/sediment properties. It should be noted, however, that 2.5 mS/cm is a relatively high limit while a recommended aesthetic guideline for drinking water purposes would be in the order of 1.5 mS/cm.

The thickest part of the freshwater lens in Wotje was found along survey line wot-04 (Fig. A2.5), which crossed the middle part of the island (Fig. 3). Assuming that Wotje has similar aquifer and sediment properties as Laura, the freshwater body along this profile gradually acquires a thickness of up to 16 m at around 270 m distance. Survey line wot-01 (Fig. A2.2) suggests the presence of a thinner freshwater body, which attains a maximum thickness of 9 m while survey line wot-05 (Fig. A2.6) suggests the presence of a relatively homogeneous freshwater body with a 9–10 m thickness. Survey line wot-03 (Fig. A2.4) indicates the presence of a high-resistivity feature at 240–280 m distance along the profile, which may be causing some localized thickening of the freshwater lens. Finally, survey line wot-02 (Fig. A2.3) reveals the presence of a very thin freshwater body that just barely attains a thickness of 4–5 m towards the middle part of the profile.

These unusually high resistivity readings, like the one observed along survey line wot-03, are hard to interpret and, generally, they are related to instrument malfunction such as a possible electrode disconnection during the survey. High resistivity readings could also be related to an anthropogenic cause, including a buried wire, metal, concrete, buried electricity lines, an old water cistern, or an unusual geological feature, such as a limestone block within the expected sands. Additional literature searches of old available historical WWII records revealed the presence of an underground shelter structure at close vicinity (~180 m southeast of the high-resistivity feature), which was targeted for bombing by the United States. However, nothing was mapped at the specific location and there is no obvious surface expression of the anomaly to indicate a possible cause. Further investigation would be required with additional geophysical techniques (including ground penetrating radar, magnetometer, and additional resistivity survey lines) to better assess the possible cause of this high-resistivity feature.

In Wormej, the two survey lines (Figs. A2.7 and A2.8) revealed the presence of a thinner freshwater lens compared to Wotje, not exceeding 4–5 m thickness and mainly present along survey line wor-01 (Fig. 4). Also, very high resistivities (> 500 Ohm.m) were recorded in the upper layer suggesting probably the coarser nature of the sediments, responsible for the thinner nature of the freshwater lens due to inadequate capacity of the sediments to withhold water. A coarser sediment structure is to be expected considering that Wormej is even more exposed, compared to Wotje, to trade winds and associated high-energy waves whose prevailing direction is from the northeast.

The proposed isolines of freshwater lens thickness presented in Figures 3 and 4 are very approximate, especially as the distance from the survey lines increases; therefore, they should be used as a guide.

The edge of the 3-m isoline, for example, is an estimate that includes salinity information from private wells.

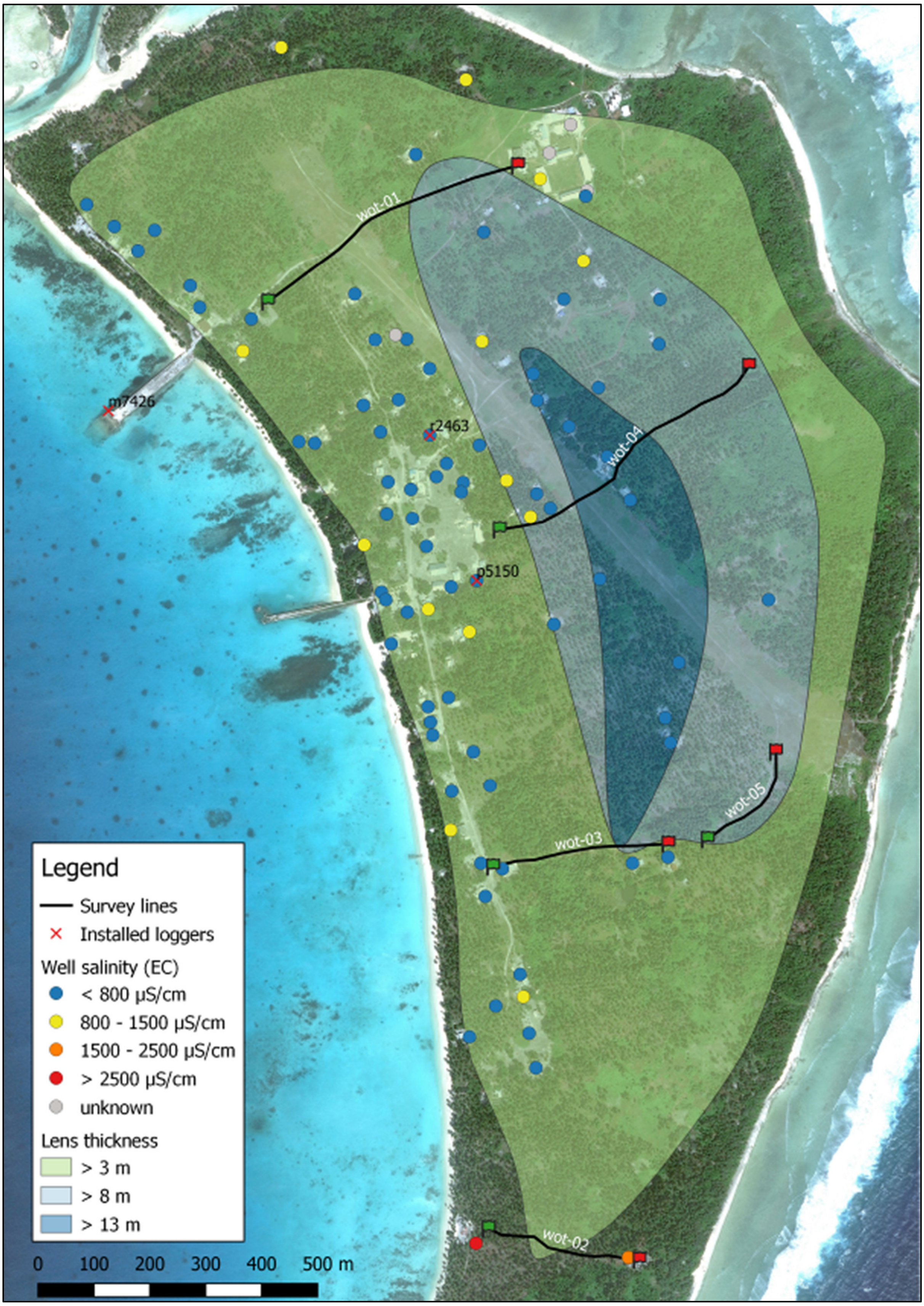

Figure 3. Freshwater lens thickness contours and salinity levels (EC) in private wells on Wotje.

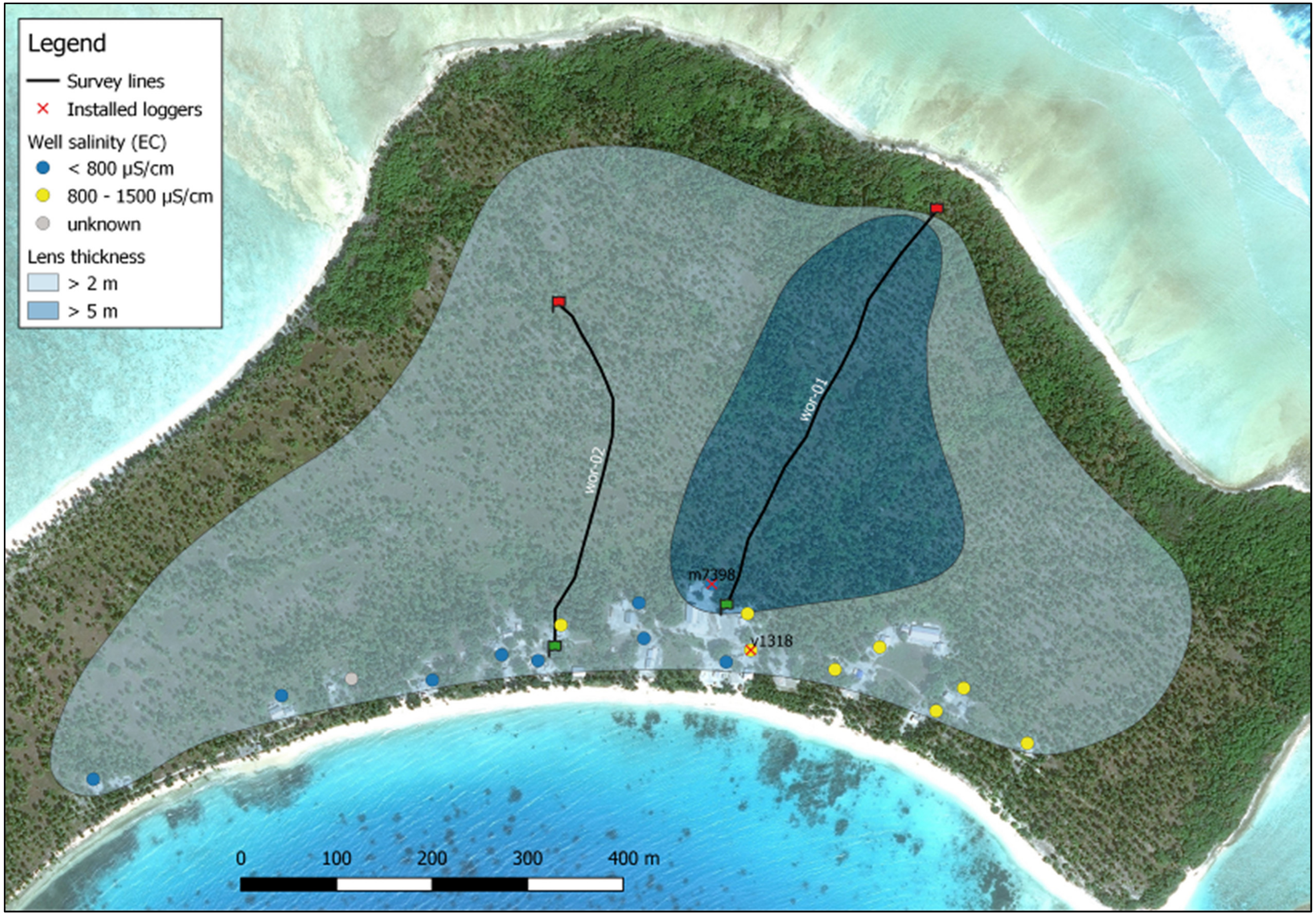

Figure 4: Freshwater lens thickness contours and salinity levels (EC) in private wells on Wormej.

4.2 External influences on groundwater

By studying groundwater level fluctuations in four private wells – as recorded by the installed loggers and compared with the seawater level fluctuations (Fig. A3) – it was possible to approximate the percentage of the tidal signal that is propagated in these four wells (Table 7). As mentioned in Section 3 of this report, the signal is propagated both horizontally and vertically, and comparing two or more wells is not straightforward. Assuming homogeneous aquifer conditions (hydraulic conductivity and effective porosity) within each island, and assuming that the two logged wells at each island are at the same depth (which is partly true), it was possible to demonstrate the exponential decay of the tidal signal as it propagates inland (Fig. 5).

When comparing the signal propagation decay between the two islands it is apparent that the aquifer on Wormej dampens the signal more abruptly than the one on Wotje. Also, a greater tidal lag was observed on Wormej (Fig. A3) despite the shorter distance of the two wells to the shore. This suggests that the permeability of the sediments on Wormej is lower. This conclusion, however, should be treated with caution as errors may have been introduced related to well construction, and assumptions related to aquifer homogeneity.

Table 7. Percentage of tidal signal propagated in four private wells.

Logger S/N	Island	Distance to shore (m)	Well total depth (m)	Tidal signal %
m7426	Wotje (sea)	0	-	100
p5150	Wotje	220	1.45	10.2
r2463	Wotje	260	1.77	8.3
m7398	Wormej	130	2.9	4.0
v1318	Wormej	65	2.9	14.1

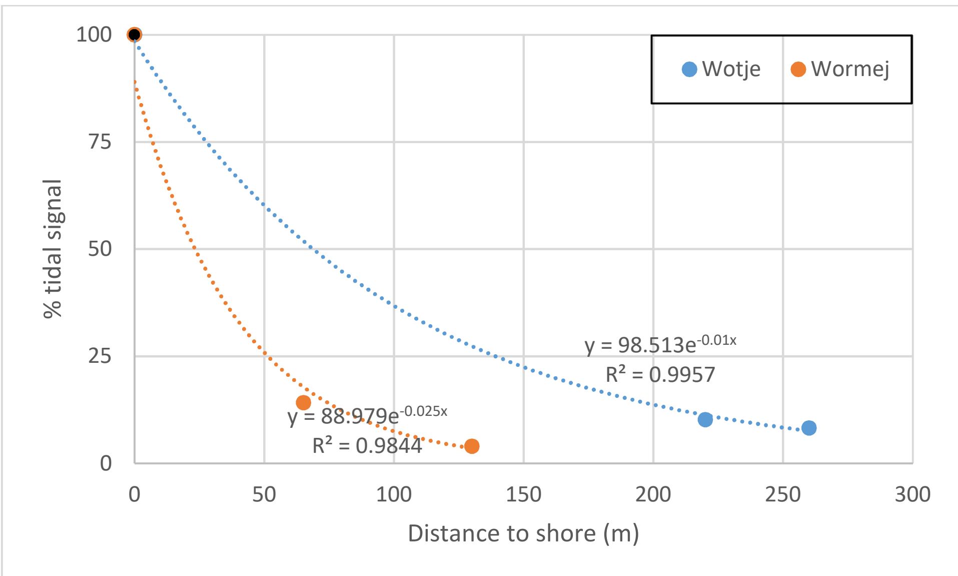

Figure 5. Tidal signal propagation on Wotje and Wormej.

4.3 Groundwater quality

In total, 107 private wells were tested for groundwater salinity, which was indirectly inferred through electrical conductivity (EC): 79 wells (74%) had an EC of less than 0.8 mS/cm, and 21 wells (20%) had an EC between 0.8 mS/cm and 1.5 mS/cm. Only two wells showed an EC higher than 1.5 mS/cm and both were located outside of the freshwater lens, based on the resistivity profiles (Fig. 3).

Out of the 22 private wells that were sampled on the two islands and analysed for coliform bacteria, 11 (50%) were identified as having less than 300 counts per mL of water while another 11 (50%) were highlighted as having too many to count. Out of these samples, 6 (29%) were devoid of *Escherichia coli* (*E. coli*), 11 (50%) had less than 10 *E. coli* counts/ml and 5 (21%) had more than 10 *E. coli* counts/ml. Boiling groundwater prior to use is highly recommended for all households on Wotje and Wormej, given the presence of total coliforms and *E. coli* bacteria, to prevent any issues related to the ingestion of contaminated water.

Groundwater quality in terms of salinity is suitable in all, but two, private wells sampled during this study. Groundwater with an EC between 0.8 mS/cm and 1.5 mS/cm is often the range in which many people may detect some 'saltiness' in taste. Salinity is an aesthetic parameter of palatability and is not considered a health risk by the World Health Organization (WHO 1996).

4.4 Groundwater resource development

Two freshwater lenses were identified and delineated on both Wotje and Wormej. Wotje, with its larger island size indicates a freshwater lens thickness of 10 m, which is suitable for groundwater development, while Wormej is identified as having a thinner freshwater lens, generally < 5 m and of limited extent, thus restricting the potential for groundwater development.

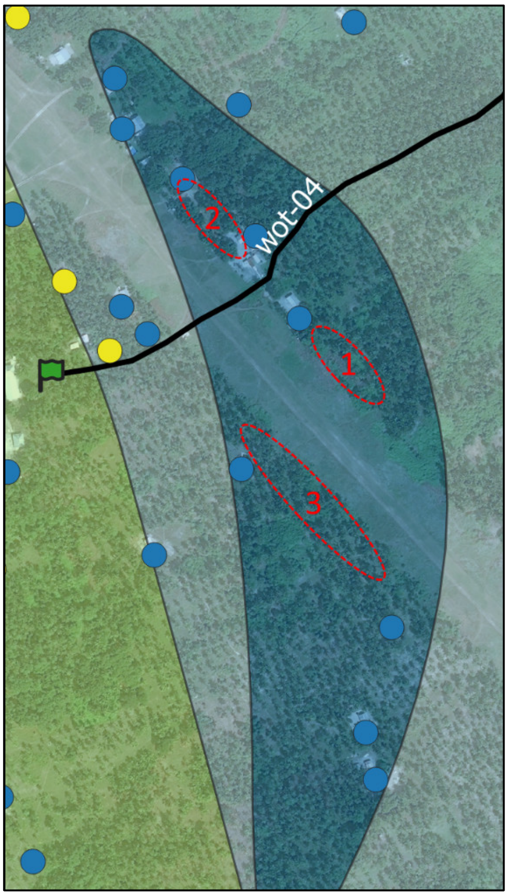

Figure 6. Proposed locations for gallery construction in Wotje.

Development of the freshwater lens on Wotje would be best achieved through the use of horizontal wells or galleries, which are located just below the water table and used to skim the freshest water. Horizontal well construction minimizes the impact of pumping, which can result in pumping-induced upconing of the saline water, or salinization of the groundwater

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 lead to a centralized closed pumping well. The horizontal wells would 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, then 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 areas where thick and unweathered reef rock is encountered, it is expected that the recharge rate may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery.

In Wotje, priority should be given to the central area where the lens has a substantial thickness of more 10 m (Fig. 3), thus allowing for the best possible production capacity and longer resilience to droughts. It is recommended to install the gallery as close as possible to survey line wot-04 to benefit from the higher certainty of the lens thickness estimates. Three suitable locations are proposed in Figure 7, with number 1 considered the most ideal due to its proximity to survey line wot-04 and the absence of households. Considering the possibility that in the future, the airport runway will be asphalted, galleries installed on either side of the runway will also benefit from the enhanced localized recharge from rainwater accumulating from and flowing off of the runway.

On Wormej, the groundwater potential and thickness of the freshwater lens is generally less than 5 m thick. A horizontal gallery for community drought proofing purposes could be located along survey line wor-01, preferably past the 90-m mark along the survey profile. The production capacity, however, is expected to be significantly lower than the one on Wotje in order to avoid the production of higher salinity water and potential salinization of the lens.

4.5 Water resources protection and management

The integrated and coordinated development and management of freshwater resources on Wotje will be key to the community's long-term health and water security. Thus, it is recommended to:

1. Consider the installation of a communal groundwater supply and horizontal gallery, based on an assessment of current water supplies and community needs under normal and extreme climatic conditions.
2. Instal flow meters and salinity meters, in future galleries and reservoirs to allow the assessment of groundwater abstraction, water usage and leakage.
3. Undertake regular rainfall analyses from the existing station to determine the temporal and spatial variability of rainfall, and to capture the periodical island-wide groundwater recharge. This will require the strengthening of links between the island government and the national weather office on the compilation, archiving and sharing of rainfall data and climate forecast.
4. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management during prolonged dry periods.
5. Develop a drought awareness and drought action plan that considers pragmatic management responses under different climatic conditions and triggers.
6. Establish appropriate water restriction or rationing actions during extreme climatic conditions across all communal water supply sources (e.g. rainwater, groundwater and desalinaited water).
7. Consider restricting land-use activities in the area of the thickest part of the freshwater lens to minimize potential contamination of the groundwater and maintain water quality suitable for potable purposes.

In view of the sensitive and fragile nature of these groundwater systems, the installation of appropriate technologies and regular routine monitoring of groundwater should be adopted to ensure the long-term availability of fresh groundwater. Appropriate protection measures against improper land-use activities is required to safeguard groundwater bodies for water supply purpose.

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Annex 1 – Maps

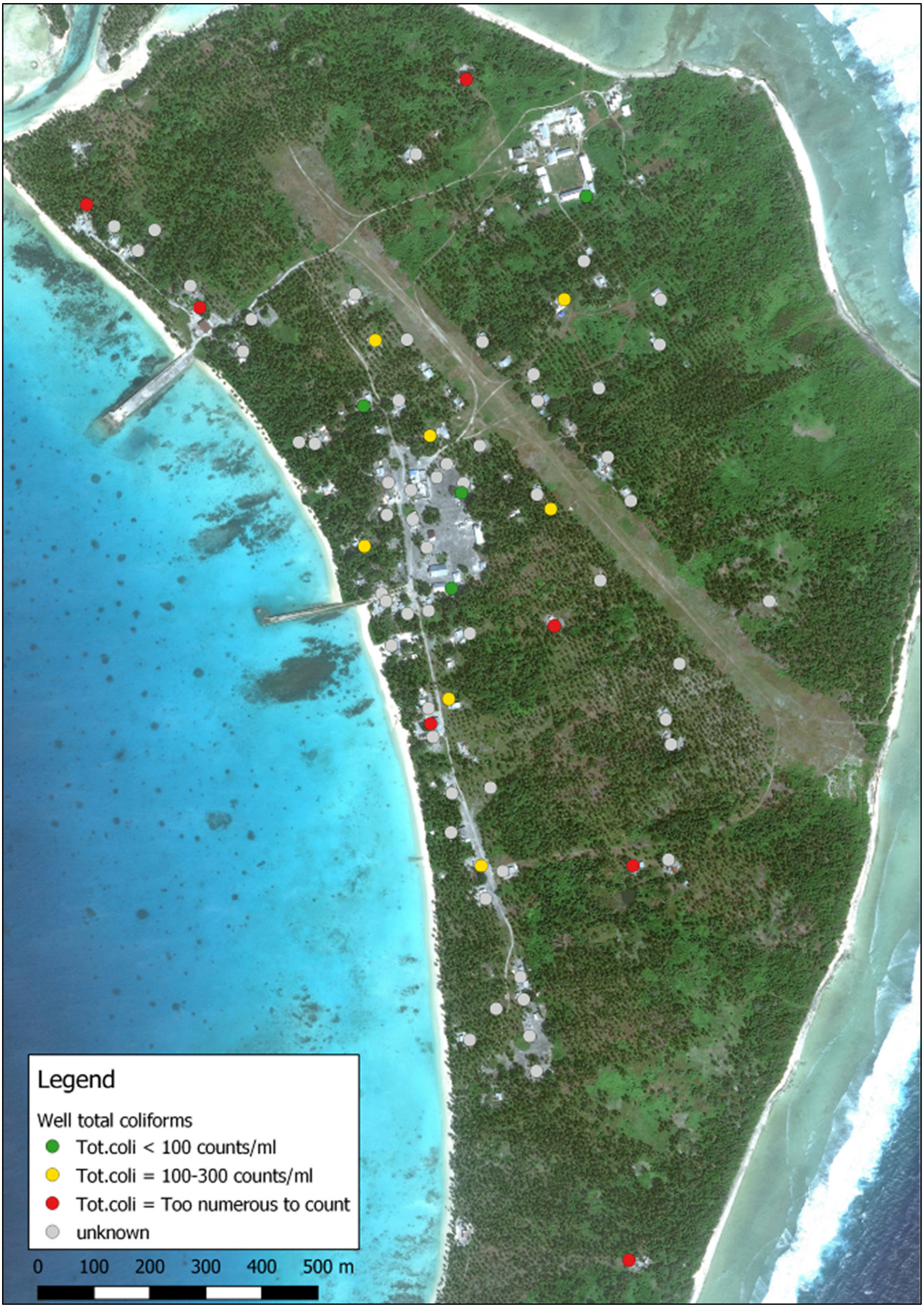

Figure A1.1. Total coliform levels in private wells on Wotje Island.

Figure A1.2. *Escherichia coli* levels in private wells on Wotje Island.

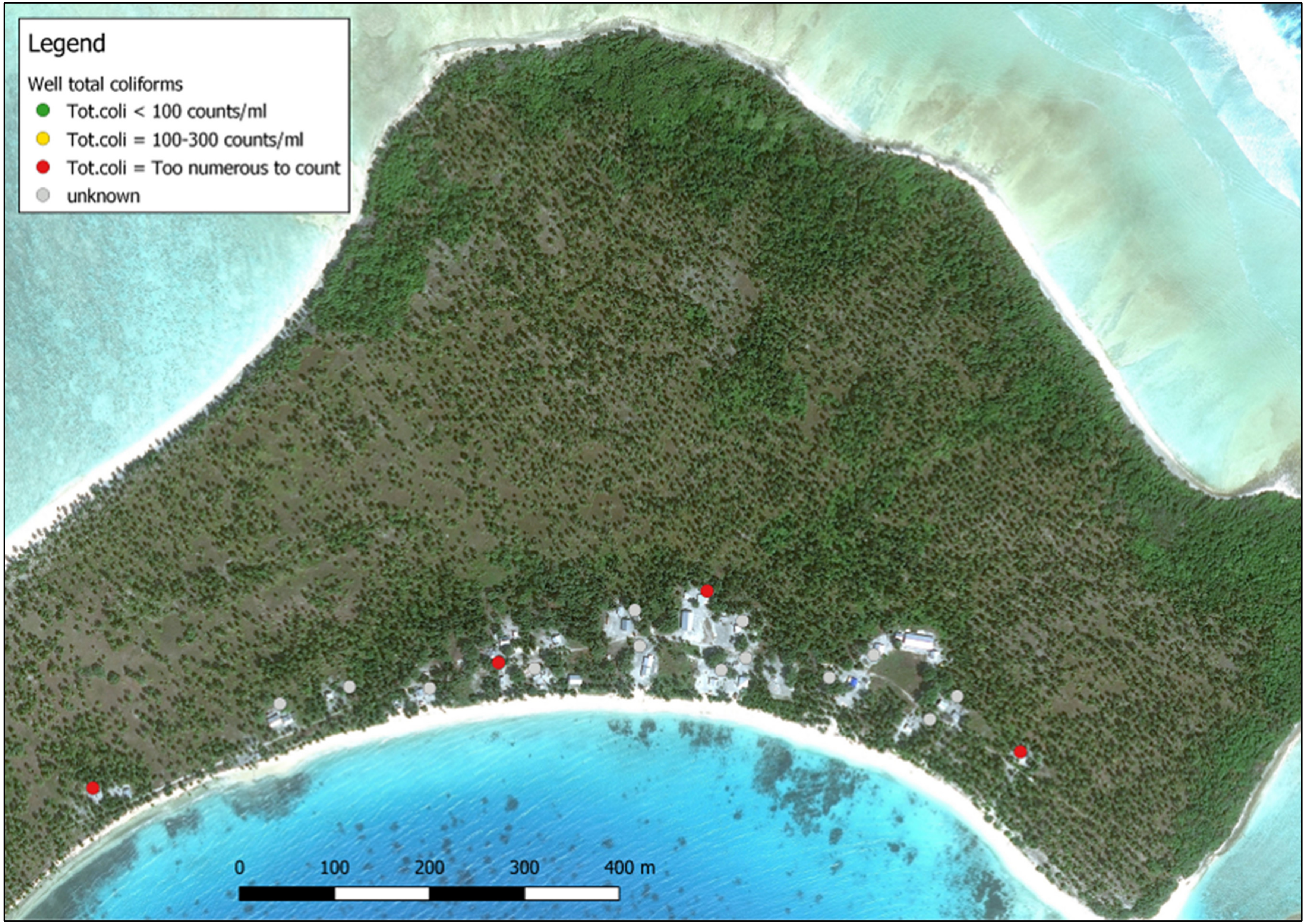

Figure A1.3. Total coliform levels in private wells on Wormej Island.

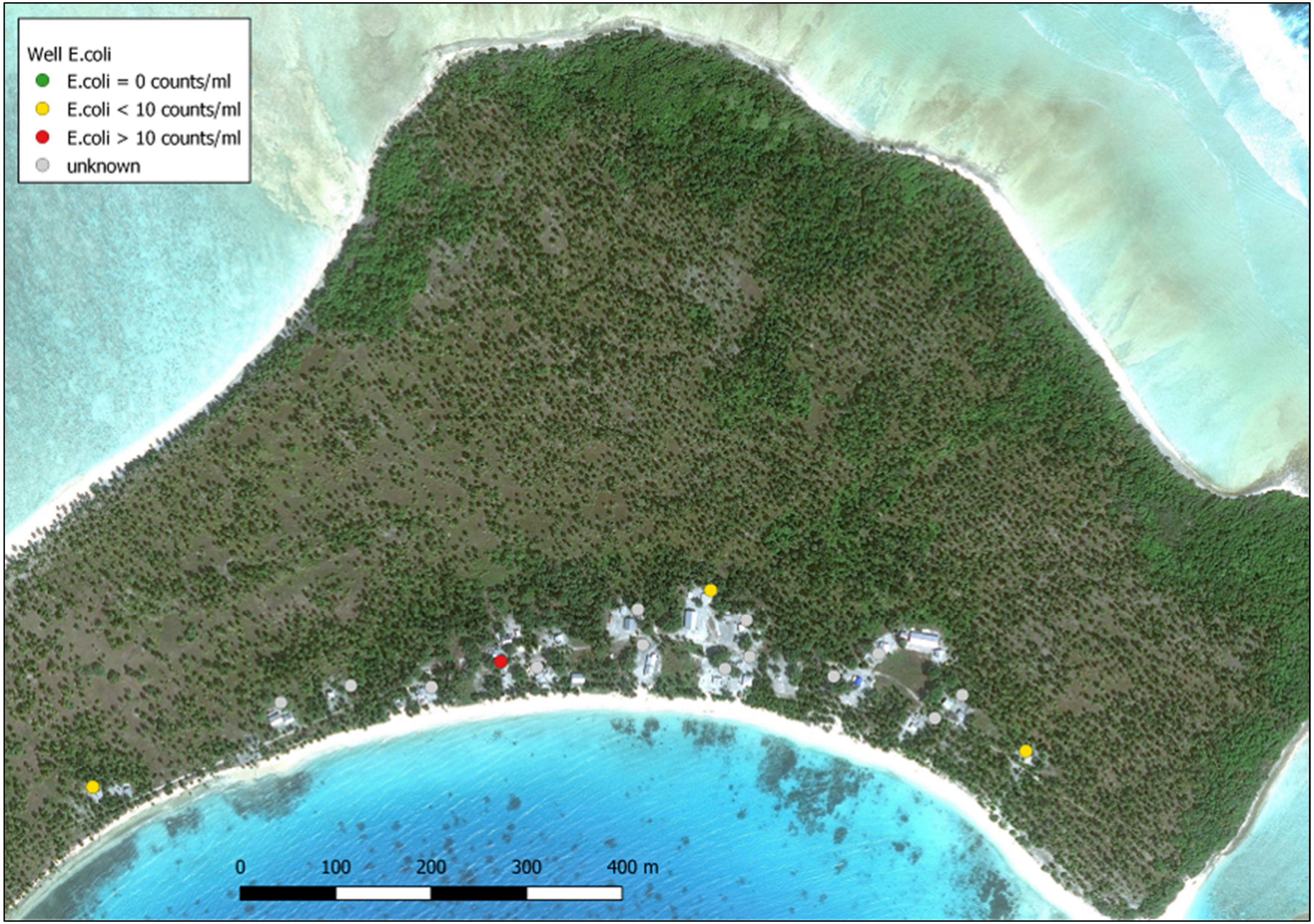

Figure A1.4. *Escherichia coli* levels in private wells on Wormej Island.

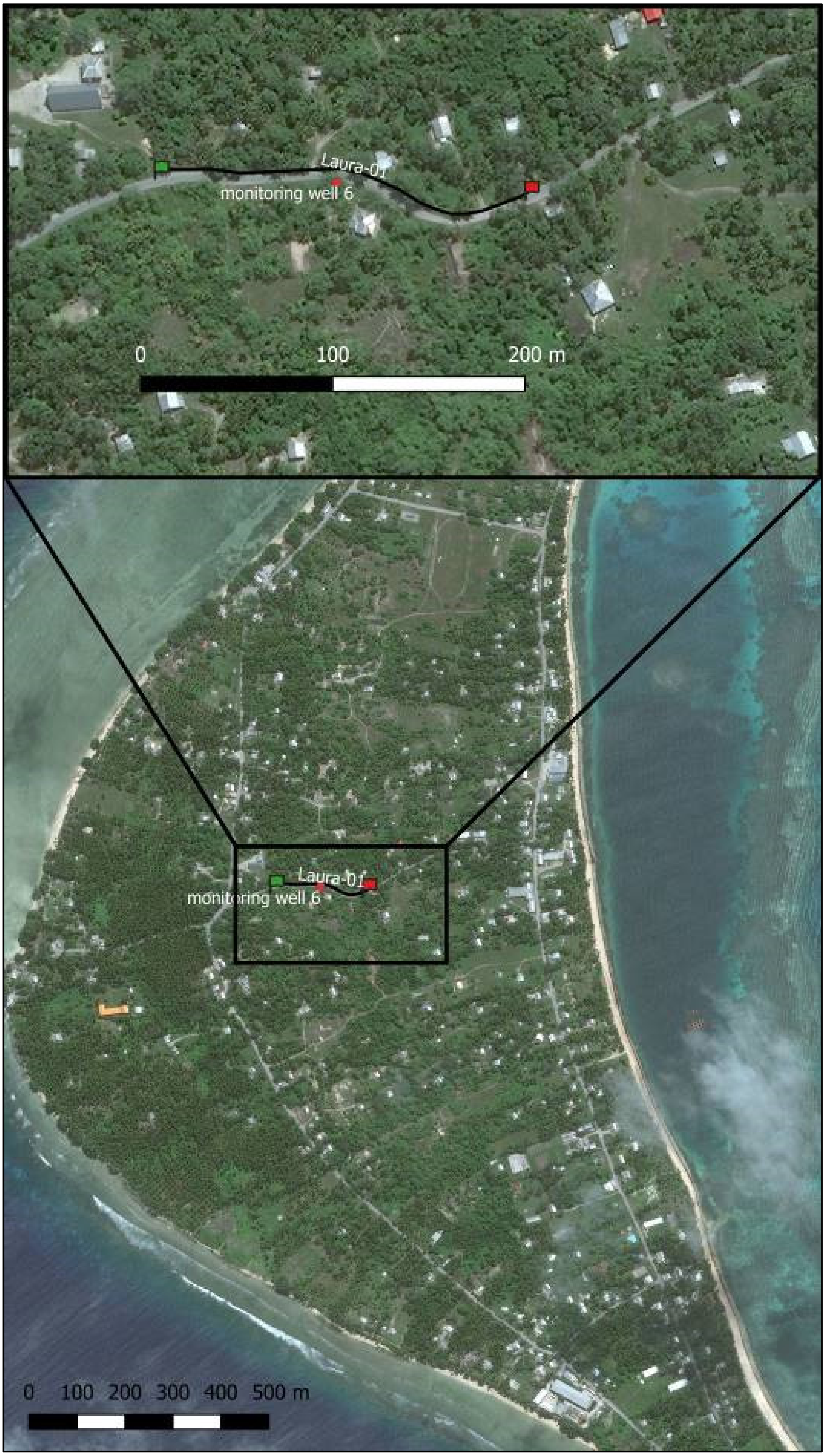

Figure A1.5. Laura, Majuro depicting the location of the test survey line along monitoring well 6.

Annex 2 – Inverted resistivity profiles

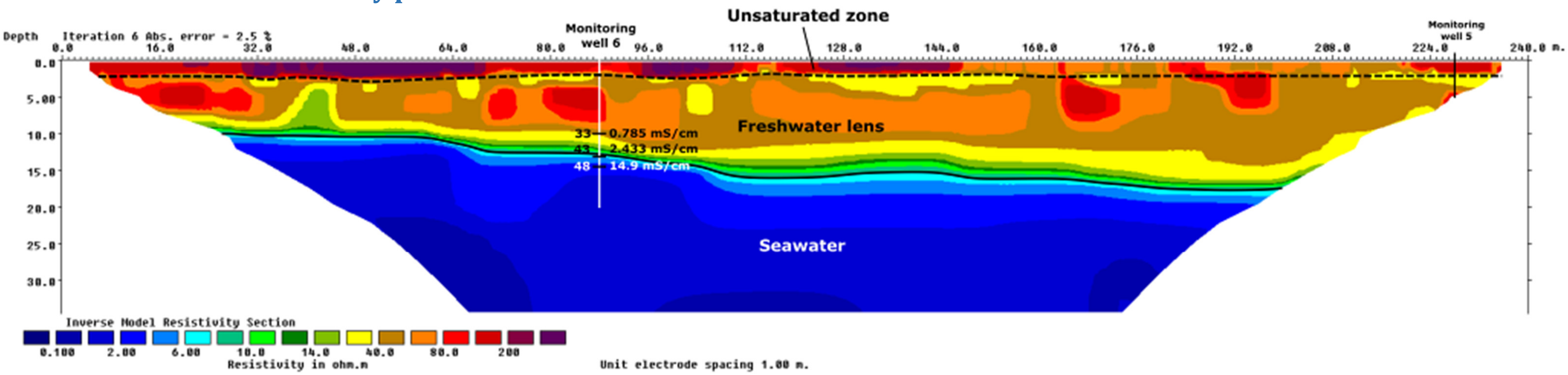

Figure A2.1. Resistivity profile Laura-01 (Majuro Atoll).

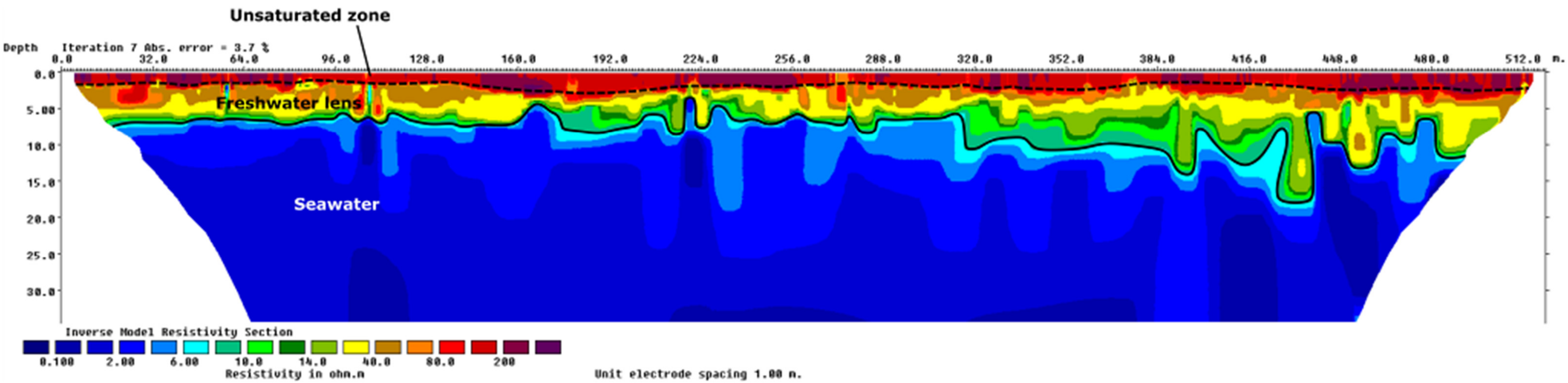

Figure A2.2. Resistivity profile Wot-01 (Wotje).

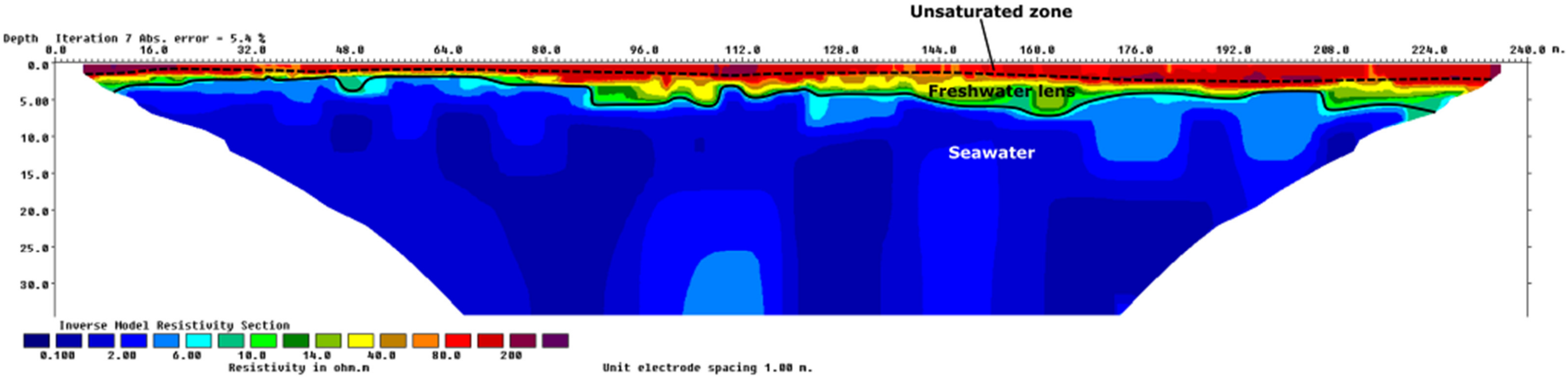

Figure A2.3. Resistivity profile Wot-02 (Wotje).

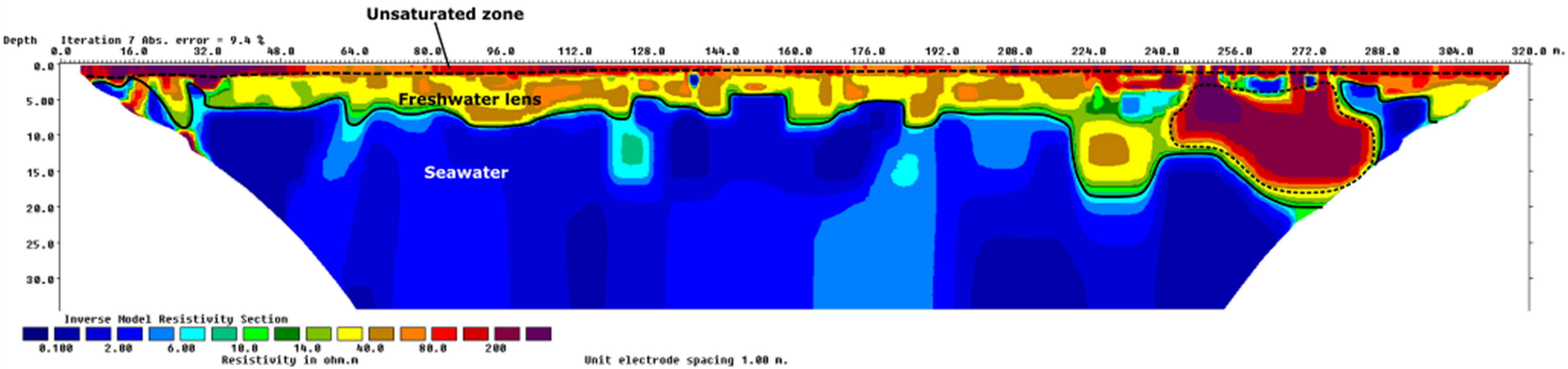

Figure A2.4. Resistivity profile Wot-03 (Wotje).

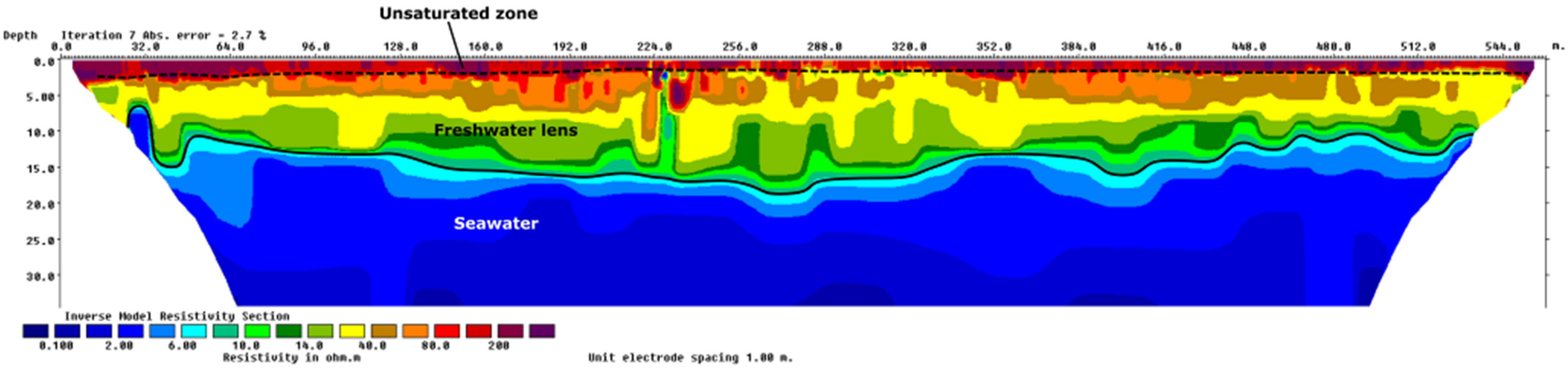

Figure A2.5. Resistivity profile Wot-04 (Wotje).

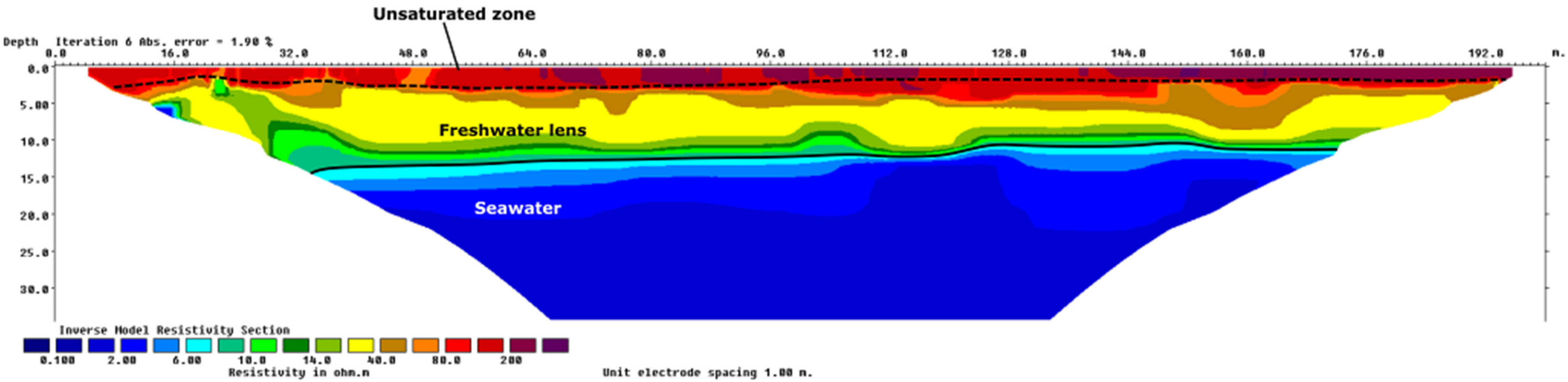

Figure A2.6. Resistivity profile Wot-05 (Wotje).

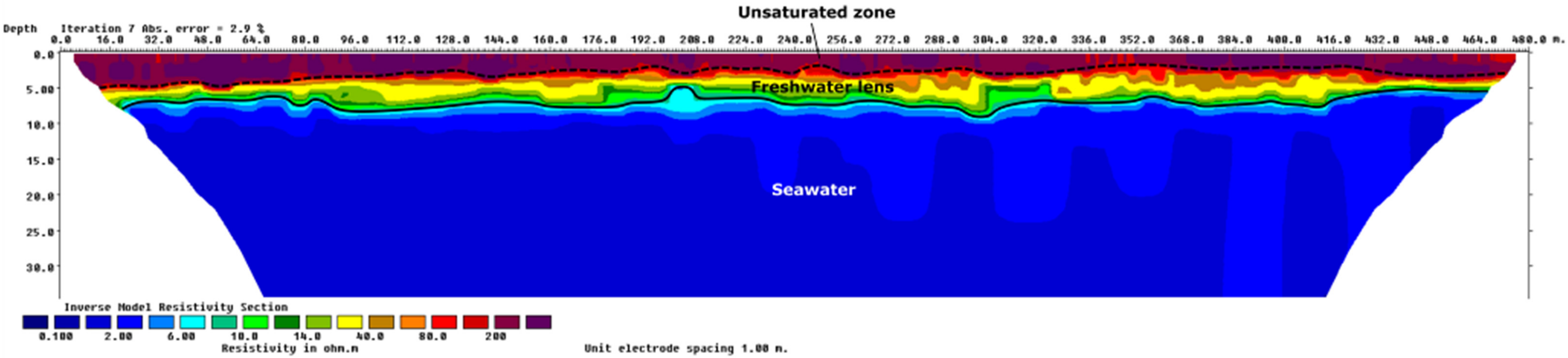

Figure A2.7. Resistivity profile Wor-01 (Wormej).

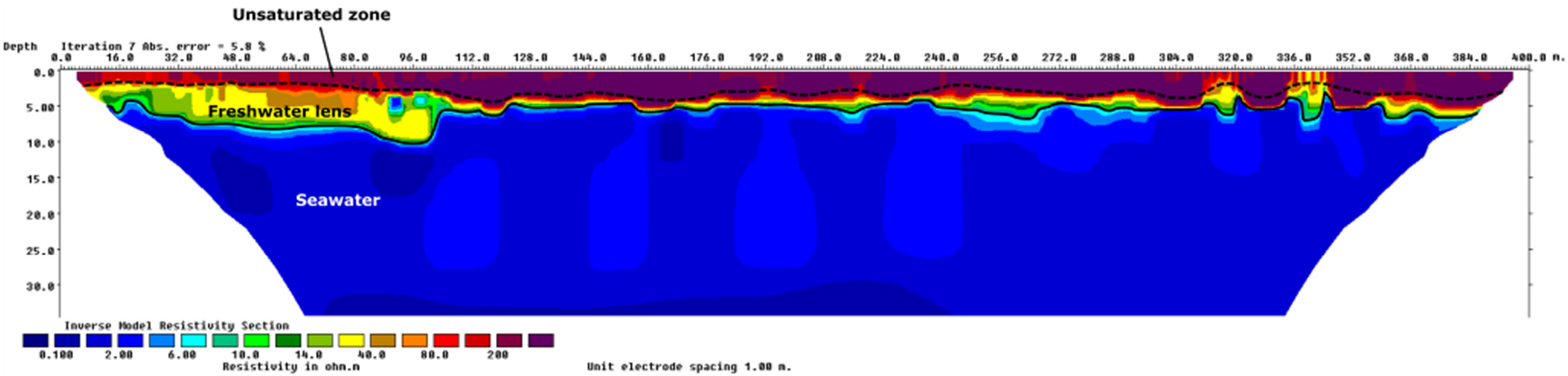

Figure A2.8. Resistivity profile Wor-02 (Wormej).

Annex 3 – Groundwater logging data

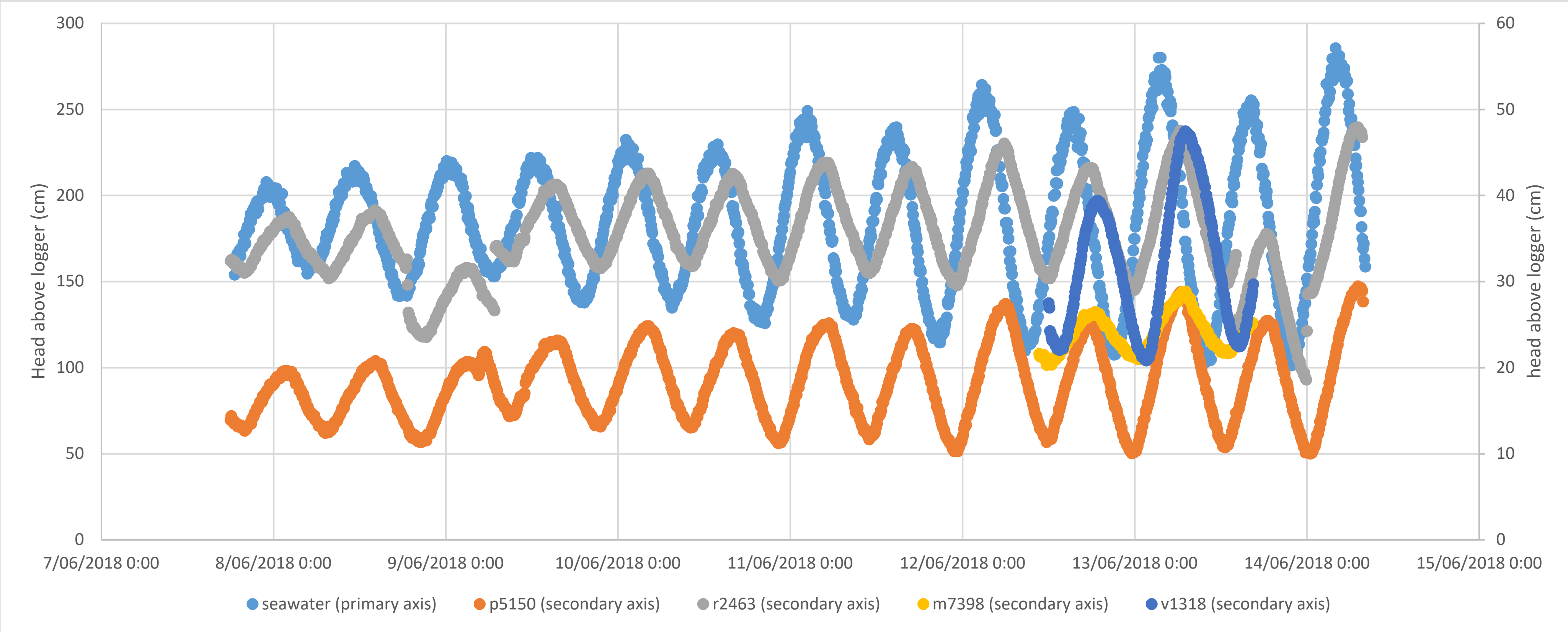

Figure A3. Tidal effect on the groundwater level as recorded in four private wells on Wotje and Wormej.

Annex 4 – Private well survey

WellID	Well Coordinates	Island	Well Type	Well Owner	Casing Type	Well Cover	Well Cover Condition	Fencing Condition	Well Apron Size	Well Apron Material	Abstraction Type	Pump Status	Use of Water	People Usage	Distance to nearest contamination source	Contamination source	Diameter Inner (m)	Parapet Height (m)	Depth to Water Table (m)	Total Depth (m)	EC Top (µS/cm)	EC Base (µS/cm)	Total Coliform Bacteria	E.coli Bacteria	Date	Time	Comments
W00	(170.23682159279232451 9.45923663564946615)	Wotje	Private	Joe Mea	Other	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	6	15	Rubbish	0.54	0.48	1.83	2.63	0.664	0.671			8/06/2018	02:15:35pm	Well is use for washing, cooking water quality is fresh. note: photo numbers 2650 2652
W01	(170.2360136298557336 9.45940111474155287)	Wotje	Public	Wotje post and bank	Cement block	Covered	Good	None	None	None	Diesel/Electric Pump	Not Working	Washing/Gardening	0	4	Latrine/Septic	0.73	0.4	1.64	2.17	0.425	0.439	140	1	7/06/2018	16:22:05	water quality fresh from well, installed diver r2463
W02	(170.23628675911257346 9.4589408770769694)	Wotje	Private	Vision Hax	Cement block	Covered	Good	None	0.3 - 0.8 m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	5	20	Latrine/Septic	0.64	0.22	1.47	1.9	0.414	0.407			8/06/2018	02:26:53pm	Fresh water but only use for washing. photo number:2653 2655
W03a	(170.23655807591259759 9.4586281597589803)	Wotje	Private	Atin Arti	Other	None	None	None	0.3 - 0.8 m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	4	15	Rubbish	0.53	0.27	1.53	1.75	0.241	0.241			8/06/2018	02:40:10pm	Water use for cooking, toilet and need well cover
W03b	(170.23677853298380569 9.45702811983193392)	Wotje	Private	patrick lanwi	Steel	Covered		None	None		Bucket/Tin		Washing/Gardening	0	20		0.58	0.59	1.61	2.04	0.506	0.506			7/06/2018	05:29:13pm	diver p5150
W04	(170.23652578217453879 9.45847330989894353)	Wotje	Private	Tatina Nijo	Other	Covered	Adequate	None	0.3 - 0.8 m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	7	20	Rubbish	0.54	0.04	0.46	1.82	0.305	0.317	3	0	8/06/2018	02:46:06pm	WQ 01 fromTatina well Photo number2660 2665
W05	(170.23612156127452977 9.45872484600475794)	Wotje	Private	Ransay Aiseia	Other	Covered		Adequate	0.3 - 0.8 m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	4	12	Latrine/Septic	0.54	0.31	1.55	2.02	0.375	0.375			8/06/2018	03:01:07pm	Fresh Water casting is a combination of drum concrete and bad rock photo numbers 2666 2670
W06	(170.23533379417295919 9.45863897245623697)	Wotje	Private	Donsay Emos	Other	Covered	Good	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	9	10	Latrine/Septic	0	0	0	0	0.388	0.388			8/06/2018	03:13:54pm	well is completely covered cannot measure dtwt and total depth Photo 2671 2673

W07	(170.23570567153728916 9.45851600137719117)	Wotje	Private	Melinda Tomeing	Cement block	Covered		None	0.3-0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	4	20	Rubbish	0.25	0.29	1.47	2.17	0.445	0.446			8/06/2018	03:22:53pm	fresh Water but use for toilet and washing photo number 2674 2679
W08	(170.23494551781675455 9.45760699541005856)	wotje	Private	Stany Tomeing	Other	Covered	Good	None	0.3-0.8m	None	Diesel/Electric Pump	Working	Toilet	4	10	Vegetation	0.67	0.09	1.15	1.68	0.836	0.836	220	2	8/06/2018	03:35:14pm	WQ02 from Stany well they also use for washing clothes photo numbers 2680-2683
W09	(170.235311581082982 9.45811551298516129)	Wotje	Private	Benjamin Bernard	Other	Partially Covered	Replace/repair	None	None	None	Bucket/Tin	None	Drinking/Cooking	4	5	Latrine/Septic	0.56	0.38	1.61	2.25	0.62	0.619			8/06/2018	03:49:59pm	fresh water needs improved cover photo 2684-
W10	(170.23573155465442142 9.45804136109022231)	wotje	Private	Benji Bernard	Cement block	Covered	Adequate	None	0.3-0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	9	10	Rubbish	0.59	0.05	1.16	1.82	0.336	0.332			8/06/2018	04:05:05pm	fresh water use for washing abd cooking only photo numbers 2688-2691
W11	(170.23596045266717169 9.45758457678186382)	wotje	Private	frezer Alvin	Other	None	None	None	0.3-0.8m	Coral rock	Bucket/Tin		Toilet	16	10	Rubbish	0.57	0.66	1.68	2.18	0.523	0.522			8/06/2018	04:13:45pm	photo numbers 2692-2696 Fresh water use for toilet snd shower
W12	(170.23522608813908619 9.4568376198734061)	wotje	Private	Jimmy Lani	Other		None	None	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	4	20	Rubbish	0.58	0.2	1.19	2.5	0.548	0.529			8/06/2018	04:22:41pm	fresh water use only for washing casting is a drum
W13	(170.23529790382553983 9.45671472863957874)	wotje	Private	Glyde Lakjohn	Other	None	None	None	0.3-0.8m	Cement	Bucket/Tin	None	Washing/Gardening	1	20	Rubbish	0.56	0.31	2.04	2.65	0.555	0.555			8/06/2018	04:28:36pm	photo number 2700-2703 well is located 10m from the graveyard
W14	(170.23564688762866126 9.45651266868736862)	wotje	Private	David Rufus	Other	None		None	0.3-0.8m	None	Bucket/Tin	None	Washing/Gardening	15	30	Rubbish	0.56	0.48	1.68	2.01	0.575	0.572			8/06/2018	04:34:43pm	casting drum photo 2704-2707
W15	(170.23598938241445921 9.45656042316596945)	wotje	Private	Johnny Luke	Cement block	None	None	None		Cement	Bucket/Tin	None	Washing/Gardening	8	8	Rubbish	0.59	0.04	1.27	1.73	0.937	0.951			8/06/2018	04:40:35pm	salty elavated salanuty
W16	(170.23636252964772098 9.45692511374623557)	wotje	Private	Standon Netwan	Cement block	Covered	Good	None	0.3-0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	10	10	Rubbish	0	0	0	0	0.477	0.477	40	0	8/06/2018	04:48:02pm	WQ3 from Standon well use for everything except for drinking well is conpletely cover can't measure
W17	(170.2366597417135381 9.4561925868779948)	wotje	Private	Melita Kamram	Coral rock	Covered	Adequate	None	0.3-0.8m	None	Diesel/Electric Pump	Working	Washing/Gardening	4	20	Rubbish	0.79	0.43	1.56	2.37	0.662	0.836			8/06/2018	04:57:08pm	well located 5m fron graveyard photo 2712-2715

W18	(170.23538520893376358 9.45599671819004861)	Wotje	Private	Beawuti Kamran	Other	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	8	0	Rubbish	0.38	0.49	2.27	2.71	0.638	0.634			8/06/2018	05:09:28pm	casing is roofing iron photo number 2716-2719 well close to coast
W19	(170.23598654991201329 9.45497299907407474)	wotje	Private	Helby Luke	Other	None	None	None	0.3-0.8m	None	Bucket/Tin	None	Washing/Gardening	7	20	Rubbish	0.59	0.14	1.35	1.76	0.521	0.521			8/06/2018	05:21:17pm	fresh water use for washing, shower photo numbers 2720-2724
W20	(170.23631730595110412 9.45512403127642287)	wotje	Private	Mellan Luke	Other	Covered	Good	None	0.3-0.8m	Cement	Bucket/Tin	None	Washing/Gardening	1	0	Rubbish	0.55	0.11	1.34	1.92	0.474	0.554	176	0	8/06/2018	05:28:06pm	WQ4 from mellan well casting is a drum photo numbers 2727-2733
W21	(170.23521136950662935 9.45945494490323746)	Wotje	Private	Veronica Lajar	Cement ring	Covered	Adequate	None	0.3-0.8m	Cement	Bucket/Tin	None	Washing/Gardening	6	10	Rubbish	0.58	0	1.3	1.6	0.579	0.589			9/06/2018	08:09:44am	well located inside home. photo 2734, 2737
W22	(170.23413986346605498 9.45927114907335742)	Wotje	Private	Emily Emos	Cement ring	Covered	Good	None	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	7	40	None	0.48	0.24	1.64	2.07	0.587	0.588			9/06/2018	08:18:48am	well is secure but no fence photo numbers 2738-2741
W23	(170.23388064493667571 9.4592955470726956)	wotje	Private	Anthony Jailar	Other	Covered	Adequate	None	0.3-0.8m	None	Bucket/Tin	None	Washing/Gardening	3	0	Rubbish	0.56	0.36	1.85	2.29	0.67	0.671			9/06/2018	08:25:15am	well is 40m from the coast photo numbers 2742-2847
W24	(170.23493153174965187 9.45988874331167651)	wotje	Private	PJ Jailar	Cement block	Partially Covered	Adequate	Good	0.3-0.8m	Coral rock	Bucket/Tin		Washing/Gardening	18	40	Rubbish	1.45	0.12	1.45	2.29	0.664	0.664	92	7	9/06/2018	08:33:59am	WQ5 from PJ Well use for drink during dry period 2748-2752
W25	(170.23550348208124205 9.45997966620749686)	wotje	Private	Obten Hax	Other	Partially Covered	Adequate	None	0.3-0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	6	15	Rubbish	0.52	0.12	1.71	2.35	0.526	0.748			9/06/2018	08:43:56am	also use for the toilet photo numbers 2753-2755
W26	(170.23601126849331422 9.46048517757475693)	wotje	Private	Jibaibe Boktok	Other	Partially Covered	Replace/repair	None	0.3-0.8m	Timber	Diesel/Electric Pump	Working	Washing/Gardening	3	10	Rubbish	0.6	0.3	1.83	2.19	0.517	0.515			9/06/2018	08:50:44am	casting is rusty drum photo numbers 2761-2764
W27	(170.23563805831096829 9.46096568689612738)	wotje	Private	Roland Luther	Steel	None	None	None	0.3-0.8m	None	Diesel/Electric Pump	Working	Washing/Gardening	3	10	Rubbish	0.57	0.15	1.05	1.84	0.659	0.654			9/06/2018	08:58:15am	rusty photo numbers 2771-2773
W28	(170.23545729112638014 9.46103477565196727)	wotje	Private	Ralina Hermios	Cement block	Covered	Good	None	0.3-0.8m	None	Diesel/Electric Pump	None	Washing/Gardening	5	15	None	0	0	0	0	0	0			9/06/2018	09:02:52am	well is conpletely and pump nit working can't measure and collect 2776-2780
W29	(170.23512264176829945	wotje	Private	Selina Hemos	Cement	Partially	Adequate	None	0.3-	Timber	Diesel/Electric Pump	Working	Washing/Gardening	7	5	Rubbish	0.57	0	1.4	1.6	0.526	0.522	320	0	9/06/2018	09:09:20am	WQ6 from Selina well. 5m from toilet photo

	9.46095678256435235)				block	Covered			0.8m																		numbers 2781-2786
W30	(170.23479288326589653 9.46170323895028353)	wotje	Private	Full Gospel Church	Other	Covered	Adequate	None	0.3-0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	3	10	Rubbish	0.56	0.32	1.08	2.24	0.641	0.648			9/06/2018	09:31:25am	algea grow from casting well fresh water photo numbers 2787-2793
W31	(170.23310651584264974 9.46129552224690862)	wotje	Private	Lonman Tawos	PVC/PE	None	None	None	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	6	10	Rubbish	0.57	0	1.36	1.78	0.626	0.624			9/06/2018	09:43:00am	no fence and cover WQ is fresh photo numbers 2794-2796
W32	(170.23296924793601193 9.4607723835449633)	wotje	Private	Randy Neptali	Steel	Covered	Good	None	0.3-0.8m	None	Diesel/Electric Pump	Working	Washing/Gardening	9	40		0.56	0.62	0	0	0.803	0.803			9/06/2018	09:50:54am	completely covered can't measure DTWT photo numbers 2797-2800
W33	(170.23226471129791548 9.46148526229586295)	Wotje	Private	Wotje power plant well	Cement block	None	None	None	<0.3m	Cement	Diesel/Electric Pump	Working	Drink/cook/wash/tlet	0	0	Rubbish	0.66	0.3	1.79	2	0.655	0.649	999	1	9/06/2018	09:58:51am	well is close to coast photo numbers 2801-2804
W34	(170.23211197888406332 9.46183973188224492)	wotje	Private	Hosina Gold	Steel	None	None	None	0.3-0.8m	Coral rock	Bucket/Tin			5	10	Rubbish	0.57	0.39	1.76	2.16	0.669	0.666			9/06/2018	10:08:36am	no cover and fence photo numbers 2804-2806
W35	(170.23153219435351957 9.46274667993106178)	wotje	Private	Berru Kiotak	PVC/PE	Covered	Adequate	None	0.3-0.8m	None	Diesel/Electric Pump	Not Working	Washing/Gardening	7	10	Rubbish	0.57	0.23	1.65	2.22	0.447	0.751			9/06/2018	10:16:40am	well is close to the coast photo numbers 2807-2811
W36	(170.23125997500468998 9.46241107810261184)	wotje	Private	Glann Lakjohn	PVC/PE	Partially Covered	Replace/repair	None	0.3-0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	7	15	Rubbish	0.54	0	1.53	1.73	0.747	0.747			9/06/2018	10:29:30am	well is close to coast photo numbers 2812-2817
W37	(170.2308739346638049 9.462806905365861)	wotje	Private	Aranto Jableke	PVC/PE	Covered	Replace/repair	None	0.3-0.8m	Coral rock	Diesel/Electric Pump	Working	Drink/cook/wash/tlet	11	10	Rubbish	0.55	0	1.48	2.08	0.759	0.761			9/06/2018	10:39:56am	well is close to coast photo numbers 2821-2824
W38	(170.23042443218201925 9.46316502958321237)	wotje	Private	Arbij Report	PVC/PE	None	None	None	0.3-0.8m	None	Bucket/Tin	None	Washing/Gardening	6	20	Rubbish	0.56	0	1.49	1.83	0.613	0.615	999	15	9/06/2018	10:49:01am	WQ8 from Arbij well. close to coast photo numbers 2826-2829
W39	(170.2335934490110958 9.46572207906126373)	Wotje	Private	Tony Pedro	PVC/PE	None	None	Adequate	>0.8m	Coral rock	Bucket/Tin	None		18	100	Rubbish	0.54	0	2.08	2.43	1.447	1.455			9/06/2018	11:11:07am	increase salinity measure. well close to southwest coast. photo 2830-2833
W40	(170.2357853221753885 9.46398200816727986)	wotje	Private	Helyes Lanwi	Coral rock	Covered	Adequate	None	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	8	15	Rubbish	0.87	0.39	2.74	3.25	0.61	0.612			9/06/2018	11:27:24am	algea grow and contaminated photo numbers 2834-2836

W41	(170.23689317007938371 9.46271669318105069)	Wotje	Private	Fandy Hemos	PVC/PE	None	None	Replace/repair	0.3 - 0.8 m	Coral rock	Bucket/Tin	None	Washing/Gardening	7	30	Rubbish	0.55	0.19	2.03	2.67	0.571	0.571			9/06/2018	11:38:00am	drink from water catchment photo numbers 2837-2840
W42	(170.23660272771206792 9.46519634850076663)	wotje	Private	Dinah L. Kamram	Cement block	Covered	Replace/repair	None	0.3 - 0.8 m	Cement	Bucket/Tin	None	Washing/Gardening	8	30	Rubbish	0.84	0.11	2.73	3.12	0.84	0.886	999	23	9/06/2018	11:52:46am	WQ9 from Dinah well. algea grow photo numbers 2843-2846
W43	(170.23781265400583607 9.46358233327502596)	Wotje	Private	NIHS well 1	Cement block	Covered	Good	None	None	None	Diesel/Electric Pump	Working	Toilet	100	3	Latrine/Septic	0.68	0.15	2.42	3.06	0.664	0.888			9/06/2018	12:07:36pm	school well. septic tank is 5m away. photo 2851-2854
W44	(170.23796121491346867 9.4640062239933922)	wotje	Private	NIHS well 2	Cement block	Covered	Good	Good	0.3 - 0.8 m	Cement	Tamana/Marakei Pump	Working	Toilet	0	5	Latrine/Septic	0	0	0	0	0	0			9/06/2018	12:15:49pm	completely covered can't measure DTWT and EC photo numbers 2857-2859
W45	(170.23830870284393768 9.46446562221991883)	Wotje	Private	NIHS WELL 3	Cement block	Covered	Good	None	0.3 - 0.8 m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	0	0	Latrine/Septic	0	0	0	0	0	0			9/06/2018	12:27:22pm	well is conpletely covered can't measure DTWT and well details photo numbers 2860-2862
W46	(170.23857567269192259 9.46338751611723161)	Wotje	Private	NIHS school principal well	Cement block	Covered	Good	None	>0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	6	10	Latrine/Septic	0	0	0	0	0	0			9/06/2018	12:34:20pm	well is conpletely covered can't measure DTWT and well details photo numbers 2863-2865
W47	(170.23855330839612066 9.4633014371457449)	wotje	Private	NIHS WELL 5	Cement ring	Covered	Good	None	0.3 - 0.8 m	None	Diesel/Electric Pump		Toilet	0	0	None	0.37	0.43	2.87	4.1	0.58	0.582	80	1	9/06/2018	12:38:40pm	WQ10 from NiHS WELL 5 photo numbers 2866-2871
W48	(170.23776338046022261 9.45996874635034501)	Wotje	Private	Lokjen Hemos	Cement block	Partially Covered	Adequate	None	>0.8m	Coral rock	Diesel/Electric Pump	None	Drink/cook/wash/tlet	5	0	Rubbish	0.58	0.47	1.74	2.19	0.46	0.523			9/06/2018	02:30:59pm	use for everything except for drinking photo numbers 2874-2878
W49	(170.23769769435600097 9.46040307476670073)	wotje	Private	Mosa Helai	PVC/PE	None		None	0.3 - 0.8 m	Cement	Bucket/Tin	None	Washing/Gardening	9	5	Rubbish	0.52	0.15	1.35	1.78	0.442	0.457			9/06/2018	02:40:26pm	algea grow casing is partly damage photo numbers 2879-2882
W50	(170.23686480497744355 9.46092900873542142)	wotje	Private	Anna Jacob	PVC/PE	Partially Covered		None	0.3 - 0.8 m	Timber	Diesel/Electric Pump	Working	Washing/Gardening	8	10	Rubbish	0.8	0.32	1.07	2.25	1.075	1.082			9/06/2018	02:46:30pm	photo numbers 2883-2886
W51	(170.23819799582901169 9.46161849888483353)	wotje	Private	solomon Rang	PVC/PE	Covered	None	None	0.3 - 0.8 m	None	Bucket/Tin	None	Washing/Gardening	6	10	Rubbish	0.86	0	1.64	2.1	0.646	0.656	200	13	9/06/2018	02:54:43pm	WQ11 from solomon well algea grow photo

																											numbers 2887-2889
W52	(170.23851753764446926 9.46224241103068664)	wotje	Private	Millson Edmond	PVC/PE	None	None	None	0.3 - 0.8 m	None	Bucket/Tin	None	Washing/Gardening	8	50	Rubbish	0.78	0.23	1.86	2.42	0.751	0.819			9/06/2018	03:00:49pm	no cover photo numbers 2893-2897
W53	(170.23976509320272044 9.46161547960209326)	Wotje	Public	Wotje health center well	Steel	Partially Covered	Adequate	None	<0.3m	Cement	Bucket/Tin	Not Working	Washing/Gardening	4	0	Rubbish	0.58	0.08	2.11	2.61	0.518	0.52			9/06/2018	03:07:07pm	pump is disconected photo numbers 2999-2902
W54	(170.239748231488079 9.46088508600349876)	Wotje	Private	Donald Lajer	PVC/PE	None	None	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	5	10	Latrine/Septic	0.63	0.16	1.93	2.4	0.502	0.505			9/06/2018	03:14:05pm	use for washing and shower photo numbers 2903-2905
W55	(170.2387609460150486 9.46017660971141261)	Wotje	Private	Prenos Gold	PVC/PE	None	Replace/repair	None	>0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	1	2	Rubbish	0.66	0.31	1.37	2.13	0.376	0.393			9/06/2018	03:20:19pm	photo numbers 2906-2909
W56	(170.23827880250397016 9.45954115096756709)	Wotje	Private	Salacer Bilimon	Cement ring	None	None	None	<0.3m	Cement	Bucket/Tin	None	Toilet	11	5	Rubbish	0.71	0	1.18	1.48	0.34	0.341			9/06/2018	03:25:37pm	photo numbers 2910-2912
W57	(170.23726598117647768 9.45866261956591714)	Wotje	Private	Kotaktil Heine	PVC/PE	Partially Covered	Replace/repair	None	0.3 - 0.8 m	Cement	Bucket/Tin	None	Washing/Gardening	10	5	Rubbish	0.86	0.48	2.13	2.76	0.88	0.88			9/06/2018	03:34:55pm	photo numbers 2913-2915
W58	(170.23765517506299716 9.45806796309634024)	Wotje	Private	Lajuar Hax	Steel	Covered	Adequate	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	16	7	Vegetation	0.57	0.38	2.42	2.96	0.731	0.874			9/06/2018	03:40:06pm	photo numbers 2917-2922
W59	(170.23797826083830387 9.45821042974158566)	Wotje	Private	Tony Edmond	Cement block	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	6	5	Rubbish	0.8	0.43	2.28	2.74	0.723	0.733	160	1	9/06/2018	03:45:00pm	photo numbers 2923-2925
W60	(170.23775503224712224 9.45844457059607358)	Wotje	Private	Kajeo Aisea	PVC/PE	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	6	10	Rubbish	0.76	0.16	1.6	2.26	0.368	0.375			9/06/2018	03:50:47pm	photo numbers 2926-2928
W61	(170.23890483188333178 9.45905142169733892)	Wotje	Private	Howard Boktok	PVC/PE	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	18	5	Rubbish	0.54	0.12	1.31	1.78	0.661	0.667			9/06/2018	04:07:35pm	photo numbers 2929-2931. close to graveyard
W62	(170.23928098143466059 9.45834421186144958)	Wotje	Private	George Manini	PVC/PE	Covered	Adequate	None	>0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	4	7	None	0.5	0.2	1.47	1.79	0.611	0.622			9/06/2018	04:16:17pm	photo numbers 2932-2935

W63	(170.23878361284559446 9.45705239480500026)	Wotje	Private	Mercy Calimlim	Unlined	Covered	Adequate	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	6	5	Vegetation	0.56	0	1.19	1.88	0.604	0.664			9/06/2018	04:24:07pm	photo numbers 2936-2939
W64	(170.23803612940545804 9.45631507411725991)	Wotje	Private	Kamram Kamram	Steel	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	3	8	Rubbish	0.57	0.25	1.26	1.76	0.342	0.365	999	5	9/06/2018	04:31:41pm	photo numbers 2940-2943.
W65	(170.24153318033233973 9.4567150140066385)	Wotje	Private	Eskel Omra	PVC/PE	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	8	100	Rubbish	0.54	0.06	1.29	1.87	0.783	0.789			9/06/2018	04:49:30pm	photo numbers 2944-2946
W66	(170.24007143777919282 9.45569470658860567)	Wotje	Private	Raninmeto	Cement block	Covered	Good	None	>0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	0	5	Vegetation	1.02	0.24	1.26	1.86	0.447	0.456			9/06/2018	04:57:03pm	well owner resides in Majuro. photo numbers 2948-2952
W67	(170.23984975439560685 9.45479185042469972)	Wotje	Private	Osineo Hax	Steel	None	None	Replace/repair	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	5	15	Rubbish	0.58	0.34	1.58	2.11	0.753	0.786			9/06/2018	05:04:00pm	photo numbers 2953-2956
W68	(170.23993425154282022 9.45438820621872367)	Wotje	Private	Tarmi Marshall	Steel	Partially Covered	Replace/repair	None	<0.3m	Cement	Bucket/Tin	None	Washing/Gardening	6	10	Rubbish	0.57	0.04	1.29	1.93	0.494	0.494			9/06/2018	05:09:15pm	photo numbers 2957-2960
W69	(170.2360613656998396 9.45450994506039244)	Wotje	Private	Tommy Jacob	Cement block	Covered	Good	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	4	10	Rubbish	0.76	0.3	1.78	2.02	0.507	0.507			11/06/2018	08:23:53am	photo numbers 2961-2963. well located at AoG church.
W70	(170.23602462123278656 9.45472246842120079)	Wotje	Private	AoG church	Cement block	Covered	Good	None	>0.8m	Cement	Diesel/Electric Pump	Working	Drink/cook/wash/tlet	4	10	None	0.58	0.61	2.07	3.87	0.594	0.594	999	999	11/06/2018	08:32:55am	photo numbers 2964-2967. well used for cooking when rainwater catchment is empty.
W71	(170.23672306892038364 9.45423832893588489)	Wotje	Private	Erjo Hanchor	Steel	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	4	5	Rubbish	0.59	0.72	2.24	2.78	0.547	0.548			11/06/2018	09:04:29am	photo numbers 2971-2973
W72	(170.23699659081594859 9.45368592821536247)	Wotje	Private	RMI National Police	PVC/PE	Covered	Adequate	None	None	None	Bucket/Tin	None	Washing/Gardening	4	5	Rubbish	0.52	0.7	1.98	2.58	0.507	0.507			11/06/2018	09:11:40am	photo numbers 2974-2977
W73	(170.23637164299256597 9.45359455921757608)	Wotje	Private	Makin Jacob	PVC/PE	Covered	Replace/repair	None	None	None	Bucket/Tin	None	Washing/Gardening	9	15	Rubbish	0.54	0	1.28	1.69	0.44	0.44			11/06/2018	09:18:25am	photo numbers 2978-2981
W74	(170.23635486965559949	Wotje	Private	Ambross Lajar	Cement	None	None	None	>0.8m	Coral rock	None	None		0	10	Rubbish	0.58	0.23	2.01	2.07	0.924	0.925			11/06/2018	09:30:00am	photo numbers 2982-2986. well not in use.

	9.45295989461458852)				block																						
W75	(170.23684611675429323 9.45241734814282175)	Wotje	Private	Gold Gold	PVC/PE	Covered	Adequate	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	7	6	Rubbish	0.53	0.29	1.55	2.25	0.541	0.54	160	1	11/06/2018	09:37:56am	photo numbers 2987-2989
W76	(170.23691865854092953 9.45187777903989357)	Wotje	Private	Ejjo Kiotak	Cement block	Partially Covered	Adequate	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	12	8	None	0.74	0.19	1.59	1.96	0.403	0.402			11/06/2018	09:47:06am	photo numbers 2990-2992
W77	(170.2374845320430552 9.45060607152111665)	Wotje	Private	Peter Lanwi	PVC/PE	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	2	8	Rubbish	0.54	0.1	1.39	1.69	0.436	0.436			11/06/2018	09:56:30am	photo numbers 2993-2995
W78	(170.23753829635080592 9.45024143559356133)	Wotje	Private	Anjeirok Naisher	PVC/PE	Covered	Adequate	None	>0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	6	25	Rubbish	0.59	0.04	1.55	1.88	0.945	0.947			11/06/2018	10:04:09am	photo numbers 2996-2998.
W79	(170.2376318359281413 9.44964799324896632)	Wotje	Private	Nesa Aisen	PVC/PE	None	None	None	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	10	100	Rubbish	0.52	0.21	1.59	1.88	0.582	0.582			11/06/2018	10:11:20am	photo numbers 2999-3001. no toilet facility.
W80	(170.23774381534542499 9.44907911236253284)	Wotje	Private	Rito Mea	PVC/PE	None	None	Replace/repair	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	11	10	Rubbish	0.56	0	0.64	0.81	0.49	0.49			11/06/2018	10:19:47am	photo numbers 3002-3004
W81	(170.23676633873571973 9.44623530407115553)	Wotje	Private	Bete Edwin	Cement block	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	7	20	Rubbish	1.08	0.48	1.62	2.21	2.1	3.2			11/06/2018	10:35:58am	photo numbers 3005-3007. well is too saline. 15-20m to sea.
W82	(170.23924969596927781 9.44600660481910381)	Wotje	Private	Samuel Lanwe	PVC/PE	None	None	None	>0.8m	Coral rock	Diesel/Electric Pump	Working	Washing/Gardening	9	20	Rubbish	0.58	0.49	2.51	2.7	1.98	1.99	999	0	11/06/2018	11:15:54am	photo numbers 3008-3010. high salinity measure dtWT and bottom.
W83	(170.23666004912777794 9.44958573280632841)	Wotje	Private	Jide Jacob	PVC/PE	None	None	Good	0.3-0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	9	10	Rubbish	0.56	0.13	1.52	1.62	0.766	0.768			11/06/2018	11:32:47am	photo numbers 3011-3013
W84	(170.23708914026673256 9.4500912744789396)	Wotje	Private	SDA church	Cement block	Covered	Good	None	>0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	1	8	None	0	0	0	0	0.606	0.606			11/06/2018	11:40:22am	photo numbers 3014-3016. well is conpletely sealed. cannot measure DTWT and well details.
W85	(170.23719677837902964 9.45232789733950973)	Wotje	Private	Lokwor Marshall	PVC/PE	None	None	Adequate	0.3-0.8m	Cement	Bucket/Tin	None	Washing/Gardening	0	6	Rubbish	0.56	0.09	1.56	1.79	0.641	0.641			11/06/2018	11:49:08am	photo numbers 3017-3019

W86	(170.23931577673099014 9.45241947652155012)	Wotje	Private	Bien Kiosha	Cement block	None	None	None	>0.8m	Cement	Diesel/Electric Pump	Working	Washing/Gardening	9	6	Rubbish	1.6	0.2	1.6	2.4	0.6	0.608	999	0	11/06/2018	11:57:16am	photo numbers 3020-3023. well is close to a pond.
W87	(170.23989210910747261 9.45251753732691391)	Wotje	Private	Branny Lakjohn	Steel	Partially Covered	Adequate	None	None	None	Diesel/Electric Pump	Working	Washing/Gardening	8	10	Vegetation	0.57	0.05	1.82	2.19	0.693	0.723			11/06/2018	12:07:04pm	photo numbers 3024-3026.
W88	(170.15096339175826756 9.55041250413186837)	Wodmej	Private	Mejwodik Elbon	Coral rock	Partially Covered	Adequate	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	13	20	Vegetation	0.97	0.28	2.28	3.16	0.862	0.934			12/06/2018	10:17:32am	photo numbers 3115-3117
W89	(170.15072841731407038 9.55029682886344133)	Wodmej	Private	Dennis Kiosha	Coral rock	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	5	10	Rubbish	0.63	0.23	2.23	2.86	0.387	0.451			12/06/2018	10:20:42am	photo numbers 3118-3120. useMejwodik Elbon's well too sometimes.
W90	(170.15093281036976691 9.55076618225721496)	Wodmej	Private	Kamore Langrine	Coral rock	Covered	Good	None	>0.8m	Coral rock	Bucket/Tin	None	Drink/cook/wash/tlet	17	10	Rubbish	1.08	0.05	2.24	2.57	0.805	0.808			12/06/2018	10:24:30am	photo numbers 3121-3123
W91	(170.15059209020341768 9.55105374312227795)	Wodmej	Private	Mark Anien	Coral rock	None	None	Good	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	5	5	Rubbish	1.05	0.14	2.67	3.05	0.678	0.679	999	9	12/06/2018	10:27:18am	photo numbers 3124-3126. Wodmej Protestant church well.
W92	(170.14994474249292011 9.55052622572426024)	Wodmej	Private	Jimmy Kiotak	Coral rock	Partially Covered	Adequate	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	9	14	Rubbish	0.75	0.33	2.23	2.48	0.715	0.717			12/06/2018	10:35:00am	photo numbers 3131-3133
W93	(170.14989715819015714 9.55087027134241318)	Wodmej	Private	Harsha Laneab	PVC/PE	Covered	Adequate	Adequate	<0.3m	Coral rock	Bucket/Tin	None	Washing/Gardening	6	7	Rubbish	0.53	0.04	2.52	3.15	0.793	0.794			12/06/2018	10:38:50am	photo numbers 3134-3136.
W94	(170.14915427792413993 9.55065535860788017)	Wodmej	Private	Abraham Hanchor	Cement block	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	8	5	Rubbish	0.92	0.07	1.92	2.46	0.928	1.29			12/06/2018	10:53:23am	photo numbers 3139-3141. well have high salinity measure at depth.
W95	(170.14893480960085981 9.55031072240505274)	Wodmej	Private	Joseph Haicom	Steel	None	None	None	None	None	Bucket/Tin	None	Washing/Gardening	5	7	Rubbish	0.77	0.2	2.05	2.49	0.694	0.692			12/06/2018	10:58:00am	photo numbers 3143-3144
W96	(170.14858906391933147 9.55036662148533821)	Wodmej	Private	Mercy Hanchor	Coral rock	Covered	None	None	>0.8m	Coral rock	Bucket/Tin	Working	Washing/Gardening	13	15	Rubbish	0.94	0.1	2.01	2.51	0.724	0.725	999	12	12/06/2018	11:04:17am	photo numbers 3145-3147
W97	(170.14792792527629217	Wodmej	Private	Kios Kiosha	PVC/PE	None	Replace/repair	Good	<0.3m	Coral rock	Bucket/Tin	None	Washing/Gardening	7	10	Vegetation	0.57	0	1.99	2.26	0.714	0.717			12/06/2018	11:11:48am	photo numbers 3148-3150

	9.55012178458795447)																										
W98	(170.14715792599579913 9.55013532657144992)	Wodmej	Private	Clark Hanchor	Cement block	None	None	None	>0.8m	Coral rock	None	None	Not used	0	10	Rubbish	0.97	0.13	0	0	0	0			12/06/2018	11:19:46am	photo numbers 3151-3153. well owner migrated. pig died inside therefore no measurement was taken.
W99	(170.14649063624597147 9.54997190172735166)	Wodmej	Private	Wodmej Health Center	Cement block	None	None	None	None	None	Bucket/Tin	None	Toilet	3	5	Rubbish	0.82	0.23	2.05	2.35	0.537	0.535			12/06/2018	11:25:16am	photo numbers 3154-3156
W100	(170.14469586588893435 9.54916039372768921)	Wodmej	Private	Bikej Kiotak	Cement block	Partially Covered	Adequate	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	6	16	Rubbish	0.78	0.28	2.34	2.89	0.624	0.624	999	1	12/06/2018	11:32:28am	photo numbers 3157-3159
W101	(170.1517657350976549 9.55022430647598242)	Wodmej	Private	Neri Juto	Cement block	None	None	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	6	5	Rubbish	0.85	0.33	2.6	3.35	0.777	0.932			12/06/2018	11:58:03am	photo numbers 3160-3162.
W102	(170.15219243604562394 9.55044119967984884)	Wodmej	Private	Wodmej Elementary School	Coral rock	Partially Covered	Replace/repair	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	0	20	Rubbish	1.17	0.24	2.43	3	0.886	0.921			12/06/2018	12:03:57pm	
W103	(170.15273000226812883 9.54982218610060229)	Wodmej	Private	Kenwel Lang	Cement block	Covered	Adequate	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	4	10	Rubbish	1.16	0.39	2.25	2.53	0.835	0.839			12/06/2018	12:09:55pm	photo numbers 3166-3168
W104	(170.15359897608314554 9.54950715162651953)	Wodmej	Private	Georgeton Bunjen	Coral rock	Partially Covered	Adequate	None	>0.8m	Coral rock	Bucket/Tin	None	Washing/Gardening	8	50	Rubbish	0.68	0.11	2.03	2.45	0.858	0.858	999	1	12/06/2018	12:15:36pm	photo numbers 3169-3171. no toilet facility.
W105	(170.15299255242030085 9.55004417815421824)	Wodmej	Private	Tila Laneab	Coral rock	Covered	Adequate	None	>0.8m	Cement	Bucket/Tin	None	Washing/Gardening	7	10	Rubbish	0.88	0.56	2.36	2.84	0.805	0.806			12/06/2018	12:23:30pm	photo numbers 3172-3174

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