Safe and Sustainable Drinking Water for Kiritimati Island Project

Groundwater Investigation
Decca and Four Wells
Kiritimati Island, Line Group, Kiribati

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Table of contents

List of figures

List of tables

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1. Introduction

1.1 Project background

As part of the Safe and Sustainable Drinking Water for Kiritimati Island project (the project), a groundwater investigation mission was carried out by the Pacific Community's (SPC) Water Resources Assessment team and Island Hydrology Service Consultant on Kiritimati Atoll between 30 May to 22 June 2023. The EUR 6.2 m project is funded by the European Union (EU) to increase access to safe and sustainable drinking water on Kiritimati Island by:

1. improving evidence-based management of water resources;
2. increasing access to safe and reliable drinking water supply; and,
3. strengthening capacity to operate, maintain and manage safe, efficient, and accountable water supply systems at the institutional, community and household levels.

This report presents the mission objectives, field investigation methodologies, results and a series of recommendations generated from this combined mission.

1.2 Mission objectives and outcomes

This field investigation mission is linked to objectives 1 and 3. Multiple investigation techniques were utilised to generate high resolution, evidence-based information to map the thickness of freshwater lenses within the Decca and Four Wells areas. The results will guide the location of new infiltration galleries that will boost access to safe drinking water in the London, Tennessee and Tabwakea communities.

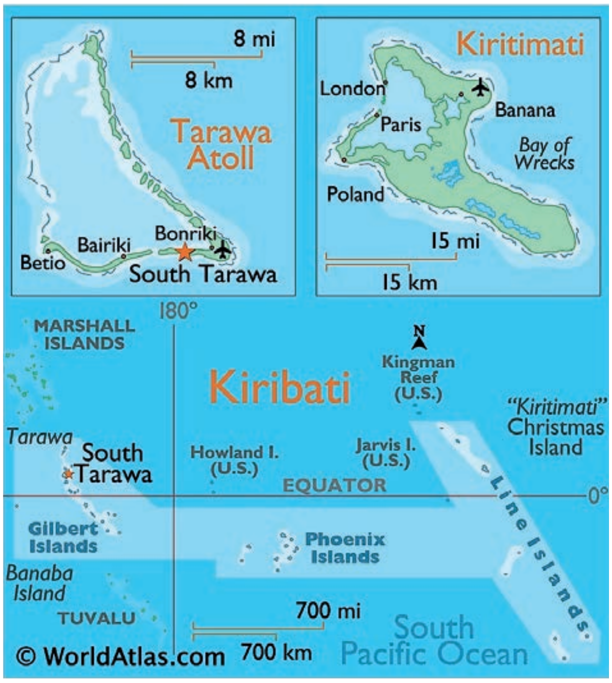
The development of new groundwater resources in atoll environments requires i) investigation of groundwater potential and identification of optimal drilling targets/locations; ii) placement of horizontal galleries and the assessment of yield and water quality; and, iii) equipping galleries with pumps and storage that align with the resource potential and community's needs.

The work reported here focused on the first component. The investigation of groundwater potential was carried out with the parallel use of three field investigation techniques: electrical resistivity, electromagnetic geophysics, and groundwater salinity monitoring. The generated detailed results will build on and integrate with existing understanding on the groundwater potential underlying Decca and Four Wells areas to inform both future gallery construction and water supply improvements. Recommendations are provided with regards to potential gallery locations, expected yields, expected groundwater quality, and relevant water resources management strategies.

2. Background

2.1 Geographical location, population and land use

Kiritimati Atoll, also known as Christmas Island, is the main island of three inhabited islands of the centre Line Group in the Republic of Kiribati. Figure 1A shows the three main island groups in Kiribati where Kiritimati is located 2°00'N, 157°30'W while Tarawa in the Gilbert Group is located 1°30'N and 173°00'E. Kiritimati is known to be the world's largest coral atoll in terms of land area (388 km^2) and rises to an average of 2–5 m above mean sea level (SPC, 2022). The atoll is located 2000 km WSW of the Hawaii archipelago and has four main inhabited centres: London (also known as Ronton, including Tennessee), Tabwakea, Banana (including Main Camp), and Poland. The atoll is administered by the Ministry of Line and Phoenix Islands Development (MLPID) with its main office situated in London.



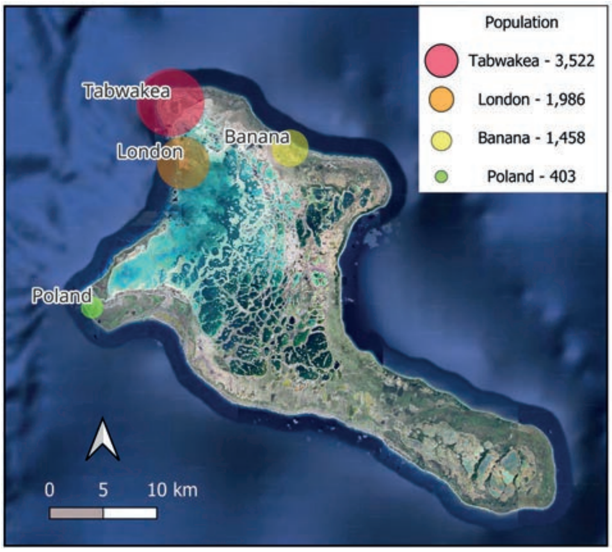


Figure 1A. Map of the three main island groups in Kiribati, namely Gilbert, Phoenix, and Line, with a focus of Tarawa, the country's main urban centre and located on the west, and Kiritimati the main government centres on the Line group located on the east.
B. Satellite image of Kiritimati Island with the location of the main populated centres namely London and Tabwakea, Banana and Poland. (Sources: https://www.worldatlas.com/maps/kiribati and Google Earth Image)

The 2020 census recorded a population of 7,369 inhabitants and 1,208 households for Kiritimati. London, Tennessee and Tabwakea are the highly populated centres, accounting for around 75% of the population on Kiritimati, and host the main government and administration offices, the port, and most of the commercial centre. The island's main airport (Cassidy International airport) is located near Banana (Figure 1A).

Table 1. 2020 population and household counts, and the projected growth expected on Kiritimati.

Community	2020 population	2020 households	2045 projected population
London and Tennessee	1,986	326	2,300
Tabwakea	3,522	577	8,100
Banana and Main Camp	1,458	239	6,700
Poland	403	66	2,600
Total	**7,369**		**19,700**

Source: Baseline report (SPC, 2022)

Kiritimati has been identified as a future growth centre by the Government of Kiribati to reduce the overpopulation issue in South Tarawa, which currently host more than 50% of the nation's population. To accommodate a projected population of around 19,700 (2.4 times the 2020 population), the Government recently opened 1,750 new residential leases and approved the construction of the new secondary school as part of future development plans. Based on the 60–100 L/p/day threshold highlighted in the Kiritimati Sustainable Water Management plan and the World Health Organization's guidance for domestic water quantity levels for low-risk health concern, the evaluation of the capacity of water supply system found that:

- Water demand of up to 3,080 people (40% of the population) can be met at 100 L/p/d, and
- Water demand of up to 5,140 people (70% of the population) can be met at 60 L/p/d.

If a conservative demand of 60 L/p/d can only serve 70% of the current population, then serious planning, investment and improvement actions should be taken to ensure the investigation and development of additional water supply to meet the expected increase in water demand.

The coarseness of the soils, low organic matter content and low soil-water retention capacity mean that land cover in Kiritimati is dominated by grassland and scrubs with very sparse patches of coconut trees (Woodroffe and Morrison, 2009). The geomorphology is characterised by mud flats, extensive hypersaline lakes, and a range of inland dunes that rise 5 m above sea level. Other prominent features include the generally steep beaches, strong berm, and two main coastal plains – a broad low-lying coastal plain adjacent to the current coastline and an older and higher plain that is dominated by sand and coral deposits with a 1 m sandy scarp bordering them.

2.2 Climate

Climatic conditions in Kiribati are generally influenced by south easterly trade winds and characterised by hot and humid conditions with highly variable but seasonal rainfall. Generally, there is more rain expected between January and June, while drier conditions are expected for the remaining months. Tarawa is located within the humid tropical zone that extends over much of the equatorial Pacific Ocean, while Kiritimati is located within a dry equatorial region, a narrow band across the central and eastern part of Pacific (Falkland and Woodroffe, 1997). The country's geographical location makes Kiribati vulnerable to El Niño Southern Oscillation (ENSO) events, be it El Niño, La Niña or Neutral. These events are usually associated with extreme climatic conditions such as droughts, tidal inundation, and storm surges. The impacts of these events threaten the security, socioeconomic capacity, and environmental health of atoll communities like Kiritimati.

Rainfall in Tarawa and Kiritimati will be comparatively used in this section to demonstrate the variability in rainfall patterns across Kiribati's island groups. The available monthly rainfall for Tarawa, collected at the Kiribati Meteorological Service (KMS) station in Betio, South Tarawa, is from January 1947 to March 2023. Available rainfall data for Kiritimati is from June 1916 to April 2023 (the rainfall station was previously located in London but was later transferred to the international airport in the 1990s). An automatic weather station was installed recently in Decca, but due to many gaps in the rainfall records, it was deemed inadequate. However, monthly rainfall analysis and drought analysis summarised here assess all available datasets for the two atolls. Special attention was given to recent data from 1990 to 2023 to provide a snapshot of the long-term rainfall trends and to help assess the rainfall patterns and potential impacts of ENSO events in the last three decades.

For the 1990–2023 period, Kiritimati atoll received a mean monthly rainfall of 91.6 mm and annual rainfall of 1,128 mm, while South Tarawa received a monthly mean of 175.6 mm and annual mean of 2,114 mm (Figure 2). Tarawa received approximately 50% more rainfall annually than Kiritimati. During the recent La Niña from 2020 to April 2023, the monthly and annual rainfall averages for Kiritimati decreased around 70% to 28.3 mm and 304 mm, respectively, and represent severely dry conditions. Table 3 shows a significant difference between the rainy periods and dry periods, suggesting that more than 50% of rainfall is received during the January–June period annually. The higher coefficient of variation observed during the dry period suggests a higher rainfall variation in Kiritimati, and thus reduces the reliability of rainfall to be harvested as an alternative drinking source during normal conditions, and likely even less reliable during droughts. Reduction in rainfall also leads to a reduction in groundwater recharge.

Table 2. *Kiribati annual and seasonal rainfall based on data from KMS from January 1990 to April 2023.*

	Yearly average rainfall (mm)	Monthly average during rainy period (mm)	Monthly average during dry period (mm)
Average	1128.29	126.6	56.4
Standard deviation	875.4	158.2	117.4
Coefficient of variation	0.78	1.3	2

Despite the difference in rainfall between Kiritimati and Tarawa, both atolls showed long periods of reduced rainfall indicating the impacts of La Niña events in 1998–2000, 2008–2009, 2010–2011, 2016–2017 and recently in 2021–2023. An assessment of the worst drought events on record in Tarawa and Kiritimati was also conducted using the Seasonal Climatic Outlook for Pacific Islands Countries (SOPIC) and summary of the ranking is presented in Table 3.

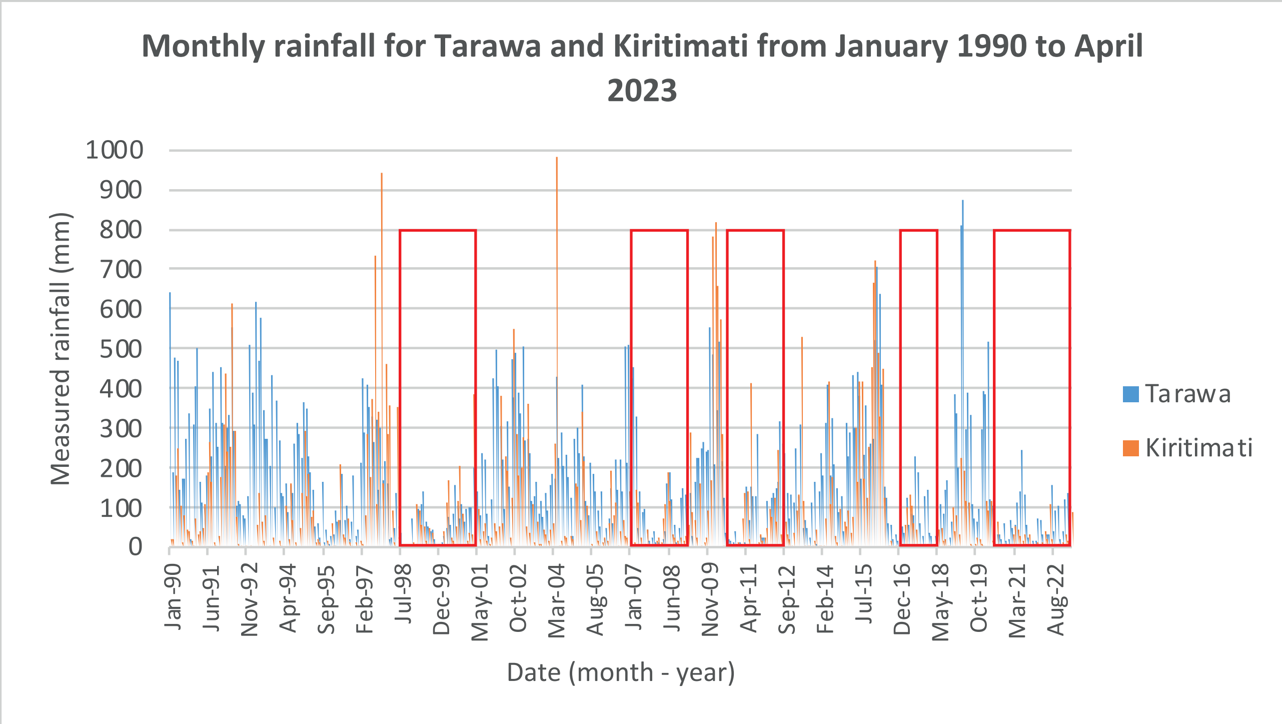


Figure 2. *Monthly rainfall records in South Tarawa (Gilbert Island Group) and Kiritimati (Line Island Group) indicating the rainfall variability and showing periods of extended drought periods.*

Table 3. *Summary of historical drought events ranking based on number of months and the ENSO state driving the event.*

Tarawa				Kiritimati			
Rank	**Period**	**Number of months**	**ENSO state**	**Rank**	**Period**	**Number of months**	**ENSO state**
1	1998–2000	38	La Niña	**1**	2021–2023	26	La Niña
2	1955–1957	29	La Niña	**2**	1967–1969	27	La Niña
3	2021–2023	25	La Niña	**3**	1954–1956	22	Neutral
4	1974–1975	16	La Niña	**4**	1971–1972	20	La Niña
5	1950–1951	15	La Niña	**5**	1993–1994	19	El Niño
6	1971–1972	15	La Niña	**6**	1985–1986	13	Neutral
7	1989–1990	12	La Niña	**7**	2018–2019	12	Neutral
8	2008–2009	19	La Niña	**8**	1974–1975	13	La Niña
9	1996–1997	14	Neutral	**9**	1996–1997	16	Neutral
10	2011–2012	20	La Niña	**10**	1989–1990	13	La Niña

Table 3 shows:

- The worst drought events for Tarawa are dominated by La Niña events (90%), with the 1998–2000 event ranked first and the recent event of 2021–2023 ranked third, while four major events between 1990 and 2023 were also in the top 10 ranking.
- The worst events recorded on Kiritimati, although dominated by La Niña events (50%), also occurred during Neutral (30%) and El Niño (10%) conditions. The recent event of 2021–2023 is ranked first while four major drought events occurring in the last three decades were also included on the list.

Kiritimati is vulnerable to drought driven by La Niña and Neutral phases, with a small probability of severe dry periods driven by El Niño. This suggests that every ENSO phase has a potential to cause severely dry weather, inducing water stress, and thereby threatening the availability, quality, and accessibility of freshwater resources on the atoll. Further, Kiritimati drought impacts can be largely amplified by the lower rainfall pattern already observed.

2.3 Groundwater occurrence and geological framework

Groundwater is the main source of freshwater in Kiritimati. On atolls, groundwater develops as thin lenses within unconsolidated sediments. These sediments are comprised of fine to medium/coarse sands and gravels layers deposited above salt-water laden karstic and highly permeable limestone. The extent and thickness of the lens is dependent on the thickness and permeability of the less consolidated sediments, and the amount of recharge from rainfall percolating through these sediments.

Decca and Four Wells, like the other reserves on Kiritimati, have undergone numerous phases of exploratory drilling between 1982 and 2015 as supported by different projects. Figure 3 shows the location of test drilling sites which were later equipped with multi-depth tubes and have been used as monitoring bores ever since. This has allowed periodical collection of depth-specific groundwater salinity across the two, helping to determine the thickness and spatial variability at each site and across the reserves.

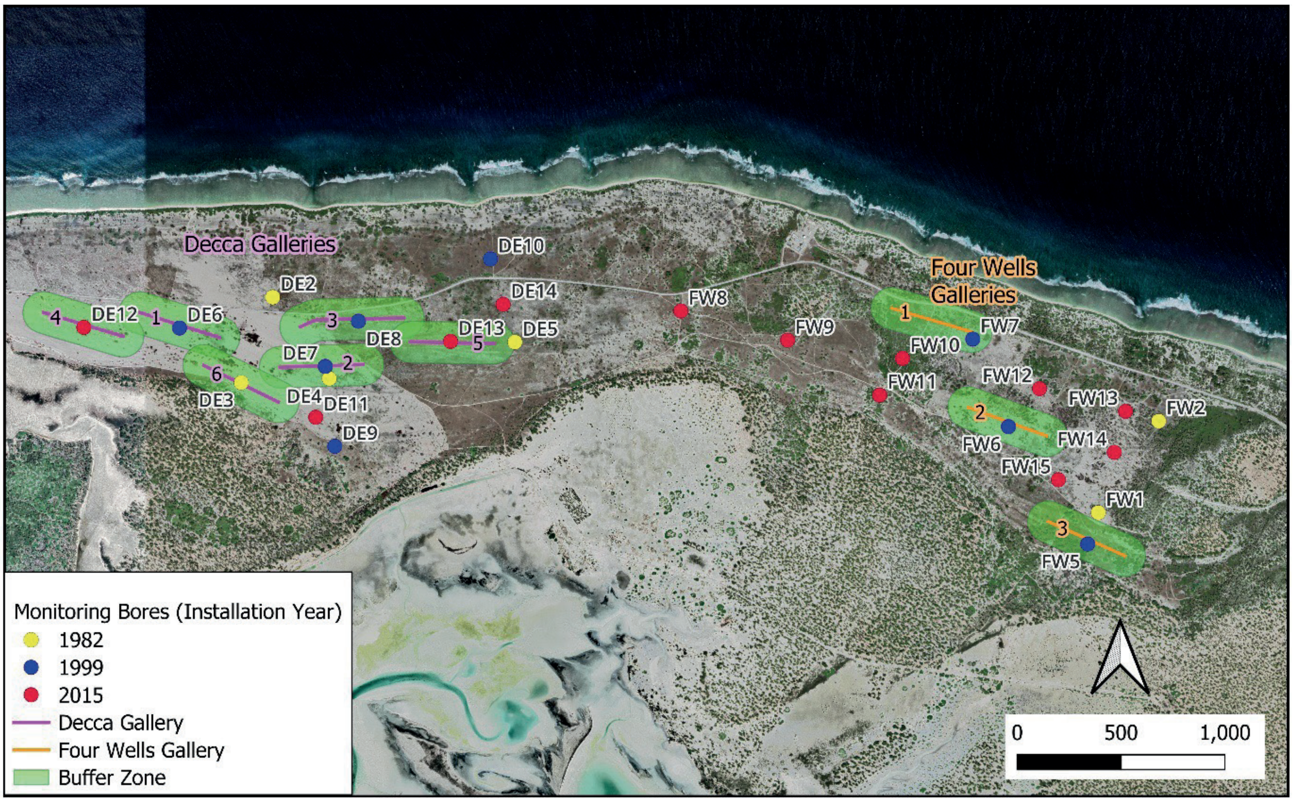


__Figure 3.__ Location of galleries and monitoring bores in Decca and Four Wells (FW).

Previous drilling results documented by Murphy (1982) and Douglas Partners Pty (1999) suggests that the underlying geological framework is composed of the following three zones: (a) in the top 3 m, loose to medium dense, light brown to grey, coarse to very fine coral silts and sand with minor organic matter; (b) unconsolidated and semi consolidated, highly weathered and permeable sand, gravel and coral beach deposits between 3 m and 8 m; and (c) a thin veneer of weathered limestone before grading into hard and consolidated limestone beyond 10 m.

The thickness and the subsurface depths of these zones are not homogeneous across the reserve. Field observation also confirmed the presence of a few patches of fine coral silts indicative of lagoonal flats occupying the western part of Four Wells, between FW8 and FW10, which are often marked by poor vegetation cover. Additionally, towards the lagoon, undulating sand dunes were observed towards the SW of Four Wells and west of gallery 3. These varying landforms across the reserves indicate the different depositional environments and tidal processes that drive the evolution of the atoll and thus will influence their varying hydraulic capacity to store and transmit groundwater. In multiple drilled boreholes, the highly weathered limestone was encountered at shallow depths (3–4 m). The freshwater lens extends well within this layer which has much lower permeability than typical porous limestone.

Previous groundwater studies across Kiritimati established recharge estimates based on the low rainfall received long-term. Falkland and Woodroffe (1997) estimated a groundwater recharge rate of 25% of mean annual rainfall to account for the 10% deep-rooted trees coverage. Based on a long-term annual rainfall mean of 1,128 mm, the annual recharge for normal conditions is estimated as 282 mm, and for the recent extremely dry La Niña conditions recording an annual rainfall average of 304 mm, the annual groundwater recharge is likely less than 76 mm due to the added impact of evapotranspiration. Groundwater storage and transmission across the reserve is dependent on the effective porosity of the dominant coral sand, and has been estimated to be 30% (Falkland, 2003).

2.4 Water supply capacity and infrastructure

Kiritimati Island has multiple groundwater reserves which are equipped with infiltration galleries, monitoring bores, series of storage tanks and a network of distribution pipes that serve and the main population centres. Four of the main groundwater reserves are Decca, Four Wells, Banana, and New Zealand Airfield. Most of the galleries, designed to be constructed parallel to the coastline, are 400 m long with two pumping wells situated 100 m from each end. Each gallery pump has a capacity 20 kL/d, (total 40 kL/day for each gallery), powered by solar panels and supplemented by either a wind or diesel generator.

The bores are equipped with a piezometer that allow for measuring salinity and depth to the water table. Additionally, multi-level 8 mm diameter nylon tubes for water quality monitoring are installed at pre-determined depths making discrete salinity measurements possible. Each monitoring depth is isolated by an impermeable layer of bentonite to prevent any mixing between sampling tubes. Groundwater from these monitoring depths is accessed through a 12 V low-flow pump with an appropriately sized connecting tube.

Decca and Four Wells groundwater reserves serve the main centres of London, Tennessee and Tabwakea. Decca, with its 14 monitoring bores and 6 galleries, pumps around 240–260 kL/day, mainly because gallery 3 has three pumping wells (east, west, and central). Four Wells has 13 monitoring bores and three galleries, which currently pump a combined daily capacity of 120 kL/day. This means that combined daily pumping yields from Decca and Four Wells is 380 kL/day if all the pumps are fully operational.

SPC (2022) highlighted that existing infrastructure is presently capable of providing up to 94 litres per person per day (L/p/d) to all members of London and Tennessee areas, and less than 20 L/p/d reticulated water to Tabwakea (Table 4). High water losses and geographical constraints continue to negatively impact the efficiency of the water supply reach.

Therefore, two key areas of project intervention were to explore the groundwater potential and determine the location of new groundwater galleries to:

a. boost access for water for Tabwakea residents, who are currently served less than 20 kL/p/d reticulated supply from Four Wells; and

b. enhance the reticulated supply for London and Tennessee.

Table 4. Summary of water supply infrastructure in Decca and Four Wells.

Site	Main distribution centres (total population)	Number of galleries (number of pumps)	Number of monitoring bores	Current pumping limits	Storage facilities
Decca	London and Tennessee	6 (13)	14	240–260 kL/day	1*22.5 kL header tank on 20 m stand located at Decca and acting as surge tank. 1*10 kL underground tank, 1*250 kL ground level tank, 1*22.5 kL tank on 6 m stand.
Four Wells	Tabwakea	3 (6)	15	120 kL/day	1*22.5 kL tank on 6 m stand.

2.5 Previous groundwater investigation, monitoring and water supply improvement works – Decca and Four Wells

Kiritimati Island has been subject to several groundwater investigation and development projects since the 1980s. Summarised in Table 5 are the major water sector investments and interventions for Decca and Four Wells, highlighting groundwater investigations and water-supply improvement work in the new areas that will feed into the current water supply system.

Long-term and recent groundwater salinity measurements have been collected at the existing galleries and multi-depth monitoring bores to help ascertain salinity fluctuation at the gallery pumping wells and to provide snapshots of the freshwater lens thickness variability at the monitoring bores. Figure 4 shows a continued decline in freshwater lens thickness from 2016 onwards. The increased rainfall derived from 2014–2016 El Niño led to high groundwater recharge and caused a significant increase in the lens of nearly 16 m and 14 m thick at Four Wells and Decca, respectively.

Table 5. Summary of water resources assessment and water supply improvements in the Decca and Four Wells areas.

Project	Years	Donor agencies	Water supply improvements
Kiritimati water resources study	1982–1983	Australian Department of Transport and Construction, Melbourne, Australia	Drilling of 4 investigation bores in Decca followed by installation of a piezometer and the equipment of multi-level monitoring tubes. Drilling of 2 investigation bores in Four Wells followed by installation of a piezometer and the equipment of multi-level monitoring tubes.

Table 5. Summary of water resources assessment and water supply improvements in the Decca and Four Wells areas (continued).

Project	Years	Donor agencies	Water supply improvements
Kiritimati Water and Sanitation (KWAS) project	1997–2002	Australian government	Construction of 3 galleries in Decca – all equipped with pumps. Construction of 3 galleries in Four Wells – all equipped with pumps. Construction of several 20 m high header tank in Decca, London and Tabwakea. Installation of wind and solar pumps with additional petrol pumps at one gallery in Decca. A 150 mm PVC transmission line pipeline installed adjacent to the A1 Road from Decca to Tabwakea, Tennessee and London. A 100 mm PVC transmission pipeline from Four Wells adjacent to the A1 Road to three low-level 20 kL ferro-cement tanks at Decca. Drilling and installation of 5 monitoring bores in Decca and 3 bores in Four Wells. Reticulation system established for Lone and Tabwakea (partial).
Improved Drinking Water Supply for Kiritimati Island Project (IDWSKIP)	2013–2018	New Zealand's MFAT and the European Union's EDF-10	Construction of 3 galleries in Decca – all equipped with pumps. Rehabilitation and relocation of wind pumps to better meet demands. Installation of solar pumps at all Decca and Four Wells galleries. Installation of strainers, flow meters, sampling points, and non-return valves at all Decca and Four Wells galleries. Installation of new solar chlorinators at Decca and Four Wells. Installation of new transmission pipeline from the Decca lens to London, isolating the Four Wells – Tabwakea system from the Decca - London/Tennessee system. Installation of five main bulk supply meters. Installation of 250 kL ground level storage tank and transfer pumps to the header tank at London village. Rehabilitation and lowering the heights of header tank stands at Tabwakea and London to decrease pressure in reticulation systems. Rehabilitation of parts of the reticulation infrastructure at London and Tennessee. Drilling and installation of 12 monitoring bores in Decca and Four Wells. Reticulation system established for Lone and Tabwakea (partial).

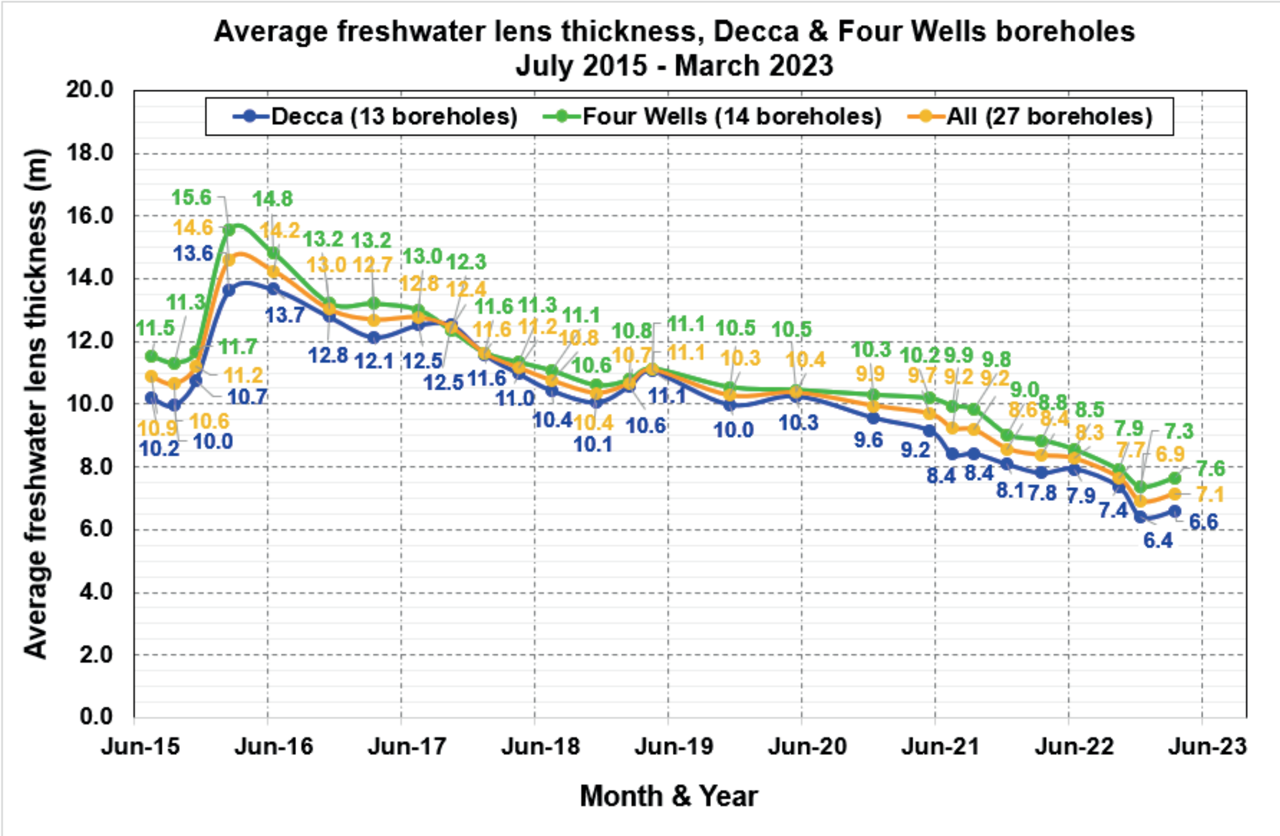


Figure 4. *Average lens thickness from 2015 to June 2023 showing an average decline of 7.5 m in lens thickness between early 2016 and mid-2023.*

Since the 2016 El Niño, there has been a continued decline in groundwater levels despite minor, temporary increases in lens thickness. The decline was exacerbated by the recent 2020–2023 La Niña, which brought prolonged and severe dry conditions, leading to impacts of ongoing gallery pumping for water supply. However, for the reserve to still have around 7 m lens thickness in early 2023 and after an annual rainfall of 304 mm, indicated the groundwater system's resilience and ability to continue supplying usable groundwater for public water supply during the drought period.

Salinity data from pumping wells at the galleries, between the 2022 and 2023 of the La Niña period were also collected as part of the project. Results show that salinity at the galleries reached elevated levels at different times which correlated well with the low monthly rainfall (Table 6 and Figure 5). Several galleries (Decca gallery pumps 2W, 3W, 3C, 5W, 5E and Four Wells galleries 1W, 1E, 2W, 2E, and 3W) showed maximum salinity above 1,500 µS/cm (Table 6). This suggests increased vulnerability in some parts of the reserve to increased salinity and reduced lens thickness due to prolonged dry period and on-going pumping – these conditions are likely to reoccur with increased frequency in the future due to climate change.

Data presented in Figure 5 demonstrate both the value of regular groundwater monitoring and the impacts of extreme dry conditions from the recent La Niña period coupled with the influence of on-going pumping from the reserve. This helped to build the understanding of the temporal and spatial variability across the groundwater reserve and would lead to improved operationalisation of the water supply system considering the heterogeneity of underlying formations and the sensitivity of the freshwater lens thickness and salinity.

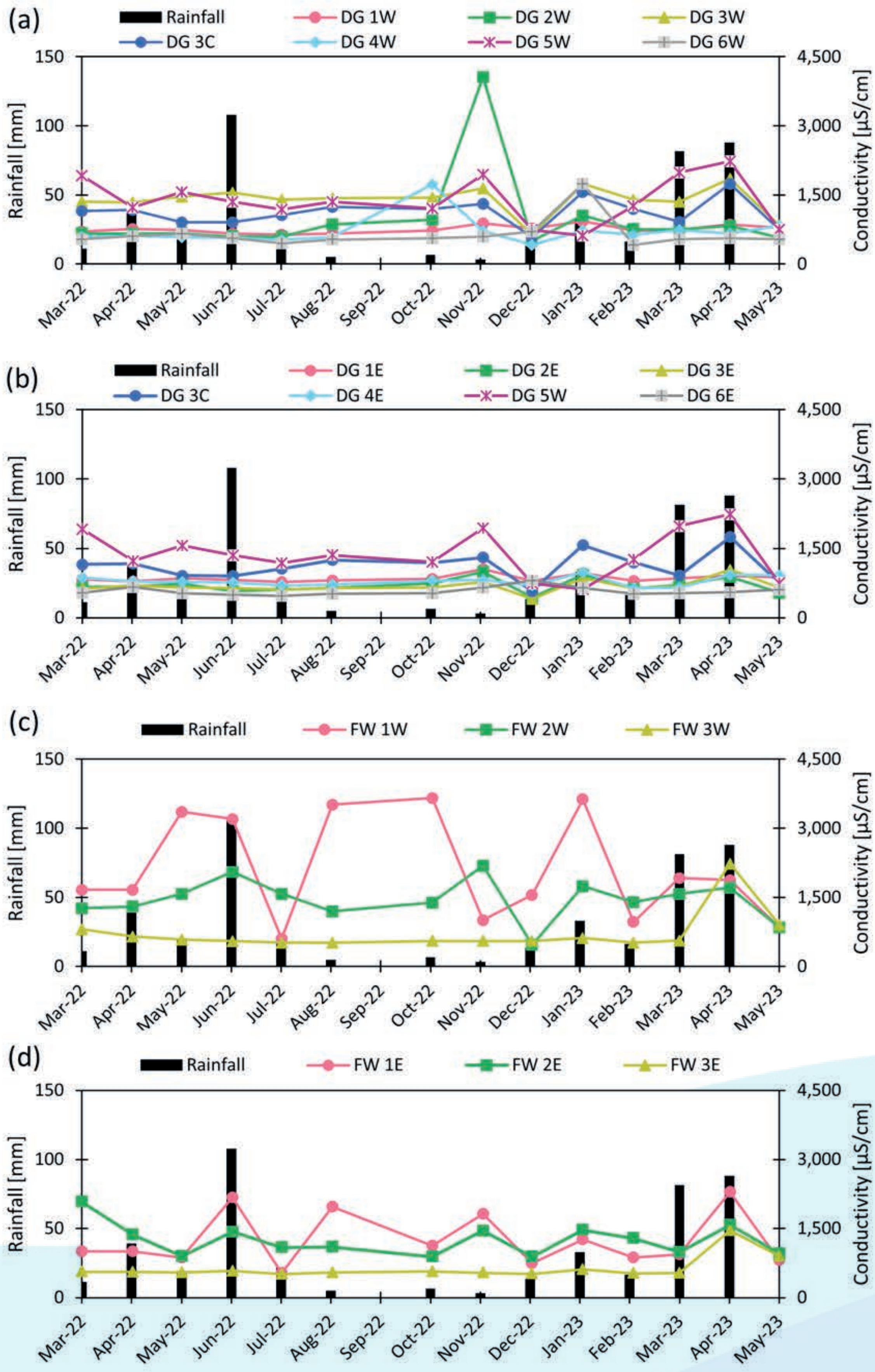


Figure 5. *Changes of groundwater salinity measured in the gallery pumping wells from March 2022 to May 2023 (**a:** west arm of Decca Gallery; **b:** east arm of Decca Gallery; **c:** west arm of Four Wells; **d:** east arm of Four Wells).*

Table 6. *Summary of the measured salinity in all the gallery pumping wells from March 2022 to May 2023.*

Gallery	Maximum salinity (µS/cm)	Average salinity (µS/cm)	Minimum salinity (µS/cm)
DG 1W	931	756	642
DG 1E	1054	853	771
DG 2W	4059	965	501
DG 2E	998	698	441
DG 3W	1856	1389	641
DG 3C	1746	1120	577
DG 3E	1044	685	409
DG 4W	1730	709	420
DG 4E	980	788	634
DG 5W	2234	1380	614
DG 5E	1713	1048	577
DG 6W	1745	643	417
DG 6E	801	575	472
FW 1W	3660	2104	601
FW 1E	2290	1241	535
FW 2W	2183	1449	472
FW 2E	2073	1245	881
FW 3W	2230	722	511
FW 3E	1450	636	504

3. Field survey methodology

3.1 Groundwater salinity monitoring and EM34 survey

Groundwater salinity monitoring was undertaken at all the existing monitoring bores in Decca and Four Wells to understand the current groundwater condition and help estimate the thickness and spatial variability of the freshwater lens (Figures 6 and 7). Freshwater is often defined as having an electrical conductivity of 2,500 µS/cm or less.

Monitoring is as follows.

1. Existing piezometers at each bore are used to measure both the depth to water table (DTWT) below ground and the salinity level. A Solinst dip meter was used to determine the DTWT while a TPS-WP84 device was used to capture salinity levels and expressed as micro-Siemens per centimetre (µS/cm) as a measure electrical conductivity (EC).
2. Salinities for discrete depths is obtained by sampling the multi-depths monitoring tubes at each site to a 12-V battery-powered low-flow pump to purge the pipes and access groundwater from pre-determined depths before measuring salinity levels from calibrated salinity meter.
3. The lens thickness at each bore is derived from the relationship between DTWT and salinity levels that were less than or equal to 2,500 µS/cm within the multi-depth tubes.

Table 7 shows the variable lens thickness measured at the bores with minimum and maximum thickness readings of 1.9 m and 10.8 m in Decca, and 5.1 m and 15.1 m at Four Wells.

Figure 6. *EM34 calibration measurements taken and centred on one of the monitoring bores.*

Figure 7. *Team undertaking groundwater salinity monitoring using a battery-powered low-flow pump, allowing groundwater to be abstracted through multiple depth 8mm nylon monitoring tubes.*

Table 7. Summary of freshwater lens thicknesses across Decca and Four Wells.

Decca boreholes			Four Wells boreholes		
Site	Total depth (m)	FW thickness (m)	Site	Total depth (m)	FW thickness (m)
DE2	15.85	6.86	FW1	27.0	12.64
DE3	24	10.82	FW2	22.0	10.77
DE4	15.95	8.15	FW4	21.0	8.04
DE5	19	9.72	FW5	17.0	13.94
DE6	16.9	10.28	FW6	17.0	8.1
DE7	16.5	6.6	FW7	16.9	10.73
DE8	16	9.65	FW8	22.0	7.57
DE9	27.7	1.93	FW9	22.0	9.83
DE10	27.7	7.4	FW10	22.0	5.08
DE11	22	4.11	FW11	22.0	5.12
DE12	22	9.28	FW12	22.0	9.87
DE13	22	10.65	FW13	22.0	10.75
DE14	22	10.47	FW14	22.0	13.7
			FW15	22.0	15.14

The electromagnetic geophysics (EM34) operates based on the principle of electromagnetic induction and uses two coils, a transmitter, and a receiver, linked by a reference cable. Falkland (2004) provided a useful explanatory summary where the transmitter and receiver coils, held by two operators, are spaced apart at defined separation distances of 10 m, 20 m, or 40 m, using the respective reference cable lengths. The coils can be placed either in a vertical (horizontal dipole (HD)) or horizontal (vertical dipole (VD)) position – the investigation of the two dipoles is 0.75x and 1.5x for the HD and VD, respectively, where x refers to the separation distance. When the transmitter is switched on, it is energised with an alternating current. This alternating current generates a primary magnetic field. This time-varying magnetic field induces small currents in the conductive materials in the subsurface ground, such as rocks or groundwater that generate a secondary magnetic field. The secondary magnetic field generated depends on the coil spacing, the operating frequency and the ground conductivity. Both magnetic fields are sensed by the receiver coil and a reading of apparent conductivity (or EM conductivity), based on the ratio of the secondary to the primary magnetic fields, is given. By analysing the characteristics of the received signal, it is possible to infer important information about the groundwater and the freshwater lens thickness.

The magnitude of the ground conductivity depends on several factors. For coral atolls the most important factors are the porosity of unconsolidated sediments and the conductivity of pore-infilling fluids (either freshwater or saline water) (Anthony, 1992).

The combination of groundwater monitoring and EM34 techniques involves the following steps:

1. Determine the thickness of the freshwater lens at each monitoring bore using the salinity measurements and variations as mentioned above.
2. Collect ground bulk electrical conductivity readings through the EM34 using horizontal and vertical dipole with 10 and 20 m separation cables centred around all the monitoring bore locations.
3. Establish a relationship between the results from 1 and 2 to confidently infer the freshwater lens thickness when EM34 survey is conducted across the reserve.

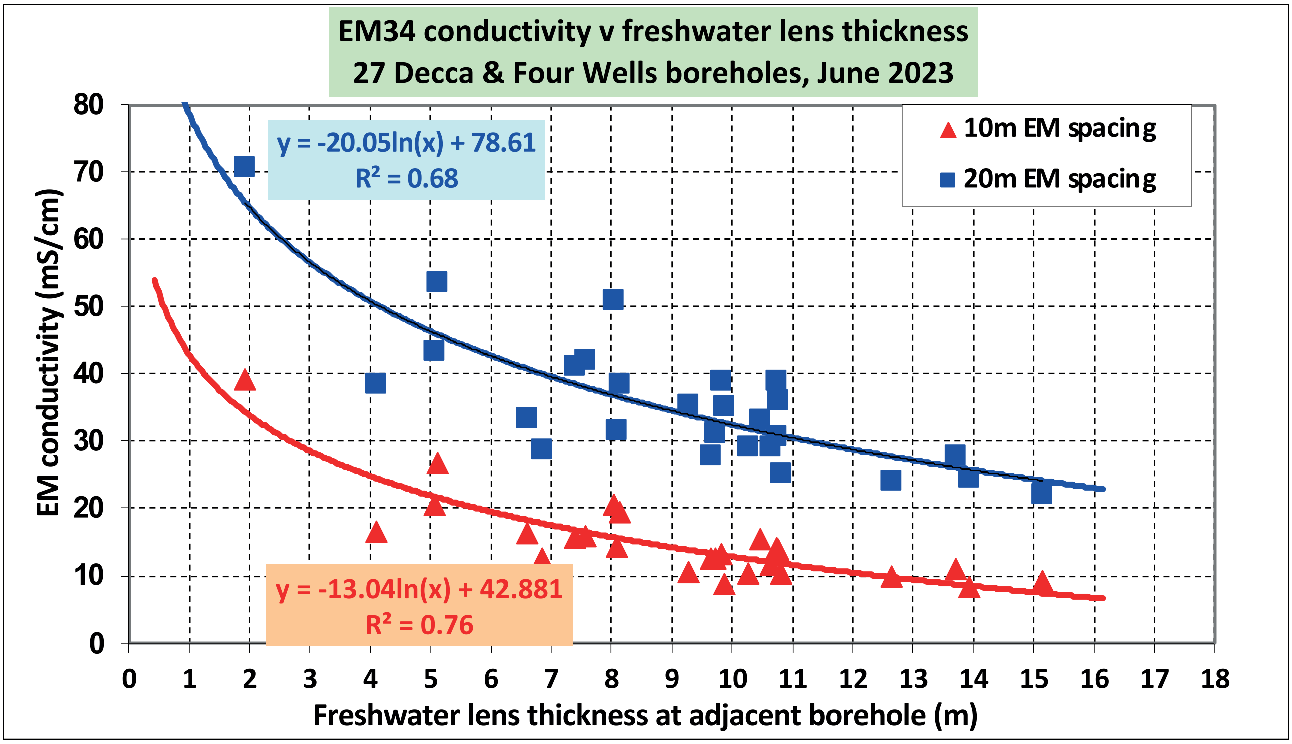


Figure 8. *EM34 calibration curve showing relationship between measured groundwater salinity and corresponding EM34 readings captured at the 27 monitoring bores.*

A total of 19 EM34 survey lines were completed, with a minimum and maximum line distance of 215 and 1,140 m and a total meterage coverage of 14 km across Decca and Four Wells. Data processing of the freshwater lens thickness derived from the EM34 survey was done by Mr Falkland using the calibration relationship (Figure 8).

The EM34 readings from the 19 survey lines were converted to freshwater lens thickness and are summarised in Table 8.

Table 8. Summary of the EM34 survey results showing maximum thickness of the freshwater lens.

EM34 line number	Spacing (m)	Distance (m)	Survey area	Maximum lens thickness (m)
1	40	514	Decca	5.3
2	60	657	Decca	8.8
3	90	687	Decca	13.9
4	100	858	Decca	13.9
4.5	40	400	Decca	11.1
5	100	1142	Decca	11.3
6	90	1119	Decca	10.7
7	90	900	Decca	10.2
8	100	934	Decca	7.9
9	90	697	Decca	6.0
10	80	478	Four Wells	6.2
10.5	90	270	Four Wells	7.3
11	90	622	Four Wells	7.0
12	80	658	Four Wells	8.3
13	80	550	Four Wells	8.6
14	90	607	Four Wells	11.4
15	90	933	Four Wells	12.9
16	90	1049	Four Wells	14.1
17	40	215	Four Wells	12.4
18	40	280	Four Wells	10.4
19	80	500	Four Wells	9.8

3.2 Electrical Resistivity Tomography (ERT) survey

ERT geophysics were used to assess, visualise, and identify the lateral and vertical variability in electrical resistivity response within the different geological units (Figures 10 and 11). 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 porosity of geological medium, hydraulic permeability, electrical conductivity (EC) or salinity of pore fluids, and clay mineralisation, and which provides insight into the underlying geology and hydrogeology.

The ABEM Terrameter LS2 from GuidelineGeo Inc. was used in combination with the multiple gradient arrays as the preferred survey protocol offering a high horizontal and vertical data resolution (Dahlin and Zhou, 2006). An electrode separation distance of 2 m and 5 m were selected to investigate in detail depths up to 30 m and 40 m respectively.

Calibration and application of ERT

A calibration line was completed at monitoring bore DE12 and near gallery 4 in Decca before the field resistivity survey was undertaken. This test line, using electrode spacing of 2 m and having a 160 m length, was necessary to allow for the in-situ verification of the recorded resistivity with groundwater salinity measured at the bores as expressed as electrical conductivity. Although other lines were completed around selected monitoring boreholes in Decca and Four Wells for additional calibration points, the results obtained at DE12 provided very good calibration in terms of displaying a well stratified subsurface model that was easily correlated against the changes in the groundwater salinity readings at multiple depths (Figure 9).

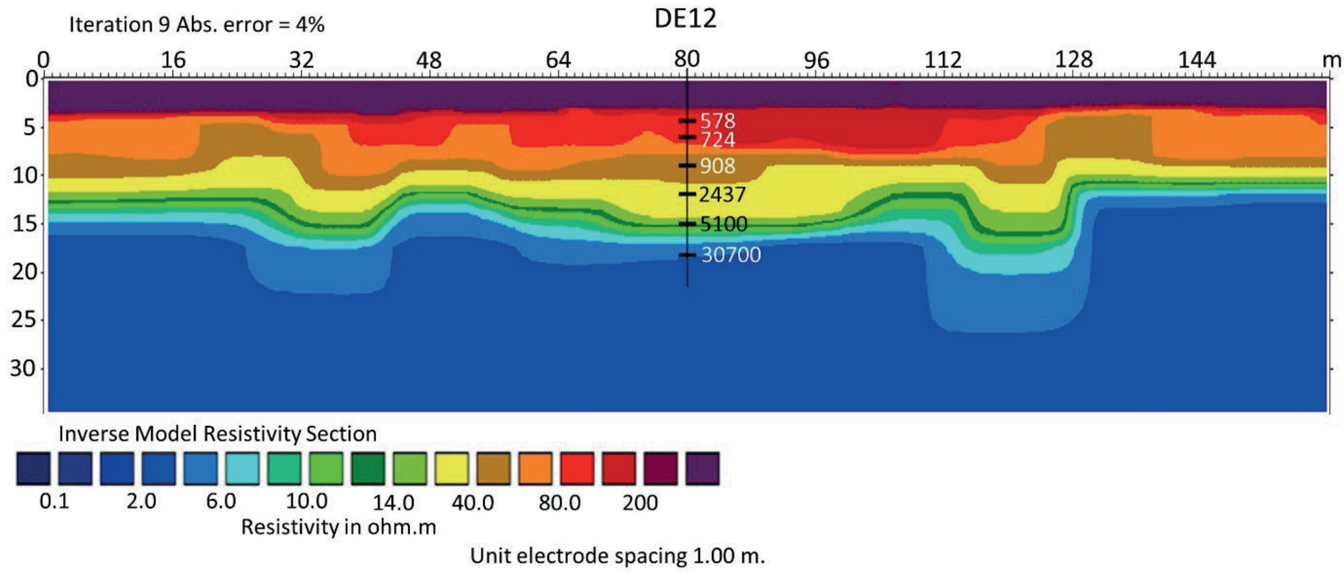


Figure 9. *Calibration results measured across monitoring bore DE12 showing layering of subsurface rock materials with the variability in resistivity and salinity influenced mainly by the abundance (or lack) of air, fresh groundwater, or saline water.*

The calibration results showed the following key information, which guided the lens mapping from the ERT survey:

- An unsaturated zone indicated by very high resistivity (>200 ohm) with a purplish colour that occupies the top 3 m.
- A fresh groundwater zone with a resistivity range of 25–200 Ohm.m (with a colour range of yellow, brown, orange, and red) and a corresponding salinity of 578–2,500 µS/cm, observed along the subsurface depth range of 2.82 m and 12 m and suggesting a lens thickness of more than 9 m.
- A brackish zone with resistivity and salinity ranges of 8–25 Ohm.m and 2,500–10,000 µS/cm, respectively, and between depth range 12–15 m.
- Saline zone with resistivity and salinity values of <8 Ohm.m (light and dark blue) and >10,000 µS/cm respectively and occupying depths beyond 15 m.

A total of 17 and 6 ERT survey lines were completed in Decca and Four Wells, respectively (Figure 12). The survey location was aimed at generating high resolution results both in areas that have little to no prior information as well as infilling surveys to improve the confidence of freshwater lens thickness estimated from EM34 data and groundwater monitoring and ultimately support the identification of new gallery sites.

Figure 10. A survey team operating the ABEM LS2 resistivity kit.

Figure 11. ERT cables laid on the ground connected to steel pegs through jumper cable and allowing the transmission of electrical signals and reception of ground response.

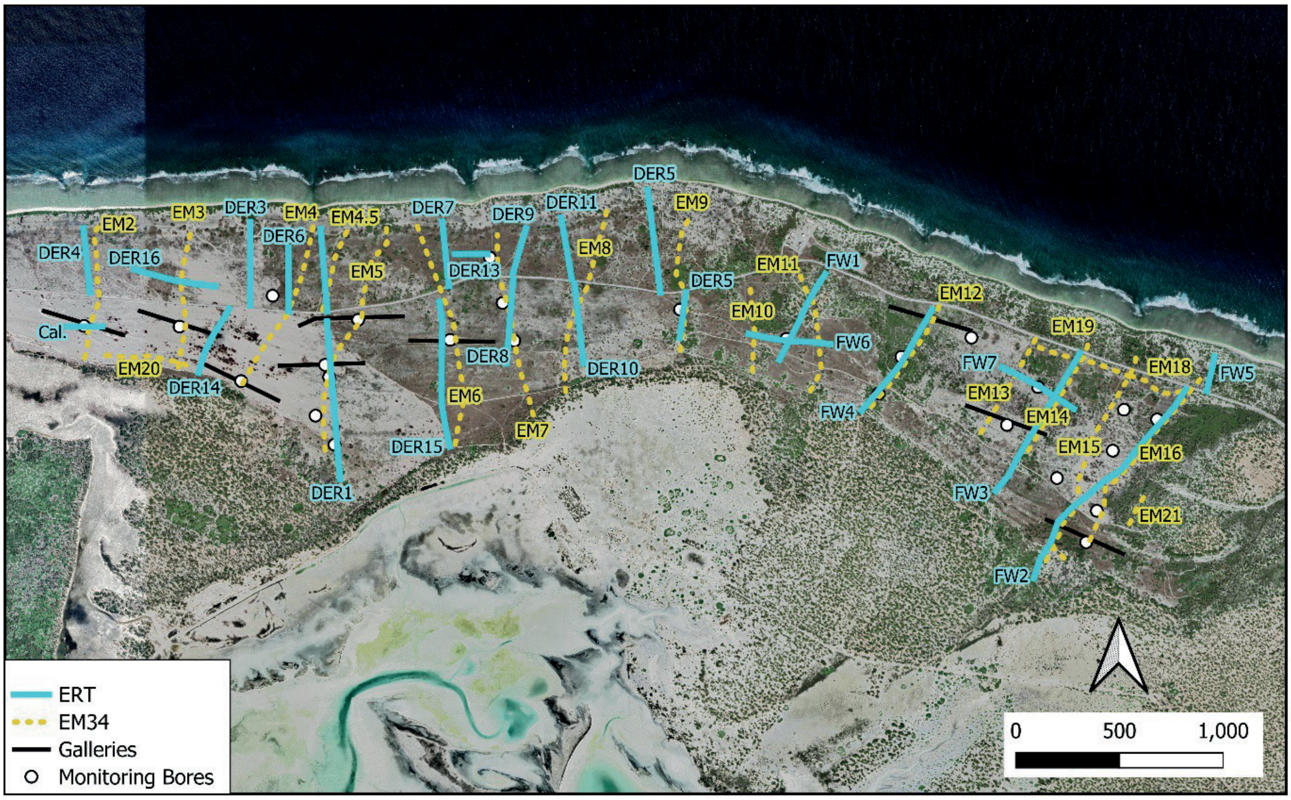


Figure 12. Field investigation map showing the location of EM34 and ERT survey lines along with existing galleries and monitoring bores.

4. Results

4.1 Groundwater monitoring and geophysics results

Key summaries from the field investigation include:

- The groundwater salinity monitoring results proved to be an important guide to understanding the current groundwater condition in terms of spatial variability of lens thickness. Near the Decca area, the freshwater lens thickness varied from 4.1–10.8 m, whilst at Four Wells, the lens ranged in thickness from 5.1–15.1 m. Overall, this showed good potential for groundwater development despite the impacts of the recent La Niña and the ongoing pumping. The thinner lens at Decca could be attributed to:
  - either a thinner water-bearing zone compared to Four Wells.
  - or the six existing galleries having a more pronounced impact from pumping compared to the three galleries at Four Wells.
- The EM34 calibration and survey allowed for the collection of good resolution data that showed the spatial variability in lens thickness and identified specific areas of optimal thickness for new galleries. Decca EM34 lines 3–7 showed good thickness of more than 9 m near the existing galleries 1, 2, 3, 4 and 5. Lines 14–18 completed in Four Wells, spanning the northeastern and southeastern sides and intersected monitoring bores 12, 13, 14 and 15 and close to gallery 3, showed good lens thickness of 10–14 m.
- The ERT lines provided good resolution both in the areas that have little to no data, such as the north of Decca as well as the infilling lines that were completed near the galleries and monitoring bores in both the areas. A summary of the general stratigraphy based on the results of the ERT survey are provided in Table 9. A lens thickness of more than 9 m was identified in places. It is critical to note that:
  - The calibration exercise offered good guidance in the groundwater investigation and mapping.
  - The long survey lines, oriented south-north, such as DER01, DER15 and DER 8 (Figure 13) in Decca and FWR2, FWR 3 and FWR 4 adequately showed the variable groundwater conditions and the location of optimal lens thickness (<9 m). The proximity of monitoring bores to these lines served as additional calibration points and in turn added to the accuracy and confidence of these datasets.
  - The short lines, oriented west-east, showed groundwater thickness variability consistent with the salinity monitoring data as previously shown by the DE12.
  - The western part of Four Wells, dominated by lagoonal flats around monitoring bore FW9 and lines FWR01, showed slightly reduced thickness whilst the eastern and northeastern areas indicated substantial lens thickness of around 10 m.

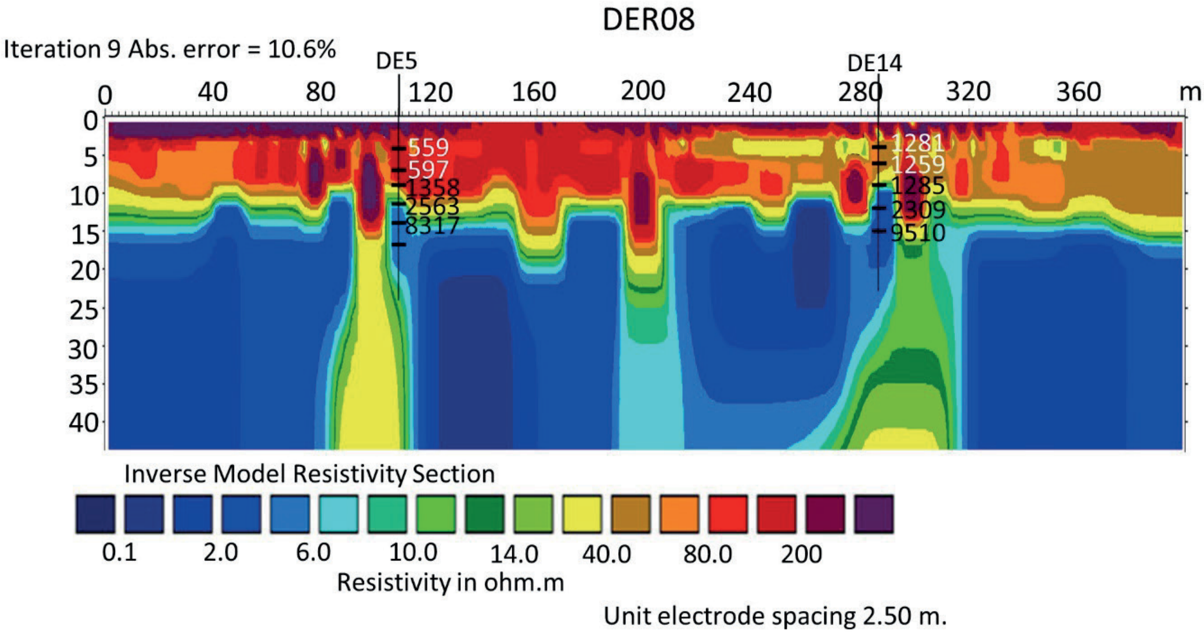


Figure 13. *DER08 showing good freshwater lens thickness as supported by the groundwater monitoring result at DE5.*

Table 9. *Summary of the geology and correlated resistivity measurements and anticipated EC of the groundwater.*

Rock and sediment type	Saturation	Indicative EC range of groundwater (µS/cm)	Bulk resistivity (Ohm.m)
Calcareous coral limestone, slightly/moderately/ highly weathered	Saline	8,000–30,000	2–6
Calcareous coral limestone, moderately/ highly weathered	Brackish	3900–6400	4–17
Gravelly coral sand	Fresh – lower	1700	10–12
Calcareous coral limestone, slightly weathered	Brackish	4000–6000	14–40
Calcareous coral limestone, slightly weathered	Fresh	640–2400	30–100
Calcareous coral limestone, moderately/ highly weathered	Fresh	550–1400	40–200
Silty gravelly sand and silty sandy gravel	Fresh	600	90–100
Calcareous coral limestone, moderately/ highly weathered	Fresh	550–1400	40–200
Calcareous coral limestone, slightly weathered	Fresh	640–2400	30–100

In integrating groundwater salinity monitoring with the two geophysical methods, two contoured zones were delineated using QGIS. The 7 m and 9 m mapped isolines of freshwater lens thickness were generated with high confidence, with strong correlation between monitoring and geophysical data (Figure 14).

The extent of the mapped freshwater lens areas clearly illustrates the Decca and Four Wells are part of the same groundwater body that is hydraulically connected contrary to previous interpretations as being separate reserves. The extent of the 7 m and 9 m contours, covering estimated areas of 3.3 and 1.9 km^2 respectively, would suggest the substantial groundwater potential to support additional gallery sites.

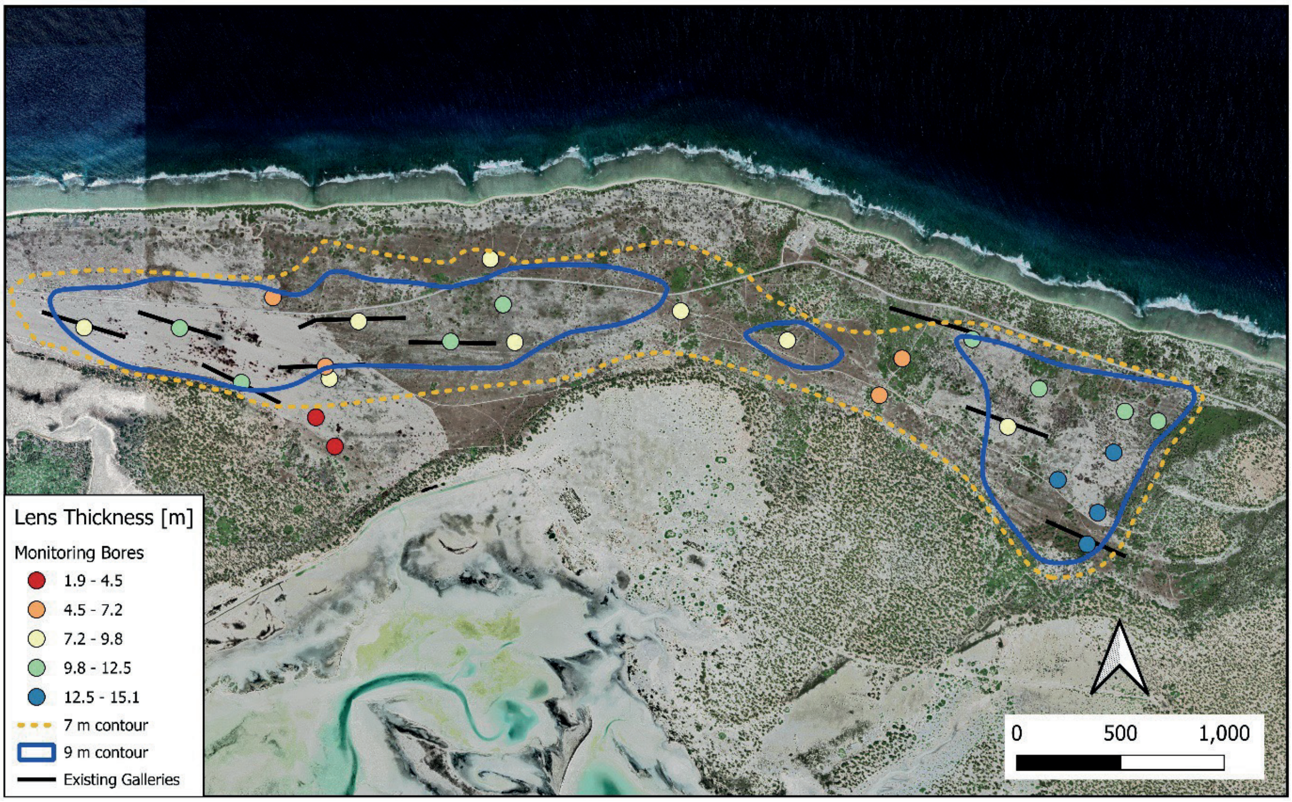


Figure 14. *Mapped freshwater lens thickness based on interpretation of the geophysical surveys and salinity measurements from the monitoring bores.*

4.2 Groundwater resource vulnerability

The groundwater salinity monitoring in the galleries and the monitoring bores presented in Section 2.5 showed both the vulnerability, and the variability of, lens thickness reduction and increased salinity across, the reserve; this was supported by some of the ERT lines. Line DER01 displayed reduced freshwater lens thickness near DE7 and very close to gallery 2 suggests a localised lens thickness reduction, possibly due to up-coning of saltwater in response to reduced recharge and pumping during the recent La Niña (Figure 15). The impacted part of the lens is expected to recover with recharge from recent rain.

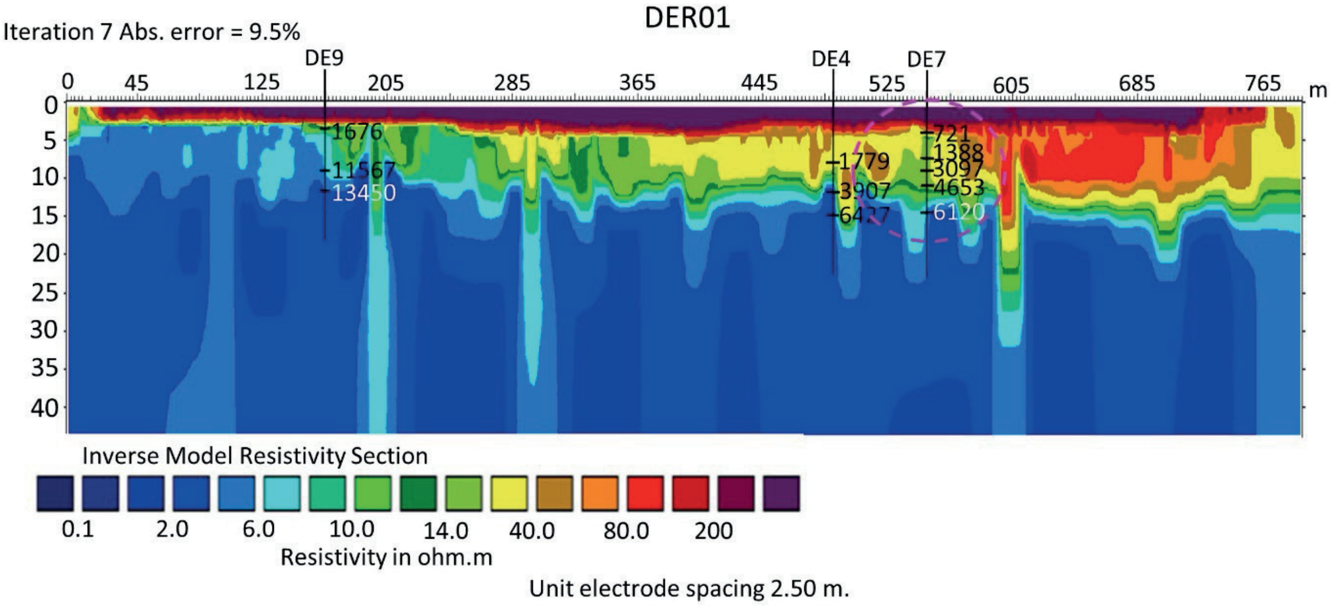


Figure 15. ERT line DER01 crossing showing reduced lens thickness near monitoring bore DE7 and where the line intersected with Decca gallery 2 (dashed circle).

A similar pattern of localised lens thickness reduction was observed in Four Wells and along profile FWR4 (Figure 16). More specifically, a reduction in freshwater lens thickness is observed near monitoring bore FW 10, between 300 and 330 m profile distance and between 550m and 560 m profile distance which aligns with FWG 1 pump. The area near FW 10 is close to the lagoonal flats and likely dominated by very fine materials of relatively lower permeability and hence less storage and transmission capacity, whilst the area near gallery 1 would suggest up-coning from abstraction.

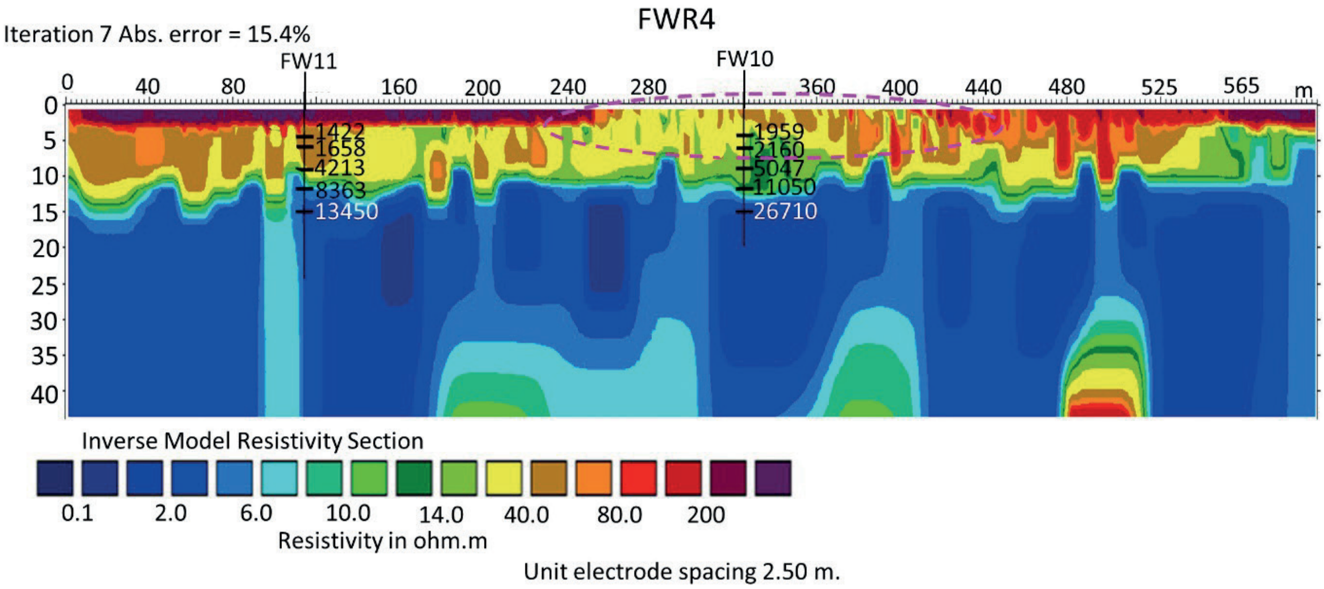


Figure 16. Localised reduction in lens thickness near monitoring FW10 and gallery pump 1 suggest impacts of over-abstraction.

4.3 Groundwater resources development

Based on series of discussion between the project manager, Mr Tony Falkland, and the SPC team, the freshwater lens mapping using the 7 m and 9 m contours allowed for the identification of 9 potential gallery sites: 5 in Decca and 4 in Four Wells (Figure 17).

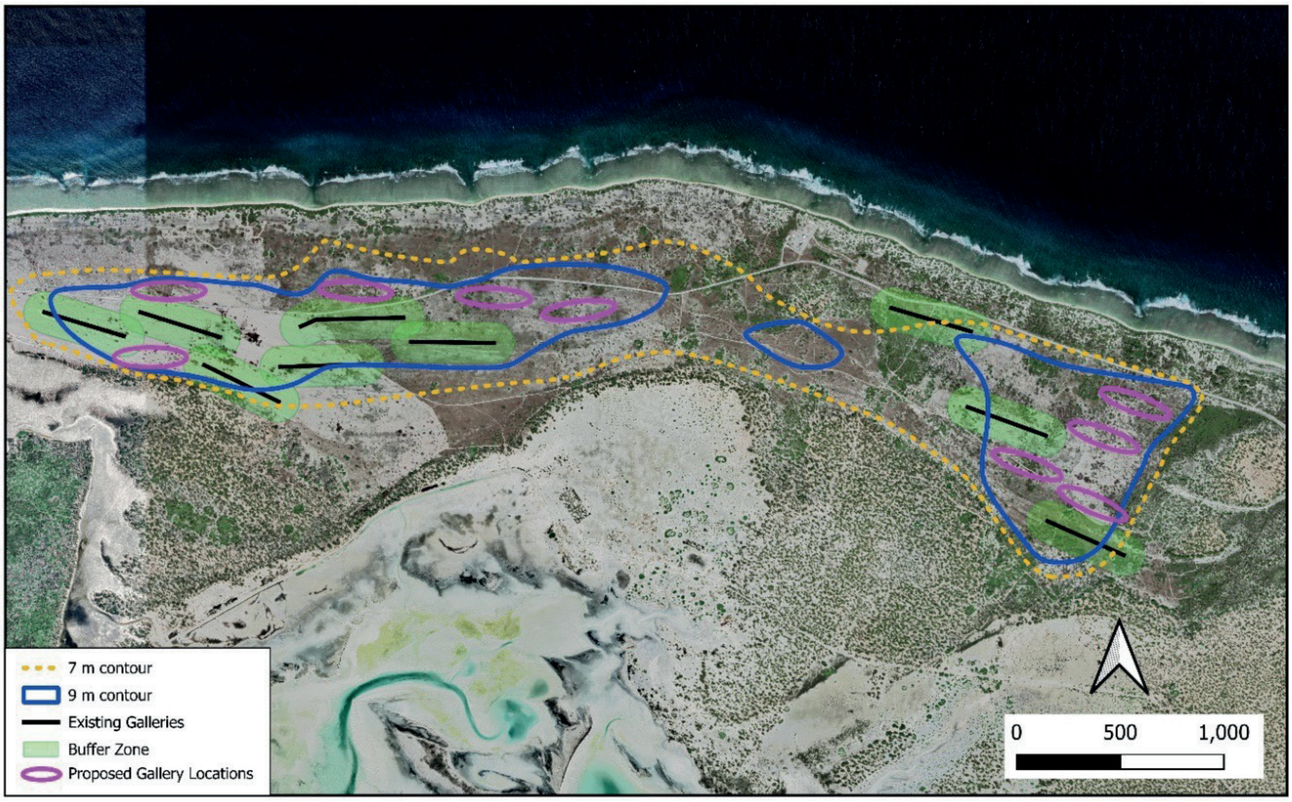


Figure 17. Lens mapping of Decca and Four Wells with potential gallery sites shown by yellow ovals.

Using the areal extent of the mapped freshwater lens and an effective porosity of 30% for the sands, a basic calculation of the total groundwater volume in relation to the volume that is abstracted on a daily and monthly basis can be performed. Results from this calculation are summarised in Table 10.

Table 10. Summarised groundwater resources capacity based on the mapped 7 m and 9 m zones and the available groundwater volume based on the effective porosity of 30% to account for atoll sands.

Decca and Four Wells	
Total area (m^2)	6,600,000
Groundwater resource – 7 m thickness zone	
Freshwater lens area (m^2)	33,000,000
Average lens thickness (m)	7.0
Lens/total land area ratio (%)	50%
Freshwater volume (m^3)	231,000,000
Available groundwater (m^3)	69,300,000
Groundwater resource – 9 m thickness zone	
Freshwater lens area (m^2)	1,900,000
Average lens thickness (m)	9.0
Lens/total land area ratio (%)	29%
Freshwater volume (m^3)	17,100,000
Available groundwater (m^3)	5,130,000

Based on the combined abstraction of 380 kL/day from the Decca and Four Wells galleries, the current pumping regime is withdrawing 0.0005% and 0.007% of the daily groundwater volume estimated for 7 m and 9 m potential zones respectively. This would suggest that the mapped reserve has very good potential and has a lot to offer in terms of substantial storage capacity to support additional gallery sites and to meet the current and future demands. The above storage capacity gives good indication of resilience; however, there is a need to consider the detailed extent of future development based on variability in rainfall and recharge estimates.

An adjustment in gallery design in both Decca and Four Wells is proposed (Falkland and Ward pers comm, 2023) to reduce gallery length to 300 m, with a single central pumping well having a maximum design yield of 40 kL/day. If all nine potential sites are developed, this would add 360 kL/day to the existing pumping regime, increasing the combined total to 740 kL/day. Such an increase in pumping would help increase and enhance access to the residents in London and Tabwakea.

5. Recommendation towards water resources development and management

Based on the integration of groundwater monitoring results with the two geophysical techniques, it is shown that Decca and Four Wells are part of a continuous and connected fresh groundwater reserve. The mapped extent and thickness of the freshwater lens offers significant potential for the development of new gallery sites providing additional capacity to support the level of abstraction required to meet projected community needs. As with any groundwater investigation, there remains some uncertainty about the hydraulic dynamics of the lens, and thus an integrated and coordinated approach will be essential to ensure the safeguard of the lens's long-term sustainability. The following improvements are suggested.

Water supply gallery expansion

As presented in Figure 17, there is potential for nine new infiltration galleries in Decca and Four Wells. These would entail 300 m long galleries with a central pumping well with a maximum design yield of 40 kL/day. It is suggested that:

- Five new galleries be installed in Decca and connect them to the existing distribution pipe network and header tank that serves London and Tennessee. This would add 200 kL/day to the existing daily yield of 260 kL/day and would lead to a combined yield of 460 kL/day.
- Four new sites be installed at Four Wells to support the planned water supply improvement at Tabwakea with the galleries to be close to or cantered around monitoring bores FW12, FW13, FW14 and FW15. This would add 160 kl/day to the existing daily yield of 120 kL/day and would lead to a combined yield of 280 kL/day.

Opportunities to strengthen water resources management

1. The repair or replacement of the AWS rainfall stations near the Decca treatment plant would allow for the collection of localised rainfall events, supporting the evaluation of temporal and spatial rainfall variability across the atoll. Gathering this information would allow for the calculation of more accurate groundwater recharge estimates. Compiling, archiving, and sharing of the rainfall and climate data would strengthen the links between the Island Council, MLPID and the KMS and enable:
    a. identification of appropriate trigger levels for rainfall and groundwater salinity to support water resources management prior to and during prolonged dry periods.
    b. establishment and/or strengthening of appropriate water restriction actions around the communities during extreme climatic conditions.
2. Support for proactive decisions and actions requires the continued training of the MLPID's Water and Sanitation team, coupled with purchase and maintenance of appropriate technologies and adequate budgetary support from the Government. Schedule groundwater monitoring, and its analysis, reporting, and dissemination of evidence-based information is essential to develop responsive groundwater management of the fresh groundwater reserve and achieve long-term sustainable abstraction.
3. Establish a telemetry system that allows for near real-time measurement, analysis and reporting of groundwater flow rate and salinity to be shared by the water supply managers. Considering the sensitivity of the groundwater salinity to extreme climatic conditions having near real-time data would allow for timely and adaptive management actions to be implemented to optimise the management of the water supply.

4. To ensure long-term operation and sustainable management of the groundwater reserve underlying Decca and Four Wells and to utilise all relevant datasets from monitoring, pumping and rainfall, groundwater numerical modelling should be undertaken to:
    a. test the capacity and variability of the mapped freshwater lens in response to:
        - current groundwater abstraction.
        - future groundwater abstraction based on the nine new galleries proposed from this investigation.
        - increasing magnitude and frequency of La Niña drought events.
    b. update the sustainable yield based on current and future abstractions in relation to the climate change projections.
    c. determine appropriate salinity and rainfall triggers for improved groundwater conservation and management actions.
5. The conjunctive use of all freshwater sources should always be encouraged at the national, communal, and household levels. This includes groundwater resources from Decca and Four Wells being utilised along with on-going rainwater harvesting and other technologies (i.e., desalination). Using alternative sources will reduce enormous pressure placed on the groundwater reserves and provide a buffer to the reserves before and during extreme weather events around the atoll.

6. References

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Morrison RJ and Woodroffe CD (2009) 'The Soils of Kiritimati (Christmas) Island, Kiribati, Central Pacific: New Information and Comparison with Previous Studies', *Pacific Science*, 63(3):397–411, doi:10.2984/049.063.0308.

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Annex 1 – Inverted resistivity profiles

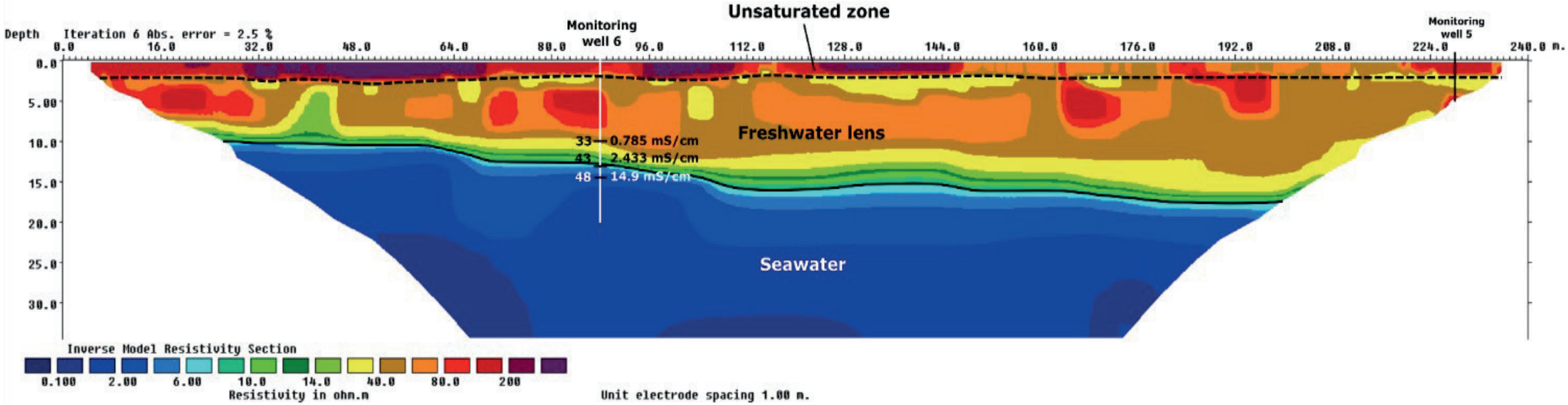

Figure A1.1. Calibration result obtained from Laura Reserve, located on Majuro Atoll in the Marshall Islands. (Antoniou et al, 2019).

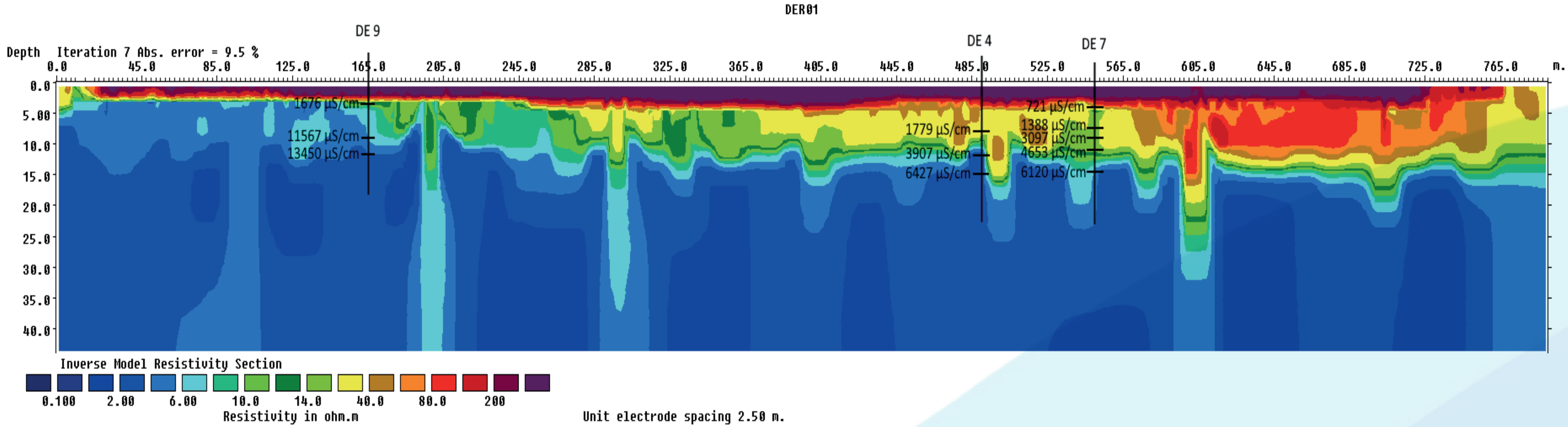

Figure A1.2. DER01 resistivity line, oriented S-N and crossing monitoring bores DE4, DE7 and DE9.

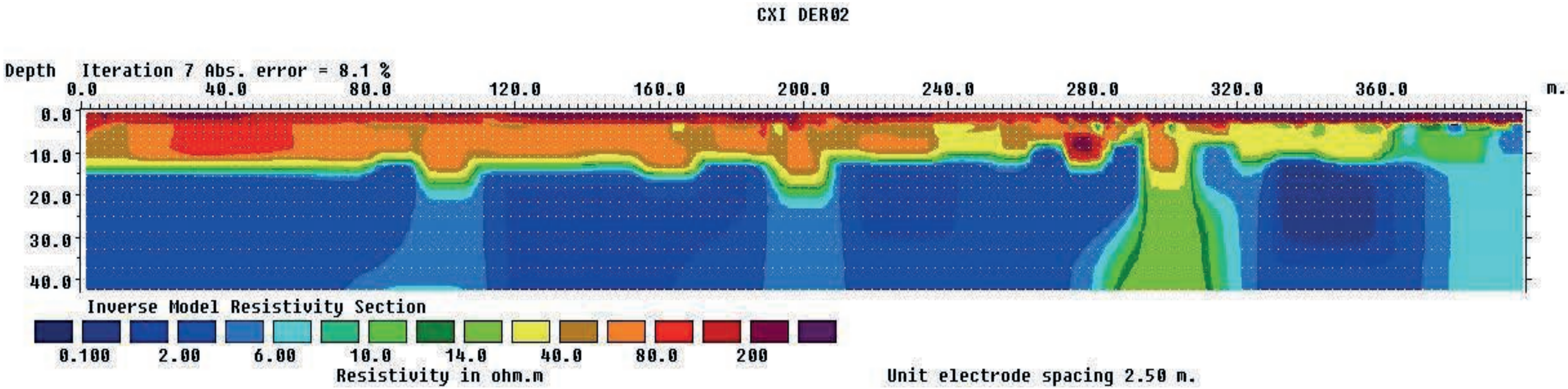

Figure A1.3. *DER02 survey line immediately north of the Decca header tank.*

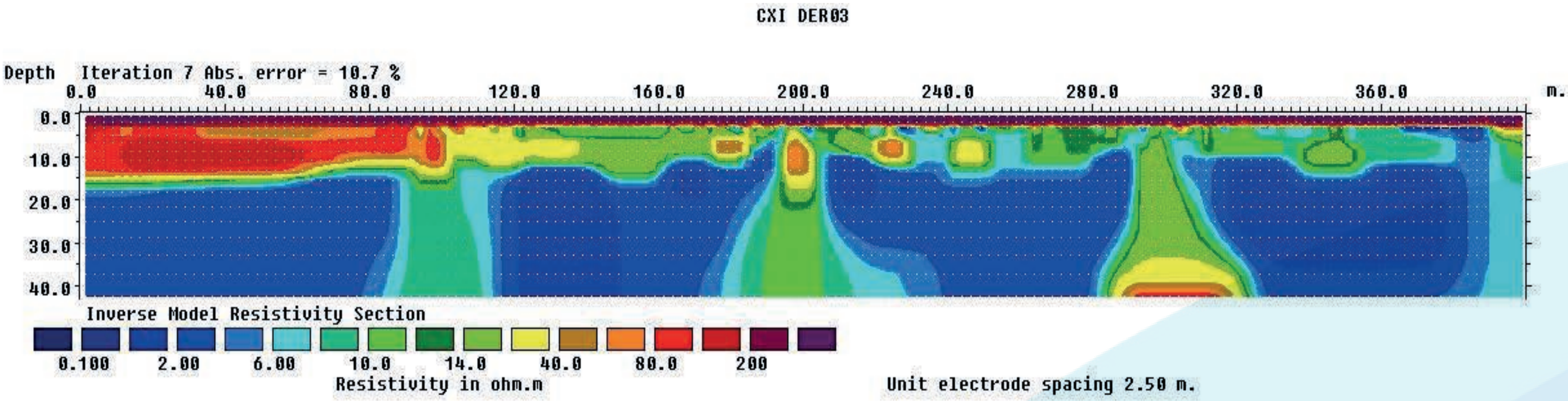

Figure A1.4. *DER04 survey line, oriented S-N, north of Decca gallery 4.*

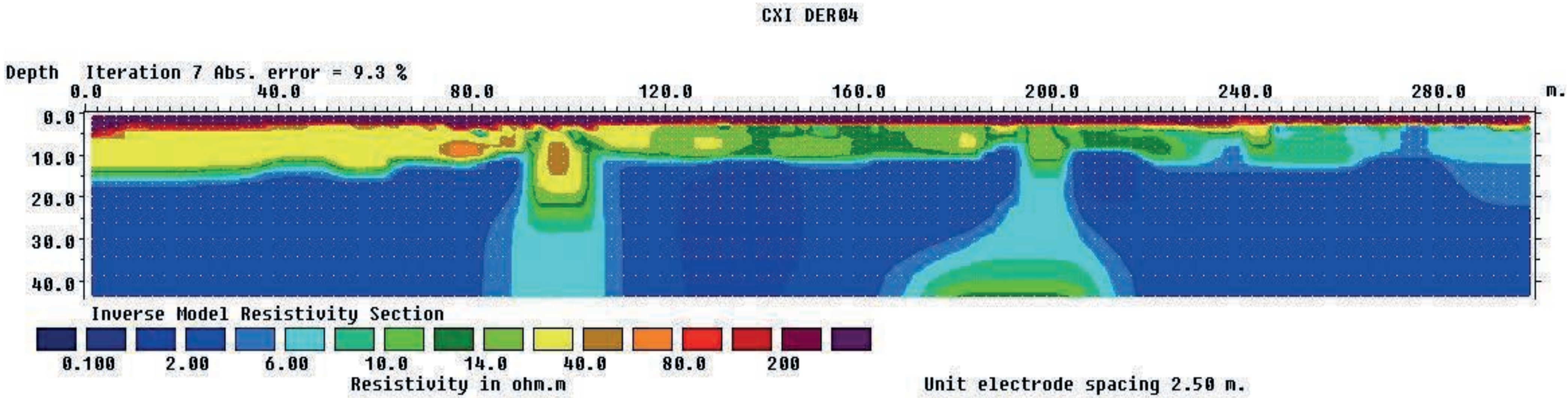

Figure A1.5. DER04 survey line, oriented S-N, completed north of Decca.

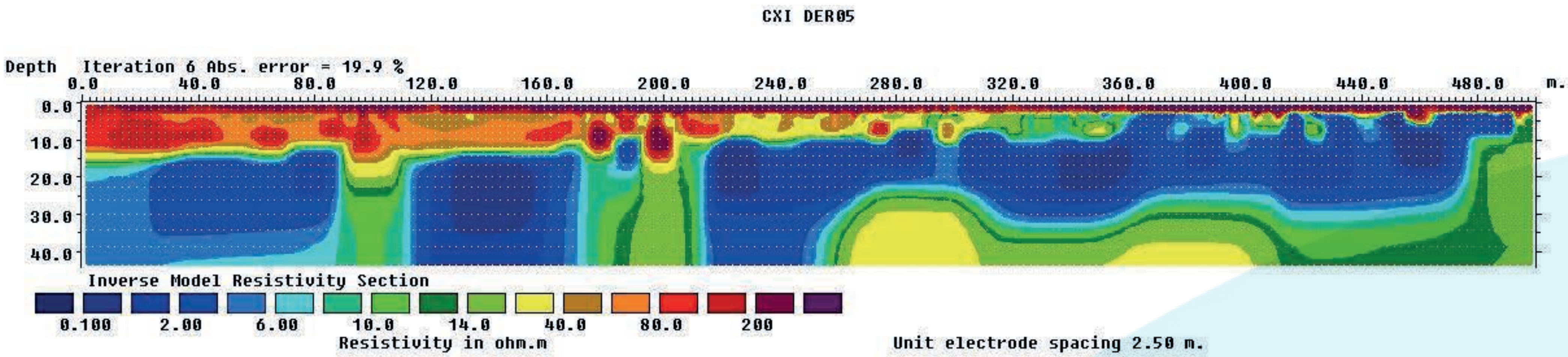

Figure A1.6. DER05 survey line, oriented S-N in Decca.

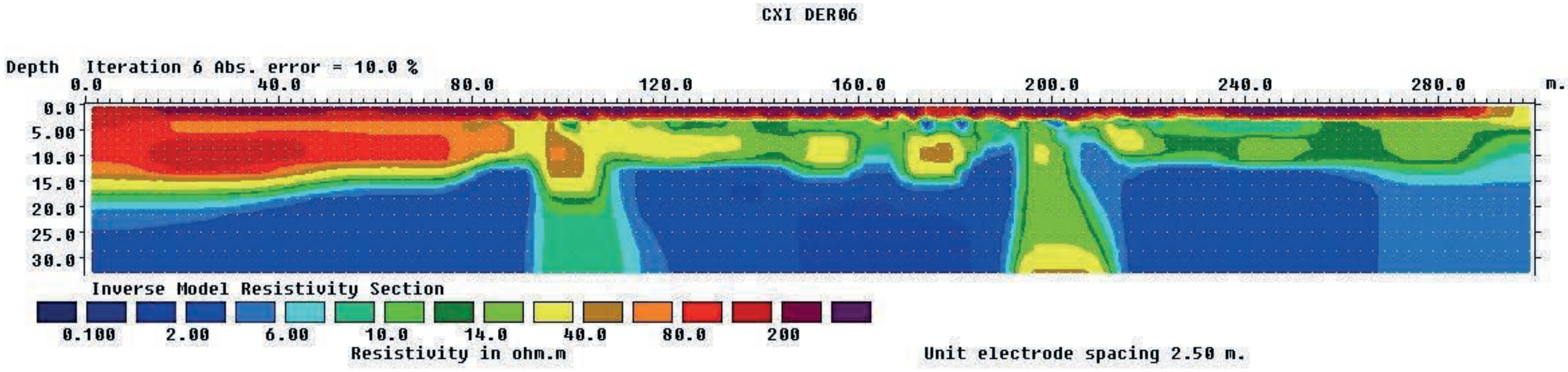

Figure A1.7. *Result from survey line DER06, oriented S-N, in Decca.*

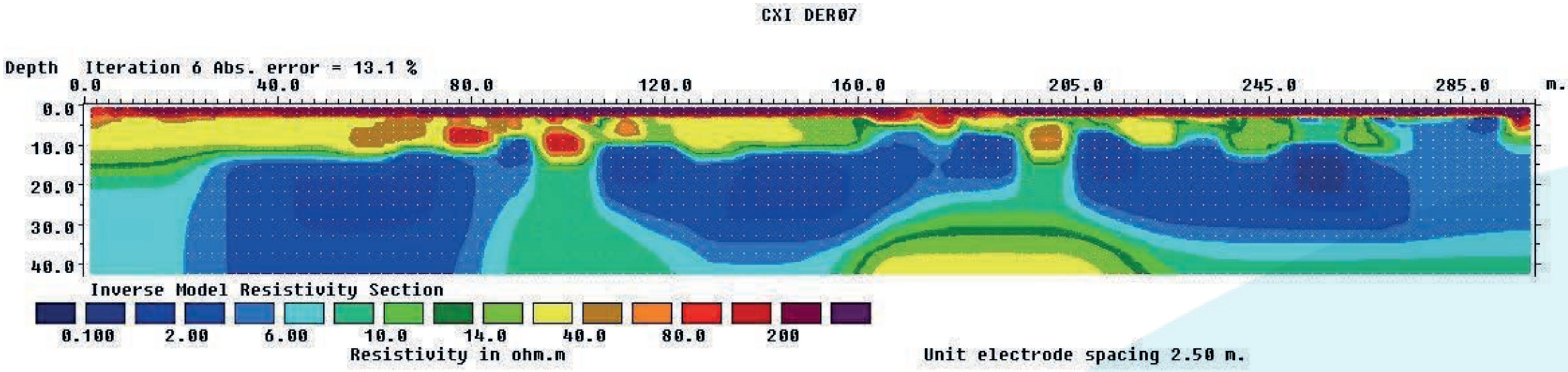

Figure A1.8. *Results from survey line DER07, oriented S-N, in Decca.*

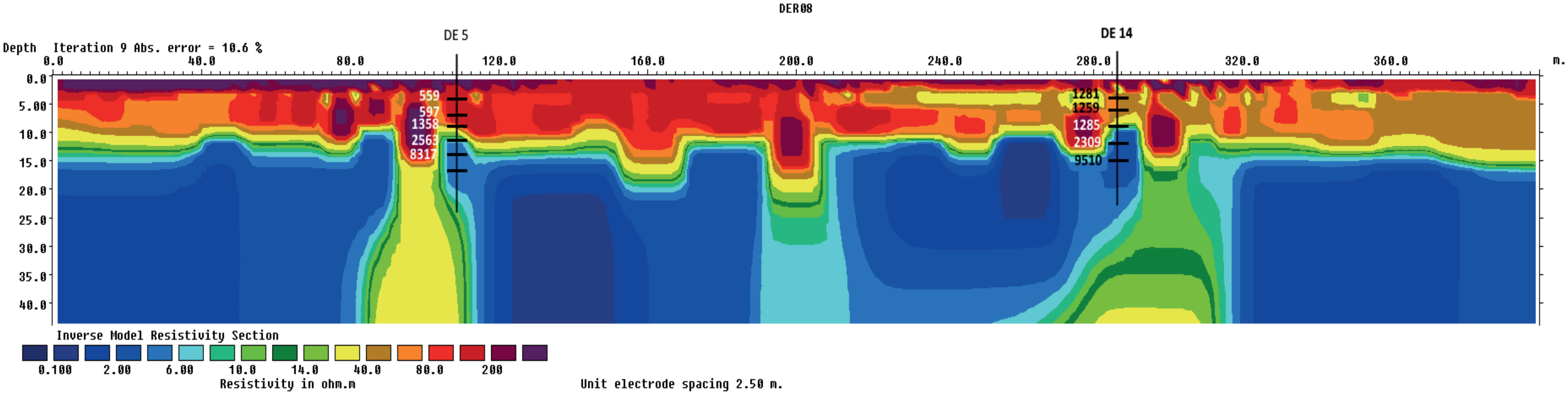

Figure A1.9. Result from survey line DER08, oriented S-N and crossing bores DE5 and DE14, in Decca.

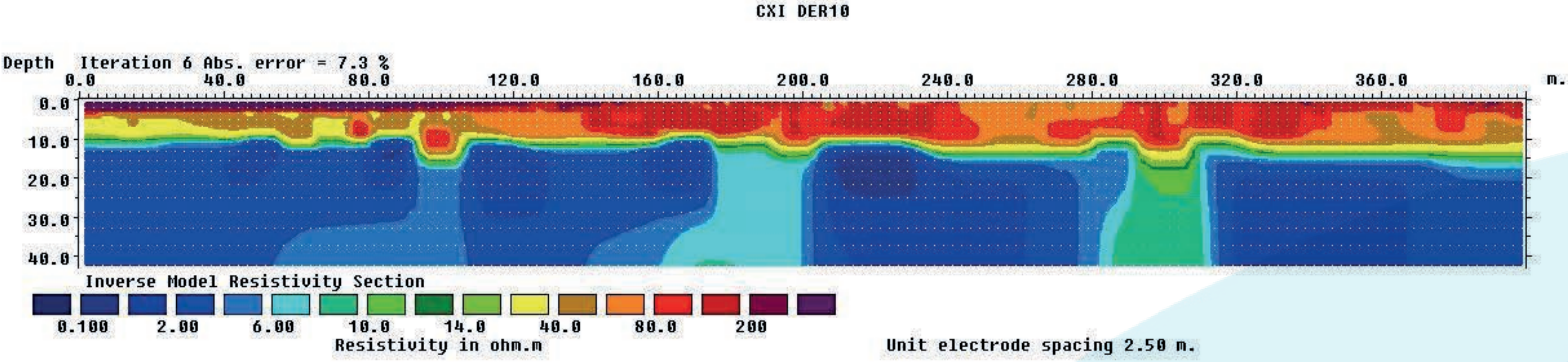

Figure A1.10. Survey results from line DER10 from Decca.

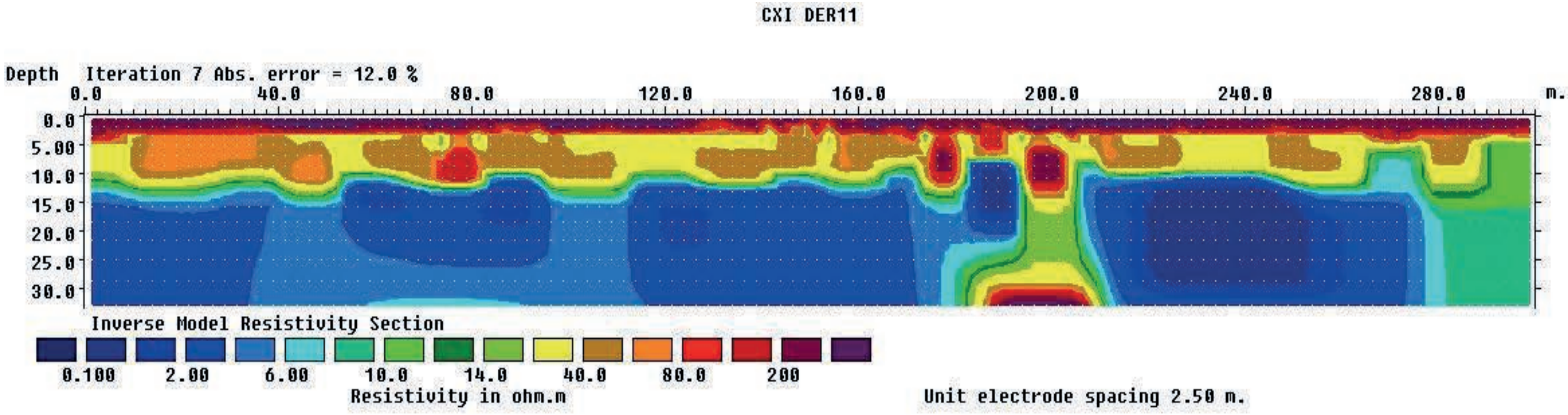

Figure A1.11. Results from survey line DER11 in Decca.

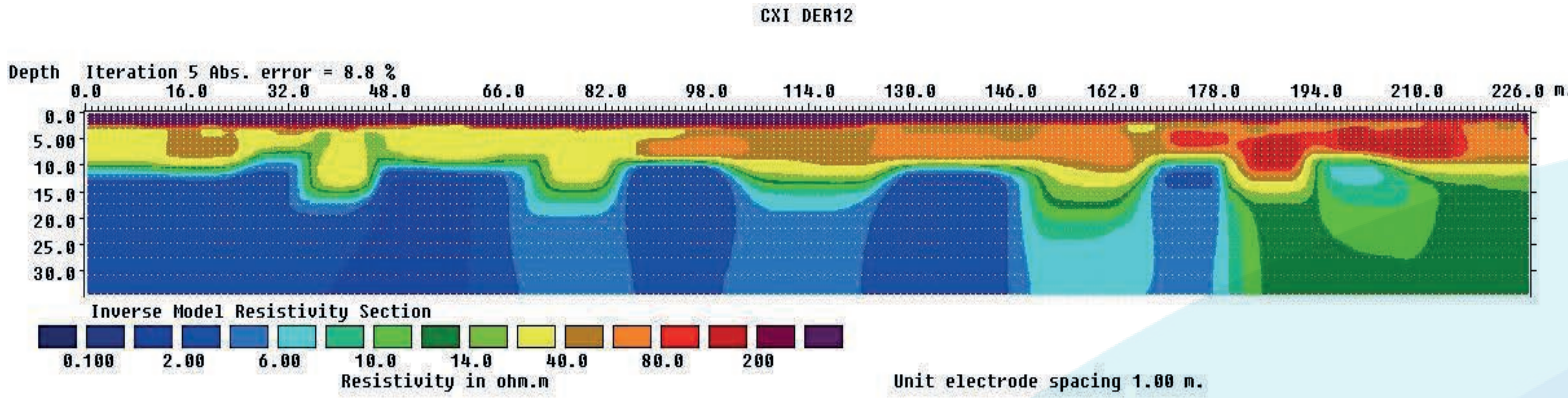

Figure A1.12. Results from survey line DER12 in Decca.

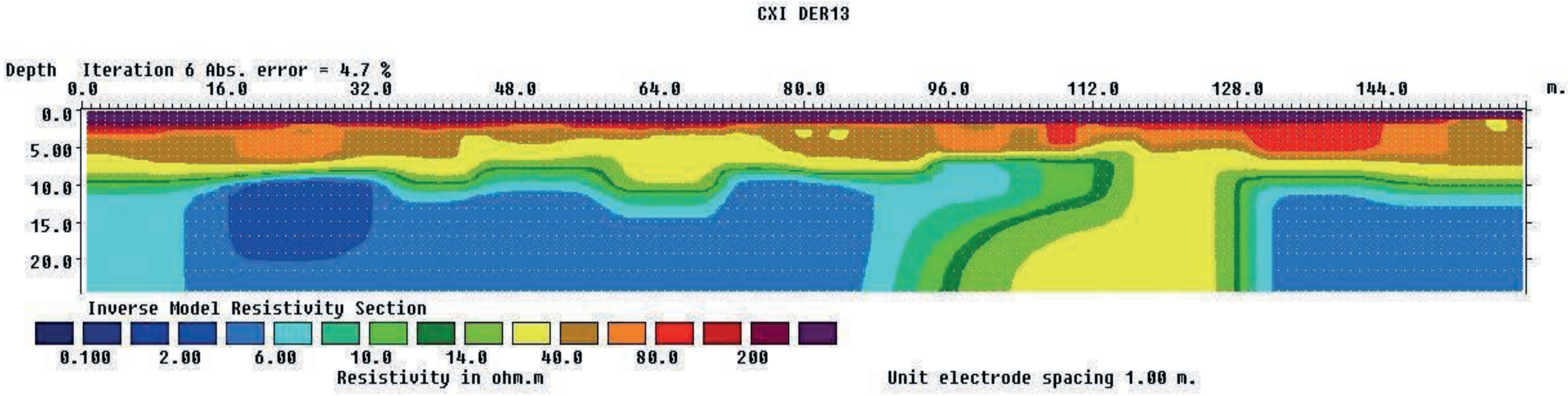

Figure A1.13. Results from survey line DER13 in Decca.

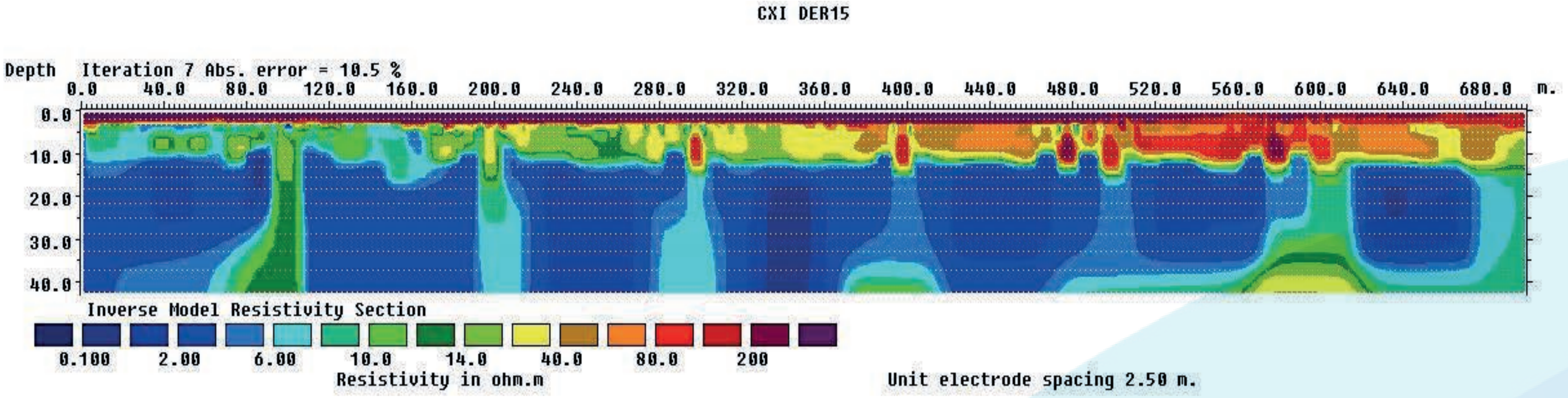

Figure A1.14. Results from survey line 15.

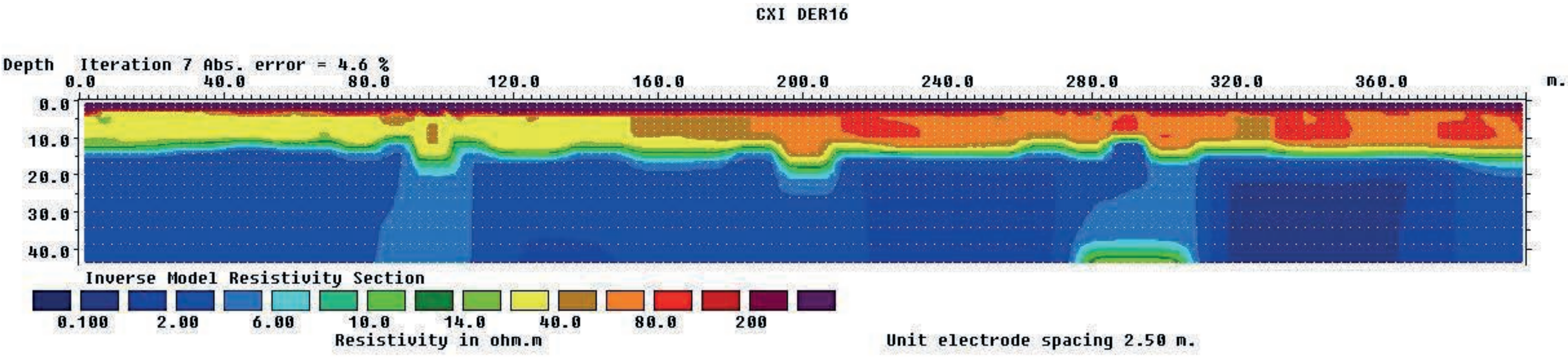

Figure A1.15. Results from survey line DER16 in Decca.

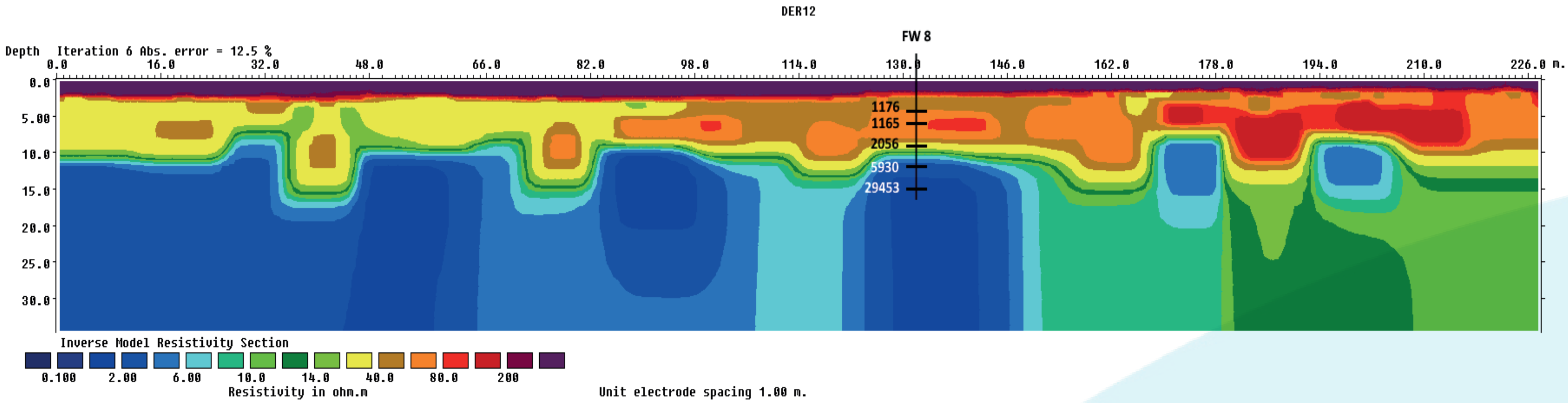

Figure A1.16. Result from survey line DER12, oriented S-N and crossing bore FW8, in Decca.

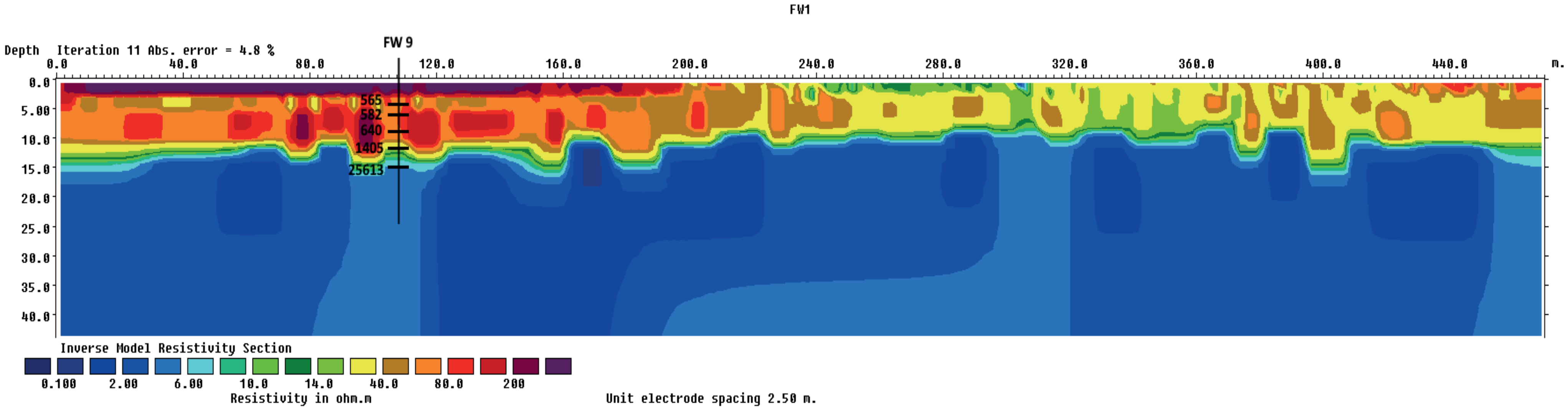

Figure A1.17. *Result from survey line FW1, oriented S-N and crossing monitoring bore FW 9, in Four Wells.*

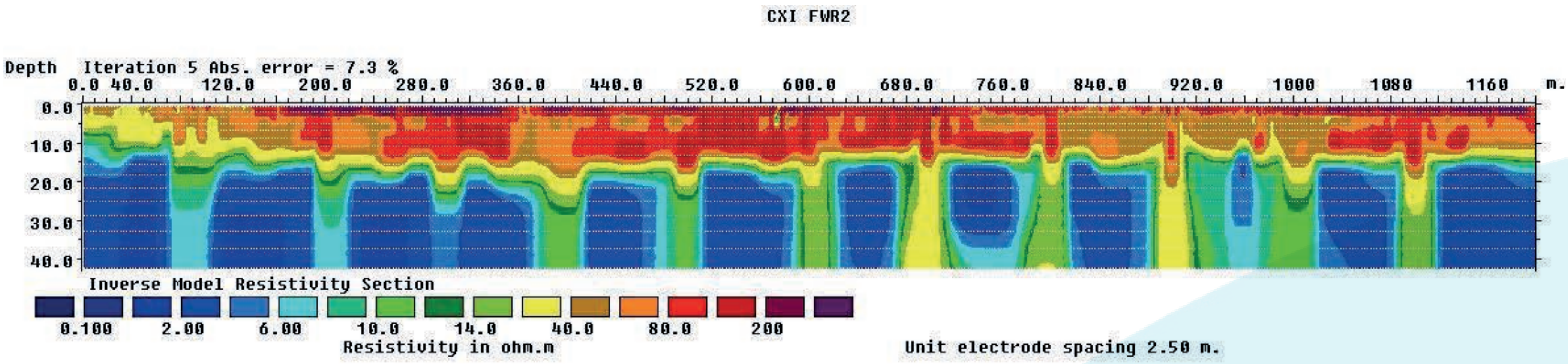

Figure A1.18. *Result from survey line FWR2, oriented S-N, in Four Wells.*

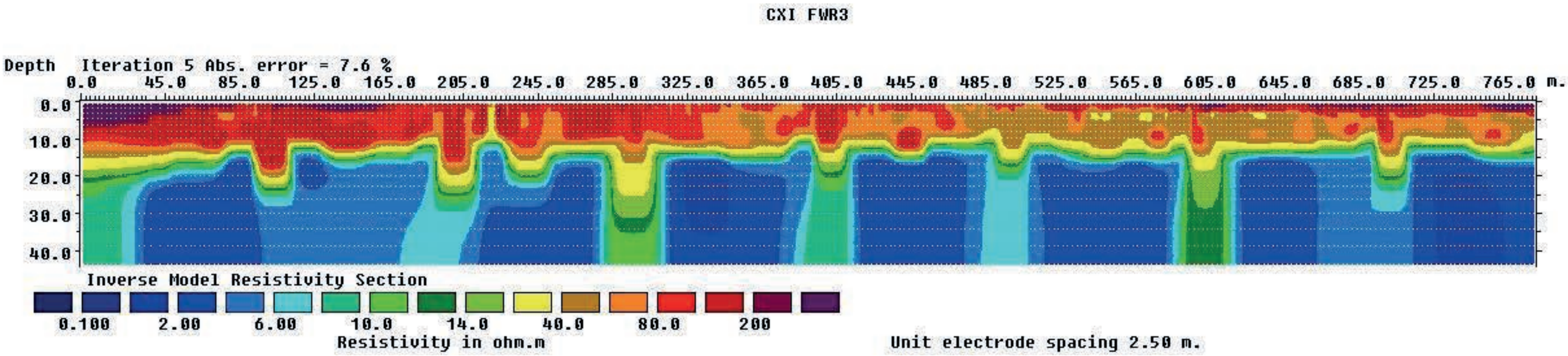

Figure A1.19. Result from survey line FW3, oriented S-N, in Four Wells.

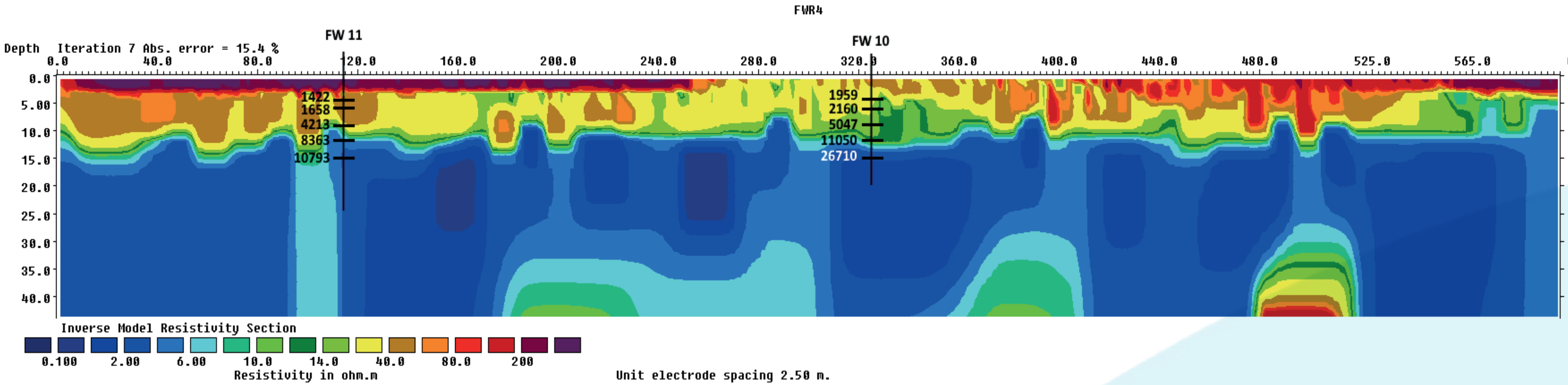

Figure A1.20. Results from survey line FW4, oriented S-N and crossing monitoring bores FW10 and FW11, in Four Wells.

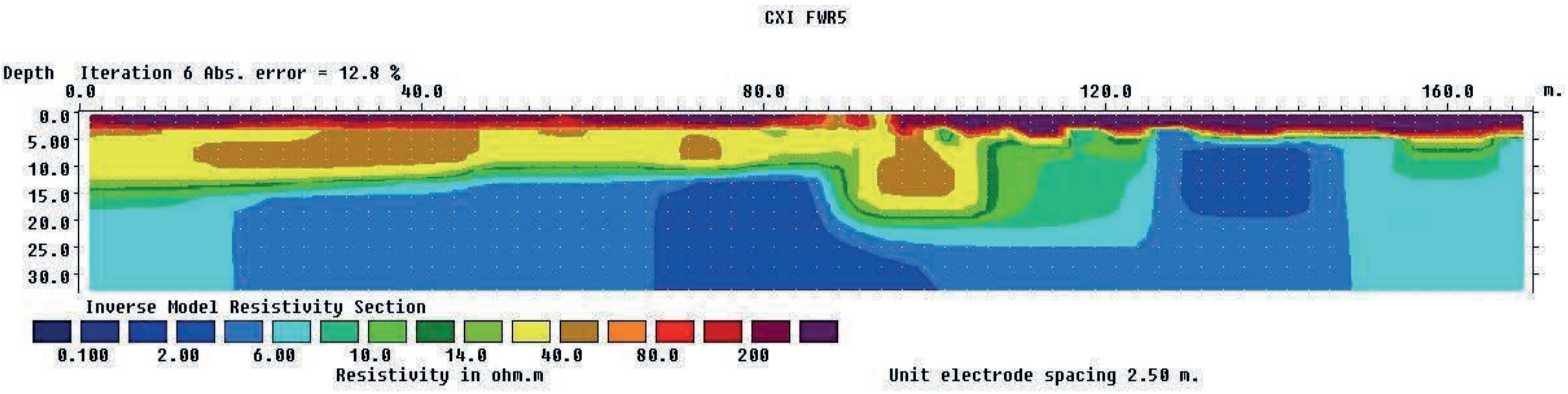

Figure A1.21. Result from the survey line FWR5 in Four Wells.

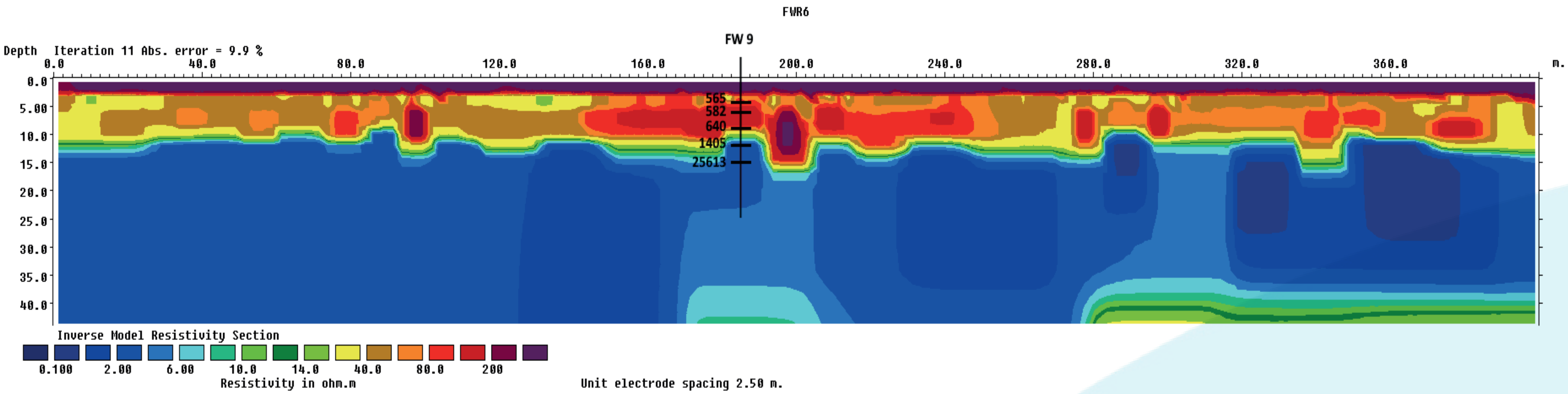

Figure A1.22. Result from the survey line FWR6, oriented W-E and cantered around monitoring bore FW9, in Four Wells.

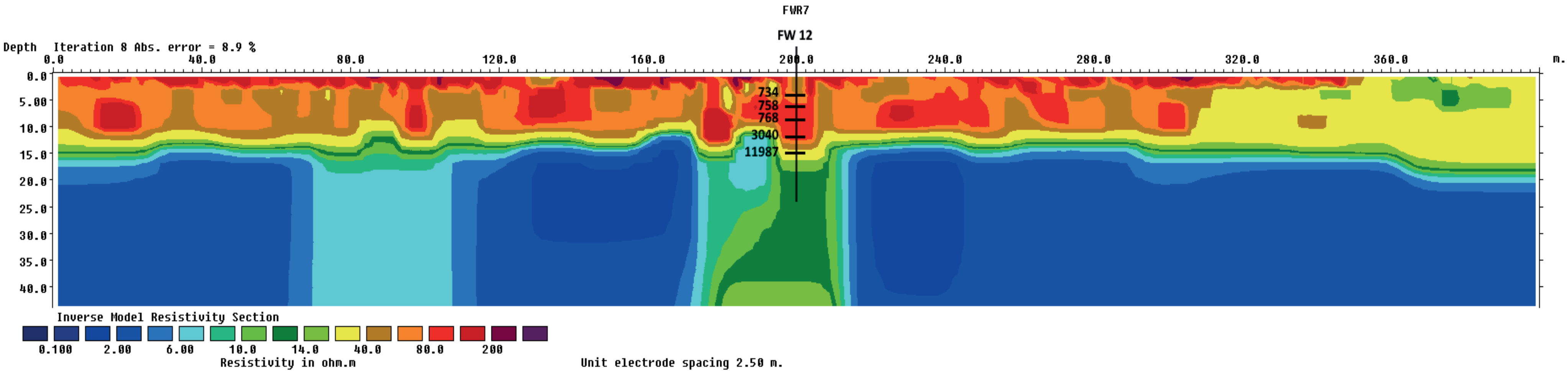

__Figure A1.23.__ Result from the survey line FWR7, oriented W-E and centred around monitoring bore FW12, in Four Wells.

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