Mine Closure 2024 – AB Fourie, M Tibbett & G Boggs (eds)

doi:10.36487/ACG_repo/2415_50

Observations from a georesistivimeter for time lapse analysis (G.Re.T.A.) in a closed red mud tailings storage facility

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Abstract

The management and monitoring of closed tailings storage facilities in perpetuity requires different considerations compared to active operating facilities. At Gove, located in East Arnhem Land in the Northern Territory, Australia, red mud ponds have been capped to prevent infiltration of surface water and re-saturation of the tailings. It is expected that the phreatic surface will drop over time, making the tailings less saturated, particularly in the upper portion of the facility. For this reason, traditional phreatic surface monitoring with vibrating wire piezometers (VWPs) is not fit for purpose as they are not capable of accurately monitoring unsaturated conditions and they do not always function when re-saturated after dry periods. Closed sites also typically have fewer personnel on site and restricted or limited access, which makes autonomous monitoring systems that require little to no maintenance highly desirable.

To address the issue of monitoring unsaturated conditions in tailings, embankments and future cover systems, a trial of a georesistivimeter for time lapse analysis (G.Re.T.A.) instrument was conducted in the embankment of a closed and capped red mud pond at Gove. This monitoring system provides a resistivity profile of the selected area to assess the evolution of the water content in the embankment and underlying tailings. The instrument was installed in July 2023 and has been providing reliable data throughout the 2023/2024 wet season. The trial embankment was selected as it is an upstream raised embankment that is well instrumented, and it has had an observed elevated phreatic surface in the past and known managed seepage.

Initial observations of the data have shown a strong data correlation between the phreatic surface interpolated by G.Re.T.A. and the VWPs in the same section as well as a response to rainfall.

Keywords: *tailings storage facility, post-closure monitoring, phreatic surface monitoring*

1 Introduction

The ongoing management and monitoring of closed tailings storage facilities (TSFs) requires different considerations compared to active operating facilities. TSFs that store red mud, a byproduct of the bauxite refining process, are typically capped during closure to prevent infiltration of surface water and re-saturation of the tailings. It is expected that the phreatic surface will lower over time, making the tailings and embankment less saturated, particularly in the upper portion of the facility (Beier et al. 2023). Traditional phreatic surface monitoring through vibrating wire piezometers (VWPs) is not always fit for purpose for closure monitoring as the instrumentation is not capable of accurately monitoring unsaturated conditions and they do not always function when re-saturated after being dry for extended periods (Slope Indicator 2013). During the post-closure period, TSFs typically have fewer personnel on site and restricted or limited access, which makes autonomous monitoring systems that require little to no maintenance highly desirable in a closure setting.

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A georesistivimeter monitoring system is being trialled at Gove, located in East Arnhem Land in the Northern Territory, Australia, to test its capability in monitoring the conditions in an embankment of a closed red mud TSF. To verify the validity of the data it is being qualitatively compared to the results of standard VWP monitoring as well as its response to rainfall infiltration.

1.1 G.Re.T.A.

The georestivimeter for time lapse analysis (G.Re.T.A.) monitoring system utilises electric resistivity tomography to interpolate zones of saturation in the soil based on the change in soil resistivity that occurs due to variances in the moisture content and inherent resistivity properties of the soil (Tresoldi et al. 2020). G.Re.T.A. is coupled with a telemetry system that allows for connectivity with a cloud-based data management and interpretation system for near real-time monitoring. The cloud-based platform is maintained by the supplier and manages the data processing and measurement visualisations. The cloud platform also enables the uploading of other environmental monitoring data sources, such as weather stations and VWPs, which allows for the seamless integration of multiple monitoring systems.

Unlike traditional VWPs that provide discrete measurements to determine the groundwater level, G.Re.T.A. provides data across the entire profile being monitored and gives an estimate of the soil's water content, if some moisture samples of the materials have been provided, across the full profile. This profile enables an assessment of the evolution of water content in the profile and can aid in the identification of preferential flow paths indicating seepage and the formation of fractures (Tresoldi et al. 2020).

1.2 Climate

The Gove Peninsula is located in East Arnhem Land, on the northern coast of the Northern Territory. The climate is classified as monsoonal, which is characterised by hot, wet and humid summers and mild, drier winters. The wet season typically runs from November to May, with April being the wettest month on average (Bureau of Meteorology 2020). Thunderstorms and heavy rainfall events are common, and on average a cyclone is expected to pass near Gove every two years. The average annual rainfall from 2003 to 2022 was 1,217 mm, based on site weather stations.

1.3 Site selection

The TSF that was selected for the G.Re.T.A. trial was constructed in 1977, and underwent three stages of raises up until its closure in 2015 and capping in 2018. The G.Re.T.A. instrumentation transect is located near the downstream edge of the TSF's northern embankment crest (see Figure 1). The typical profile section of this embankment is shown in Figure 2, it is an upstream raised section that overlies red mud. The G.Re.T.A. system has been installed in a configuration that allows for measurements up to a depth of approximately 23 m at the midpoint of the transect. This means that the cross-section includes resistivity readings from embankment lifts, red mud and foundation materials. The embankment lifts are typically comprised of dispersive sandy silty clay material that has been compacted and the foundation is weathered laterite overlain by sandy silty clay.

Figure 1 G.Re.T.A. transect location (image source: Google Earth 2014)

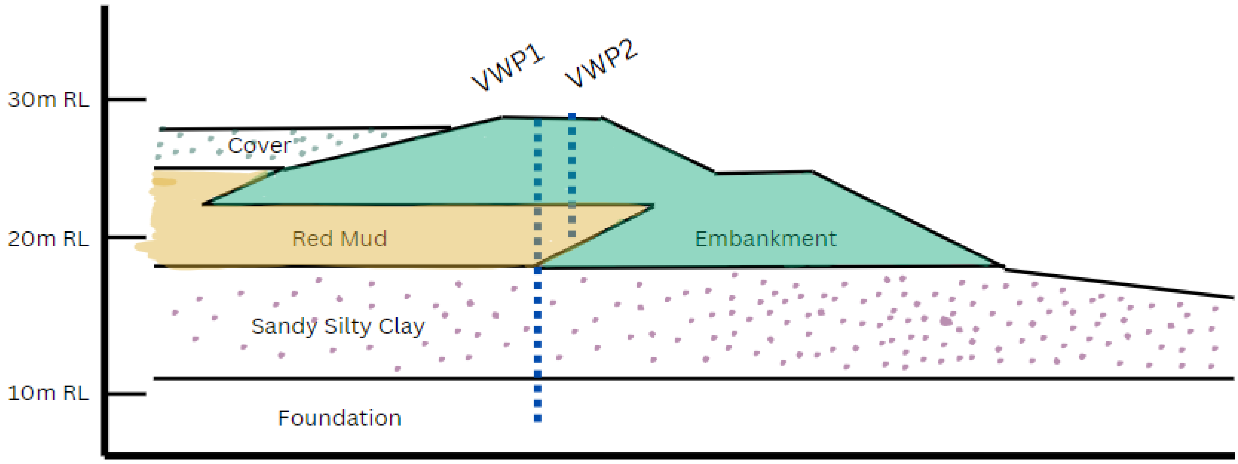

Figure 2 Typical embankment cross-section (not to scale)

1.4 Soil resistivity profiles

The red mud contains aluminium and other trace metals such as iron, titanium and vanadium, which means that it has a high conductivity and low resistivity (Khairul et al. 2019). Additionally, the red mud has an average moisture content of 60% in situ, which further reduces the resistivity of the material. The low resistivity of the soil does not adversely affect the G.Re.T.A. system's ability to interpolate phreatic surface within the material. It does, however, reduce the ability to interpolate some results from the data — such as preferential flow paths within the materials, as that requires significant differences in the material conductivity to interpolate confidently. The embankment material also appears to have low resistivity properties, likely due to the aluminium content that is naturally occurring in the area and interaction with the red mud over time.

1.5 Installation

The G.Re.T.A. system consists of an IP66 box (control box) attached to a 3 m pole and housing a 4G modem router, power unit, battery, main processing unit, signals driving unit, signals switching units and cable connections. Two 70.5 m-length cables, which run in opposite directions from the control box, are each attached to 24 electrodes. The unit also has a solar panel to recharge the battery and provide power to the system. The array creates a triangular depth profile, with the centre of the array being the deepest at 23.3 m and the shallowest at 0.8 m on each end.

The G.Re.T.A. system can be installed using electrode plates or rods, depending on the application that is desired. The Gove system utilises electrode plates that have been placed in a 141 m-long, 0.5 × 0.5 m trench at 3 m spacing (see Figure 3). Each electrode was covered with enough bentonite and soil mix to completely cover it. This was compacted with water to obtain a good connection between the electrodes and soil before the trench was backfilled with embankment material. The trench was surveyed to establish the vertical and horizontal location of the instrumentation. The electrodes were then connected to the control box located in the centre of the 140 m transect.

(a) (b)

Figure 3 Installation of electrode plates: (a) Electrodes attached to cable laid out in parallel to the trench; (b) The excavated trench before electrode installation

The G.Re.T.A. system was installed at the Gove TSF on 19 July 2023 to allow for the trial to be undertaken for a full wet season.

1.6 Data corroboration

The area that was selected at Gove for the field trial of the G.Re.T.A. system is well instrumented with VWPs in the same transect as the electrodes. This was determined to be advantageous to the project as it allows for corroboration of the data that is being received from the G.Re.T.A. system. The VWPs are installed at 21.7 m RL and 15.3 m RL, and are in the middle and eastern edge of the transect, respectively. The phreatic surface within the embankment is known to be responsive to rainfall events, with the installed VWPs showing fluctuations post rainfall events. An example resistivity profile with the integrated VWPs is shown in Figure 4.

In addition to the VWP data, site-specific rainfall data is collected and plotted with the G.Re.T.A. data to ascertain the system's response to rainfall events and the subsequent increase in soil moisture content.

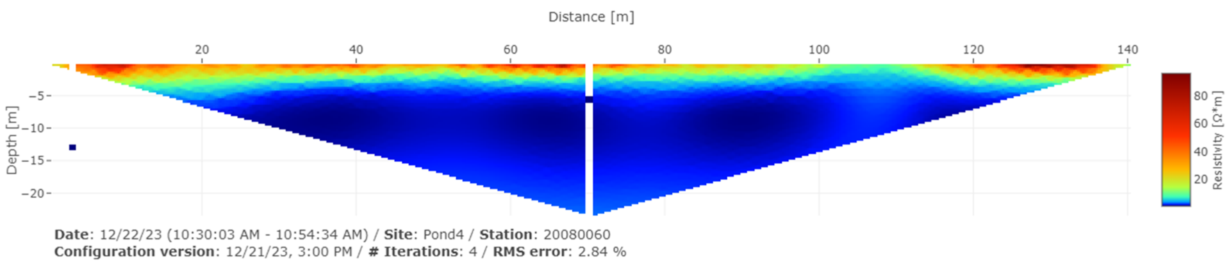

Figure 4 Resistivity profile with vibrating wire piezometers on 22 December 2023

2 Results

2.1 Rainfall infiltration

To better understand the profile's response to surface water infiltration, the average resistivity values were analysed for the top 4 m of the embankment transect only. Given that the phreatic surface is approximately 4–5 m below the embankment surface, according to VWP measurements, there will be little change in resistivity below 4 m due to the saturated conditions.

The average resistivity measurements over the full period of the G.Re.T.A. trial (22 July 2023 to 14 May 2024, as of writing) displayed in Figure 5 show that there are three distinct periods during the trial. From the end of July 2023 to the beginning of October 2023, the average resistivity value is increasing throughout the dry season. This is to be expected as the wet season ended two months prior, and the area experienced less frequent rain during this period. Between mid-October 2023 and mid-December 2023, the resistivity value remained relatively constant at approximately 17.6 Ωm for the final months of the dry season, when almost no rain was recorded. As the wet season began, the average resistivity is seen to decrease from mid-December 2023 through to mid-May 2024 as rainfall events occur more frequently.

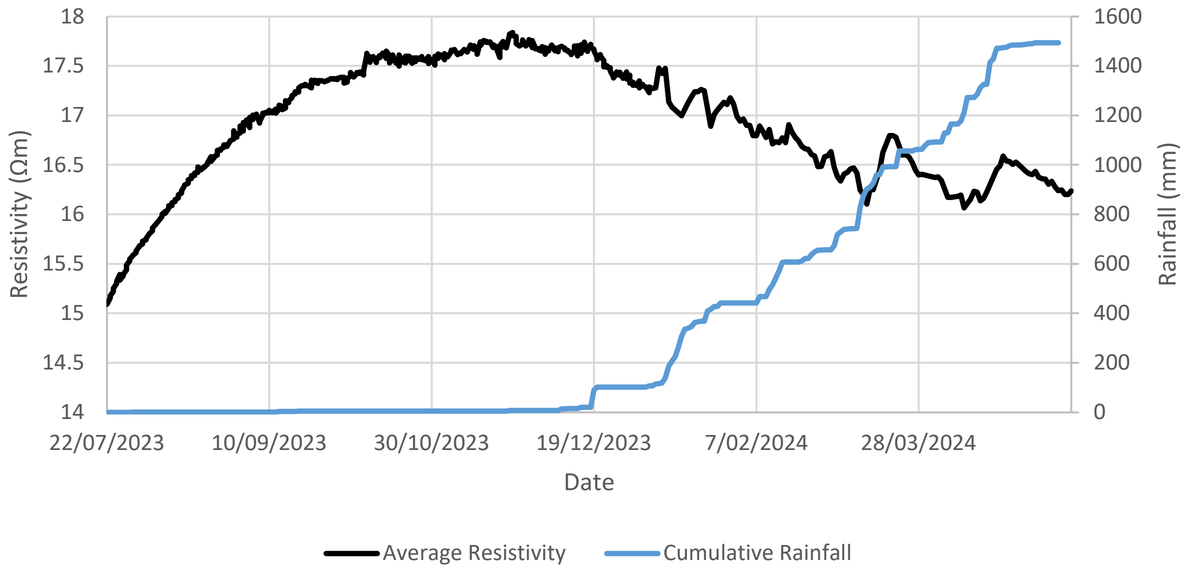

Figure 5 Graph of average resistivity in the top 4 m of the embankment and cumulative rainfall for the period between 22 July 2023 and 14 May 2024

The average resistivity in mid-May 2024 is still 8% higher than the beginning of the trial period, which is to be expected when comparing the phreatic surface in the embankment in the middle of the wet season versus in the middle of the dry season (see Table 1).

Table 1 Average resistivity for key dates during the trial period

Date	Average resistivity (Ωm)
22 July 2023	15.094373
1 October 2023	17.362224
22 December 2023	17.553459
14 May 2024	16.23483

Observing the resistivity profiles of the top 4 m of the transect for 22 July 2023 and 14 May 2024, shown in Figures 6 and 7, respectively, changes in the profile can be noted. This change between the beginning and end of the trial period is further exemplified in the change in resistivity profile in Figure 8. The blue areas indicate a decrease in resistivity, suggesting the presence of moisture due to rainfall in the wet season, as expected. However, most of the profile indicates an increase in resistivity which matches the increase of approximately 1 Ωm between the average resistivity in July 2023 and May 2024.

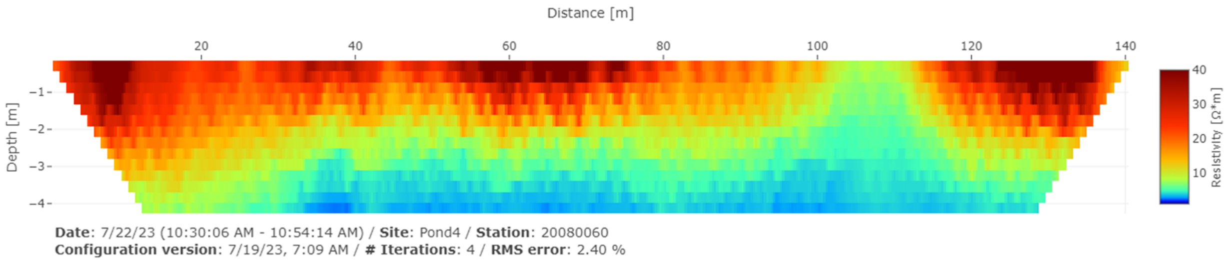

Figure 6 Resistivity profile (top 4 m) on 22 July 2023

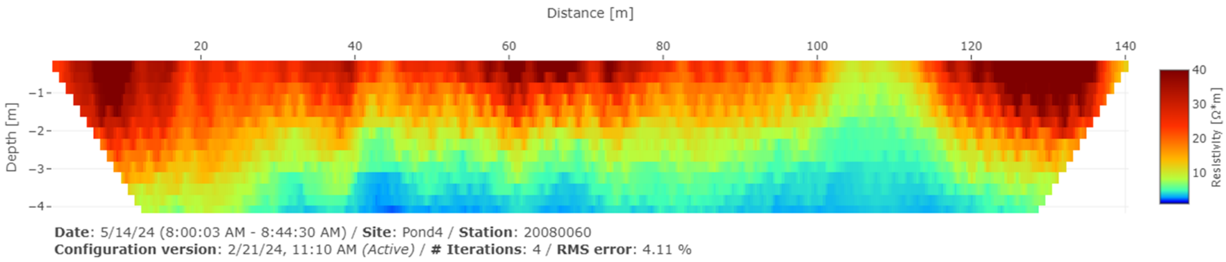

Figure 7 Resistivity profile (top 4 m) on 14 May 2024

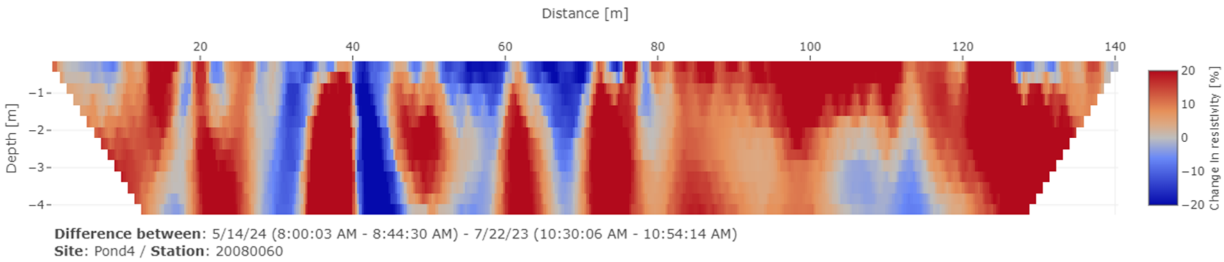

Figure 8 Change in resistivity (top 4 m) between 22 July 2023 and 14 May 2024

The relationship between rainfall and resistivity in the top 4 m of the embankment can be further exemplified by observing three different scenarios: a dry period; a dry to wet to dry period; and a wet period.

Figure 9 shows the average resistivity and cumulative rainfall for the first week of November 2023, noting that no rainfall occurred in October 2023 so there is no residual rainfall infiltration in the lead up to 1 November 2023. It is evident that when there is no rainfall the resistivity measurement is steady.

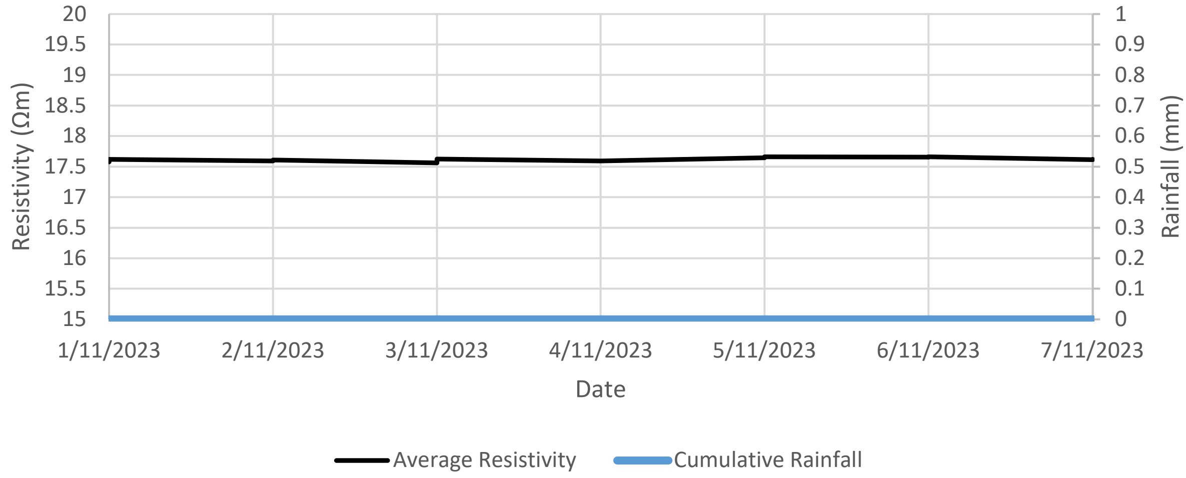

Figure 9 Graph of average resistivity in the top 4 m of the embankment and cumulative rainfall for the period between 1 November and 7 November 2023

Similarly, when comparing the resistivity profiles of the top 4 m of the embankment between 1 and 7 November 2023 (see Figures 10 and 11, respectively), there is not a notable difference in the two profiles. This is confirmed by Figure 12, which shows less than ± 5 % change in resistivity within the profile.

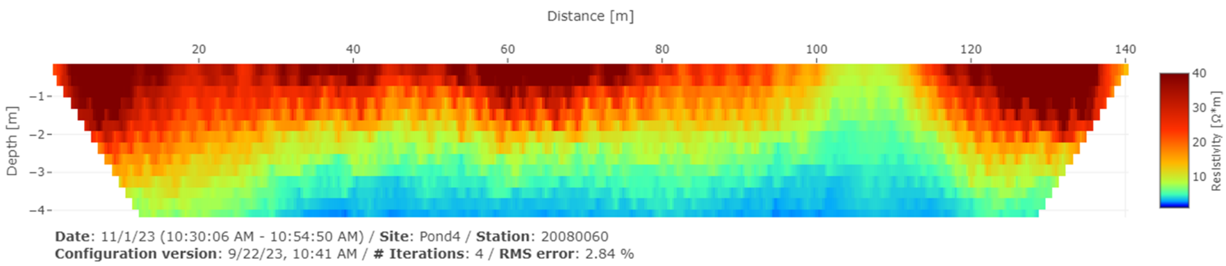

Figure 10 Resistivity profile (top 4 m) on 1 November 2023

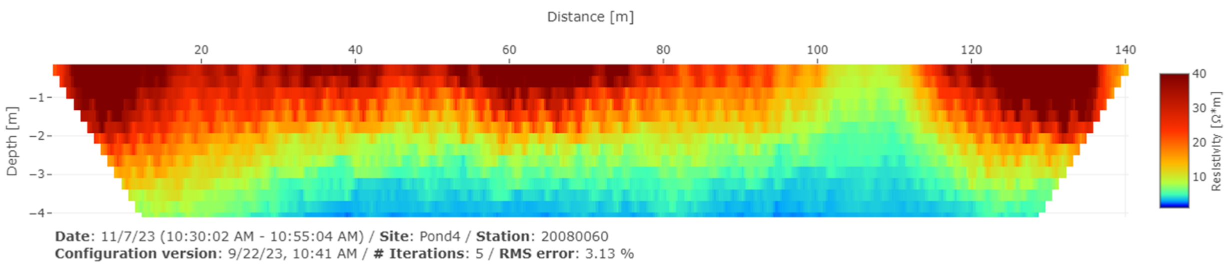

Figure 11 Resistivity profile (top 4 m) on 7 November 2023

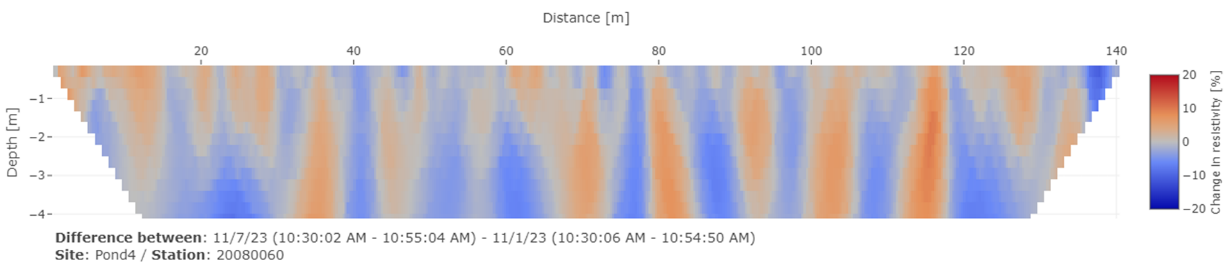

Figure 12 Change in resistivity (top 4 m) between 1 and 7 November 2023

Figure 13 shows results from 1 December 2023 to 4 January 2024, which had a period of no rainfall for a week between 1 and 8 December 2023, then experienced rainfall on and off between 9 and 21 December 2023. This was followed by another two weeks with no rainfall.

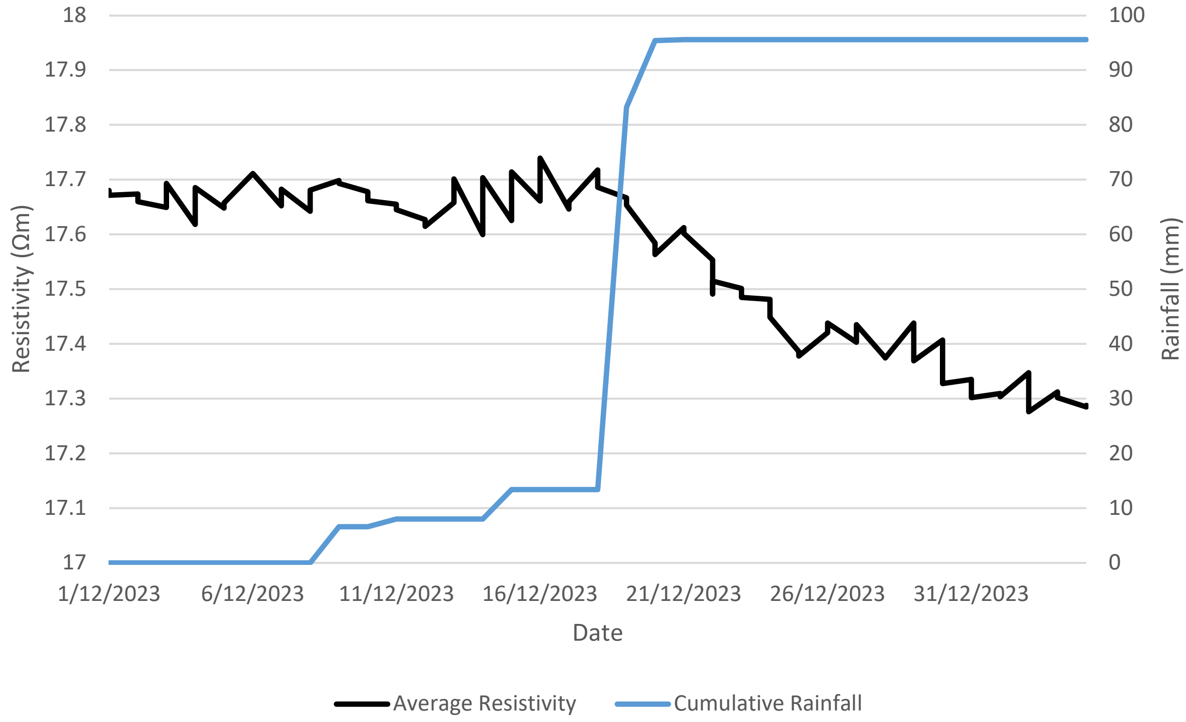

Figure 13 Graph of average resistivity in the top 4 m of the embankment and cumulative rainfall for the period between 1 December 2023 to 4 January 2024

A small spike can be observed in the average resistivity value following the initial dry period, however, the response in the resistivity reading following rainfall is more evident. After the rainfall between 9 and 21 December 2023 there is a clear decline in resistivity values during the no-rainfall period in the following two weeks, which indicates an increase in moisture content. This is to be expected as water would be infiltrating through the embankment following a period of rainfall.

There are subtle changes in the resistivity profile of the top 4 m of the embankment between 1 December 2023 and 4 January 2024 that indicate some drying in the top section of the embankment as rainwater infiltrated through to the lower portion of the embankment two weeks after rainfall occurred (see Figures 14 and 15, respectively). This is further exemplified in Figure 16, which shows an overall decrease in resistivity that indicates areas of infiltration and some patches of higher resistivity where drying occurred.

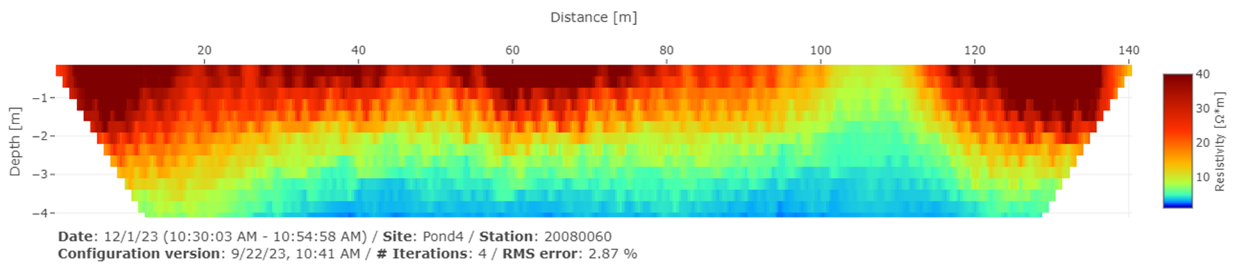

Figure 14 Resistivity profile (top 4 m) on 1 December 2023

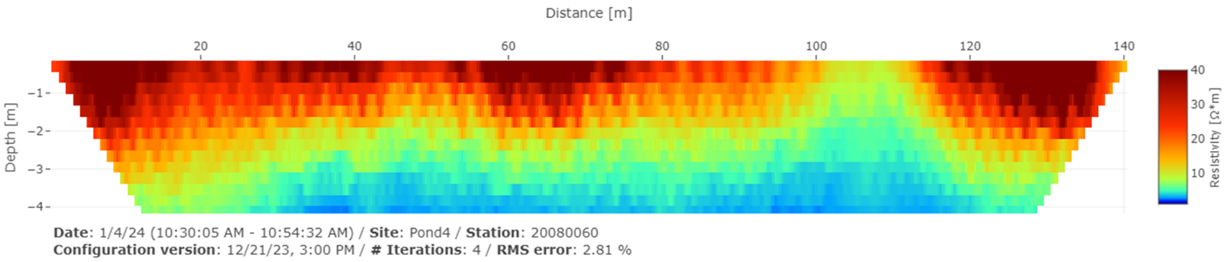

Figure 15 Resistivity profile (top 4 m) on 4 January 2024

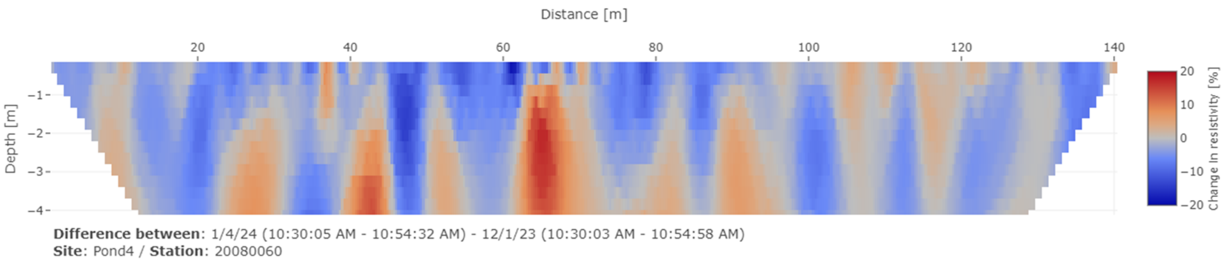

Figure 16 Change in resistivity (top 4 m) between 1 December 2023 and 4 January 2024

Similar observations are also seen when analysing the period between 1 April and 10 May 2024, which is during the Gove wet season and predominantly has days with rainfall (see Figure 17). A decrease can be seen in the resistivity values until 16 April 2024 as the cumulative rainfall increases. A slight increase occurs until 23 April 2024, which may be due to several instances of no rainfall in the previous days. However, as the cumulative rainfall continues to increase from 23 April to 10 May 2024 there is a clear decline in resistivity values.

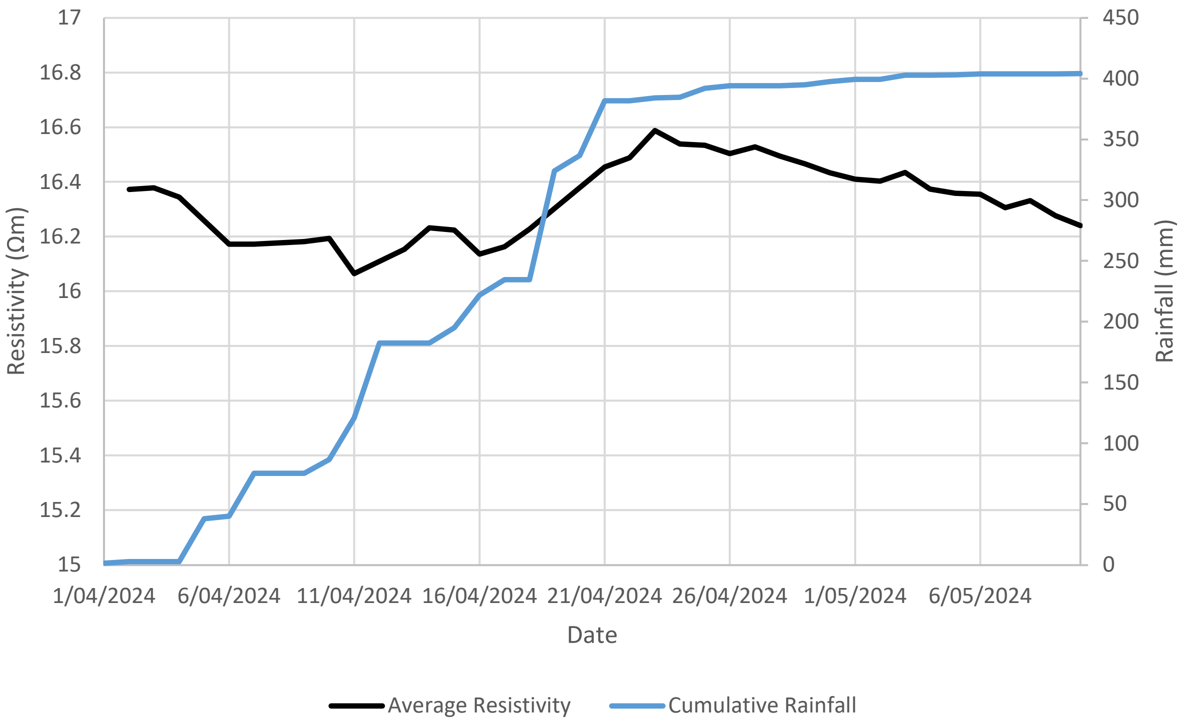

Figure 17 Graph of average resistivity in the top 4 m of the embankment and cumulative rainfall for the period between 1 April and 10 May 2024

While it is difficult to observe the changes in the resistivity profiles when comparing Figures 18 and 19, Figure 20 clearly demonstrates that there were changes in the resistivity profile between 2 April and 10 May 2024, with predominantly a decrease in resistivity.

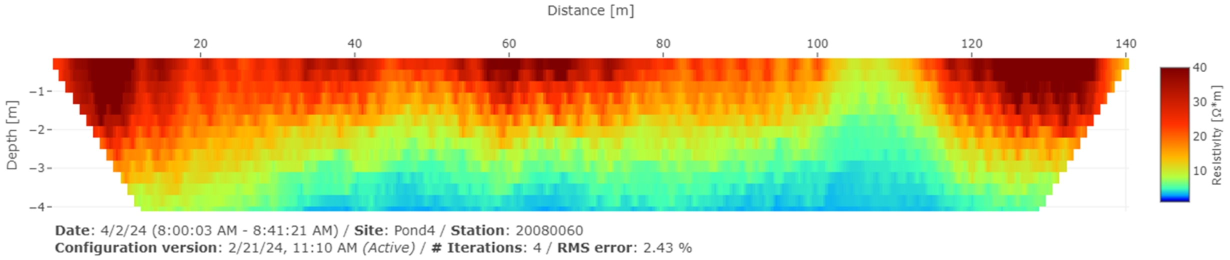

Figure 18 Resistivity profile (top 4 m) on 2 April 2024

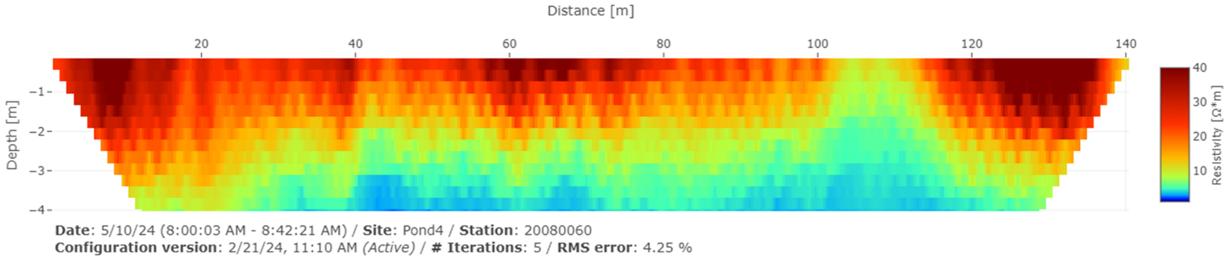

Figure 19 Resistivity profile (top 4 m) on 10 May 2024

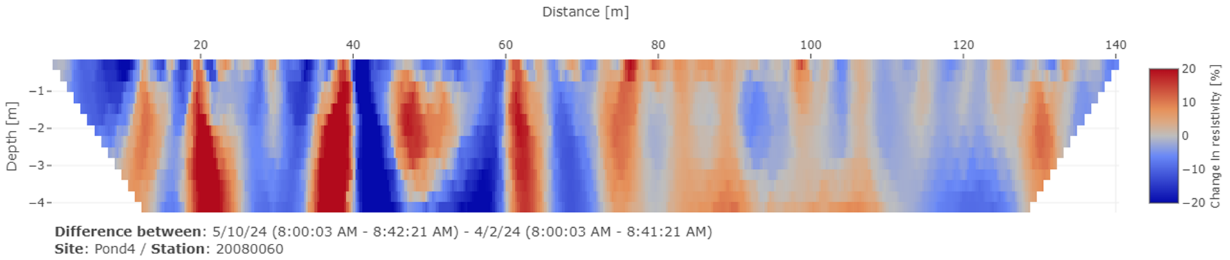

Figure 20 Change in resistivity (top 4 m) between 2 April and 10 May 2024

2.2 Phreatic surface level

The G.Re.T.A. system has also shown a strong correlation between the phreatic surface level shown in the resistivity profiles and the porewater measurements from the site VWP uploaded to the cloud platform (VWP 2 at an approximately 70 m distance in the resistivity profile). On the profile, as shown in Figure 21, the resistivity decreases with depth in the top of the embankment until a depth of around 4–5 m. Below this zone the resistivity remains consistent, with resistivity values less than 5 Ωm throughout the lower profile, which is interpreted as saturated soil. Therefore, the area depicted by the green to blue transition between approximately 4 to 5 m demonstrates the phreatic surface level. Comparing this area to the VWP measurement, although it is a discrete point, shows that there is a correlation between the demonstrated and measured phreatic surface. This correlation has been noted throughout the trial period and is demonstrated in the resistivity profiles shown in Figures 21 to 25. These profiles have been taken from days within the analysed periods discussed in Section 2.1.

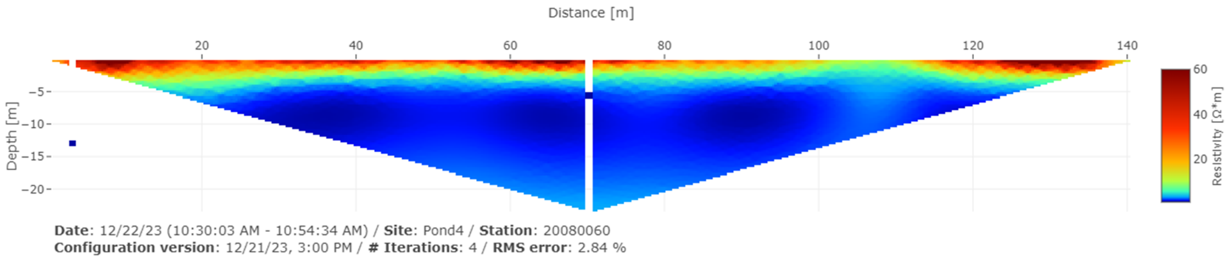

Figure 21 Full resistivity profile on 22 December 2023 (day of VWP integration with cloud platform)

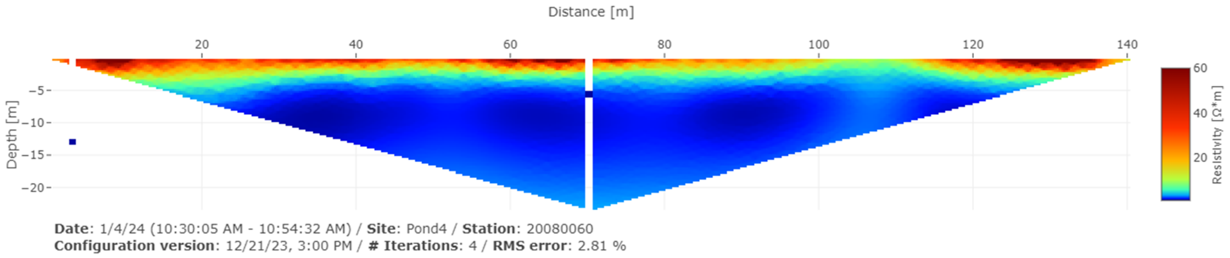

Figure 22 Full resistivity profile on 4 January 2024

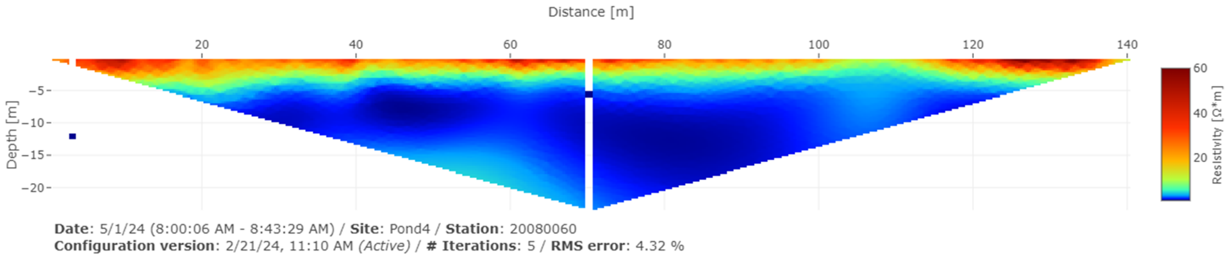

Figure 23 Full resistivity profile on 1 May 2024

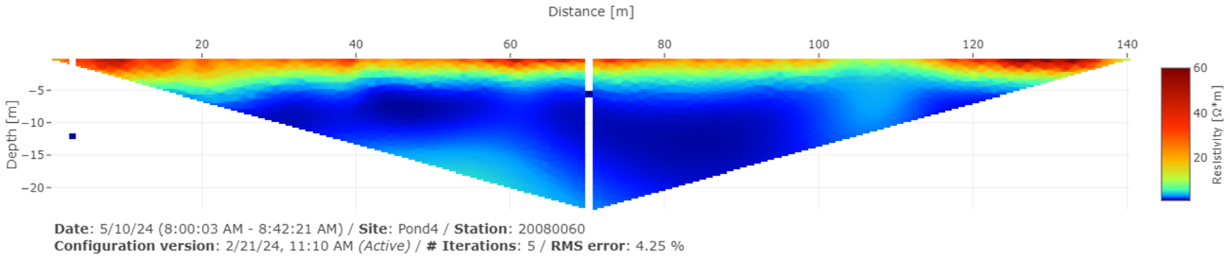

Figure 24 Full resistivity profile on 10 May 2024

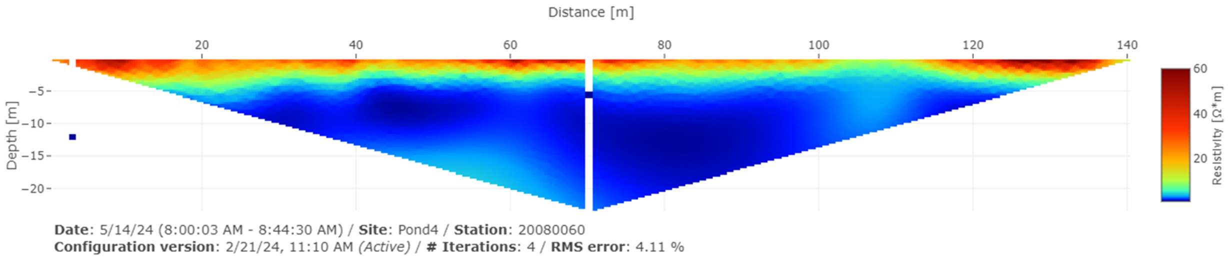

Figure 25 Full resistivity profile on 14 May 2024

The correlation between the interpolated and measured surface can also be seen when comparing the VWP porewater pressure measurements with the average resistivity values for the area in line with VWP 2 at this same elevation for the same scenarios as in Section 2.1

Figure 26 shows the change in phreatic surface elevation and average resistivity over the trial period. As the phreatic surface elevation decreases throughout the period of August to December 2023 (which is the end of the dry season), an increase in resistivity is also observed. Then both values have smaller variations between December 2023 and January 2024. Due to a gap in VWP measurements from early February 2023 to late March 2023, comment cannot be made on the correlation with resistivity values during this period.

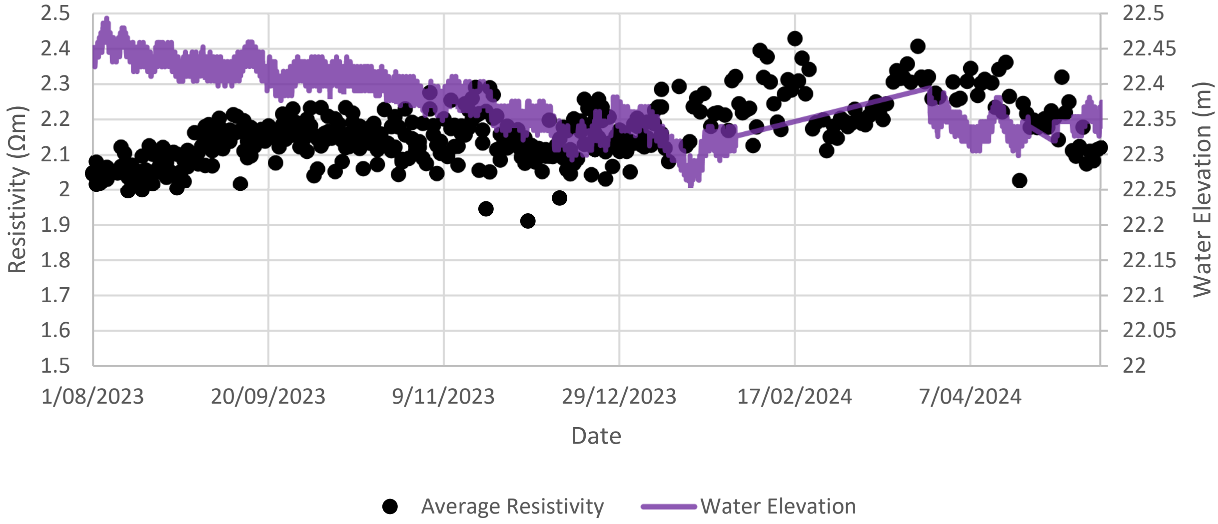

Figure 26 Graph of average resistivity at the phreatic surface identified by VPW 2 and phreatic surface elevation for the period between 1 August 2023 and 14 May 2024

During the week between 1 and 7 November 2023 when no rainfall occurred, the phreatic surface elevation remained constant, with values ranging between 22.25 and 22.4 m. During this time the average resistivity remained constant, as demonstrated in Figure 27.

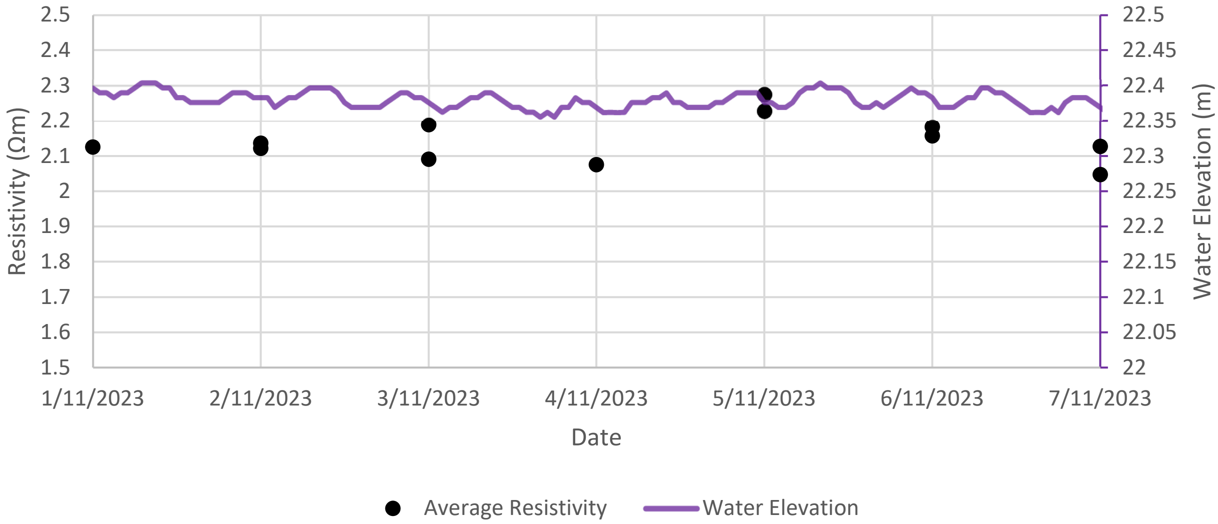

Figure 27 Graph of average resistivity at the phreatic surface identified by VWP 2 and phreatic surface elevation for the period between 1 and 7 November 2024

Figure 28 shows the results between 1 December 2023 and 4 January 2024. Both measurements stay consistent during the first week with no rainfall and there is a slight decrease in the phreatic surface level following this as the embankment dries. A slight increase in resistivity is also observed during this time. Although rainfall occurred between 9 and 21 December 2023 there is a delayed response in phreatic surface elevation as the rainfall infiltrates the embankment and an increase in phreatic surface elevation is seen between 18 and 27 December 2023. During this time a decrease in resistivity values is apparent. Following this, both values remain consistent again as no rainfall occurred in the remaining time.

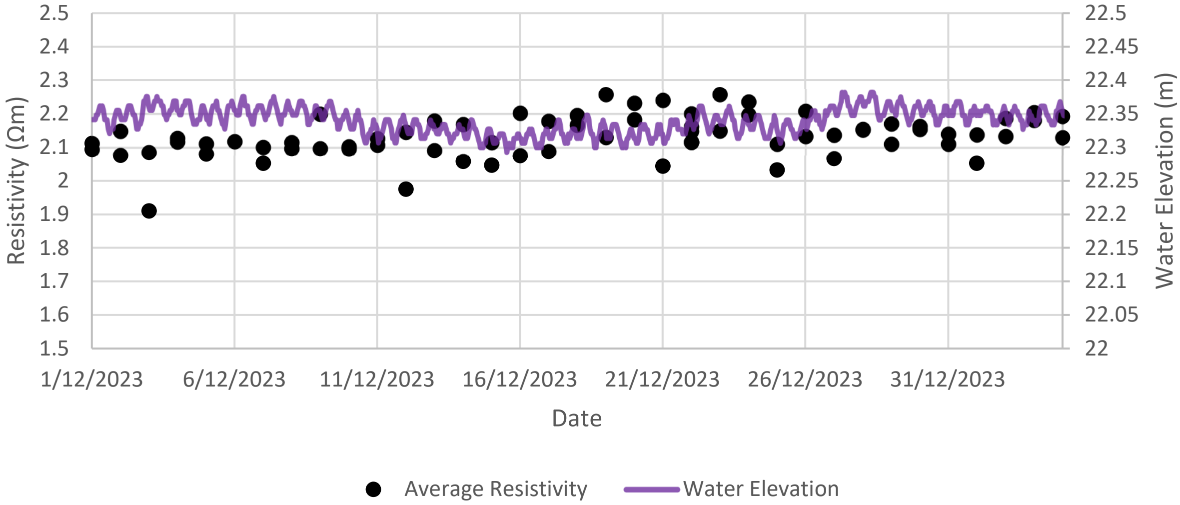

Figure 28 Graph of average resistivity at the phreatic surface identified by VWP 2 and phreatic surface elevation for the period between 1 December 2023 and 4 January 2024

The correlation is less evident during the entire April/May 2024 period, as shown in Figure 29, due to the missing VWP data. However, the period between 1 and 16 April 2024 still demonstrates the expected behaviour. Between 1 and 7 April 2024 the phreatic surface elevation decreased and we see a corresponding rise in the average resistivity value. Then between 7 and 16 April 2024 the phreatic surface elevation increased and the average resistivity generally decreases. Similarly, there is a rise and fall in the phreatic surface elevation between 6 and 14 May 2024, during which time there is also a corresponding decrease then increase in average resistivity values.

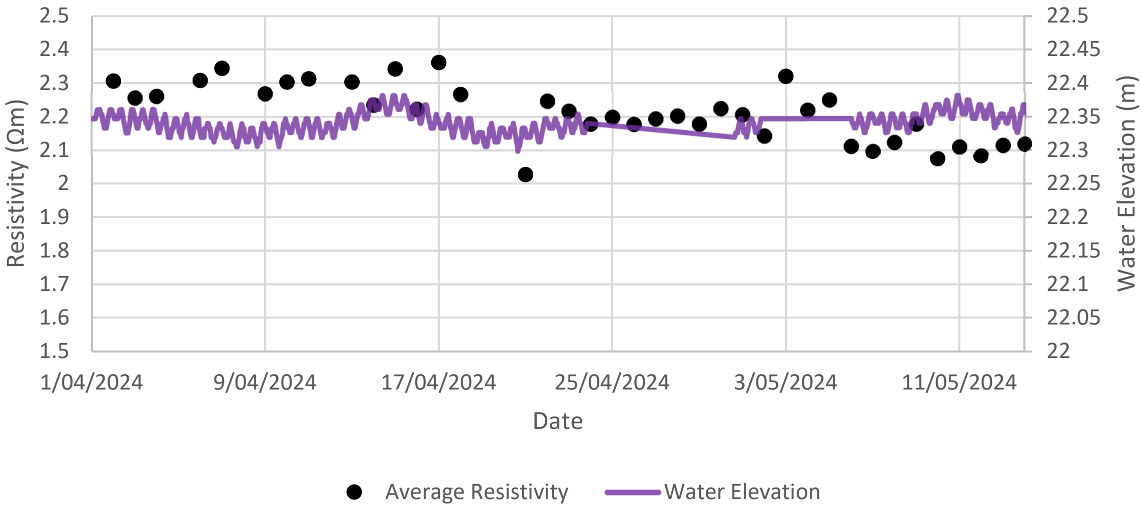

Figure 29 Graph of average resistivity at the phreatic surface identified by VWP 2 and phreatic surface elevation for the period between 1 April and 14 May 2024

3 Conclusion

The trial of the G.Re.T.A. system in the closed red mud TSF at Gove has demonstrated its effectiveness in monitoring phreatic surface levels and interpreting soil moisture dynamics, despite the challenges posed by the high conductivity and low resistivity of red mud. The system's integration with porewater measurements from the site VWPs has confirmed a strong correlation between resistivity profiles and the VWP phreatic surface levels. This correlation is evident across various wet and dry scenarios and over different periods, indicating the system's reliability in tracking phreatic surface fluctuations as well as moisture changes if calibrated with a soil sample.

The resistivity profiles consistently reflect the impact of rainfall infiltration on soil moisture within the embankment, displaying clear patterns of increased resistivity during dry periods and decreased resistivity during wet periods, as is expected. This behaviour is particularly visible in the top 4 m of the embankment, where rainfall infiltration is most rapid. However, the low resistivity nature of the soil and red mud reduces the system's ability to detect subtle features such as preferential flow paths.

For this reason, in the context of this trial, the G.Re.T.A. system was deemed more suitable for monitoring trends within the phreatic surface of the embankment than for monitoring day-to-day changes.

The next steps for the project are to obtain material samples to test for moisture content and to calibrate the system readings to provide moisture content interpretation. Moisture content of the soil is a valuable output for closure, particularly when monitoring cover system performance to assess parameters such as net percolation and soil suction.

In the overall closure context, the G.Re.T.A. system provides valuable data on variable recharge and phreatic surface drawdown that occurs in cover systems, embankments and tailings material via an autonomous system requiring little maintenance following installation.

Acknowledgement

We would like to acknowledge and thank Greta Tresoldi and Andrea Certo from L.S.I Lastem for their partnership during this trial and support in analysing the data. We also thank the Rio Tinto Research and Development team.

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