Clybucca Wetlands Water Quality Analysis

WRL TR 2025/04, October 2025

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Water Quality Analysis

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1 Introduction

1.1 Project background

The Clybucca Wetlands (hereafter “Clybucca”) are located on the Macleay River floodplain on the New South Wales (NSW) mid-north coast approximately 18 km upstream of the ocean entrance (see Figure 1-1 and Figure 1-2). The wetland area spans across approximately 15 km^2 of the Clybucca floodplain. Floodplain drainage works at Clybucca began in 1880 to remove standing water from the floodplain in an effort to facilitate and subsequently improve agricultural productivity. In 1893, a large flood resulted in the entrance of the Macleay River (formerly located at Grassy Head) to break out at South West Rocks (Telfer, 2005). The entrance was subsequently trained at this location reducing the distance of Clybucca to the ocean by approximately 6 km and increasing the tidal influence within Clybucca Creek. Works to excavate Andersons Inlet downstream of the floodgates further increased the tidal connectivity to the Clybucca floodplain. The scale of the floodplain drainage works was significantly increased in the 1960s and 1970s when large scale infrastructure was constructed, including the installation of the Menarcobrinni floodgates (Figure 1-3) and Seven Oaks Drain (Figure 1-4). Together, these changes drain large portions of the Clybucca floodplain and largely exclude the tide from reaching the floodplain, however, they have also resulted in significant environmental degradation. As a consequence of these works, large volumes of acid (pH ~3) and/or low oxygen “blackwater” is regularly discharged into the downstream Macleay River estuary (Tucker et al., 2023).

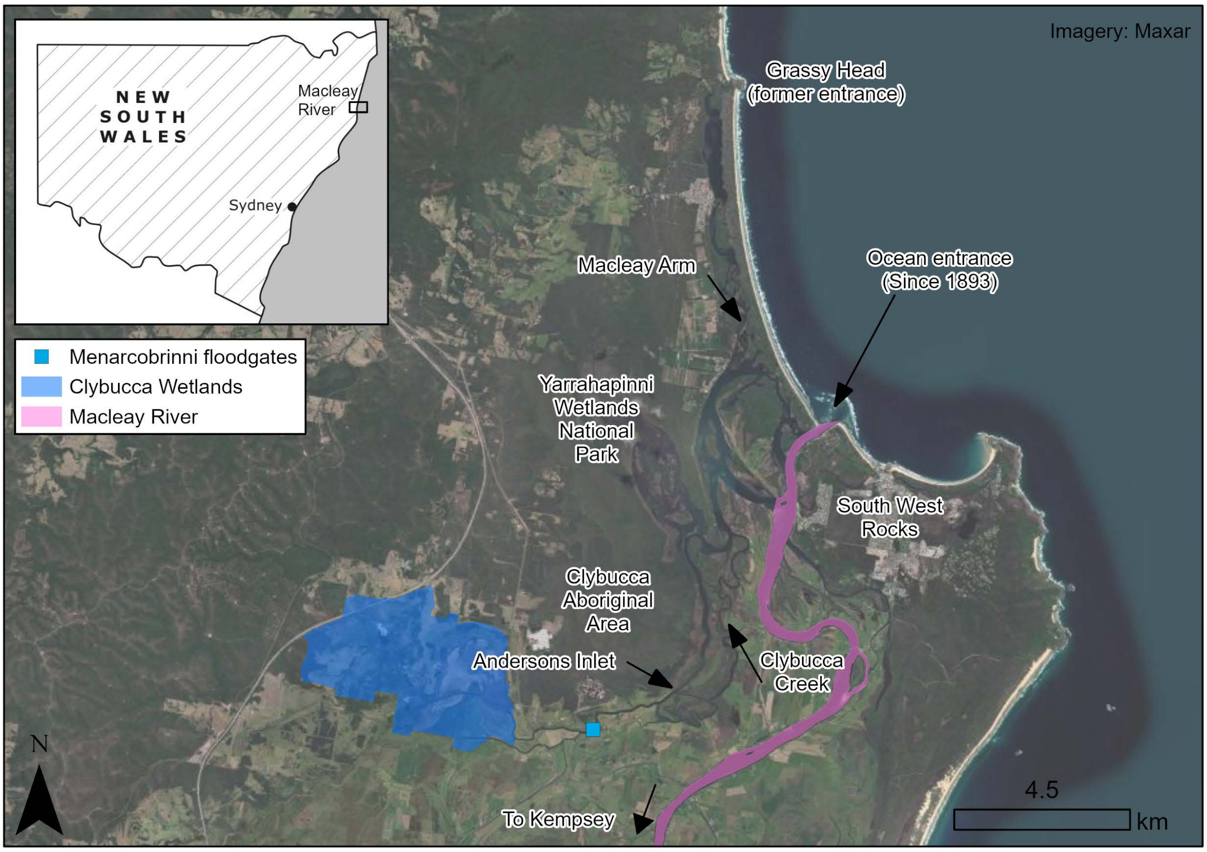

Figure 1-1 Project context

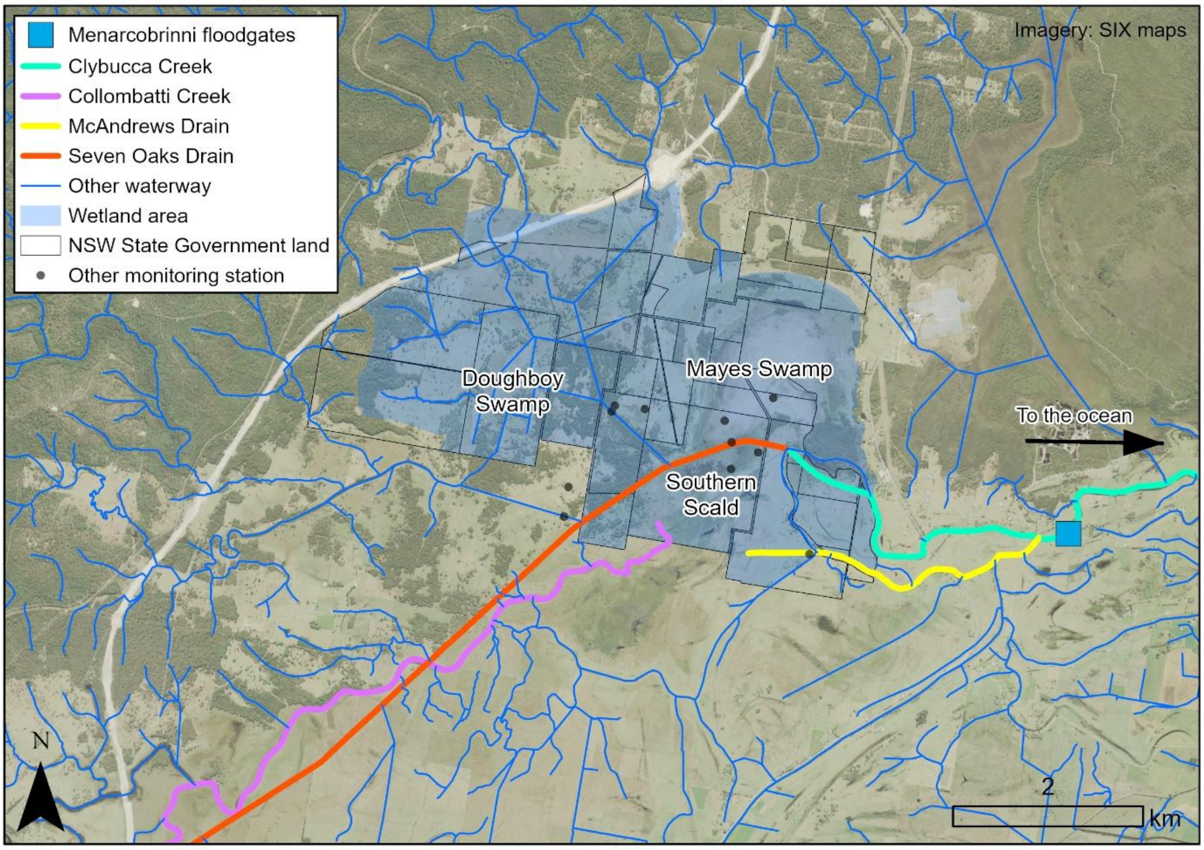

Figure 1-2 The Clybucca Wetlands and monitoring stations

Figure 1-3 The Menarcobrinni floodgates located 3 km downstream of the wetland

Figure 1-4 Seven Oaks Drain passing between the Southern Scald (left) and Mayes Swamp (right)

The environmental impacts of floodplain drainage works at Clybucca have been recognised since the early 1970s (Tulau, 2011). This resulted in a range of efforts to remediate the impacts associated with the drainage of acid sulfate soils beginning in the early 1990s (Tulau and Naylor, 1999). Initial works were carried out by Kempsey Shire Council who worked with local landowners to implement a range of paddock scale remediation measures (KSC, 2004). More recently, it has been recognised that a catchment scale approach is required for effective restoration (Rayner et al., 2020). This has influenced NSW State Government agencies who have worked towards securing the public ownership of large hydrologically connected portions of Clybucca, including areas generating the worst water quality. Subsequently, a range of investigations have also been completed seeking to address poor water quality issues associated with low oxygen blackwater and acid discharges from the site (Glamore and Rayner, 2017; Rayner and Glamore, 2017; Tucker et al., 2021; Rayner and Tucker, 2023). The overarching and ongoing restoration of Clybucca rehabilitation project is being led by the Clybucca Wetlands Government Working Group which includes representation from North Coast Local Land Services, Kempsey Shire Council, the NSW National Parks and Wildlife Services, the NSW Department of Climate Change, Energy, the Environment and Water, the NSW Department of Primary Industry and Regional Development Fisheries, Transport for NSW, the NSW Environment Protection Agency and Crown Lands. Note, community consultation and engagement activities, including with the Seven Oaks Drainage Union who manage the drainage network, has been an important aspect of the Clybucca rehabilitation project.

Over the years, a range of environmental monitoring campaigns have supplemented the restoration activities at Clybucca. Early campaigns were led by Kempsey Shire Council and included monitoring of water quality parameters over a 7-year period from 1998 to 2005 (Haskins, 1999; KSC, 2004; Bush et al., 2006). More recently, an extensive monitoring network (as shown in Figure 1-2) was established in November 2021 by the NSW State Government and includes fixed position photography, water level and water quality stations (Tucker, 2024).

1.2 About this report

The following report provides a review of the water quality data collected at Clybucca from November 2021 to January 2025. The objective of this report is to identify water quality trends captured by the monitoring stations and provide insight into the management of Clybucca. In addition to the analysis of water quality data collected at Clybucca (Section 3), this investigation has also included:

- An assessment of the influence of the management of the Menarcobrinni floodgate on water quality (Section 4)
- Comparison of recent water quality data with historical monitoring data (Section 5)
- Comparison of the water quality at Clybucca to the water quality at another NSW coastal floodplain (Section 6)

Findings from these analyses have been used to provide recommendations for an approach to quantify the impacts of poor water quality discharging from Clybucca on the broader Macleay River estuary (Section 7).

Funding of this project was provided through:

a) the NSW Estuary Asset Protection (NEAP) Program - This program is part of the Riparian Stabilisation Package managed by the NSW Department of Primary Industries and Regional Development and is jointly funded by the NSW and Australian Governments under the Disaster Recovery Funding Arrangements, and
b) the NSW Marine Estate Management Strategy, which is a program developed by the NSW Marine Estate Management Authority to coordinate the management of the marine estate.

This report includes the following sections:

- Section 1: Introduction (this section)
- Section 2: Background information on climate driven water quality trends
- Section 3: Analysis of water quality data
- Section 4: Menarcobrinni floodgates management
- Section 5: Comparison with historical water quality data
- Section 6: Comparison with water quality of Big Swamp, Manning River
- Section 7: Quantifying water quality impacts on the Macleay River estuary
- Section 8: Conclusion
- Section 9: References

2 Background information on climate driven water quality trends

2.1 Preamble

The climate plays a significant role in influencing the floodplain hydrology and water quality discharging from coastal floodplains like Clybucca. The following section provides background information linking various climate drivers to the hydrology and water quality of coastal floodplains. Section 2.2 provides a conceptual understanding of typical hydrology and water quality processes that influence water quality discharged from NSW coastal floodplains. Following this, a description of key climate drivers and how they act on different timescales are discussed (Section 2.3). This provides important context for the interpretation of later sections of this report.

2.2 Conceptual overview of water quality processes

The prevailing climate plays a significant role in influencing floodplain hydrology across coastal floodplains like Clybucca (e.g. causing flood or drought conditions). This, in turn, drives different processes which can influence water quality (e.g. changing salinity levels, causing the discharge of sulfuric acid, or generating blackwater).

Figure 2-1 provides a conceptual overview for how catchment rainfall can influence the water quality associated with coastal floodplains and their waterways, including four stages:

- **Panel A:** During dry conditions, salinity levels in an estuary are at their highest (approaching 35 parts per thousand (ppt) in the lower estuary). High salinity levels can sometimes occur in the drainage networks surrounding coastal floodplains, especially if the floodgate infrastructure leaks. During this time, small volumes of acidic water can be discharged from the drainage systems due to the drainage of acid sulfate soils. However, the downstream waterways are resilient to the small volumes of acidic runoff due to the natural acid buffering capacity of marine saltwater. Limited standing water on the floodplain means that there is no decay of water intolerant grasses, so dissolved oxygen levels are typically in a healthy range.
- **Panel B:** During a large rainfall event, large volumes of fresh water will push saltwater out of the drainage network turning the system (and parts of the estuary) fresh. Due to the high volume of freshwater, this also means that any potential acidic runoff is diluted. Inundation durations have not yet caused decay of organic material, and dissolved oxygen remains high.
- **Panel C:** In the days and weeks following a rainfall event, increased freshwater flows holds back saltwater intruding back into the drainage network (the salinity in the downstream estuary may now have started to recover as marine influence begins to increase). Prolonged inundation of water on the floodplain can cause the breakdown of organic matter which flows into the waterways, consumes oxygen in the water column, and causes blackwater. This strips the oxygen from the water column and, in extreme cases, can consume oxygen in the downstream estuaries as well, causing mass deoxygenation. Surface water levels remain high, so drainage of acid sulfate soils from the groundwater remains limited.
- **Panel D:** As water levels continue to recede, the drainage network continues to be characterised by freshwater conditions (drainage of freshwater from the floodplain means only sections of the estuary closer to the ocean entrance are influenced significantly by saltwater).

The presence of floodgates further prevents tidal intrusion into floodplain drainage networks. At this stage, drainage of acid sulfate soils is exacerbated, and large volumes of acid are generated. Since the waterways remain fresh, the impact of acidic drainage is then maximised as it cannot be buffered by the saltwater. Eventually, as freshwater inflows reduce and the tidal influence increases, the system can revert to **Panel A**, where there is enough saltwater to buffer acidic inflows to the receiving estuary.

There is a significant body of research which discusses the wide-ranging impacts of acid sulfate soils and low oxygen blackwater. This is outlined further in Section 7 in the context of understanding the impacts of water quality discharging from Clybucca on the wider Macleay River estuary.

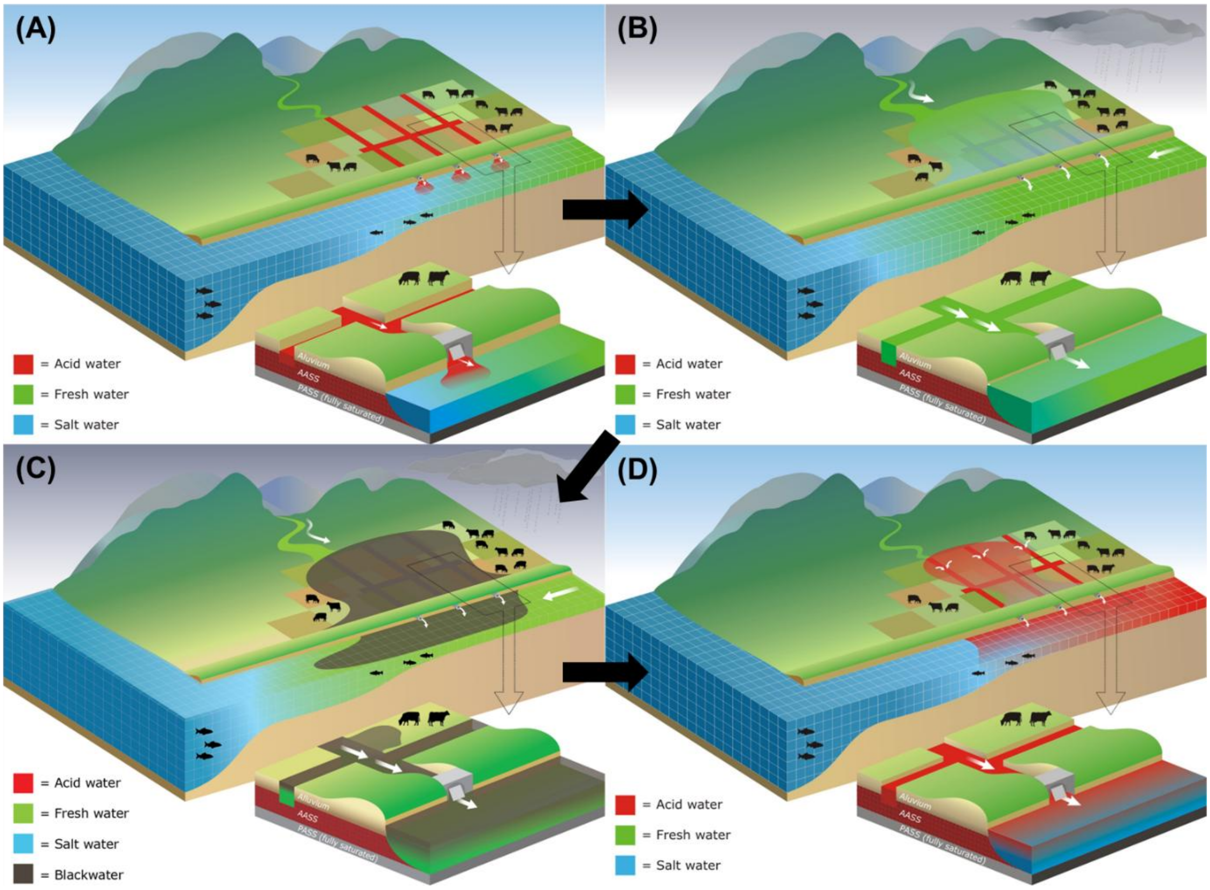

Figure 2-1 Hydrological influence on the water quality processes of coastal floodplains (adapted from Johnston et al. (2003) Ruprecht et al. (2018) and Waddington et al. (2022))

2.3 Description of climate drivers

2.3.1 Overview

The climate, and therefore floodplain hydrology and water quality processes, are variable, making it difficult to interpret water quality data. The following sections provide a brief description of various climate drivers, specifically focusing on how they influence catchment rainfall and floodplain hydrology. This will provide context for the interpretation of water quality trends at Clybucca. Examples of climate drivers which act on various timescales include:

- Seasonality – changes from month to month (Section 2.3.2)
- El Niño Southern Oscillation – changes from months to years (Section 2.3.3)
- Interdecadal Pacific Oscillation – changes from years to decades (Section 2.3.3)
- Climate change – changes gradually over multiple decades (Section 2.3.4)

When assessing water quality at Clybucca it should be considered within the context of these climate drivers and their potential influence on the floodplain hydrology.

2.3.2 Seasonality

Throughout the year, seasonal changes in the climate will influence the hydrological conditions and subsequently water quality across the floodplain at Clybucca. Seasonal shifts in temperature are well understood and influence evaporation which decreases in the winter months and increases in the summer months. A similar seasonal pattern can be observed when looking at long-term monthly average rainfall at Clybucca (see the black bars in Figure 2-2). Increased rainfall is more likely to occur at the end of summer (January to March) while decreased rainfall is expected towards the end of winter (July to September).

Observations of rainfall between 2022 and 2024 (Figure 2-2) demonstrates that while there is an underlying seasonal signal, rainfall shows significant variability from year to year. Annual rainfall for 2022, 2023 and 2024 was 1,828 mm, 592 mm, and 1,153 mm, respectively (BOM, 2025e). Rainfall during the monitoring period is compared to the long term annual average of 1,113 mm (between 2002 to 2024) (BOM, 2025e), and shows a range of conditions including wet (2022), dry (2023) and average (2024) years. Despite a significantly wetter than usual year in 2022, a seasonal trend in rainfall can be observed in 2023 with higher rainfall in summer compared to winter. The rainfall in 2024 was also representative of average seasonal rainfall totals, with the exception of larger rainfall in April and September.

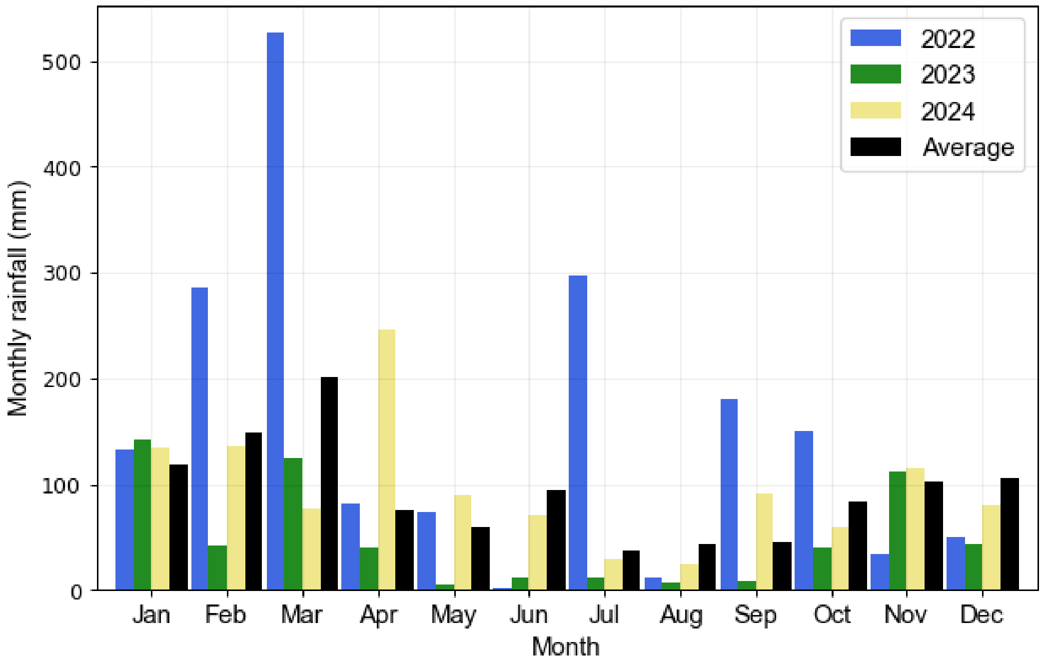

Figure 2-2 Monthly rainfall at Kempsey from 2022 to 2024 (coloured) compared against the average between 2001 and 2025 (black) (data from BOM (2025e))

2.3.3 Interannual and interdecadal climate drivers

In addition to sub-yearly fluctuations in the climate, there are also a range of interannual and interdecadal climate drivers which will influence the prevailing climate on the eastern coast of Australia. The El Niño Southern Oscillation (ENSO) is an example of an interannual climate driver that results from tropical trade winds across the Pacific Ocean. ENSO will tend to influence the east Australian rainfall climate on a timescale of months to years (BOM, 2025d). ENSO can be classified into three different phases, neutral, El Niño and La Niña, where:

- Neutral phases occur most of the time and typically coincides with average rainfall conditions
- El Niño phases typically coincide with below average rainfall conditions (i.e. drought)
- La Niña phases typically coincide with above average rainfall conditions (i.e. flood)

The processes driving water quality at Clybucca are influenced by rainfall and, as a result, by ENSO and other interannual climate drivers. It can therefore be expected that long-term trends in water quality will correlate with these climate drivers.

ENSO provides an example showing interannual influences on climate at Clybucca. The Southern Oscillation Index (SOI) can be used to indicate the ENSO phasing. Typically, a sustained SOI above 7 indicates La Niña, while a sustained SOI below -7 indicates El Niño. Figure 2-3 shows the SOI for water quality in 2022 to 2025 and can be analysed to understand the prevailing climate conditions:

- Throughout 2022 there was a sustained SOI above 7 indicating a likely La Niña event. During this period, above average rainfall and wetter than average conditions were observed at Clybucca. The largest rainfall event, rated as a 20% annual exceedance probability event (AEP), occurred during this period in July 2022. This was following two consecutive 50% AEP events in March 2022.

- In 2023, the SOI shifted to below -7 indicating El Niño and drier conditions. The 9 months between March 2023 and November 2023 were the driest period recorded during monitoring with over 200 days between rainfall events with an exceedance probability greater than 12 exceedances per year (12EY).
- Throughout 2024 the SOI varied initially indicating dry conditions in January (SOI < -7) and shifting to indicate wet conditions in December (SOI > 7). Overall, the SOI tended to indicate overall neutral state throughout the year. This was reflected in rainfall observations throughout 2024 which were similar to long term average totals.

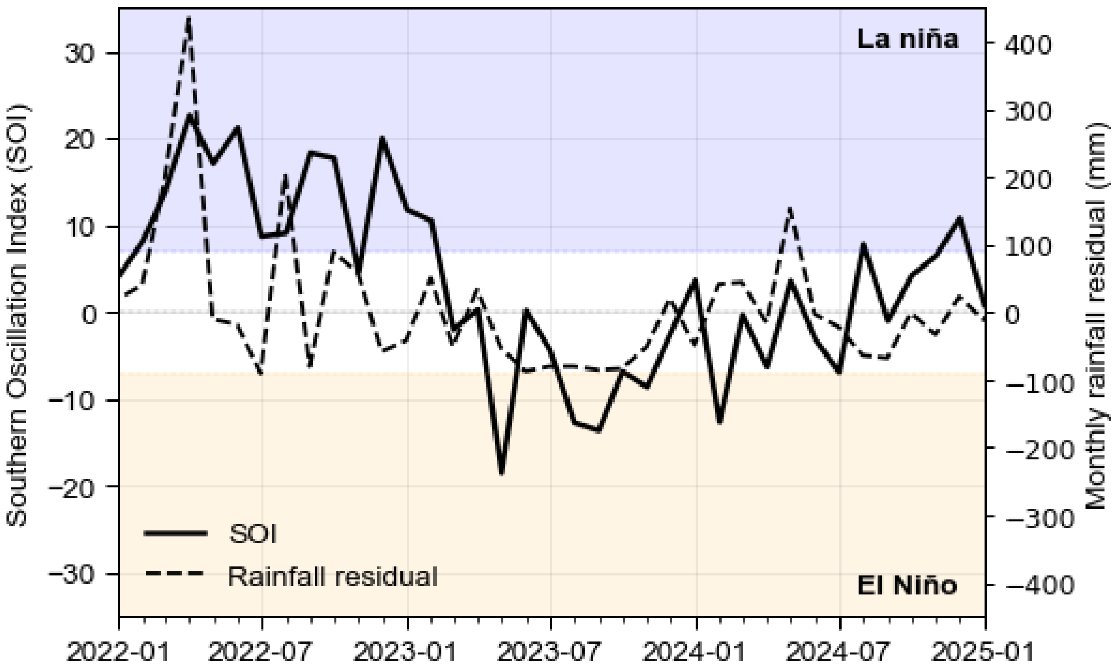

Figure 2-3 Residual rainfall (i.e. monthly rainfall minus the average monthly rainfall) compared to the Southern Oscillation Index (data accessed from BOM (2025e) and BOM (2025f))

Note, ENSO is just one of the interannual climate drivers. For example, the Indian Ocean Dipole is another well-known driver that will influence the climate of eastern Australia (BOM, 2025a). The combination of these drivers and others operating at different timeframes (e.g. the Southern Annular Mode) increases the complexity of the prevailing conditions.

Climate variability can also be affected by drivers with longer term, interdecadal patterns. An example of this is the Interdecadal Pacific Oscillation (IPO) (Power et al., 1999).The IPO is a 20 to 30 year oscillation which influences a range of climate variables on the east coast of Australia including rainfall, streamflow, flood risk and ENSO (Heidemann et al., 2023; Henley et al., 2015). The IPO fluctuates between positive and negative states relating to temperatures in the tropical Pacific Ocean (Power et al., 1999). Research has indicated that, when the IPO is negative, the severity of ENSO events are magnified (i.e. La Niña events are wetter and El Niño events become drier) (King et al., 2013). In recent years, data developed by Henley et al. (2015) has indicated that the IPO has been trending negative.

2.3.4 Climate change

Due to the release of greenhouse gases into the atmosphere, the world is currently in a period of increased warming. In Australia, the average temperature has increased by ~1.5 °C in the last 100 years (CSIRO and BOM, 2024). Research has shown (CSIRO and BOM, 2024) that temperature increases of this magnitude can significantly influence a range of climate variables, such as:

- Changes to rainfall which may mean drought conditions are more likely to occur. This is often variable depending on seasonality, however, observations have shown a decrease by around 9% from April to October in the southeast of Australia.
- Heavy rainfall events are becoming more intense (i.e. more rain falls over a shorter duration).
- Sea level rise will change tidal dynamics across the Macleay River estuary. Since the construction of the Menarcobrinni floodgates in the 1960s, there is likely to have been at least 0.05 m of sea level rise based on current estimates (Tucker et al., 2023).

Due to the relatively short dataset (3 years) and high variability of the data collected, trends due to climate change cannot yet be identified at Clybucca. Subsequently, no further analysis of its influence on water quality data has been assessed.

3 Analysis of water quality data

Summary points

- Water quality data is extremely variable and depends on a range of factors including the prevailing climate, floodplain drainage and geography.
- No clear seasonal trends in water quality data were observed.
- Interannual trends in water quality were influenced by long-term climate drivers (e.g. the El Niño Southern Oscillation).
- Increased rainfall resulted in lower pH and lower conductivity levels.
- A clear positive correlation between pH and conductivity was observed indicating that saltwater from the estuary can buffer acidic water.
- Conductivity and pH data supported the conceptual understanding of floodplain processes discussed in Section 2.2.

3.1 Preamble

The following section details the analysis of quality controlled water quality data collected at Clybucca. Concepts discussed in this chapter build upon the conceptual understanding of floodplain hydrology and water quality drivers outlined in Section 2. The analysis has been broken into three stages:

1. Section 3.2 provides an overview of the water quality dataset and some general observations.
2. Section 3.3 examines how the influence of climate drivers is observed within water quality data collected at Clybucca on seasonal and interannual timescales.
3. Section 3.4 analyses individual hydrological events to identify trends based on event size and duration.

Prior to the analysis of water quality data at Clybucca, a quality control exercise was conducted. Tucker (2024) details the instrumentation used, accuracy and the calibration methodology. For this investigation, data was downloaded and visually inspected. Where erroneous data was identified, this was removed using expert judgement. Note, the dissolved oxygen sensors malfunctioned early in the monitoring period and following the assessment was deemed unreliable for the majority of the analysis.

3.2 Overview of water quality dataset

Water quality data was collected from November 2021 to January 2025 (at which point it was downloaded and analysed for this assessment). Quality controlled timeseries data has been provided in Appendix A for all parameters measured. Table 3-1 provides a summary for the range of values measured throughout the monitoring period at each station. Note, data was not always available at each station (Figure 3-1).

The largest influence on water quality observations was found to be the prevailing climate conditions. This has subsequently been analysed in detail within Section 3.3 and Section 3.4.

Station location was also identified as a factor influencing the measured water quality. For example, conductivity typically decreased with distance upstream. Similarly, a decrease in the pH was observed for further upstream stations, likely due to reduced capacity for saltwater to buffer pH. Despite these aforementioned factors, the range of values recorded at all stations remained similar throughout the entire monitoring period, highlighting the variability of water quality across Clybucca.

Table 3-1 Maximum and minimum range of water quality measurements (stations are ordered from downstream (Station 4) to upstream (Station 3))

Parameter	Station 4 range*	Station 1 range	Station 2 range	Station 3 range	Total range (all stations)
Conductivity (µS/cm)	0 to 56,977	0 to 54,370	0 to 47, 271	0 to 57,470	0 to 57,470
pH	-	3.3 to 8.7	3.0 to 7.9	3.0 to 7.9	3.0 to 8.7
Dissolved oxygen (mg/L)	-	0 to 8.7	0 to 9.5	0 to 8.8	0 to 9.5
Redox potential (mV)	-	-464 to 536	-384 to 525	-446 to 552	-464 to 536
Temperature (°C)	11.6 to 30.1	8.0 to 30.7	10.2 to 32.4	10.8 to 30.9	8.0 to 32.4

* Only temperature and conductivity were measured at Station 4.

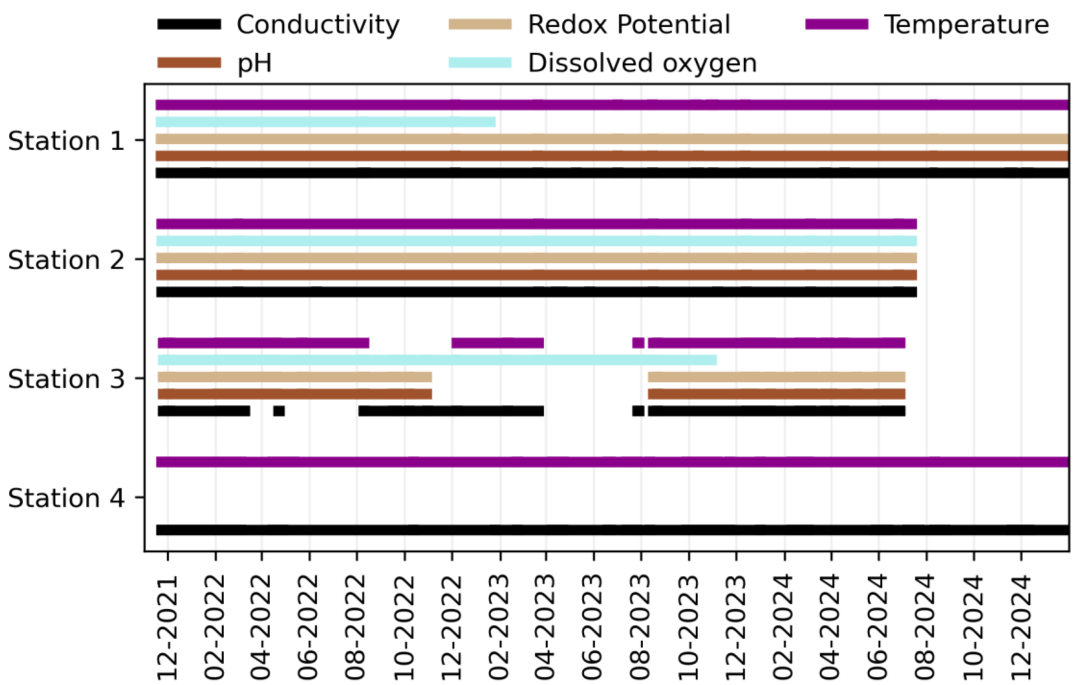

Figure 3-1 Times when water quality data was available for each station

3.3 Influence of climate drivers on water quality

3.3.1 Seasonal drivers of water quality

As discussed previously in Section 2, climate drivers can significantly influence the water quality associated with coastal floodplains due to their influence on floodplain hydrology. Some of these drivers (i.e. the IPO and climate change) operate over long timescales and require long term interdecadal data to effectively assess. As such these long-term drivers have not been assessed here. Instead, this section focuses on analysing the short-term seasonal and interannual climate drivers (such as ENSO) to understand how they have influenced the water quality at Clybucca.

Analysis of climate influences on water quality showed no clear seasonal trends for the 3 years of monitoring from 2022 to 2024. A range of analyses aiming to identify seasonal trends in water quality data has been provided in Appendix B. The absence of a clear trend was likely due to the large rainfall events occurring throughout the monitoring period, especially in 2022 and 2024 where large rainfall occurred outside of the most typical wet season (January to March).

3.3.2 Interannual drivers of water quality

Further analysis of the data indicated that there was an interannual trend in the rainfall dataset, associated with the El Niño Southern Oscillation (ENSO). This led to the analysis of annual statistics for what were identified as wet (2022), dry (2023) and average (2024) years. Figure 3-2 shows the annual water quality statistics for each year of monitoring at Clybucca.

Conductivity decreases during wet years and increases during dry years. Wet conditions throughout 2022 clearly resulted in a lowering of conductivity throughout the Clybucca system. Higher salinity levels were observed during 2023, which was a drier than average year. Typically, a lower conductivity would be expected to occur further upstream, characteristic of freshwater inflows pushing saltwater from the system during wet conditions and the subsequent inflow of saltwater (e.g. through leaky floodgates) during dry conditions. While this was the case in 2022, Station 3 was missing data during a wet period in 2023 and Stations 2 and 3 were missing data for long periods in 2024. This meant that this trend was not observed for those years, however it is likely that this was still the case (as indicated by Station 2 in 2023 compared to Station 1).

Analysis of the data also indicated that wet weather results in lower pH (acidic) conditions at Clybucca. This confirms the conceptual model that wet conditions result in the export of acid from acid sulfate soils and that the lack of saltwater (which contains carbonates and bicarbonates that buffer acid) limits the buffering of acidity during these periods. For long-term periods when data was available at all stations, the acidity was found to decrease (i.e. the pH increased) further downstream which suggests that it is being buffered by saltwater that has flushed into the drainage network via the floodgates. This trend also indicates that areas upstream of the monitoring stations are a source of acidic waters.

Analysis of the redox potential data also indicated that downstream Station 1 behaved differently to the upstream stations. The redox potential at Station 1 remained high throughout all conditions, potentially due to frequent mixing with downstream saline water. Stations 2 and 3 tended to have a positive redox potential during wet conditions and a lower redox potential during dry conditions. It is possible that this trend occurs due to higher energy flow conditions during wet times that more readily oxygenates the water column. During drier and lower energy conditions, redox potential decreases, particularly at locations where the sensors were deeper in the water column. Low energy conditions with low redox potential can result in the formation of mono-sulfidic black ooze (MBOs) (Sullivan et al., 2018) as was observed at Clybucca by Rayner et al. (2020) during drought conditions in 2019.

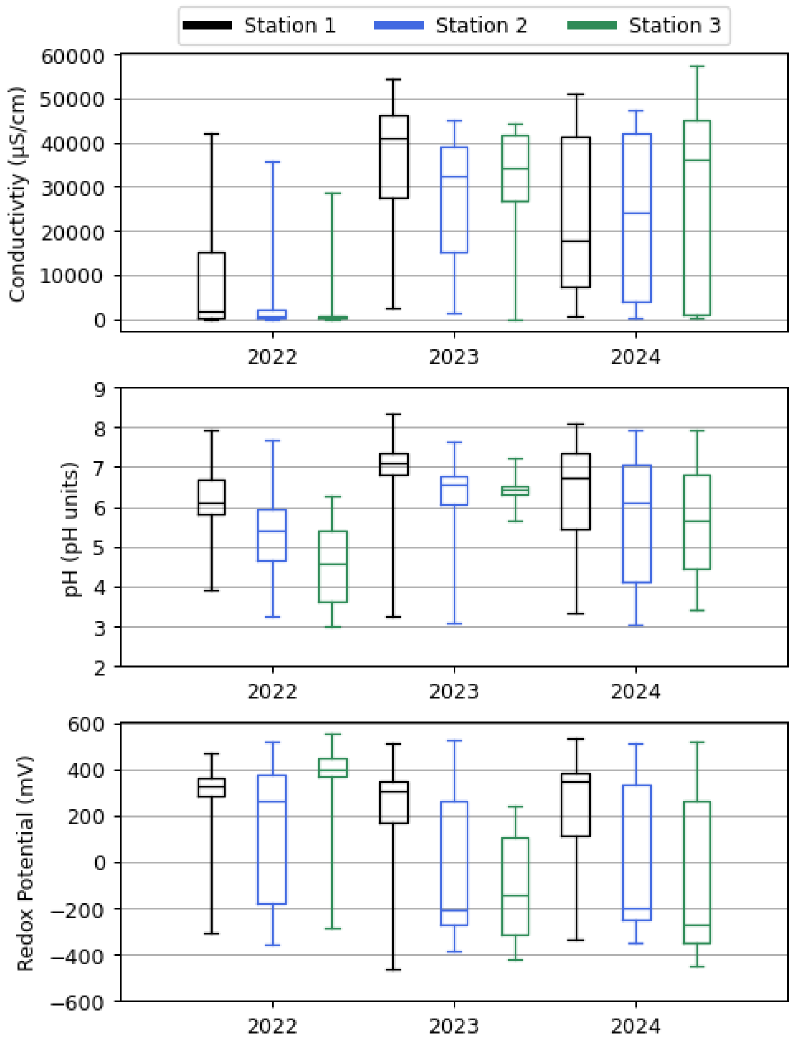

Figure 3-2 Annual water quality statistics for pH, conductivity and redox potential at each station (box indicates 25th and 75th percentile with the median bar inside, whiskers indicate total data range)

3.3.3 Impact of rainfall on interannual drivers of water quality

To provide further insight into the influence of prevailing wet and dry conditions on water quality, annual data was separated into wet and dry conditions, as shown in Figure 3-3. Dry conditions were defined as times when there had been less than 60 mm of rainfall in the preceding 30 days, and there was no significant rainfall event (i.e. with an occurrence probability of 12 EY or less) in the last 14 days.

During dry conditions, conductivity levels throughout the system are higher (Note, Stations 2 and 3 are exceptions to this in 2024 due to limited data). This demonstrates the ability for wet conditions to push downstream salinity within the system. Indeed, salinity was always highest at the downstream station (Station 1).

Interestingly, in 2022 and 2024, the pH at Stations 2 and 3 tended to be lower during dry conditions than wet conditions. This is likely in response to continued groundwater drainage mobilising acid generated from acid sulfate soils after 30 days, following a wet event during wetter than average years. Once long-term dry conditions set in (as occurred in 2023), there is limited groundwater drainage and subsequently higher pH conditions prevail across the site.

Separating wet and dry conditions did not indicate any additional trends for the redox potential data.

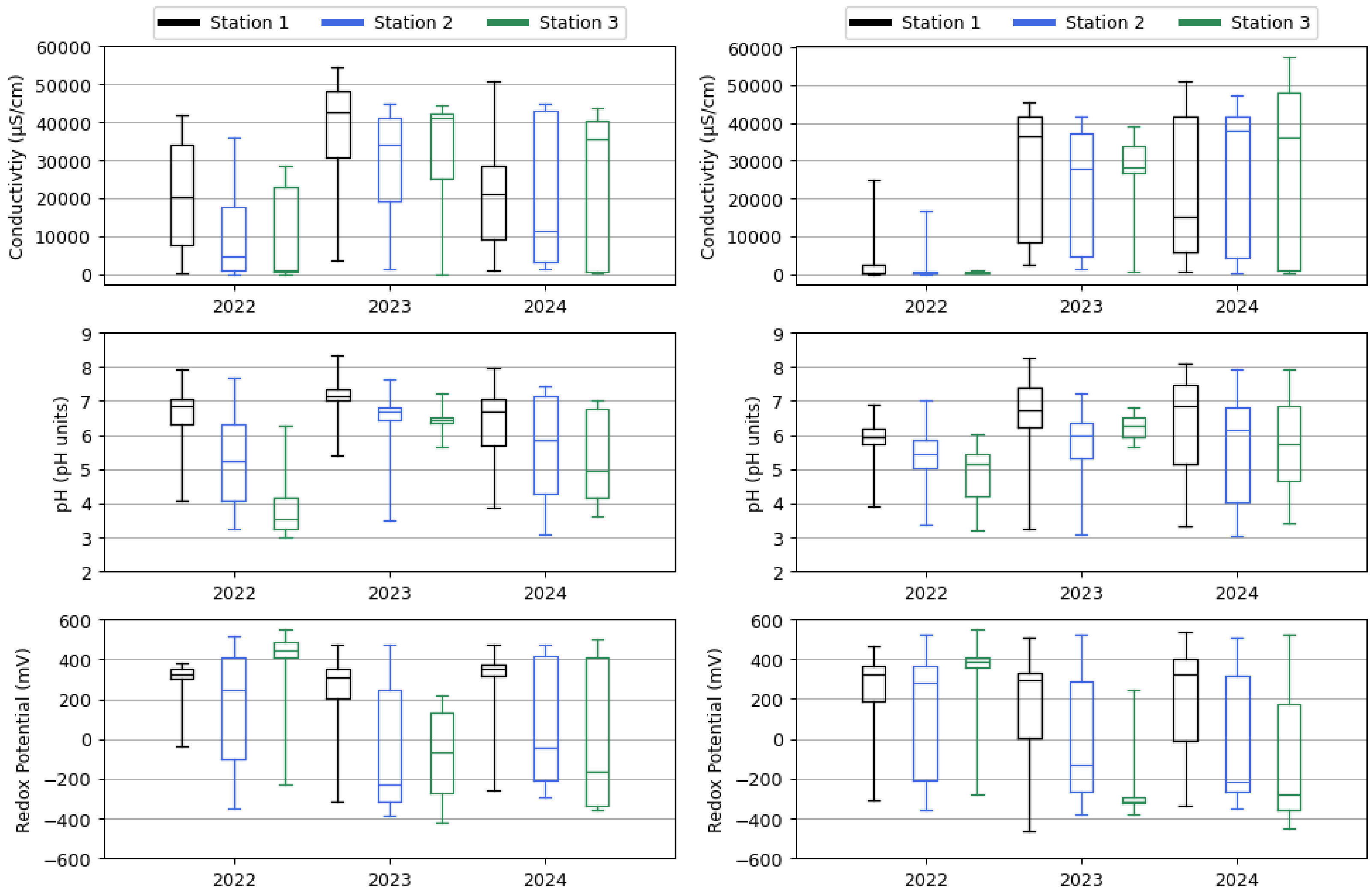

Figure 3-3 Annual water quality statistics for dry (left) and wet (right) conditions (box indicates 25th and 75th percentile with the median bar inside, whiskers indicate total data range)

Note, interpretation of this data needs to consider data gaps for Station 2 and Station 3 (especially for conductivity measurements during 2024).

3.4 Influence of dry and wet events on water quality

3.4.1 Summary of rainfall events

Twenty-four (24) rainfall events with an average recurrence interval greater than or equal to 1 month were observed from November 2021 to January 2025, as shown (and labelled) in Table 3-2. The largest event (event 7) occurred in July 2022 when 213 mm fell over 3 days. The longest period between events occurred in 2023 prior to a rainfall event in November (event 14) when 219 days elapsed without significant rainfall. A total of nine rainfall events with a return frequency greater than or equal to 12 Exceedances per Year (EY) occurred in 2022 and 2024, compared to four in 2023. Rainfall events which occurred in 2022 were generally larger, with a total of 1,359 mm falling across the nine events in 2022, compared to 629 mm across the nine events in 2024.

While 24 events were identified throughout the monitoring period, there were limited instances of comparable events having occurred. While similar sized events occurred, antecedent conditions (e.g. event 3 versus 4), event duration (e.g. event 2 versus 17) or proceeding events (e.g. event 3 cannot be compared to event 18 as event 19 occurred just 6 days later) meant that the water quality response for a wet weather event was not comparable. When accounting for these parameters, the following events provided the best comparison:

- Comparison 1: event 1 (21/11/21) and event 9 (22/9/2022), both 3 EY events
- Comparison 2: event 1 (21/11/21) and event 14 (22/9/2022), both 3 EY events
- Comparison 3: event 2 (31/12/2021) and event 21 (27/9/2024), both 6 EY events
- Comparison 4: event 5 (20/5/2022) and event 22 (16/11/2024), both 12 EY events
- Comparison 5: event 9 (22/9/2022) and event 14 (4/11/2023), both 3 EY events
- Comparison 6: event 16 (28/1/2024) and event 20 (1/6/2024), both 6 EY events
- Comparison 7: event 17 (24/02/2024) and event 23 (1/12/2024), both 6 EY events

Two significant dry periods were observed during the monitoring period. These occurred between events 13 and 14 and between events 20 and 21.

The response of water quality to these wet and dry events is discussed in Section 3.4.2 and Section 3.4.3, respectively.

Table 3-2 Significant rainfall events from November 2021 to January 2025*

#	Start date	End date	Total rainfall (mm)	Exceedance probability	Days of rain	Days since last event
1	21/11/2021	28/11/2021	130	3 EY	8	37
2	31/12/2021	9/01/2022	70	6 EY	10	33
3	23/02/2022	7/03/2022	379	50% AEP	13	45
4	24/03/2022	1/04/2022	333	50% AEP	9	17
5	20/05/2022	25/05/2022	48	12 EY	6	49
6	2/07/2022	3/07/2022	42	12 EY	2	38
7	6/07/2022	8/07/2022	213	20% AEP	3	3
8	3/09/2022	5/09/2022	71	4 EY	3	57
9	22/09/2022	25/09/2022	82	3 EY	4	17
10	18/10/2022	26/10/2022	121	3 EY	9	23
11	30/12/2022	2/01/2023	48	12 EY	4	65
12	23/01/2023	27/01/2023	53	12 EY	5	21
13	24/03/2023	30/03/2023	72	6 EY	7	56
14	4/11/2023	8/11/2023	85	3 EY	5	219
15	15/01/2024	19/01/2024	57	12 EY	5	68
16	28/01/2024	31/01/2024	52	6 EY	4	9
17	24/02/2024	28/02/2024	63	6 EY	5	24
18	5/04/2024	8/04/2024	172	50% AEP	4	37
19	14/04/2024	24/04/2024	60	12 EY	11	6
20	1/06/2024	3/06/2024	48	6 EY	3	38
21	27/09/2024	1/10/2024	75	6 EY	5	116
22	16/11/2024	17/11/2024	41	12 EY	2	46
23	1/12/2024	2/12/2024	61	6 EY	2	14
24	15/01/2025	19/01/2025	93	3 EY	5	44

*Exceedance probability presented is the maximum which occurred during the rainfall event.
EY = Exceedances per Year, AEP = Annual Exceedance Probability.
Rainfall data from BOM (2025e).

3.4.2 Comparison of wet events

The following section provides a discussion based on the comparison of water quality responses at Clybucca for similar sized rainfall events. Figures and analysis comparing similar rainfall events have been provided in Appendix C.

The comparison of rainfall events highlighted that there is significant variability which influences the water quality at Clybucca, even for similar sized events. Reasons for this variability likely include:

- Differing antecedent and subsequent conditions
- Rainfall variability and catchment routing (e.g. rainfall will not fall evenly across the catchment and subsequently, even similar sized rainfall events will result in different runoff)
- Prevailing long term climate drivers (e.g. ENSO, see Section 2.3.3)
- External influences (e.g. floodgate leakage)

The variability of water quality was different for each parameter measured. The strongest trend in water quality response to rainfall events was observed for conductivity, which showed a decrease correlating to larger rainfall events (see Figure 3-4). There was still variability within the conductivity data meaning this trend was only clear for events with over 100 mm of rainfall.

Data showed that acidic runoff occurred as a response to rainfall events, however, the scale and magnitude of this response was not readily predictable and did not clearly correlate with the size of rainfall events. Figure 3-5 shows the average pH following various sized rainfall events. This data indicated that larger rainfall events resulted in less variability (likely due to the dilution of acid events), however, pH measurements did not correlate well with the amount of rainfall.

When assessing more complex water quality parameters (i.e. dissolved oxygen and redox potential), even greater variability was observed, further highlighting the complexity of processes governing them.

While there was significant variability in water quality responses to rainfall, the response of water quality parameters still confirmed the conceptual model of acid sulfate soil drainage outlined in Section 2.2. While high variability meant that similar sized rainfall events were not comparable quantitatively, the response to rainfall was comparable qualitatively. For example, rainfall resulted in a drop in conductivity (as freshwater flushed throughout the system), albeit the degree of freshening varied between events. As another example, pH often responded predictably to rainfall, initially increasing (due to dilution) before dropping in the weeks following rainfall (in response to groundwater drainage of acid sulfate soils). This can be seen in Figure 3-6 which illustrates this response at Station 2 and Station 3 for a rainfall event which occurred in September 2023. Note, the increase in pH from mid-October at Station 2 (which is further downstream than Station 3) was likely a result of tidal buffering as the system recovered from the rainfall event.

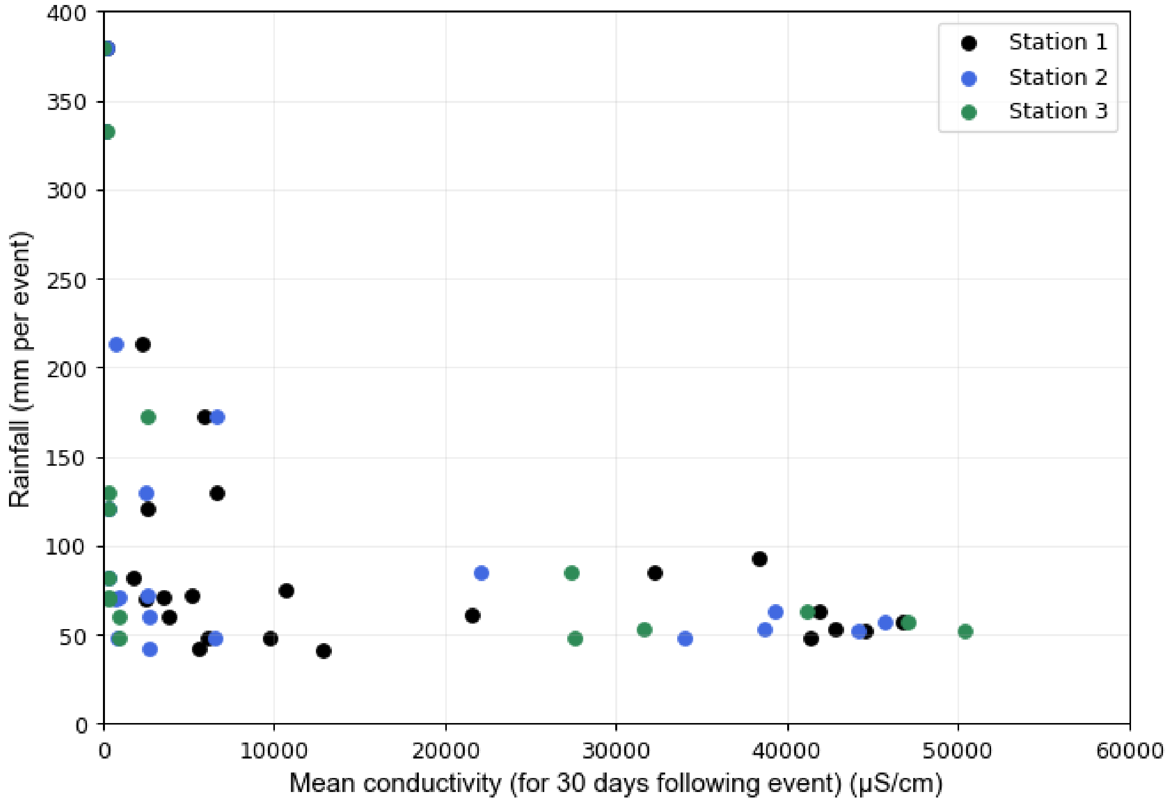

Figure 3-4 Mean conductivity for the 30 days following an event at each monitoring station

Rainfall data from BOM (2025e).

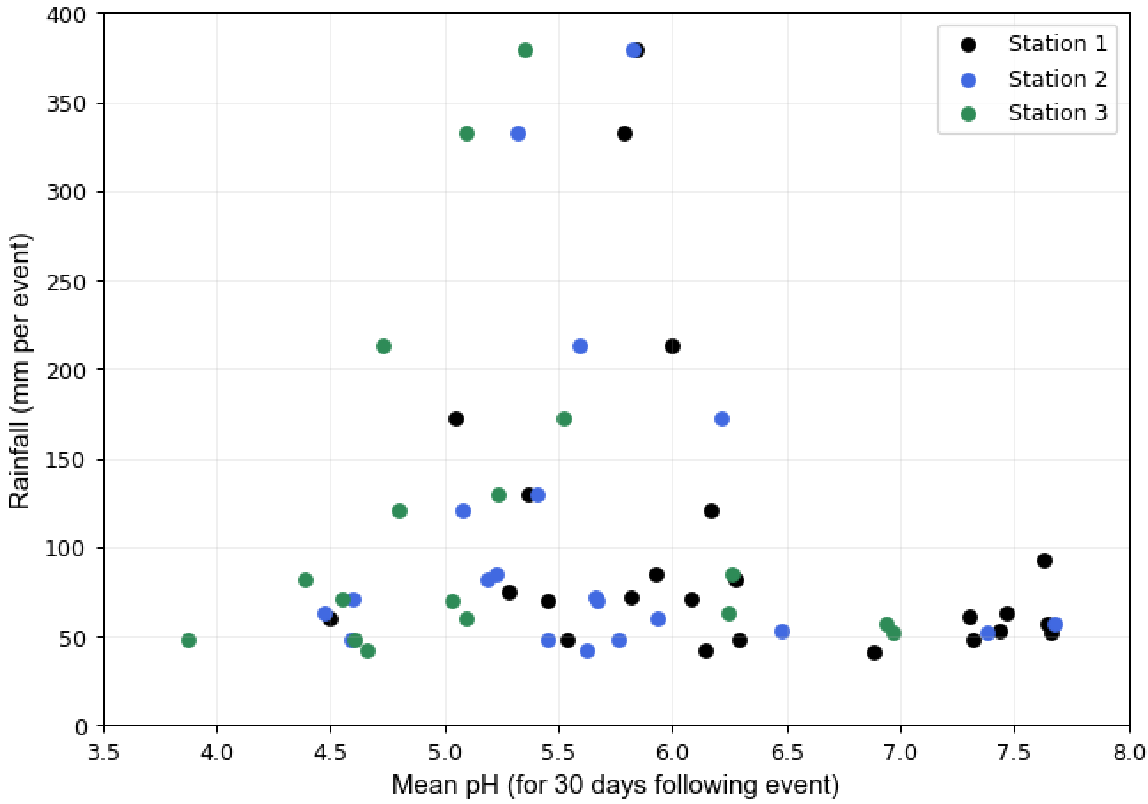

Figure 3-5 Mean pH for the 30 days following an event at each monitoring station

Rainfall data from BOM (2025e).

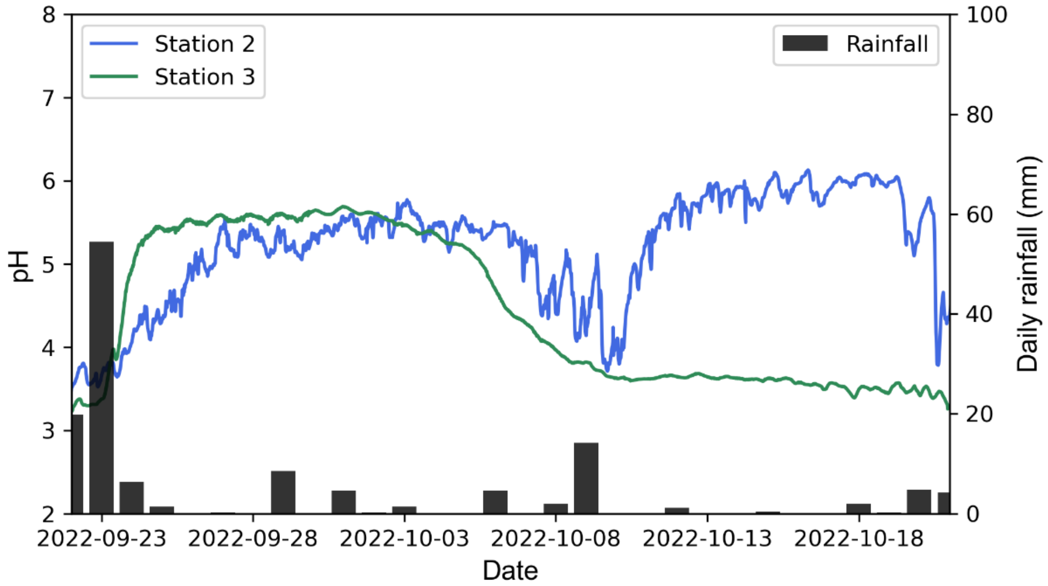

Figure 3-6 Example of pH response to a rainfall event at Station 2 and Station 3

Rainfall data from BOM (2025e).

3.4.3 Comparison of dry periods

Two significant dry periods occurred throughout the monitoring period (see Figure 3-7):

- **Dry period 1**: 30/3/2023 to 4/11/2023 (219 days without a significant rainfall event)
- **Dry period 2**: 3/6/2024 to 27/9/2024 (116 days without a significant rainfall event)

Understanding the prevailing conditions before and during each event provides essential context for interpreting water quality responses. For example, after prolonged dry periods, the conductivity in the lower estuary begins to approach that of seawater (~55,000 µS/cm) as the volume of freshwater catchment inflows reduces and subsequent tidal cycles allow increased exchange of saltwater to push further upstream. This can then have an influence on water quality, such as through the increased buffering of low pH water exported from acid sulfate soils.

The first dry period was the longest and coincided with El Niño conditions in 2023. It began following a 6EY event in early March and finished in November. Over the length of the first dry period, 126 mm of rainfall fell averaging at 0.6 mm/day.

The second dry period was shorter in duration than the first, however, it still occurred over winter and spring seasons (June to August) and following a 6EY event. The second dry period was slightly wetter than the first, averaging rainfall of 0.8 mm/day. The water quality response was qualitatively similar for the two dry periods, however, some differences associated with the magnitudes of change were observed (discussed below). Note, due to the long duration of the dry periods, there were a number of instances where data was unavailable.

Conductivity increased throughout the duration of each dry period. The first and longer dry period resulted in the highest conductivity levels (~50,000 µS/cm after approximately 190 days). Conductivity levels at Station 4, located downstream of the floodgates, provides a good indicator for salinity levels in the lower Macleay River estuary. Higher conductivity levels at Station 4 indicated that the lower Macleay River estuary in general had higher conductivity levels towards the end of the first dry period compared to the end of the second dry period. While still showing an increasing trend, the conductivity following the second event was much more variable, taking ~100 days to increase above 30,000 µS/cm compared to ~50 days during the first dry event. Small but persistent rainfall during the first 100-day period was likely a key contributor to this slow recovery (the first dry period had 63 mm in the first 100 days compared to 91 mm for the second dry period (BOM, 2025e)). Analysis of data for the wider Macleay River catchment (BOM, 2025c) also indicated that the second period was wetter in general and therefore would have resulted in the slower recovery of the wider Macleay River estuary.

The pH at Clybucca also increased throughout the duration of each dry period. Comparison of pH and conductivity data indicated a strong relationship, especially when the conductivity is above 15,000 µS/cm (Figure 3-8). This is due to the buffering capacity of saltwater which neutralises acid generated in the system. The highest variability in pH for both events occurred in the first 2 months of the dry periods. This variability was likely due to factors discussed in Section 3.4.2 (i.e. antecedent conditions, catchment, etc.). Rainfall acts to recharge the groundwater which drains over longer time frames (e.g. months), as opposed to surface runoff (typically days to weeks), which is the main reason why acidity persists into dry periods. A significant increase in pH only occurs once acidic groundwater drainage slows sufficiently, so that it can be buffered by saltwater.

Analysis of the redox potential data did not indicate any clear trends and was limited by data availability.

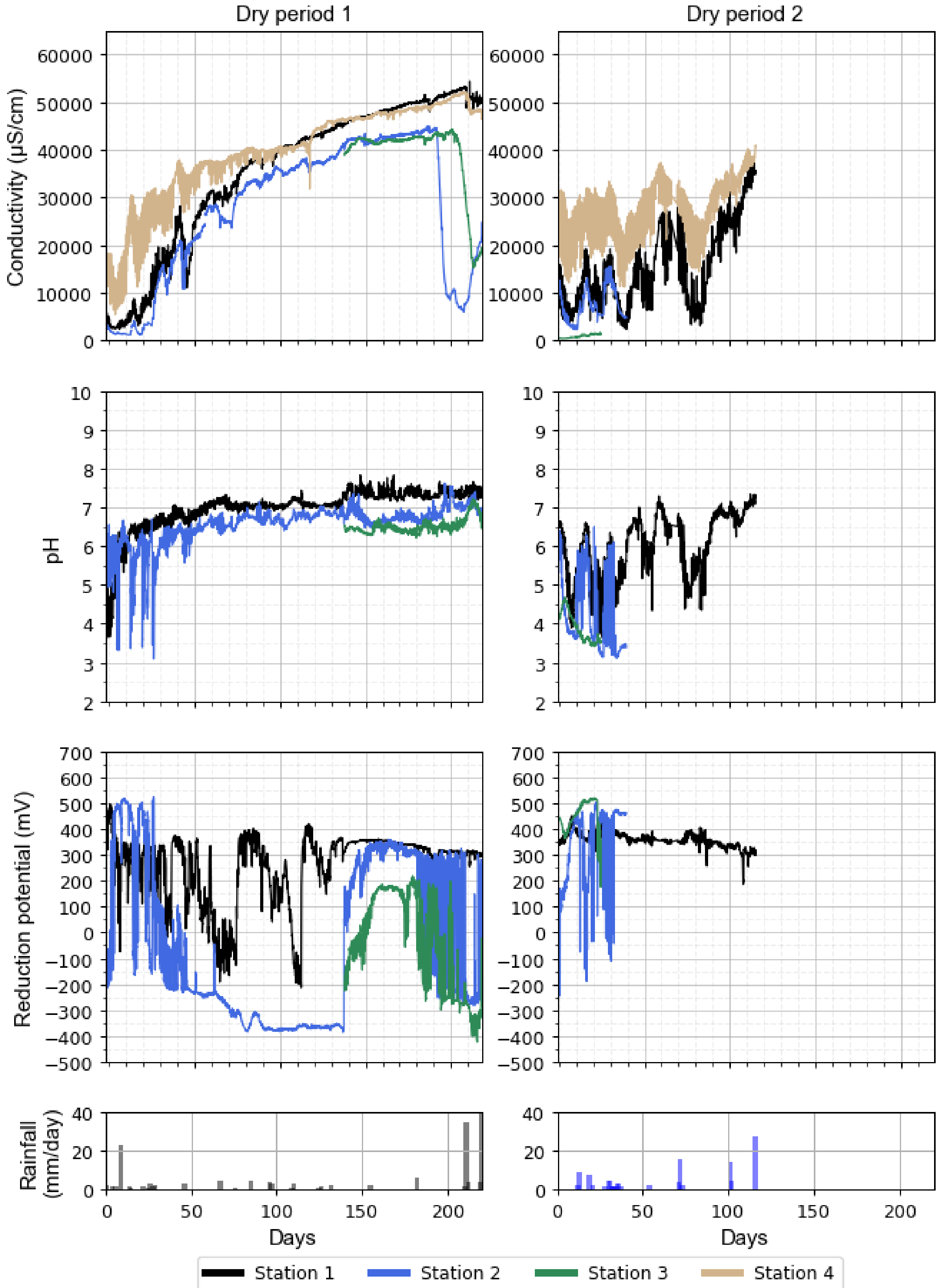

Figure 3-7 Comparison of two dry periods (period 1: 30/3/2023 to 4/11/2023; period 2: 3/6/2024 to 27/9/2024)

Rainfall data from BOM (2025e).

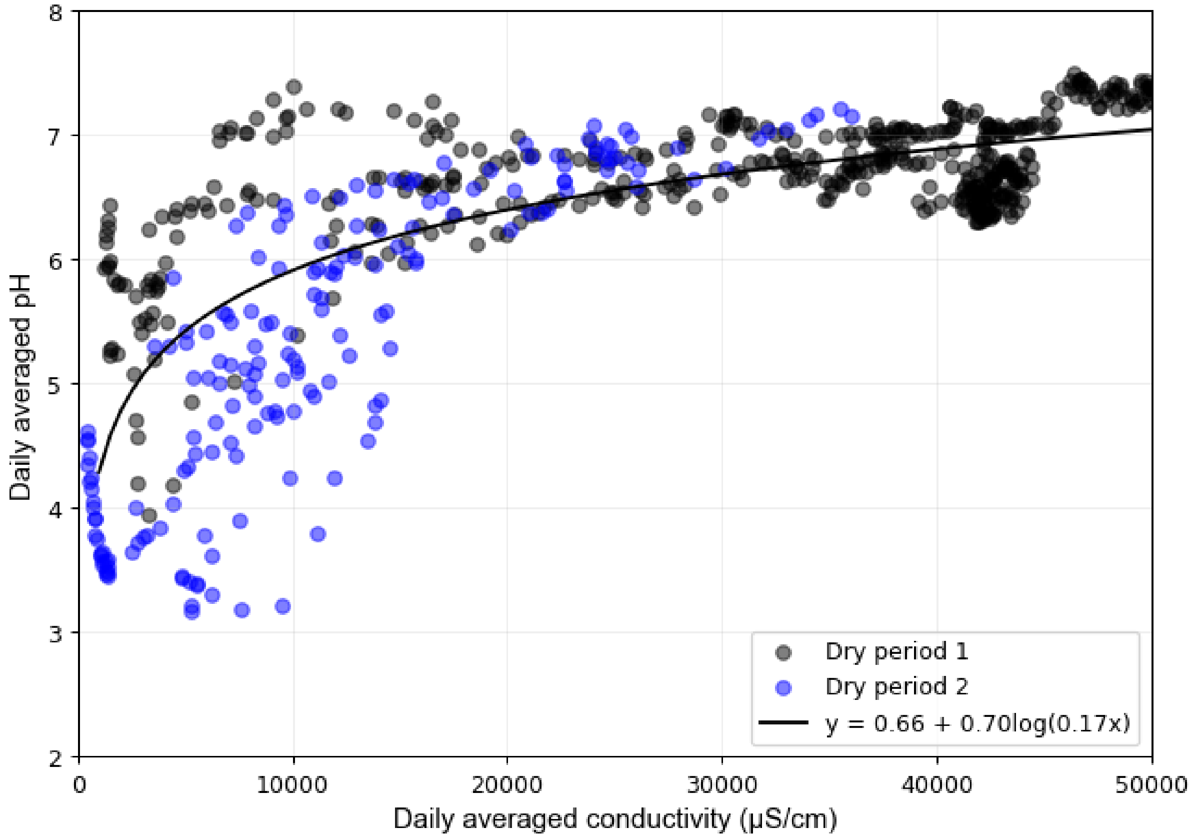

Figure 3-8 Daily averaged pH versus daily averaged conductivity for each dry period

4 Menarcobrinni floodgates management

Summary points

- Maintenance records of the Menarcobrinni floodgates are limited.
- There is significant leakage through the Menarcobrinni floodgates due to flow over the top of the floodgate flaps or debris wedging the floodgate flaps open.
- Two floodgate flaps were removed allowing two-way flow through the Menarcobrinni floodgates from September/October 2022 to February 2023.
- When the two floodgate flaps were removed the conductivity levels in the Clybucca drainage network increased at a faster rate.
- Increased tidal flushing within the Clybucca drainage network results in increased buffering of acid sulfate soils.

4.1 Preamble

The Menarcobrinni floodgates are a large hydraulic structure that controls flow through Clybucca Creek (Figure 4-1). It is located approximately 3 km downstream of the Collombatti-Clybucca floodplain (see Figure 4-2). The structure consists of a series of 21 culverts (1.8 m wide by 2.1 m high) each equipped with a hinged floodgate that allows flow in one direction (downstream) (Rayner et al., 2020). Occasionally the floodgates leak when they are jammed open by debris, when the rubber floodgate seals become damaged, or when there is a fault in a floodgate (e.g. the hinge breaks). When this occurs, some flow can pass upstream unless drop boards are installed on the structure (e.g. see the far-right culvert in Figure 4-1). Subsequently, the floodgates require regular maintenance to ensure they remain fully functional. Note, the elevation of the weir (or top of the structure) (~1.1 m AHD) is relatively low compared to the highest tide levels (~0.95 to 1.00 m AHD). Subsequently, water can overtop the structure from the downstream side when there are tidal anomalies coinciding with these high tides.

Figure 4-1 The upstream side of the Menarcobrinni floodgates (25 June 2024)

Figure 4-2 The Menarcobrinni floodgates (foreground) and Collombatti-Clybucca floodplain (background) (25 June 2024)

At the end of 2022 and beginning of 2023, two of the floodgates were removed and no drop boards were installed, allowing saltwater to flow upstream for a period of time. This provides an ongoing opportunity to assess how allowing tidal flushing upstream of the floodgates may influence water quality, and help inform the ongoing management of the Menarcobrinni floodgates. The following Section 4.2 provides a review of historical floodgate management. Following this, an analysis of water quality data during the period when floodgates were removed is provided in Section 4.3.

4.2 Maintenance and condition data

4.2.1 Kempsey Shire Council maintenance data

The Menarcobrinni floodgates were constructed in the 1960s under the Macleay Valley Flood Mitigation Scheme and are owned and operated by Kempsey Shire Council (Rayner et al., 2020; Tucker et al., 2023). In recent years, Kempsey Shire Council has conducted at least two detailed inspections of the floodgate structure:

- May 2012: The floodgate was observed to be in poor condition with extensive concrete cancer throughout the structure. While there was no evidence of structure failure it was recommended that it be monitored every 6 to 12 months. At the same time a range of repairs were recommended.
- January 2018: The structure was observed to be in very poor condition. It was noted that all floodgates had been refurbished.

In 2023, Kempsey Shire Council replaced the two floodgate flaps which had fallen into Clybucca Creek. It is likely that other inspections have been completed, however, no records of such inspections were available.

4.2.2 WRL floodgate observations

When completing routine maintenance of the water quality monitoring network, WRL also collected ad-hoc information regarding the status of the Menarcobrinni floodgates. WRL's observations are outlined in Table 4-1. These observations have been collected opportunistically. Exact dates for maintenance (e.g. re-installation of floodgates) are not known and the level of detail for each observation may also vary. Nevertheless, this record can help provide some insight into the ongoing management of the Menarcobrinni floodgates and assist with the interpretation of water quality data.

Table 4-1 WRL observations of Menarcobrinni floodgates

Inspection date	Notes*
22 November 2021	Leaks were observed through floodgate flaps 14 and 19. Drop boards were observed on floodgate 13.
28 April 2022	A large flow was observed through floodgate 1. A drop board was observed on floodgates 18 and 13. Floodgate 13 was observed to have one hinge detached.
5 December 2022	Drop boards were observed on floodgate 13.
21 March 2023	Drop boards were observed on floodgate 13. A large tide was occurring on the downstream side and flow was observed over the top of the drop boards on floodgate 13.
23 March 2023	Two floodgate flaps had been completely removed and placed on top of the structure (drop-boards may have been in place but no observations were recorded). Exact floodgates were not recorded.
15 August 2023	Drop boards were observed on floodgate 1.
12 December 2023	Drop boards were observed on floodgate 1. A leak was observed through floodgate 12.
4 March 2024	Drop boards were observed on floodgate 1. A leak was observed through floodgate 12. Vegetation was observed to have wedged the floodgate flap open.
25 June 2024	Small leaks were observed through floodgates 1, 7, 12, 14 and 19. Moderate leaks were observed through floodgates 11 and 21. Drop boards were observed on floodgate 1.

*Note: Observations were taken opportunistically during water monitoring network maintenance. Some key floodgate events may not have been recorded. Observations should only be used to confirm when leaks or maintenance occurred. Additional leaks and maintenance may have occurred that were not recorded.

In addition to these observations, WRL was also in contact with a local landholder who provided the following observations:

- 02/12/2022 – Two floodgates had their flaps removed allowing two-way flow for some time since last correspondence in August 2022.
- 27/02/2023 – The two floodgates had been reinstated to ensure one-way flow approximately 2 weeks previously.

4.3 Influence of tidal connectivity on water quality

4.3.1 Identification of period when floodgates were open

To analyse the influence of floodgate removal, it is first important to establish when the floodgates were removed. An analysis of water level and salinity data was completed in an attempt to exactly identify these dates. Due to the underlying variability in rainfall conditions and leakage of the floodgates (even when they are maintained) meant that specific dates could not be determined.

In the absence of exact dates, using expert judgment of water level and salinity data was used alongside maintenance records to estimate the likely dates for opening and closure:

- Gates opened: September/October 2022
- Gates closed: prior to 23/02/2023

4.3.2 Influence of tidal connectivity on water quality

During the period when the two floodgate flaps were removed, there was only one event where significant tidal intrusion occurred. This began at the start of November 2022 and lasted approximately 100 days. By comparison, across the entire monitoring period from November 2021 to January 2025, eleven other significant tidal intrusion events occurred when the floodgates were functioning as normal. These events can likely be attributed to leaks or overtopping of the floodgates.

A comparison of conductivity measurements during tidal flushing events is provided for Station 1 and Station 2 in Figure 4-3 and Figure 4-4, respectively. Limited conductivity data was available for Station 3 and a meaningful comparison could not be provided for this location for the period when the floodgates were open. At both Station 1 and Station 2, increases in conductivity initially occurred faster when the floodgates were open, given similar initial conductivity levels. Data indicated that the rate at which conductivity levels increases is also highly dependent the catchment conditions (i.e. inflow of fresh rainwater). Note, the initial conductivity of the system plays a significant role in determining the duration of recovery.

Analysis of pH data did not provide a clear indication of either improvement or deterioration in conditions associated with the opening of the two floodgate flaps. As described in Section 2, pH levels are highly dependent on the prevailing climatic conditions, resulting in inherent variability. This variability cannot be accurately assessed through a single comparison event. Nevertheless, data did indicate a strong correlation between high conductivity and neutral pH conditions (see previously in Figure 3-4). It can therefore be inferred that the increased conductivity resulting from the two opened floodgates acted to improve water quality (reduce acidity) within the system.

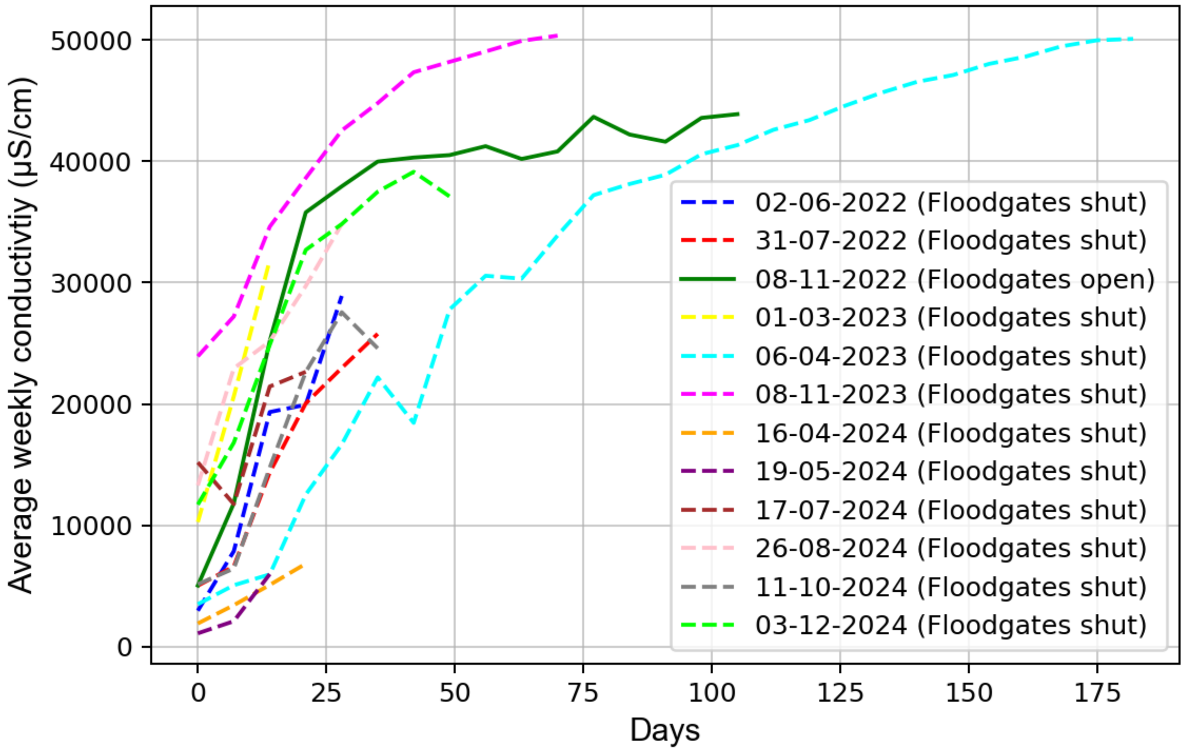

Figure 4-3 Comparison of conductivity increase due to tidal flushing Station 1 when two floodgates were opened versus shut

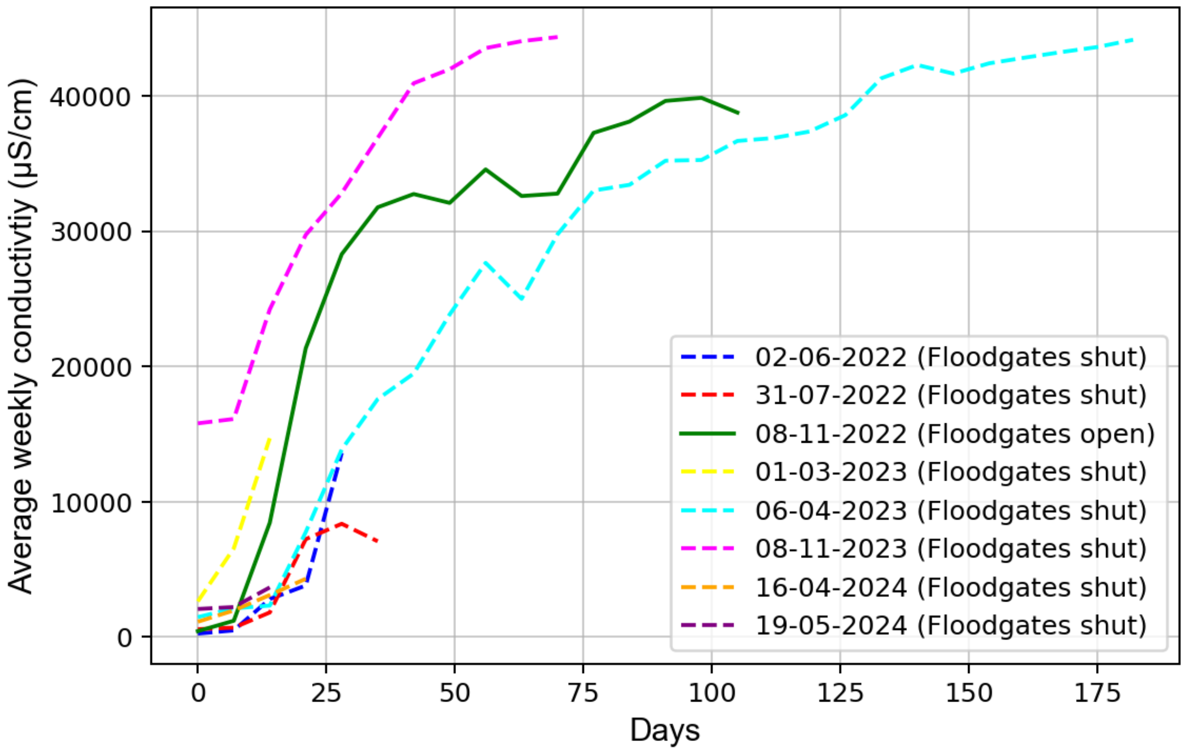

Figure 4-4 Comparison of conductivity increase due to tidal flushing Station 2 when two floodgates were opened versus shut

5 Comparison with historical water quality data

Summary points

- Water quality data was collected at Clybucca during an 8-year period from 1998 to 2005 by Greenspan Technical Services.
- Data was available during a dry period from 2002 to 2004 for analysis.
- In recent years conductivity levels have increased at a faster rate in areas upstream of the Menarcobrinni floodgates.
- A positive correlation between conductivity and pH was observed in both monitoring periods indicating the tidal buffering of acidic runoff.
- There has been no clear improvement in the severity of acid discharge events since the early 2000s.

5.1 Preamble

Work to restore the acidic landscape at Clybucca has been underway since the early 1990s. In the late 1990s, this included the collection of a range of water quality parameters. The following section compares water quality data collected during these investigations with the data collected in the current monitoring program. This section has been divided into two sections. A description of the historical monitoring data is provided in Section 5.2, including an assessment of its quality. Following this, a comparison of the historical and current water quality data was completed (Section 5.3).

5.2 Historical water quality data collection

5.2.1 Greenspan Technical Services data

Long-term water quality data was collected upstream and downstream of the Menarcobrinni floodgates from 1998 to 2005 by Greenspan Technical Services (hereafter referred to as Greenspan) to inform the Clybucca Acid Sulfate Soils Hot Spot project (KSC, 2004; Glamore and Rayner, 2017). This data has previously been analysed by Haskins (1999), Enginuity Design (2003), KSC (2004), Bush et al. (2006), and Glamore and Rayner (2017).

Water quality data was collected by Greenspan at two stations located upstream and downstream of the Menarcobrinni floodgates. The exact locations of the Greenspan monitoring stations are unknown. Bush et al. (2006) stated that the upstream station was approximately 300 m upstream of the floodgates, while the second station was immediately downstream of the gates. Infrastructure for a monitoring station still exists on the upstream side of the floodgates, however, this may have been the third station identified separately by KSC (2004).

Water quality data measured by Greenspan included measurements of temperature, conductivity, pH, oxidation reduction potential and dissolved oxygen. The water quality data was supplemented by measurements of water levels and discharge, however, discharge was only measured at the upstream stations.

Limited information is available regarding the quality of the Greenspan dataset. There is no metadata that complements the existing dataset. Plots of this dataset are available within several reports, while digitised data is available for a period from March 2002 to August 2005. Table 5-1 summarises notes on data quality provided in literature.

Table 5-1 Notes on quality of Greenspan dataset

Literature source	Notes on data quality
Haskins (1999)	Data gaps can be attributed to telemetry transmission failure. In these instances, no data is available. Cleaning of sensors (as occurred in 18/9/1999) can cause step changes for some data. Erroneous spikes in data (specifically noting level and conductivity) can occur. Conductivity is measured in increments of 200 µS/cm.
Enginuity Design (2003)	Analysis of data did not include commentary on its quality.
KSC (2004)	Three long-term monitoring stations were identified. Two managed by Greenspan (upstream and downstream of the floodgates) and one managed by Kempsey Shire Council (upstream of the floodgates). Discharge data was considered to be inaccurate.
Bush et al. (2006)	Further analysis of discharge data indicated that there were substantial periods where data was erroneous, likely due to coverage by drain sediment (ooze).
Glamore and Rayner (2017)	Poor accuracy of discharge data was identified, referencing previous onsite observations.

Data collected by Greenspan was presented by Glamore and Rayner (2017), for a period from 1998 to 2004 for the site upstream of the floodgates. Several gaps are present throughout the data record , and it remains unclear whether these are due to quality control measures or instrument failure, as noted by Haskins (1999). In several instances, noticeable shifts in the data are evident (e.g. at the end of January 2004), likely resulting from maintenance operations on the sensors. Digital versions of this dataset were not available for the analysis completed in this study.

One record of digitised water quality data was available for a period from March 2002 to August 2004. This data included water level, pH, conductivity, dissolved oxygen and oxidation reduction potential data at the upstream and downstream locations (discharge was also measured at the upstream location). An analysis was undertaken to confirm the source of the data as its only identifier was provided in its filename which indicated that it was data from Clybucca Creek upstream and downstream of the floodgates. Comparison with the data presented by Glamore and Rayner (2017) showed that the water level data in the digitised dataset was clearly the same. However, significant discrepancies were observed for conductivity, pH and dissolved oxygen data. Enginuity Design (2003) presented a dataset collected by Greenspan from March 2002 to November 2002. Comparison of the digitised dataset with the Enginuity Design (2003) data showed a clear match for upstream and downstream stations for water level, conductivity, pH, oxygen reduction potential and dissolved oxygen data.

Since water levels within the digitised data clearly matched water levels observed at Clybucca there is evidence to support that water quality data is also from the same station. One explanation is that the data presented by Glamore and Rayner (2017) is actually the third water quality data station mentioned by KSC (2004) as it only includes data for an upstream station. Data presented by Enginuity Design (2003), which included information at upstream and downstream stations, could in fact have been part of the Greenspan dataset. Similarities between water quality data presented by Enginuity Design (2003) and Glamore and Rayner (2017) indicate that this explanation is highly plausible. The data types in the digitised dataset also matches the records of Bush et al. (2006), who noted that temperature data was unavailable for their analysis.

In the absence of further information, the digitised dataset that matches data presented by Enginuity Design (2003) has been used for the comparison in this study. Note, this data has been used cautiously due to the limited metadata available describing its exact origin. This limitation is reflected in the interpretation and any conclusions drawn from the dataset.

5.2.2 Previous WRL data collection

In addition to the Greenspan water quality dataset, WRL has previously collected long-term conductivity data downstream of the Menarcobrinni floodgates on two occasions:

- February 2015 to July 2015 (Glamore and Rayner, 2017)
- February 2018 to September 2019 (Rayner et al., 2020)

Details regarding the quality of these datasets is provided within the respective WRL reports.

5.3 Comparison of historical data

5.3.1 Comparison of rainfall and conductivity

Figure 5-1 shows the annual rainfall measurements since 2002 highlighting years where water quality data has been collected. The comparison shows there was significant rainfall variability between years where monitoring occurred. Data collected by Greenspan from 2002 to 2004 occurred during drier than average years. Data collected by WRL included both dry and wet years.

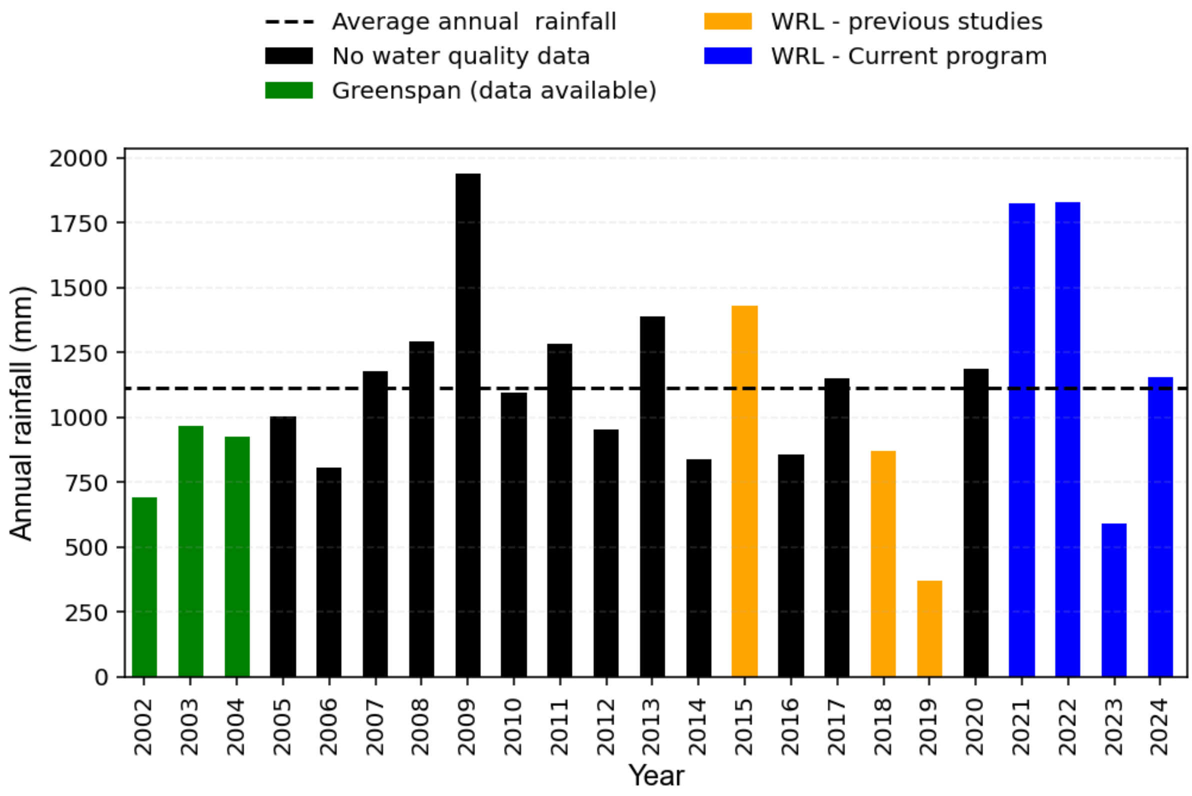

Figure 5-1 Comparison of annual rainfall for different years of water quality monitoring

Rainfall data from BOM (2025e).

The year-on-year variability in rainfall is especially evident when comparing conductivity data downstream of the Menarcobrinni floodgates (Figure 5-2). Years with above average rainfall (such as 2015, 2021, and 2022) all recorded a significant number of conductivity measurements below 5,000 μS/cm and reduction in conductivity measurements above 40,000 μS/cm.

During the driest year this period (2019), conductivity levels remained above 25,000 μS/cm (note, data was only available until September in 2019). A comparison of conductivity data measured in 2002 and 2023, when both years received similar rainfall, showed that conductivity trends have not changed significantly over the past two decades. This is somewhat expected given that conductivity levels will be controlled by intrusion of ocean waters to the Macleay River estuary and not any changes across the Clybucca floodplain.

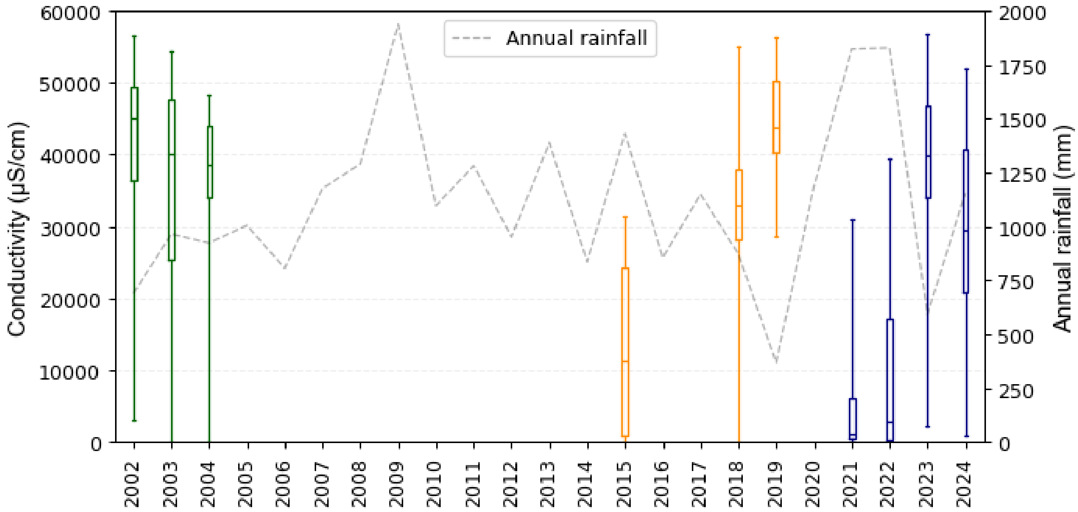

Figure 5-2 Conductivity measurements downstream of the Menarcobrinni floodgates as recorded by Greenspan (green), Glamore and Rayner (2017) and Rayner et al. (2020) (orange), and the existing monitoring program (blue)

Rainfall data from BOM (2025e). Boxes indicate 25th and 75th percentile with the median bar inside, and whiskers indicating the total data range.

Conductivity data was also measured by Greenspan immediately upstream of the Menarcobrinni floodgates (Figure 5-3). Conductivity levels upstream of the floodgates measured by Greenspan were typically lower than levels downstream reflecting the operation of the one-way floodgates. Interestingly, when comparing measurements collected by WRL (blue in Figure 5-2 and Figure 5-3), the conductivity upstream of the floodgates was similar to the conductivity downstream. The cause of this is uncertain, however, potential reasons may include:

- Greenspan data loggers were located further upstream than WRL data loggers
- The floodgates were open or leaking more often during the later period, likely due to aging infrastructure

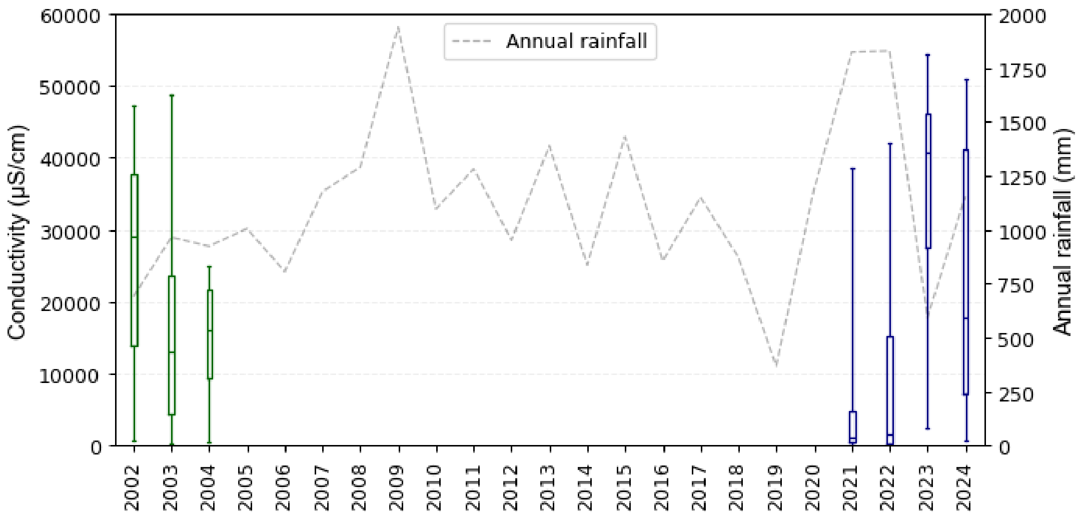

Figure 5-3 Conductivity measurements upstream of the Menarcobrinni floodgates as recorded by Greenspan (green) and the existing WRL monitoring program (blue)

Rainfall data from BOM (2025e). Boxes indicate 25th and 75th percentile with the median bar inside, and whiskers indicating the total data range.

5.3.2 Comparison of pH data

5.3.2.1 Annual pH measurements

A comparison of the annual pH levels measured by Greenspan and WRL is shown in Figure 5-4. Measurements exhibit considerable variability from year to year, largely influenced by prevailing climatic conditions. As identified in Section 3.3.2, drier years typically resulted in higher pH levels. This held true in 2002 and 2004, while 2003 had a lower-than-expected median pH for a dry year. While remediation works were implemented in October 2003 (KSC, 2004), this cannot be definitively linked to an improvement from remediation. The median pH values were similar for 2002 and 2023 (years with comparative rainfall), suggesting that natural variability in acidity may obscure the effects of remediation works.

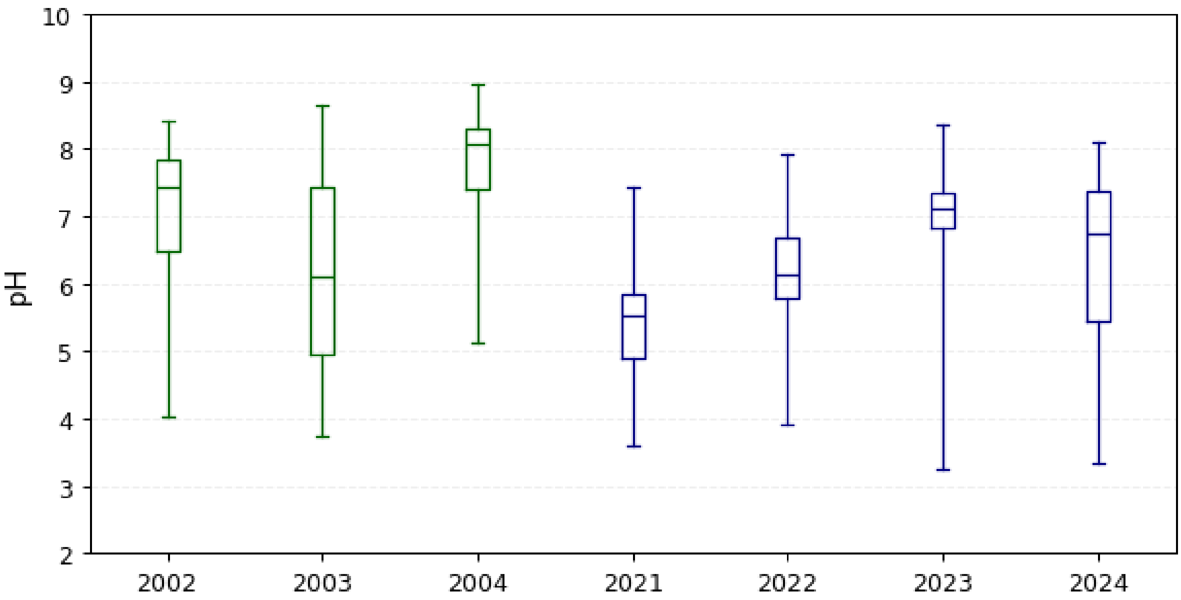

Figure 5-4 pH measurements upstream of the Menarcobrinni floodgates as recorded by Greenspan (green) and the existing monitoring program (blue)

Boxes indicate 25th and 75th percentile with the median bar inside, and whiskers indicating the total data range.

5.3.2.2 Comparison of pH discharge events

To further identify any long-term changes in pH, rainfall events between 2002 and 2004 were first identified (see Appendix C). These events were subsequently compared to events of comparable intensity after November 2021 to identify whether there were noticeable changes in pH discharges. A total of six comparable events were identified across the combined periods:

- Comparison 1: Event 9 (22/09/2022) and event 42 (24/02/2004), both 3 EY events
- Comparison 2: Event 12 (23/01/2023) and event 37 (22/11/2003), both 12 EY events
- Comparison 3: Event 16 (28/01/2024) and event 35 (27/05/2003), both 6 EY events
- Comparison 4: Event 16 (28/01/2024) and event 38 (5/12/2003), both 6 EY events
- Comparison 5: Event 18 (5/04/2024) and event 27 (27/03/2002), both 50% AEP events
- Comparison 6: Event 20 (1/06/2024) and event 29 (17/02/2003), both 6 EY events

No notable changes in pH were observed across comparisons 1 through 4, despite the occurrence of similar rainfall (ranging from 12 EY to 3 EY). This could indicate that the drivers of acid discharge at Clybucca have remained consistent over the 20-year period between the two data collection campaigns. That is, similar rainfall events under similar antecedent conditions continue to influence pH at Clybucca in a consistent manner. While a pH response was observed for comparison 6, a second rainfall event on 27/02/2003 meant that the comparison was not like-for-like and unsuitable for analysis. As a result, comparison 5 was the only one deemed suitable for detailed analysis and is further discussed and presented in Figure 5-5. Note, comparisons 1 through 4 and comparison 6 have been presented graphically in Appendix C.

Figure 5-5 illustrates a similar pH response to a 50% AEP rainfall event that occurred in March 2002 and April 2024 (comparison 5). In both instances, pH levels fell from neutral (~7) to acidic (~4). The pH levels dropped more gradually for the 2024 event (over 7 days) compared to the 2003 event (2 days), however, this was likely due to the different rainfall patterns. Once pH levels dropped, they fluctuated between pH 4 and pH 6 for 40 to 50 days before recovering to neutral levels. Some rainfall fell in the months following the 2024 event which may have delayed the recovery following this event. Fluctuation in pH levels following the rainfall event is most likely due to tidal flows throughout the system on both occasions. The pH measurements were taken at a location near the Menarcobrinni floodgates where conductivity data indicated there were some tidal inflows.

Based on this analysis of pH data, there is no clear indication that remediation works implemented to date (KSC, 2004; Rayner and Tucker, 2023) have reduced the discharge of acid following rainfall events.

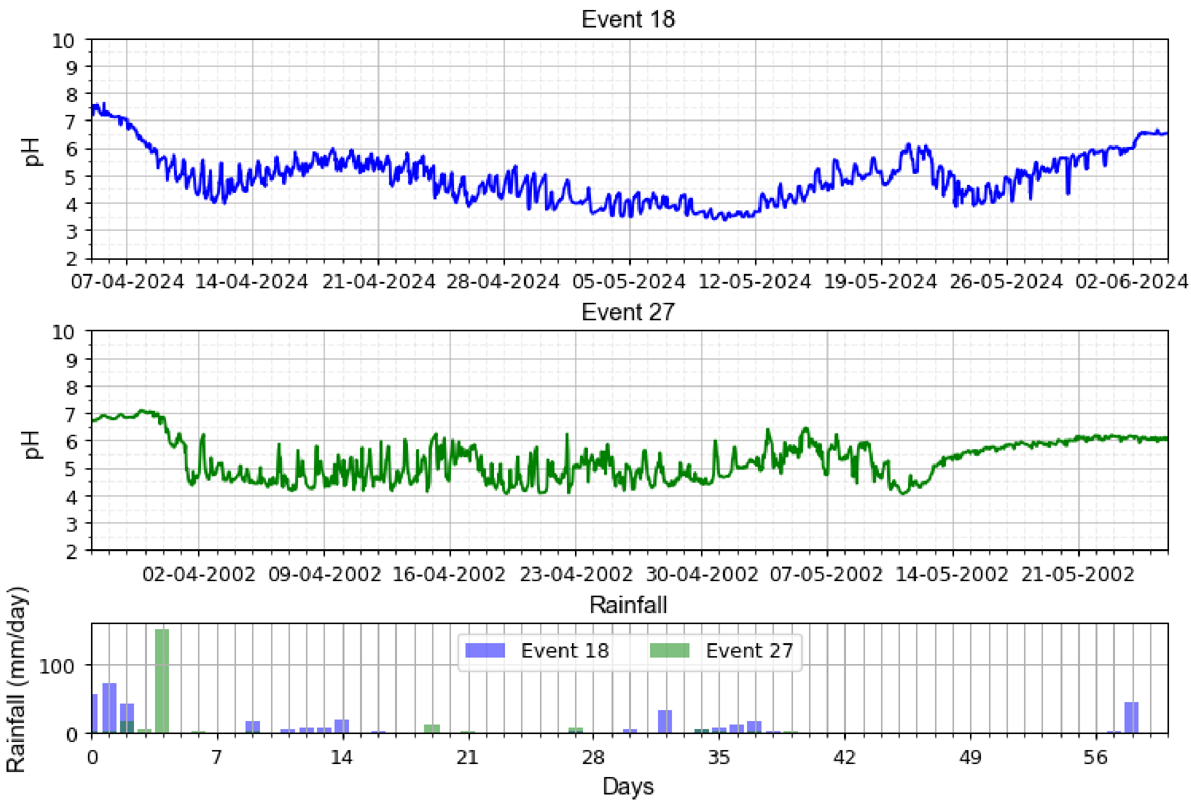

Figure 5-5 Comparison of pH levels following event 18 (5/04/2024) and event 27 (27/03/2002) upstream of the Menarcobrinni floodgates

5.3.3 Comparison of dry periods

Greenspan monitoring data included three prolonged dry periods (>90 days) without significant rainfall events (rainfall data from BOM (2025e)):

- **31/3/2002 to 25/12/2002**: 268 days, average rainfall 1.0 mm/day
- **29/5/2003 to 25/10/2003**: 148 days, average rainfall 0.7 mm/day
- **25/3/2004 to 17/10/2004**: 205 days, average rainfall 0.9 mm/day

These events have been compared in Figure 5-6 to the dry periods that occurred in 2023 and 2024 (see Section 3.4.3). Note, Greenspan data was only available until August 2004 for the analysis.

The first 30 days of each dry period are somewhat similar. Conceptually, this period is characterised by the drainage of freshwater from the floodplain followed by groundwater drainage. The conductivity measured during this period was below 20,000 μS/cm for Greenspan and WRL data. This is expected as a result of the freshwater catchment inflows draining from the system. The lowest pH was measured during this initial drainage for all dry periods. This is characteristic of acidic groundwater drainage originating from the acid sulfate soils underlying the Clybucca floodplain.

A steady increase in conductivity levels was measured approximately 60 days into each dry period, with the exception of the period starting in June 2024. As discussed in Section 3.4.3, this difference was likely caused by small but persistent rainfall during the first 100 days of the dry period. Likewise, 30 mm of rainfall in June 2003 also lowered the conductivity, and prolonging the recovery. The rate at which conductivity levels increased varied between all dry periods, however, the increase in conductivity was observed to be quicker in recent years (Table 5-2). The reasons for this change could include:

- Underlying variability in floodplain conditions (e.g. climate or antecedent conditions)
- The Menarcobrinni floodgates now leak significantly more after an additional 20 years of aging
- Modifications to floodplain drainage (e.g. remediation works)

Note, sea level rise is also expected to result in small increases to salinity intrusion in the Macleay River estuary (Mason et al., 2025). The influence of this change is unlikely to be discernible in this data series due to high variability in other environmental drivers on salinity intrusion. However, into the future it can be expected that sea level rise may increasingly contribute to higher conductivity levels observed at Clybucca.

Table 5-2 Days for conductivity to rise from 5,000 μS/cm to 20,000 μS/cm

Dry period start date	Days
31/03/2002	46
29/05/2003	85
25/03/2004	98
30/03/2023	29
03/06/2024	20

A consistent relationship between conductivity levels and pH was observed across all monitored dry periods (Figure 5-7). Once the conductivity rises above 15,000 µS/cm, there is a strong correlation with neutral pH conditions (note, this was previously identified in Section 3.4.3). This is most likely due to the natural buffering of acid with bicarbonates in seawater. While no significant difference identified between the Greenspan and WRL datasets regarding the relationship between pH and conductivity, individual events can be variable. For example, comparison of pH to conductivity for the 2004 Greenspan event showed that low conductivity levels will not always result in low pH levels.

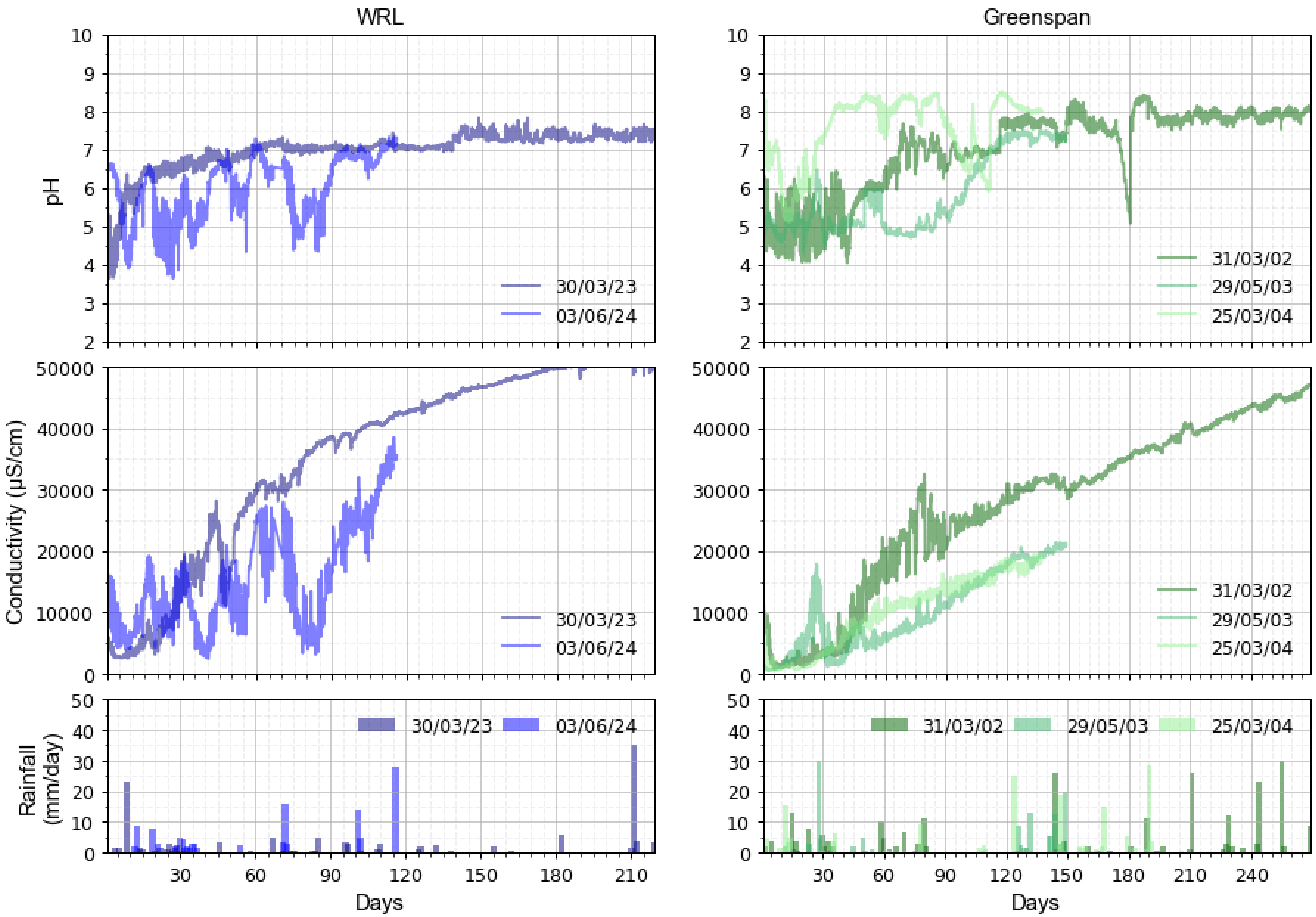

Figure 5-6 Comparison of pH and conductivity upstream of the Menarcobrinni floodgates during recovery periods

Rainfall data from BOM (2025e).

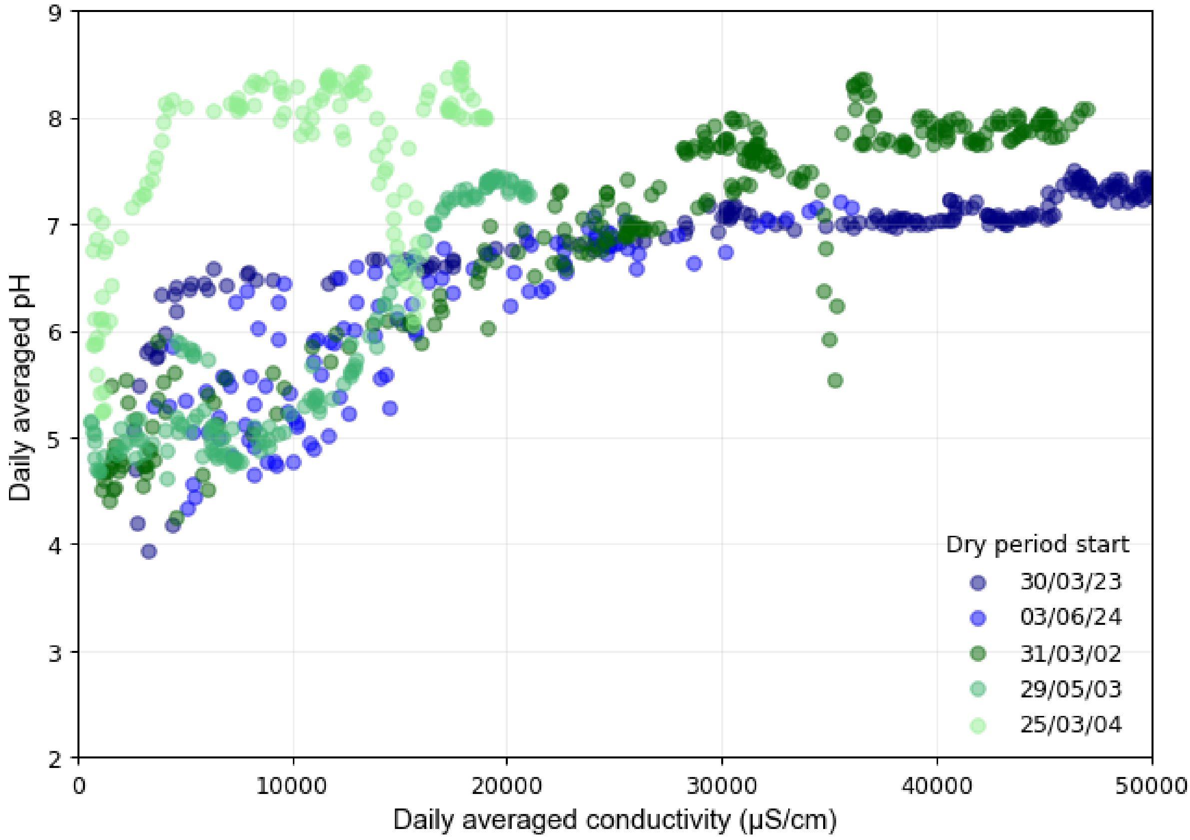

Figure 5-7 Daily averaged pH versus daily averaged conductivity upstream of the Menarcobrinni floodgates for each dry period

6 Comparison with water quality of Big Swamp, Manning River

Summary points

- Rainfall data indicated that events often occur on a regional scale spanning the 100 km between Big Swamp and Clybucca.
- The water quality at Big Swamp and Clybucca was influenced by individual rainfall events and was largely independent of seasons.
- Interannual trends associated with the El Niño Southern Oscillation resulted in more acidic water occurring at Clybucca and Big Swamp during wet years.
- The water quality at Big Swamp and Clybucca was influenced by the distance of monitoring stations from the downstream estuary.
- Trends observed at Clybucca and Big Swamp highlight the need for regional governance regarding the management of acid sulfate soil affected coastal floodplains.

6.1 Preamble

Big Swamp is an approximately 2,000 hectare coastal floodplain located on the Manning River estuary on the NSW mid-north coast, approximately 100 km south of Clybucca (Glamore et al., 2014). Recognising the environmental opportunity, a large proportion of the floodplain was restored into coastal wetland habitat in 2012 by MidCoast Council (Harrison et al., 2019). A range of restoration activities have continued across the site and in 2014 a water quality monitoring network was installed to measure the progress of these efforts (Ruprecht et al., 2024f). This monitoring has been maintained until present day and regular analysis of the monitoring data has been conducted (Ruprecht et al., 2024d; Ruprecht et al., 2024a; Ruprecht et al., 2024e; Ruprecht et al., 2024b; Ruprecht et al., 2024c; Ruprecht and Harrison, 2024).

This section compares the water quality data measured at Clybucca and Big Swamp to identify trends that may inform the management of coastal floodplain systems on a regional scale. The following section presents a comparative analysis of the two datasets. A brief overview of the Big Swamp monitoring program is first provided in Section 6.2. Section 6.3 provides the results of the two datasets comparison and identify regional trends.

6.2 Overview of the Big Swamp dataset

The Big Swamp monitoring program has included seven monitoring stations since its establishment in 2014. One station (Angelina Swamp) was decommissioned in 2020, while two new stations (Coralville Bridge and Manning River) were established in 2020 (Figure 6-1). The Manning River station is located approximately 9 km upstream of the Manning River's entrance to the ocean.

All monitoring stations measure the following data (WRL, 2025):

- Water level
- pH
- Temperature
- Conductivity
- Dissolved oxygen

Note, monitoring of Big Swamp began following the implementation of remediation activities. Furthermore, Big Swamp never had a major floodgate installed on Pipeclay Canal, unlike the Menarcobrinni floodgates on Clybucca Creek. This means that the Big Swamp monitoring network measures overall higher conductivity levels, as it is better connected to the estuary. In comparison, most of the Clybucca monitoring network is located upstream of the Menarcobrinni floodgates and typically records a freshwater influenced signature.

Since the Clybucca monitoring network was only installed in late 2021, it was determined that the comparison of the two datasets would be completed for the years 2022, 2023 and 2024. A comparison of the distance of each water quality station from the ocean entrance is shown in Table 6-1.

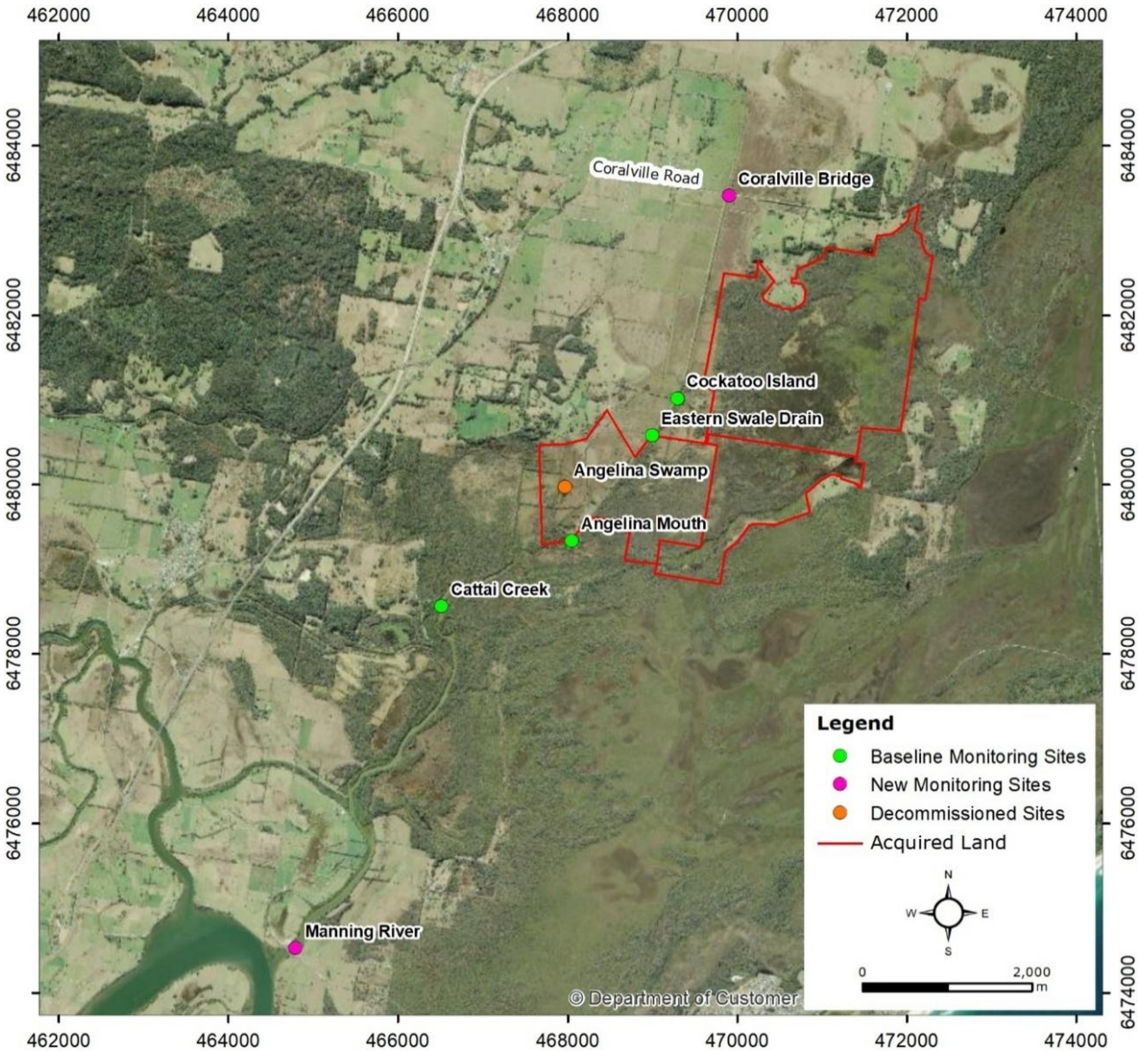

Figure 6-1 Big Swamp monitoring locations (WRL, 2025)

Table 6-1 Station distance from the ocean entrance of the estuary

Location	Station ID	Approximate distance from the ocean (km)	Upstream of a floodgate?
Clybucca	Station 4	14.5	No
Clybucca	Station 1	14.9	Yes
Clybucca	Station 2	18.7	Yes
Clybucca	Station 3	21.0	Yes
Big Swamp	Manning River	8.9	No
Big Swamp	Cattai Creek	14.0	No
Big Swamp	Angelina Mouth	16.0	No
Big Swamp	Angelina Swamp	16.6	No
Big Swamp	Eastern Swale Drain	17.5	No
Big Swamp	Cockatoo Island	18.1	No
Big Swamp	Coralville Bridge	20.6	No

6.3 Comparison of water quality data

6.3.1 Rainfall climates

The rainfall climates at Clybucca and Big Swamp have been compared using data from nearby rainfall stations at Kempsey and Moorland, respectively (Table 6-2). Analysis of rainfall data indicated that similarly to Clybucca (as discussed previously in Section 2.3.3), rainfall trends at Big Swamp were influenced by ENSO. Rainfall data from Moorland characterised 2022 as a wetter than usual year compared to 2023 (drier than average year) and 2024 (approximately average year).

When comparing the total rainfall volumes between sites, Big Swamp generally received more rainfall than Clybucca (~106 mm per year). This was the case in 2023 and 2024, where Big Swamp received over 110 mm additional rainfall compared to Clybucca. In 2022, a wetter than usual year, the annual rainfall at both locations was similar, with a difference of only 31 mm recorded across the year (in this instance Clybucca received more rainfall).

Table 6-2 Comparison of rainfall between Clybucca and Big Swamp from 2022 to 2024

Year	Annual rainfall (Clybucca)[1] (mm)	Annual rainfall (Big Swamp)[2] (mm)	Difference (mm)
Average*	1,113	1,219	106
2022	1,828	1,797	31
2023	592	703	111
2024	1,153	1,285	132
Total (2022 to 2024)	3,573	3,785	212

[1]BOM (2025e), 2BOM (2025b), *Calculated from 2002 to 2024 for both sites.

Figure 6-2 shows the monthly rainfall at Clybucca and Big Swamp throughout the 3-year monitoring period. While Big Swamp received slightly more rainfall, Figure 6-2 demonstrates that the monthly rainfall was quite similar at both locations. Notably, substantial rainfall recorded in March and April 2022 was very similar at both sites. This indicates that the climate driving the rainfall had a regional influence capable of extending across the 100 km between the two sites. Note, an analysis of long-term rainfall at Big Swamp indicated that the wet season is more likely to extend into April compared to Clybucca (see Section 2.3.2). Nevertheless, as shown in Figure 6-2, rainfall can occur throughout the year and may not necessarily follow these long-term seasonal trends.

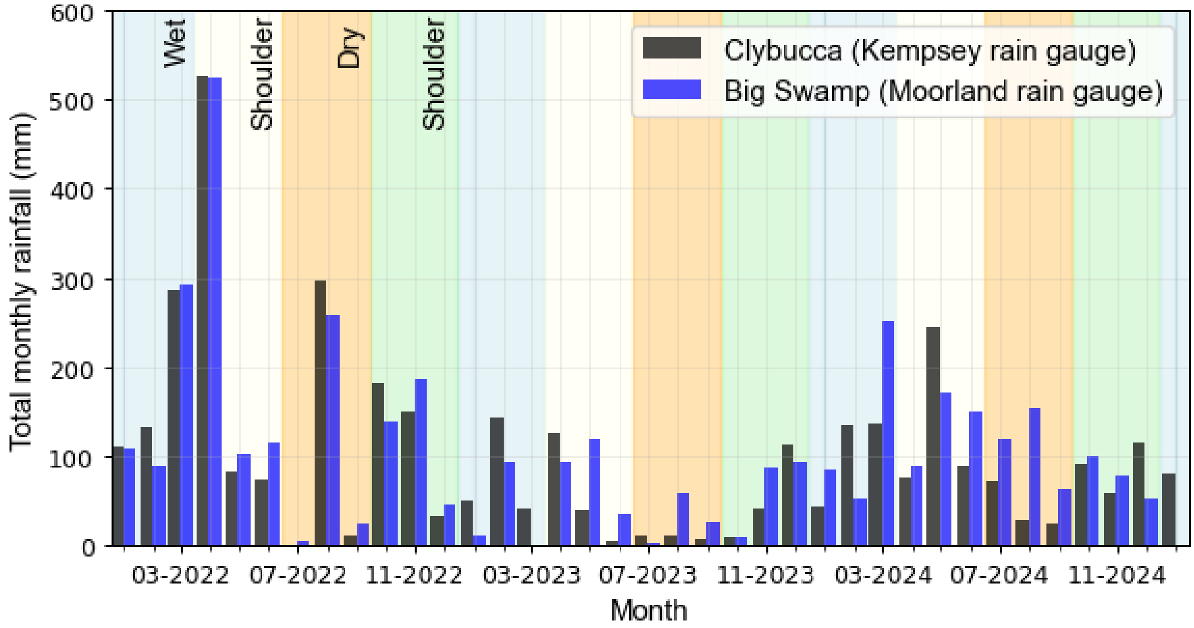

Figure 6-2 Comparison of monthly rainfall data for the nearby stations to Clybucca and Big Swamp (wet, dry and shoulder seasons are indicated with different shades) (BOM, 2025e; BOM, 2025b)

6.3.2 Comparison of seasonal data

Seasonal water quality data collected at Clybucca and Big Swamp has been compared in Figure 6-3. Due to quality issues, dissolved oxygen data could not be compared between the sites. Seasons have been divided into wet, dry and shoulder seasons, based on the rainfall data as discussed in Section 2.3.2. Note, additional analysis of the seasonality of the Clybucca data was previously discussed in Section 3.3.1.

The water temperature at Clybucca and Big Swamp was similar throughout the different seasons. Higher temperatures were observed from January to March and lower temperatures from July to September at both sites. Temperatures at Clybucca were marginally hotter than the temperatures at Big Swamp.

Conductivity data from Clybucca and Big Swamp showed that stations further upstream tend to have lower salinity levels at both sites. Analysis of salinity found higher salinity levels from January to March and lower salinity levels from April to June at both sites. While January to March is typically the wet season, from 2022 to 2024 larger rainfall volumes fell in March towards the end of this period showing that the wetlands do not necessarily always follow the average seasonal pattern. As a result of rainfall, lower salinity levels were observed later in the April to June period. A possible cause for higher summer salinity levels observed from January to March could be related to increased evaporation, however, further investigation is required. The influence of the floodgates at Clybucca can be observed through the slightly lower maximum salinity values compared to Big Swamp.

Throughout the year there was a clear trend of increasing acidity with distance upstream both at Big Swamp and Clybucca. This is consistent with the conceptual understanding of acid generation and tidal flushing, which can be expected across other NSW drained coastal floodplains. This trend is likely related to the buffering capacity of seawater which has a greater effect at downstream locations where there are higher salinities. At Clybucca, the most acidic conditions were observed from April to June, likely resulting due to the drainage of the floodplain following wet conditions rather than seasonality. At Big Swamp the pH levels were also low from April to June, however, at the two stations furthest upstream, the lowest pH was observed during the dry season from July to September. One possible reason for this could be the higher rainfall which occurred from July to September in 2023 and 2024 at Big Swamp compared to Clybucca. Over the 3 years of monitoring, Big Swamp recorded a larger range of pH values from most acidic (pH < 3) to most basic (pH > 9) when compared to Clybucca.

6.3.3 Comparison of interannual data

Interannual water quality data collected at Clybucca and Big Swamp has been compared in Figure 6-4. Due to quality issues, dissolved oxygen data could not be compared between the sites. Note, additional analysis of the annual water quality trends at Clybucca was previously discussed in Section 3.3.2.

Analysis of water temperature data did not identify any clear interannual trends at Clybucca or Big Swamp. In 2024, the Big Swamp temperature data had increased variability, however, this is likely a result of sensor malfunction during this year which resulted in some stations having less than 50% data recovery (WRL, 2025).

The effect of ENSO is clearly visible in the conductivity data measured at Clybucca and Big Swamp. The lowest conductivity levels were observed in 2022, a wetter than usual year. Conversely, in 2023, a drier than usual year, higher conductivity levels were observed. In 2024, sensor malfunctions at Clybucca meant that low conductivity values which occurred in the later (and wetter) part of the year were not captured (Figure 6-4 shows higher than expected values at these stations in 2024). Excluding this data, the conductivity levels observed in 2024 at Clybucca and Big Swamp are indicative of average conditions and fall between the wet and dry conditions experienced in 2022 and 2023, respectively. As observed in the seasonal data, there is a clear trend that stations located further upstream have lower conductivity levels.

As identified previously, stations located further upstream were also observed to be more acidic. This is likely to due, in part, to the buffering capacity of seawater. At Clybucca, and for the downstream stations at Big Swamp, lower pH levels occur during La Niña (i.e. 2022 wet conditions) and higher pH levels occur during El Niño (i.e. 2023 dry conditions). However, comparison of upstream stations at Big Swamp indicated that this may not always be the case. At Big Swamp, the Coralville Bridge and Eastern Swale Drain stations more acidic conditions were observed in 2024. In analysis completed by Ruprecht and Harrison (2024) the Eastern Swale Drain station was identified as an acid hot spot. This highlights that there can be localised influences which impact water quality in addition to regional trends like ENSO.

6.4 Summary of regional water quality trends

Analysis and comparison of water quality data collected at Clybucca and Big Swamp provides the following insights into the regional water quality trends associated with drained coastal floodplains:

- Water quality trends are influenced by the proximity and connectivity of the coastal floodplain to the estuary. At both Clybucca and Big Swamp, a significant trend was observed where salinity and pH levels were dependant on the distance and connectivity of stations to the estuary. Stations located further from the estuary were generally more acidic and fresher (i.e. had lower conductivity).
- The El Niño Southern Oscillation (ENSO) has a significant impact on the water quality of NSW coastal floodplains. At both Clybucca and Big Swamp, La Niña conditions resulted in an increase in freshwater conditions across the floodplains. This meant that the buffering capacity of the estuary was reduced and the potential for acid discharge was increased. This resulted in acid being more frequently observed during 2022 (a La Niña year) at both sites.
- Sub-yearly seasonality does not have a clear influence on the water quality across NSW coastal floodplains on a regional scale. During the monitoring period, poor water quality occurring from April to June was associated with rainfall events and not necessarily the typical wet season.

These findings highlight the potential environmental impact which can occur simultaneously on a regional scale as a result of modified coastal floodplains. Subsequently, there is a need for regional governance regarding the management of acid sulfate soil affected coastal floodplains.

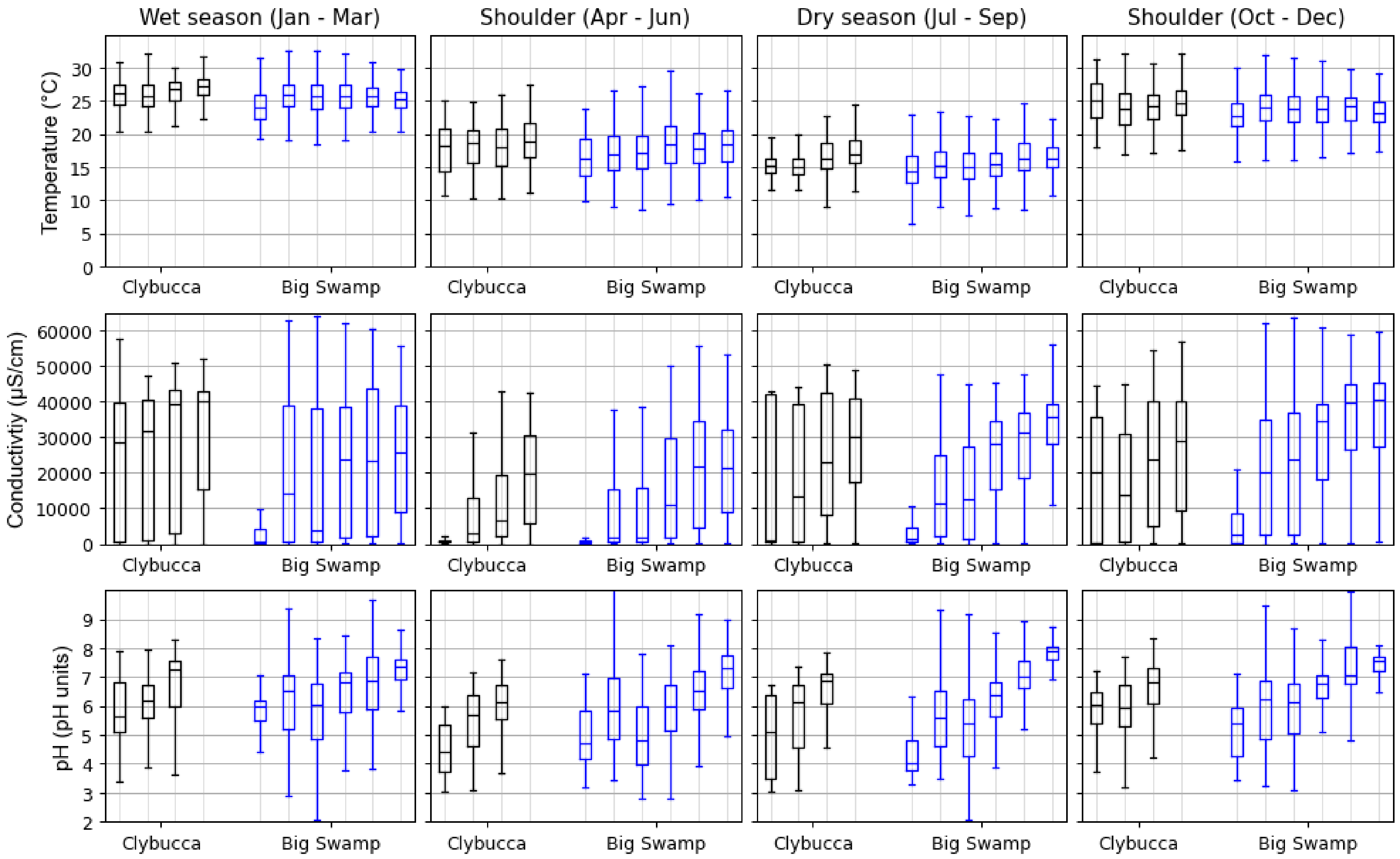

Figure 6-3 Seasonal comparison of water quality data collected at Clybucca (black) and Big Swamp (blue) – stations are ordered from upstream to downstream left to right (box indicates 25th and 75th percentile with the median bar inside, whiskers indicate 1.5 times the interquartile range)

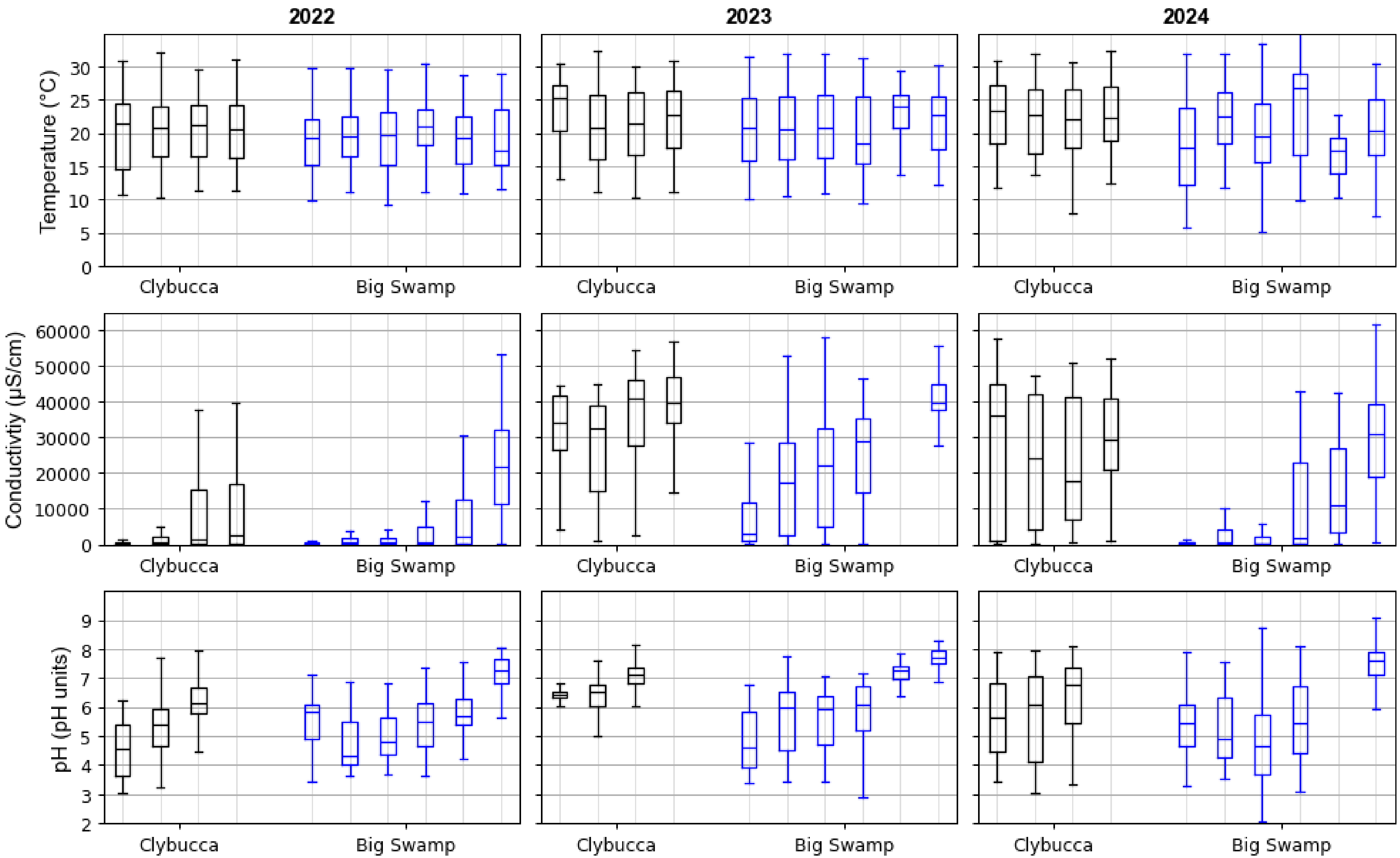

Figure 6-4 Interannual comparison of water quality data collected at Clybucca (black) and Big Swamp (blue) – stations are ordered from upstream to downstream left to right (box indicates 25th and 75th percentile with the median bar inside, whiskers indicate 1.5 times the interquartile range)

7 Quantifying water quality impacts on the Macleay River estuary

Summary points

- In the worst recorded event, up to 170 Olympic sized swimming pools worth of acid with a pH of 3 (e.g. vinegar) was discharged from Clybucca to the Macleay River estuary.
- In a worst-case scenario, blackwater generated at Clybucca has the potential to strip the entire Macleay Arm of oxygen.
- A three-step methodology to assess the impacts of poor water quality discharging from Clybucca on the broader Macleay River estuary is proposed:
  1. Pollution extent analysis
  2. Targeted monitoring field campaign
  3. Mitigation assessment

7.1 Preamble

As identified by Tucker et al. (2023), poor water quality and environmental impacts associated with Clybucca will have flow on effects to the health of the Macleay River estuary. The following section shifts the focus of this report from the water quality measured across the Clybucca floodplain to understanding the broader impact of poor water quality generated at Clybucca on the downstream estuary. As a first step, the pollution that is discharged from the Menarcobrinni floodgates at Clybucca is quantified (see Section 7.2). Following this, a recommended methodology has been developed to provide guidance on how the impacts from Clybucca on the wider Macleay River estuary should be assessed and remediated (Section 7.3).

7.2 Estimates of pollution volumes

7.2.1 Discharge volume calculation

Estimates of discharge from Clybucca have been determined by comparing water level observations collected immediately upstream of the Menarcobrinni floodgates during the monitoring period to an elevation-volume relationship, as shown in Figure 7-1. For any given tidal cycle, the discharge was determined to be the volume held within the drainage network at high tide, minus the volume held in the drainage network at low tide.

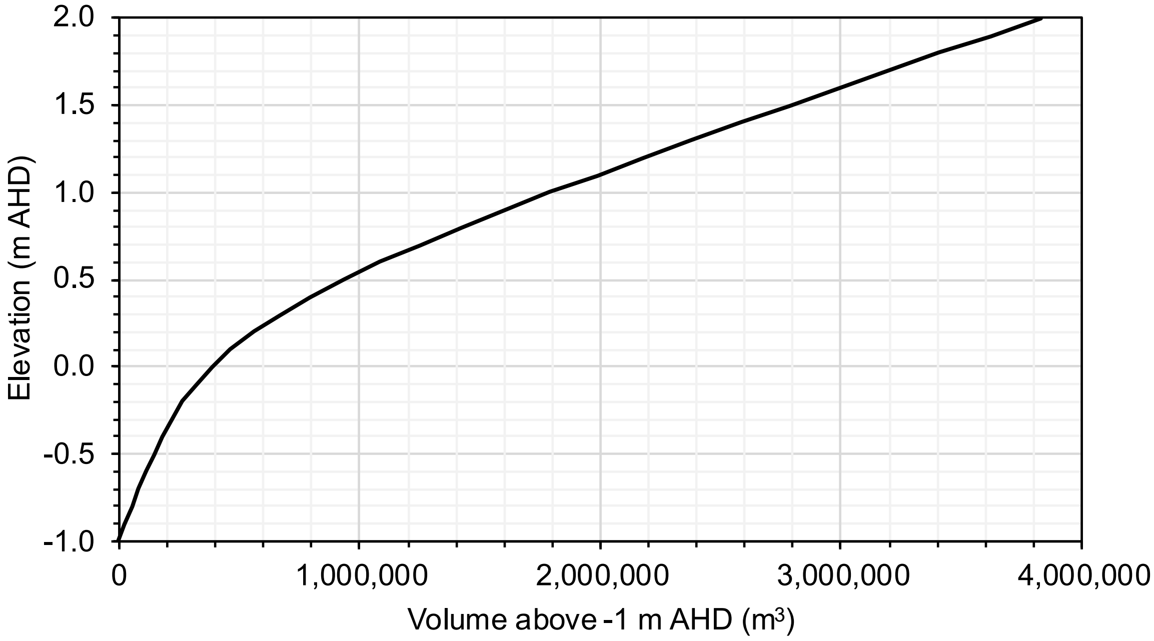

Figure 7-1 Volume of water in the Clybucca drainage network above -1 m AHD

The elevation-volume relationship (Figure 7-1) was determined using the numerical model developed for Clybucca by Rayner et al. (2020). This takes into account detailed drain geometry and features such as culverts and weirs which may prevent the discharge of water once water levels fall below a certain elevation. The elevation-volume relationship does not consider floodplain storage. It is therefore assumed that during a given tidal cycle, only water within the drainage network leaves the system. This assumption may result in the underestimation of outflow volumes in certain conditions (i.e. where water draining from the floodplain also contributes to outflows). Conversely, the method employed also assumes that water levels in the drainage network fall at the same rate across the drainage network, which can overestimate outflow volumes under certain circumstances. Despite these limitations, the accuracy of these estimates has been deemed fit for purpose. These estimates could be improved by dynamically simulating observed water levels and calculating discharges using the Rayner et al. (2020) numerical model.

7.2.2 Estimate of acid discharge

Estimates of acid discharge were calculated from the average pH between high and low tides as measured at the station immediately upstream of the Menarcobrinni floodgates. As pH is measured on a logarithmic scale, the pH data was converted to acidity (measured as moles of H^+ ions) before being averaged.

Four acid discharge events were observed during the monitoring period where the pH dropped below 4. Comparison of these events showed that the total discharge of acid from Clybucca varied between events (Table 7-1). Previously, Glamore and Rayner (2017) estimated that approximately 220 Olympic swimming pools of acid with a pH of 3 is generated from Clybucca during a single event. The analysis completed here showed an event that occurred between April and July 2024 resulted in the discharge of approximately 170 Olympic swimming pools worth of acid with a pH of 3 were discharged into the Macleay River estuary. Note, the Glamore and Rayner (2017) estimate considered the volume of acid within the drainage network and not necessarily the volume discharged. This previous estimate was also based on a worst-case scenario with a pH of 3 generated throughout the system where measurements indicated that an average pH around 4 is more common.

Table 7-1 Estimate of total acid volume discharged to the Macleay River estuary

ID	Start	End	H^+ ions (moles)	Estimated discharge volume (m^3)	Average event pH	Equivalent number of Olympic swimming pools of acid (pH = 3)*
1	18/03/2023	27/05/2023	17,000	3,470,000	5.3	7
2	6/11/2023	29/11/2023	92,000	1,440,000	4.2	37
3	6/04/2024	31/07/2024	425,000	13,140,000	4.5	170
4	28/09/2024	24/10/2024	35,000	490,000	4.1	14

* Assuming the volume of one Olympic Swimming pool is 2,500 m^3

7.2.3 Estimate of oxygen demand discharge

Estimates of oxygen demand have been calculated using the measurements of dissolved oxygen at the monitoring station located immediately upstream of the Menarcobrinni floodgates. During the monitoring period, one event was clearly identified where water with no dissolved oxygen was discharged into the estuary from the floodgates for a period of 10 days (4 March to 14 March 2022). Over this period, it is estimated that 11,000,000 m^3 of blackwater with no dissolved oxygen was discharged to the Macleay River estuary. Note, this estimate does not consider contributions from Kinchela Creek or the Belmore River which contribute the largest risk of blackwater to the Macleay River estuary (Tucker et al., 2023).

The oxygen demand of blackwater will depend on a range of environmental factors such as temperature, type of vegetation, and time since inundation. In the best-case scenario, blackwater discharged will not have an oxygen demand and will simply mix with downstream receiving waterbodies (i.e. the Macleay River estuary). On the other hand, it has been estimated that every litre of blackwater generated from water intolerant pasture grasses can consume up to 100 milligrams (mg) of oxygen in receiving waterbodies (Southern Cross GeoScience, 2019; Vithana et al., 2019). This means that for every 1 litre of blackwater, a further 12 litres of water could become deoxygenated.

In comparison to the tidal exchange in the Macleay River estuary (Allsop and Kadluczka, 2003), the maximum blackwater generated from Clybucca each tidal cycle is equivalent to the volume of water entering the Macleay Arm each tidal cycle. In other words, in a worst-case scenario, blackwater generated at Clybucca could cause the entire Macleay Arm to become anoxic.

7.3 Recommendations to quantify the impacts on the Macleay River estuary

7.3.1 Overview

The following section provides a recommended methodology that could be used to assess the impact of acid and blackwater pollution from Clybucca on the broader Macleay River estuary. Table 7-2 summarises a list of key impacts to estuaries that have been identified to result from acidic runoff from acid sulfate soils and the discharge of deoxygenated blackwater from coastal floodplains. Many of these impacts relate to the environment and aquatic life, however, there is often flow on impacts to industry (e.g. oyster farming).

Table 7-2 Summary of impacts on estuaries from acid sulfate soils and blackwater*

Impacts from acid sulfate soils	Impacts from blackwater
Habitat degradation. Reduced oyster growth rates and productivity. Fish kills and oyster mortality (e.g. from exposure to acid and metals). Increased susceptibility to fish disease (e.g. red spot). Reduced resources for aquatic food. Reduced ability for fish to migrate. Impact to fish spawning and recruitment. Changes to communities of water plants. Weed invasion by acid tolerant vegetation. Damage to infrastructure due to subsidence or corrosion. Degradation of water quality (e.g. through stratification and changes solubility of chemicals).	Mass fish kills and mortality of invertebrates (e.g. crustaceans). Decrease in aquatic diversity (especially for sessile flora and fauna). Impacts to aquatic food chains. Forced migration and subsequent overcrowding of habitat. Aquatic life become more susceptible to disease. Impact fish spawning and recruitment. Forced closure of the fishing industry within estuaries impacting commercial and recreational users. Degradation of water quality(e.g. through impacts to water chemistry).

*Adapted from Aaso (2000), Dawson (2002), Dove (2003), Dove et al. (2003), Tulau (2007), Southern Cross GeoScience (2019), Rayner et al. (2023) and Waddington et al. (2023).

To understand how acid sulfate soils and blackwater are impacting the Macleay River estuary, the extent, or footprint, of the impact needs to be determined. One method for determining the impact footprint of discharges from Clybucca is through hydrodynamic water quality modelling (e.g. Rayner et al. (2015) and Mosley et al. (2021)). Typically, developing suitable numerical models like this require an extensive field monitoring campaign to supplement them for the purpose of calibration and validation. They are also often limited by the assumptions regarding the complex chemical reactions which occur during the discharge of pollutants from coastal floodplains.

An alternative method for determining the impact footprint is directly via a field monitoring program. A suitably designed program can enable for tracking of pollutants throughout an estuary and identify the extent of their impact. This type of program can be supplemented by numerical modelling, although instead of simulating water quality processes, the model can be used to optimise monitoring locations. This requires a much simpler numerical model, which in many cases already exists for coastal estuaries in New South Wales, including the Macleay River estuary (e.g. Tucker et al., 2023).

The following sections provides a three-step methodology to assess the impacts of poor water quality discharging from Clybucca on the broader Macleay River estuary:

Step 1: Pollution extent analysis – Section 7.3.2
Step 2: Targeted monitoring field campaign – Section 7.3.3
Step 3: Mitigation assessment – Section 7.3.4

7.3.2 Step 1: Pollution extent analysis

The first step in quantifying water quality impacts is to determine the likely extent of the Macleay River estuary that may be affected by poor water quality from Clybucca. This is a preliminary step which aims to identify key locations within the Macleay River estuary that are likely to be impacted and subsequently, should be monitored during a targeted field monitoring campaign (i.e. Step 2).

For this step it is recommended to develop or utilise an existing numerical model of the Macleay River estuary (e.g. Tucker et al., 2023; Mason et al., 2025) to identify the potential impact of water discharging from Clybucca. At this stage, the complex biogeochemistry that influences water quality within the estuary would not be considered. Instead, this model would simulate hydrodynamic conditions to understand the conservative mixing processes throughout the Macleay River estuary.

Examples of a model being utilised like this are shown in Figure 7-2 and Figure 7-3. In these examples, the spread of pollution and relative contribution of different water sources (i.e. the ocean, upper catchment, lower catchment and point source inputs) to the makeup of the water at different locations within the estuary were identified. A similar model could be implemented for the Macleay River estuary for key water sources (such as the ocean, the Clybucca floodplain, the main Macleay River and other key systems such as Kinchela Creek and the Belmore River). This would identify areas of the Macleay River estuary that are most impacted by poor water quality from Clybucca.

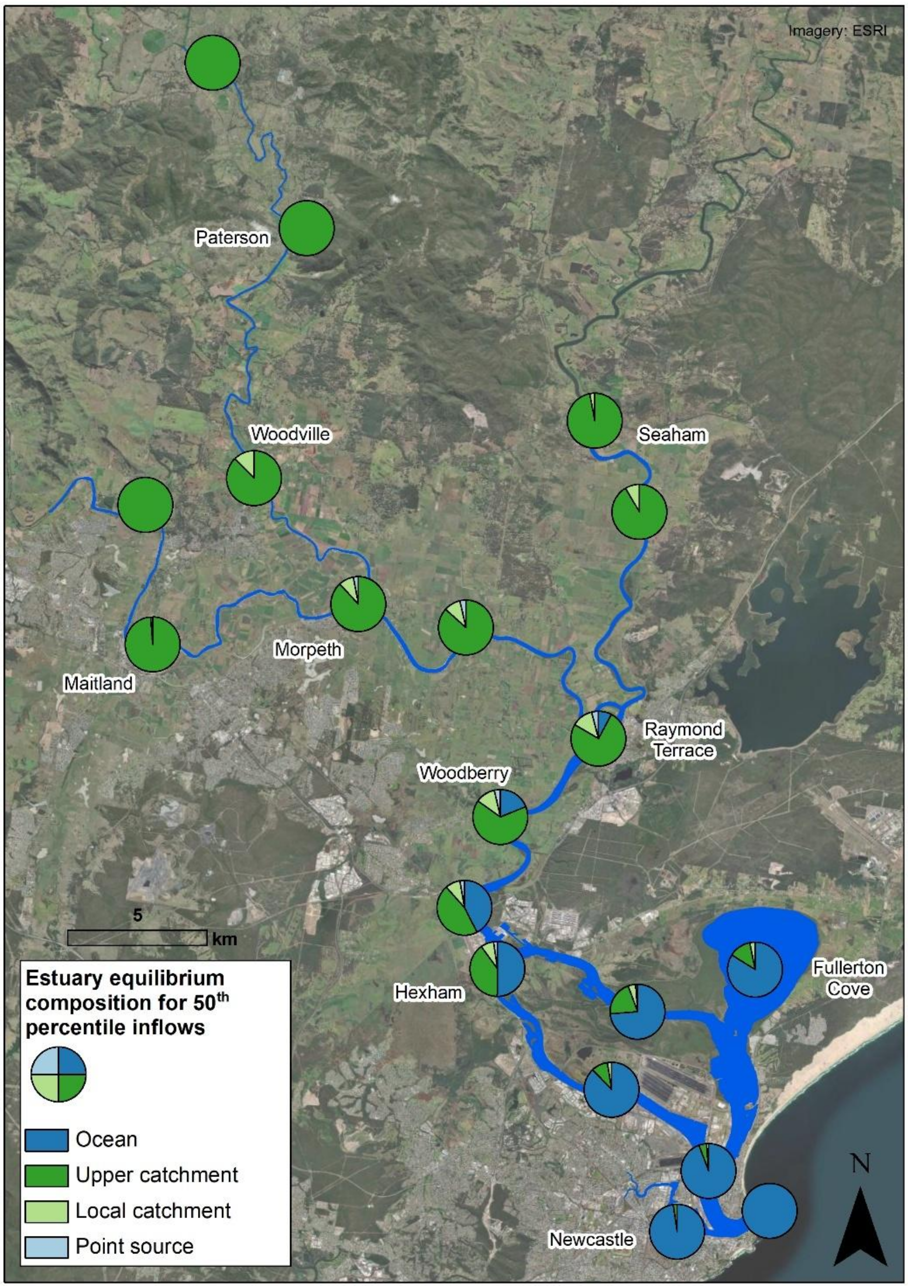

Figure 7-2 Example of a conservative hydrodynamic mixing model (from Tucker et al., 2024)

Figure 7-3 Example showing the transport of pollutants throughout an estuary (Harrison et al., 2025)

7.3.3 Step 2: Targeted field monitoring campaign

Step 2 focuses on measuring and quantifying the impact of water quality discharged from Clybucca at key locations throughout the Macleay River estuary. It is recommended that this program includes two components:

1. Deployment of high frequency long-term water quality monitoring stations
2. Event based impact assessment

It is recommended that locations for high-frequency long-term water quality monitoring stations be determined based on the findings from the numerical modelling completed in Step 1. The existing monitoring station located upstream of the Menarcobrinni floodgates should also be maintained/upgraded as part of this monitoring program as a key indicator of water quality leaving Clybucca. One of the key difficulties for this monitoring program will be distinguishing between different sources of poor-quality water. The numerical model developed in Step 1 will assist in identifying where this may be an issue and could be utilised to help design an appropriate monitoring network to ensure different water quality sources are distinguishable. The number of stations to be deployed throughout the estuary should be determined based on the Stage 1 modelling, however, it is anticipated that at least two more stations would require to be installed at key locations in the estuary. As a minimum, these new monitoring stations should measure water levels (corrected to Australian Height Datum), salinity, pH and dissolved oxygen at a timestep of 15 minutes. Stations should be regularly calibrated and maintained to ensure the quality of the data they are collecting.

In addition to the long-term monitoring, it is recommended that event-based monitoring be completed following acid sulfate soil and blackwater discharges from Clybucca to further our understanding of the complex water quality processes at play. For example, metal flocculation, acid-at-a-distance and tidal buffering all need to be considered for acid sulfate soil discharges (Rayner et al., 2015). For blackwater events there is considerable uncertainty regarding the biochemical oxygen demand, reaeration rates and expected behaviour within an estuary when carbon loading varies (Southern Cross GeoScience, 2019). Collection of in-situ water quality samples throughout the estuary, at locations identified using the numerical model in Step 1, would provide insight into the impacts of discharges from Clybucca on the Macleay River estuary. This new data would allow for the quantification of complex biogeochemistry on an event-by-event basis. The size and impact of poor water quality discharge events can vary significantly (i.e. acid events occurred on timeframes from weeks to months, all with different impacts). It is therefore recommended that at least three different sized events be monitored at the key locations identified throughout the Macleay River estuary on a weekly basis until the conditions have returned to average (i.e. neutral acidity and oxygen saturation above 4 mg/L). Field investigations measuring water quality could also be supplemented by flow measurements at key locations identified using the Step 1 modelling results. To further understand the sources of different pollutants within the Macleay River estuary, event-based sampling events could be supplemented with tracer experiments. In these experiments, water discharging from a known location (e.g. the Menarcobrinni floodgates) is dosed with an environmentally friendly tracer which can then be measured at key locations throughout the estuary to determine mixing rates throughout the estuary.

A similar event-based monitoring program was successfully implemented on the Manning River to investigate acidic discharge events from a comparable coastal floodplain (Ruprecht et al., 2018), with the study highlighting the practicality and effectiveness of such an investigation.

7.3.4 Step 3: Mitigation assessment

Once the extent (Step 1) and impacts (Step 2) of poor water quality discharge events from Clybucca have been quantified, the focus can be shifted on determining the most appropriate actions to mitigate these impacts. It is recommended that a mitigation assessment approach be conducted to address poor water quality being discharged from Clybucca (Figure 7-4). First, the assessment should prioritise actions to be implemented at Clybucca, the primary source of the pollution. Secondly, the assessment should identify a range of activities that can be implemented to protect important natural assets within the Macleay River estuary. A mitigation assessment would be an important tool which could supplement other management strategies (e.g. the Macleay River estuary Coastal Management Program) and improve the health of the estuary.

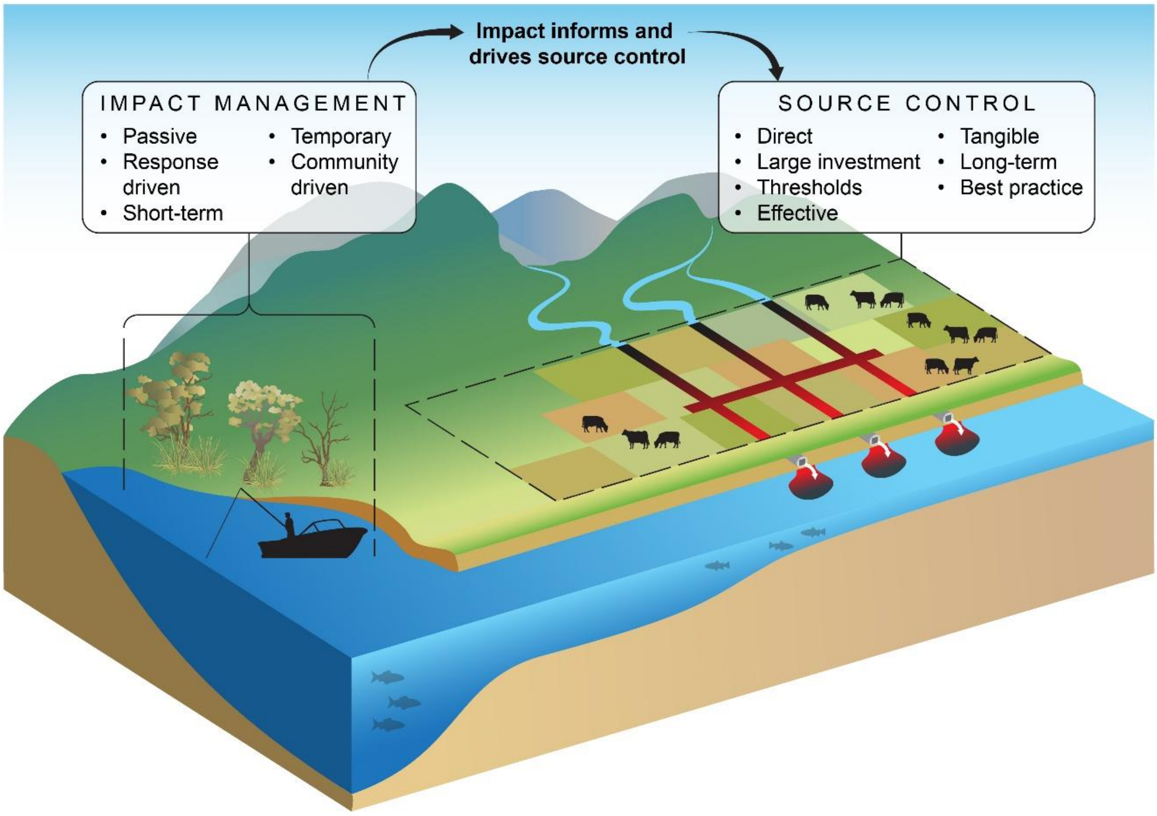

Figure 7-4 Mitigation assessment approach

The best method for reducing the impacts from poor water quality discharging from coastal floodplains is to prevent the discharge at the source. Poor water quality is being discharged from Clybucca into the Macleay River estuary on a large scale. Many investigations have been completed at Clybucca identifying the causes of poor water quality (Enginuity Design, 2003; KSC, 2004; Glamore and Rayner, 2017; Rayner et al., 2020; Rayner and Tucker, 2023). These studies demonstrate that remediation of this site will require significant investment to reduce the production of acid and blackwater. Step 1 and Step 2 of this methodology will link poor water quality being generated within Clybucca to the impacts within the Macleay River estuary. The mitigation assessment should identify how activities to improve Clybucca at the source (i.e. source control activities) result in improvements across the wider Macleay River estuary.

To assist with this assessment, it is recommended that water quality thresholds are identified. These are points whereby the impacts from Clybucca result in unacceptable environmental impacts within the Macleay River (e.g. dissolved oxygen levels drop below 4 mg/L in the Macleay Arm, impacting aquatic life). This can then be linked to a range of physical factors that result in water quality thresholds being met. This will assist in targeting remediation efforts and prioritise those source control activities which have the largest benefit to the estuary. This assessment may consider (for example):

- Inundation elevation following a flood (i.e. is there a height where floods cause worse environmental impact?)
- Antecedent conditions (i.e. how are back-to-back events related to environmental impacts?)
- Floodplain vegetation type (i.e. does abundance of one type of vegetation cause an event to be worse?)

While source control activities will always be the most effective to address poor water quality associated with Clybucca, there may also be passive options for managing the impacts at downstream locations (i.e. impact management activities). One of the outcomes of the Step 1 and Step 2 investigations will be the identification of areas or natural assets within the Macleay River estuary which are most impacted by water discharged from Clybucca. As an example, this may consider areas of important indigenous heritage, valuable for community recreation, or known areas of significant environmental importance (e.g. Yarrahapinni Wetlands National Park, the Clybucca Aboriginal Area, and the Clybucca Historical Site – which include the largest aboriginal midden complex in temperate Australia that also extends into the Clybucca Wetlands (NPWS, 2007; Knuckey, 2016)). It is recommended that the mitigation assessment identify key natural assets of significant value that may be impacted by Clybucca and determine impact management activities to help protect and reduce harm to these assets. In many instances, options for impact mitigation activities will need to consider a passive approach (as they do not treat the source of the pollution). For example, blackwater events are typically associated with mass fish kills which makes waterways unsafe to swim in. Impact management options for an important primary contact recreation asset may involve raising community awareness and informing them of the risks associated with this poor-quality water. Another example may include quantifying the economic costs associated with temporary or ongoing loss of an asset to justify source control investment at Clybucca. In many instances, the outcomes of impact management activities may inform and drive the implementation of a source control activity (Figure 7-4).

The recommended mitigation assessment approach aims to provide clear, science based and economically sound evidence to invest at Clybucca to improve poor water quality. It will target actions that provide an optimised return on investment and result in long term improvements to the environmental health of the Macleay River estuary.

8 Conclusions

Extensive development of the Clybucca floodplain has resulted in poor quality water discharging into the Macleay River estuary (Tucker et al., 2023). Acidic runoff from the drainage of acid sulfate soils and low oxygen blackwater regularly discharges from the floodplain impacting downstream receiving waters. Over the last 10 years, several investigations have been undertaken to identify and implement works to improve the water quality at Clybucca (Glamore and Rayner, 2017; Rayner and Glamore, 2017; Rayner and Tucker, 2023; Rayner et al., 2020; Tucker, 2024; Tucker et al., 2021). The majority of these works were implemented following NSW State Government purchases of a large proportion of the 15 km^2 lowest lying land. As part of these works, an extensive monitoring network has been established to measure the water quality at Clybucca (Tucker, 2024). This report has reviewed the water quality data collected at Clybucca over the past three years (2022 to 2024) to determine the current state of the wetland. Furthermore, this water quality data has been used to assess:

1. How the Menarcobrinni floodgates influence water quality
2. Changes in water quality since the last long term monitoring campaign two decades ago
3. How water quality at Clybucca is similar to another restored coastal floodplain (Big Swamp, Manning River) located approximately 100 km south

The data analysis showed that the water quality at Clybucca is inherently linked to catchment rainfall events. Observations provided evidence that water quality at Clybucca behaves as expected for a drained coastal floodplain (Rayner et al., 2015; Waddington et al., 2023). Both blackwater and acid runoff occur in response to rainfall events. Analysis of water quality data collected from 2002 to 2004 at Clybucca had similar trends to data collected from 2022 to 2024 demonstrating that over at least the past 20 years acid and blackwater runoff has impacted the environment.

Analysis of water quality data showed that discharges of poor water quality can occur throughout the year and are not limited to specific seasons. However, the data also highlighted that the El Niño Southern Oscillation (ENSO) drives long-term interannual water quality trends. Data measured at Clybucca were representative of three distinct phases of the ENSO cycle, wet (2022), dry (2023) and average (2024) conditions. Wet years were typically found to be associated with worse water quality, as frequent rainfall events generated acid and blackwater. The analysis also demonstrated similar trends at both Clybucca and Big Swamp where wetter than average years typically resulted in worse water quality, highlighting that this is an issue shared amongst developed coastal floodplains across NSW.

Poor water quality from Clybucca will continue to impact the Macleay River estuary until significant catchment scale restoration works can be effectively implemented. The analysis completed here identified that in one acid runoff event, approximately 170 Olympic sized swimming pools of acid with a pH of 3 can be discharged into the Macleay River estuary. Furthermore, in a worst-case scenario, it was estimated that Clybucca has enough blackwater potential to cause the deoxygenation of the entire Macleay Arm for 10 consecutive days.

Understanding the importance of improving Clybucca for the health of the wider Macleay River estuary, this report has outlined a three-step approach to address poor water quality. The methodology includes identifying the footprint of the impact, qualitatively measuring this impact, and then implementing a range of activities to improve water quality. The methodology proposes to target the source of the problem, while acknowledging some important natural assets may benefit from passive impact management measures. The approach is generic and could be used to target poor water quality discharging from a range of coastal floodplains across NSW. In addition, the outcomes are designed to improve the water quality throughout the entire downstream estuary.

The analysis presented in this report confirms that further action is still required to improve the water quality discharging from Clybucca. It has shown that poor water quality from Clybucca has been affecting the Macleay River estuary consistently over the last two decades. Furthermore, while there are clear records for the last 20 years, poor water quality from Clybucca has significantly impacted the Macleay River estuary over the past 60+ years as a result of flood mitigation works constructed in the 1960s (such as the installation of the Menarcobrinni floodgates). A focused and concerted effort is required more than ever to ensure the health of the Macleay River estuary, and similar coastal systems, can be managed and maintained sustainably into the future.

9 References

Aaso, T. 2000. Towards sustainable landuse within acid sulfate soil landscapes: A Case Study on the Maria River, New South Wales Australia. Lund University, Sweden.

Allsop, D. & Kadluczka, R. 2003. DIPNR Macleay River Estuary Tidal Data Collection April - May 2003. Manly Vale, NSW, Australia: NSW Department of Commerce, Manly Hydraulics Laboratory.

BOM. 2025a. *Australian Climate Influences* [Online]. Available: https://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=introduction [Accessed August 2025].

BOM. 2025b. *Daily rainfall Moorland (Denro-An)* [Online]. Australian Government Bureau of Meteorology. Available: http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=060024 [Accessed June 2025].

BOM. 2025c. *Daily rainfall, Uralla (Blue Nobby)* [Online]. Australian Government Bureau of Meteorology. Available: http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=2024&p_c=-651941892&p_stn_num=57091 [Accessed July 2025].

BOM. 2025d. *El Niño Southern Oscillation (ENSO)* [Online]. Australian Government Bureau of Meteorology. Available: http://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=enso [Accessed February 2025].

BOM. 2025e. *Kempsey, New South Wales Daily Weather Observations* [Online]. Australian Government Bureau of Meteorology. Available: http://www.bom.gov.au/climate/dwo/IDCJDW2069.latest.shtml [Accessed February 2025].

BOM. 2025f. *Southern Oscillation Index (SOI) since 1876* [Online]. Australian Government Bureau of Meteorology. Available: http://www.bom.gov.au/climate/enso/soi/ [Accessed February 2025].

Bush, R. T., Keene, A., Sullivan, L. A. & Bush, M. L. 2006. Water Quality Analysis of ASS Hot Spots. Lismore, NSW, Australia: Southern Cross University.

CSIRO & BOM 2024. State of the Climate 2024. CSIRO and Bureau of Meteorology, Commonwealth of Australia.

Dawson, K. 2002. Fish Kill Events and Habitat Losses of the Richmond River, NSW Australia: An Overview. *Journal of Coastal Research*, 216-221.

Dove, M., Sammut, J. & Callinan, R. 2003. Identification of Environmental Factors, With Particular Reference to Acid Sulfate Soil Runoff, Causing Production Losses in Sydney Rock Oysters (Saccostrea glomerata). Sydney, Australia: The University of New South Wales.

Dove, M. C. 2003. *Effects of estuarine acidification on survival and growth of the Sydney rock oyster Saccostrea glomerata.* UNSW.

Enginuity Design 2003. Collombatti-Clybucca Acid Sulfate Soil "Hot Spot" Area Management Plan. Bellingen, NSW, Australia: Enginuity Design Civil and Environmental Engineering Consultants.

Glamore, W. C. & Rayner, D. S. 2017. Collombatti-Clybucca Floodplain Remediation Feasibility Study. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Glamore, W. C., Ruprecht, J. E., Rayner, D. S. & Smith, B. 2014. Big Swamp Rehabilitation Project Hydrological Study. Manly Vale, NSW, AUstralia: UNSW Sydney Water Research Laboratory.

Harrison, A. J., Glamore, W. C. & Costanza, R. 2019. Cost Benefit Analysis of Big Swamp Restoration Project. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Harrison, A. J., Mason, M., Doherty, Y. & Miller, B. M. 2025. Assessing the impact of sewage overflows on oyster harvest areas: User Guide. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratoru.

Haskins, P. G. 1999. Kempsey Shire Council Water Quality Records Clybucca Creek Floodgates. Coffs Harbour, NSW, Australia: Department of Land and Water Conservation.

Heidemann, H., Cowan, T., Power, S. B. & Henley, B. J. 2023. Statistical relationships between the Interdecadal Pacific Oscillation and El Niño–Southern Oscillation. *Climate Dynamics,* 62**,** 2499-2515.

Heimhuber, V., Glamore, W., Bishop, M., Dominguez, G., Scanes, P. & Ataupah, J. 2019. Module-1 Introduction; Climate change in estuaries – State of the science and guidelines for assessment. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Henley, B. J., Gergis, J., Karoly, D. J., Power, S., Kennedy, J. & Folland, C. K. 2015. A Tripole Index for the Interdecadal Pacific Oscillation. *Climate Dynamics,* 45**,** 3077-3090.

Johnston, S., Kroon, F., Slavich, P., Cibilic, A. & Bruce, A. 2003. Restoring the balance: Guidelines for managing floodgates and drainage systems on coastal floodplains. Wollongbar, NSW, Australia: NSW Agriculture.

King, A. D., Alexander, L. V. & Donat, M. G. 2013. Asymmetry in the response of eastern Australia extreme rainfall to low-frequency Pacific variability. *Geophysical Research Letters,* 40**,** 2271-2277.

Knuckey, G. 2016. A shell midden at Clybucca, near Kempsey, New South Wales. *Australian Archaeology,* 48**,** 1-11.

KSC 2004. Collombatti-Clybucca Acid Sulfate Soils Hot Spot Final Report. Kempsey Shire Council.

Mason, M., Harrison, A. J., Gilbert, D. M. & Miller, B. M. 2025. Assessment of the impacts of climate change on saline dynamics in the Macleay River estuary. Draft ed. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Mosley, L. M., Wallace, T., Rahman, J., Roberts, T. & Gibbs, M. 2021. An integrated model to predict and prevent hypoxia in floodplain-river systems. *J Environ Manage,* 286**,** 112213.

NPWS 2007. Clybucca Historical Site Plan of Management. NSW National Parks and Wildlife Service.

Power, S., Casey, T., Folland, C., Colman, A. & Mehta, V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics,* 15**,** 319-324.

Rayner, D. S. & Glamore, W. C. 2017. Clybucca Wetlands Remediation Management Plan. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Rayner, D. S., Glamore, W. C. & Ruprecht, J. E. 2015. Predicting the buffering of acid plumes within estuaries. *Estuarine, Coastal and Shelf Science,* 164**,** 56-64.

Rayner, D. S., Harrison, A. J., Tucker, T. A., Lumiatti, G., Rahman, P. F., Juma, D., Waddington, K. & Glamore, W. C. 2023. Coastal Floodplain Prioritisation Study – Background and Methodology. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Rayner, D. S. & Tucker, T. A. 2023. Pacific Highway Upgrade Biodiversity Offset Program: Hydrological assessment - Clybucca offset properties. Manly vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Rayner, D. S., Tucker, T. A. & Glamore, W. C. 2020. Clybucca Wetlands Management Options Study. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C. & Harrison, A. J. 2024a. Big Swamp Rehabilitation Project: 2018 Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C. & Harrison, A. J. 2024b. Big Swamp Rehabilitation Project: 2020 Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C. & Harrison, A. J. 2024c. Big Swamp Rehabilitation Project: 2021 Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C. & Harrison, A. J. 2024d. Big Swamp Rehabilitation Project: Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C., Harrison, A. J. & Chan, J. 2024e. Big Swamp Rehabilitation Project: 2019 Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C., Harrison, A. J. & Gawlik, E. 2024f. Big Swamp Wetland: Monitoring Review. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Ruprecht, J. E., Glamore, W. C. & Rayner, D. S. 2018. Estuarine dynamics and acid sulfate soil discharge: Quantifying a conceptual model. *Ecological Engineering,* 110**,** 172-184.

Ruprecht, J. E. & Harrison, A. J. 2024. Big Swamp Rehabilitation Project: January 2022 to June 2023 Annual Monitoring Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Southern Cross GeoScience 2019. Episodic estuarine hypoxia: resolving the geochemistry of coastal floodplain blackwaters – Summary of project findings. Southern Cross GeoScience Technical Report No. 119. Lismore, NSW, Ausatralia: Southern Cross University.

Sullivan, L. A., Ward, N. J., Bush, R. T., Toppler, N. R. & Choppala, G. 2018. National Acid Sulfate soils Guidance: Overview and management of monosulfidic black ooze (MBO) accumulations in waterways and wetlands. Canberra, Australia: Department of Agriculture and Water Resources.

Telfer, D. 2005. Macleay River Estuary Data Compilation Study. Grassy Head, NSW, Australia: GECO Environmental.

Tucker, T. A. 2024. Clybucca Wetlands Monitoring November 2021 to February 2024. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Tucker, T. A., Martino, J. C., Harrison, A. J. & Broderick, T. 2024. Water quality evaluation for the Hunter River estuary. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Tucker, T. A., Rayner, D. S. & Glamore, W. C. 2021. Assessing coastal wetland rehabilitation: Clybucca wetlands. *Australasian Coasts & Ports 2021 Conference.* Christchurch, New Zealand.

Tucker, T. A., Rayner, D. S., Harrison, A. J., Lumiatti, G., Rahman, P. F., Gilbert, D. M. & Glamore, W. C. 2023. Macleay River Floodplain Prioritisation Study. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Tulau, M. J. 2007. Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales. Department of Environment and Climate Change.

Tulau, M. J. 2011. *Lands of the richest character: agricultural drainage of backswamp wetlands on the North Coast of New South Wales, Australia : development, conservation and policy change : an environmental history.* PhD thesis, Southern Cross University.

Tulau, M. J. & Naylor, S. D. 1999. Acid Sulfate Soil Management Priority Areas in the Lower Macleay Floodplain. Sydney, NSW, Australia: Department of Land and Water Conservation.

Vithana, C. L., Sullivan, L. A. & Shepherd, T. 2019. Role of temperature on the development of hypoxia in blackwater from grass. *Sci Total Environ,* 667**,** 152-159.

Waddington, K., Harrison, A., Rayner, D., Tucker, T. & Glamore, W. 2023. Estuarine Hypoxia—Identifying High Risk Catchments Now and Under Future Climate Scenarios. *Water Resources Research,* 59.

Waddington, K., Khojasteh, D., Marshall, L., Rayner, D. & Glamore, W. 2022. Quantifying the Effects of Sea Level Rise on Estuarine Drainage Systems. *Water Resources Research,* 58.

White, N. J., Haigh, I. D., Church, J. A., Koen, T., Watson, C. S., Pritchard, T. R., Watson, P. J., Burgette, R. J., McInnes, K. L., You, Z. J., Zhang, X. B. & Tregoning, P. 2014. Australian sea levels-Trends, regional variability and influencing factors. *Earth-Science Reviews,* 136**,** 155-174.

WRL 2025. 2024 Big Swamp Monitoring Program Summary Report. Manly Vale, NSW, Australia: UNSW Sydney Water Research Laboratory.

Appendix A Timeseries data

The following section provides timeseries data for each of the water quality stations:

- Station 1
  - November 2021 to April 2022 - Figure A-1
  - May 2022 to October 2022 -Figure A-2
  - November 2022 to April 2023 -Figure A-3
  - May 2023 to October 2023 -Figure A-4
  - November 2023 to April 2024 -Figure A-5
  - May 2024 to October 2024 -Figure A-6
  - November 2024 to January 2025 -Figure A-7
- Station 2
  - November 2021 to April 2022 - Figure A-8
  - May 2022 to October 2022 -Figure A-9
  - November 2022 to April 2023 -Figure A-10
  - May 2023 to October 2023 -Figure A-11
  - November 2023 to April 2024 -Figure A-12
  - May 2024 to July 2024 -Figure A-13
  - From July 2024 the station malfunctioned
- Station 3
  - November 2021 to April 2022 - Figure A-14
  - May 2022 to October 2022 - Figure A-15
  - November 2022 to April 2023 - Figure A-16
  - May 2023 to October 2023 - Figure A-17
  - November 2023 to April 2024 - Figure A-18
  - May 2024 to June 2024 - Figure A-19
  - From June 2024 the station malfunctioned
- Station 4
  - November 2021 to April 2022 - Figure A-20
  - May 2022 to October 2022 -Figure A-21
  - November 2022 to April 2023 -Figure A-22
  - May 2023 to October 2023 -Figure A-23
  - November 2023 to April 2024 -Figure A-24
  - May 2024 to October 2024 -Figure A-25
  - November 2024 to January 2025 -Figure A-26

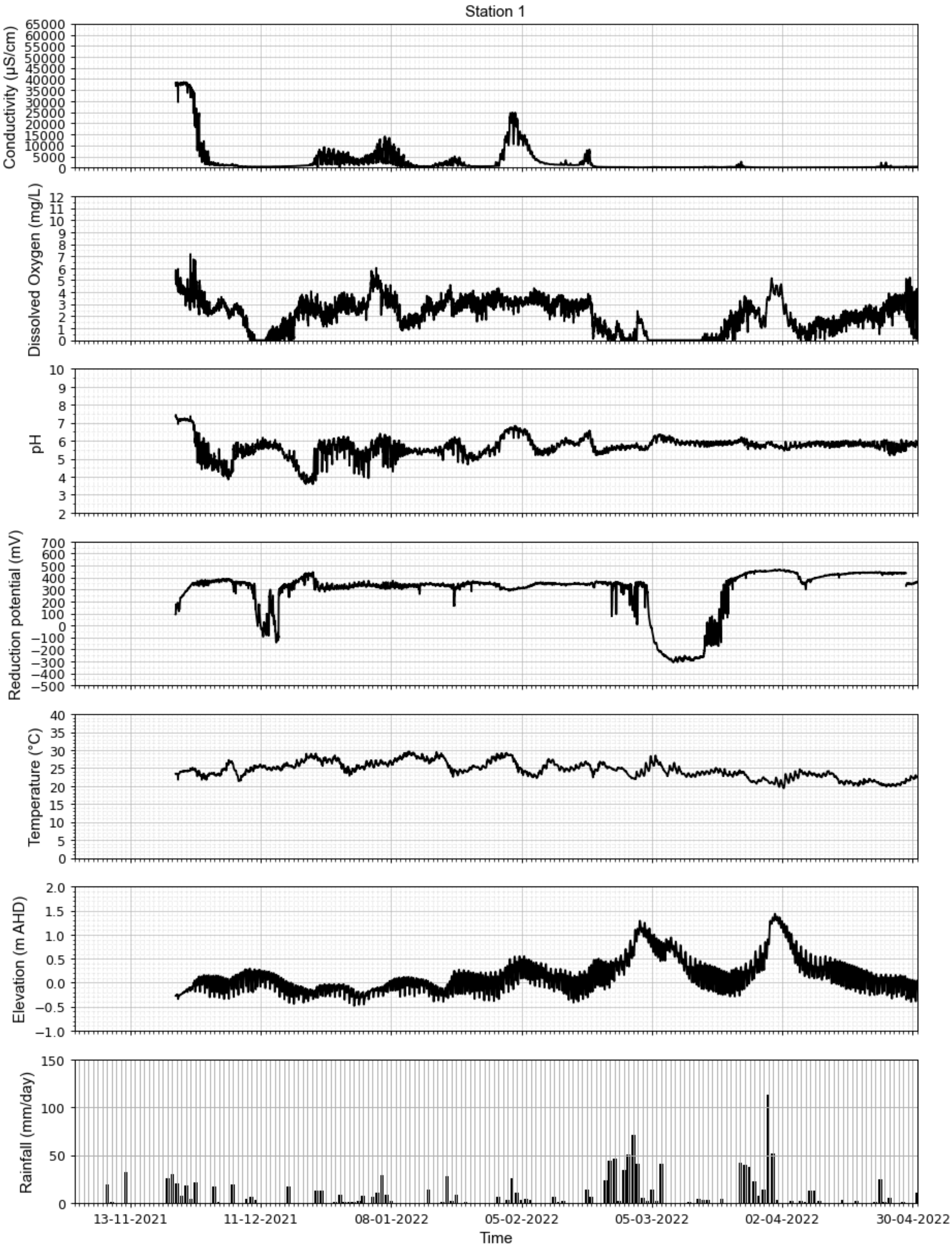

Figure A-1 Water quality data for Station 1 (November 2021 to April 2022)

Rainfall data from BOM (2025e)

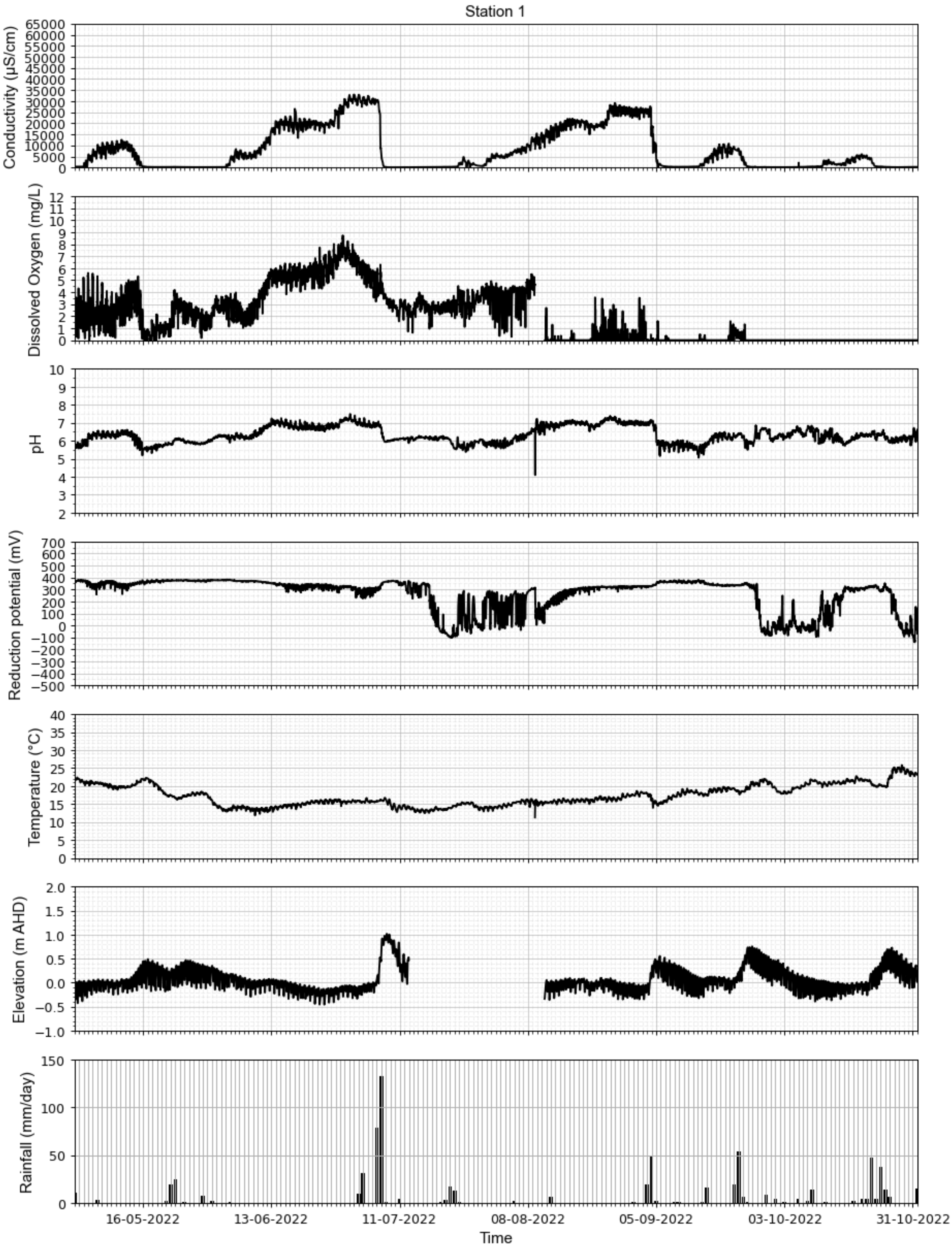

Figure A-2 Water quality data for Station 1 (May 2022 to October 2022)

Rainfall data from BOM (2025e)

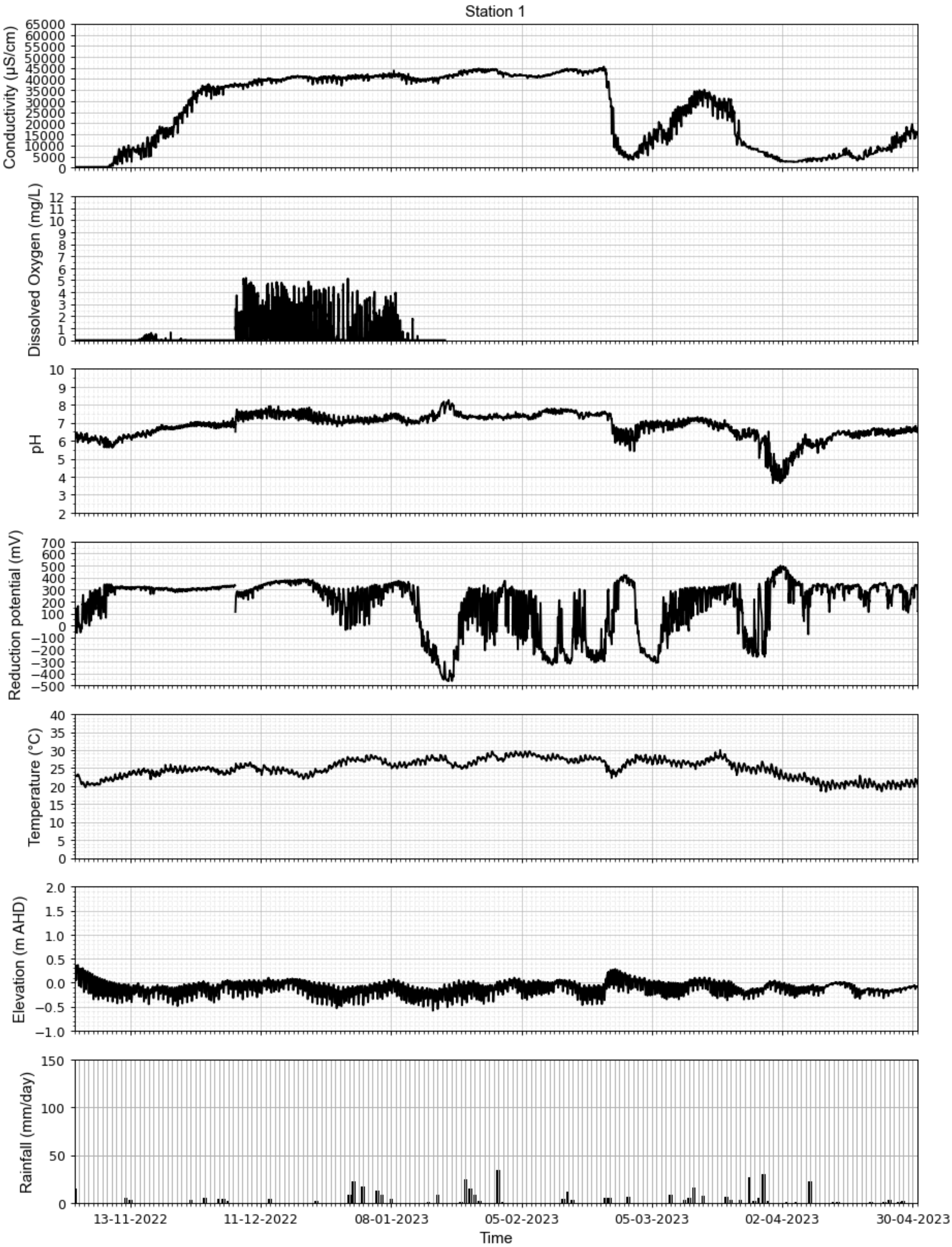

Figure A-3 Water quality data for Station 1 (November 2022 to April 2023)

Rainfall data from BOM (2025e)

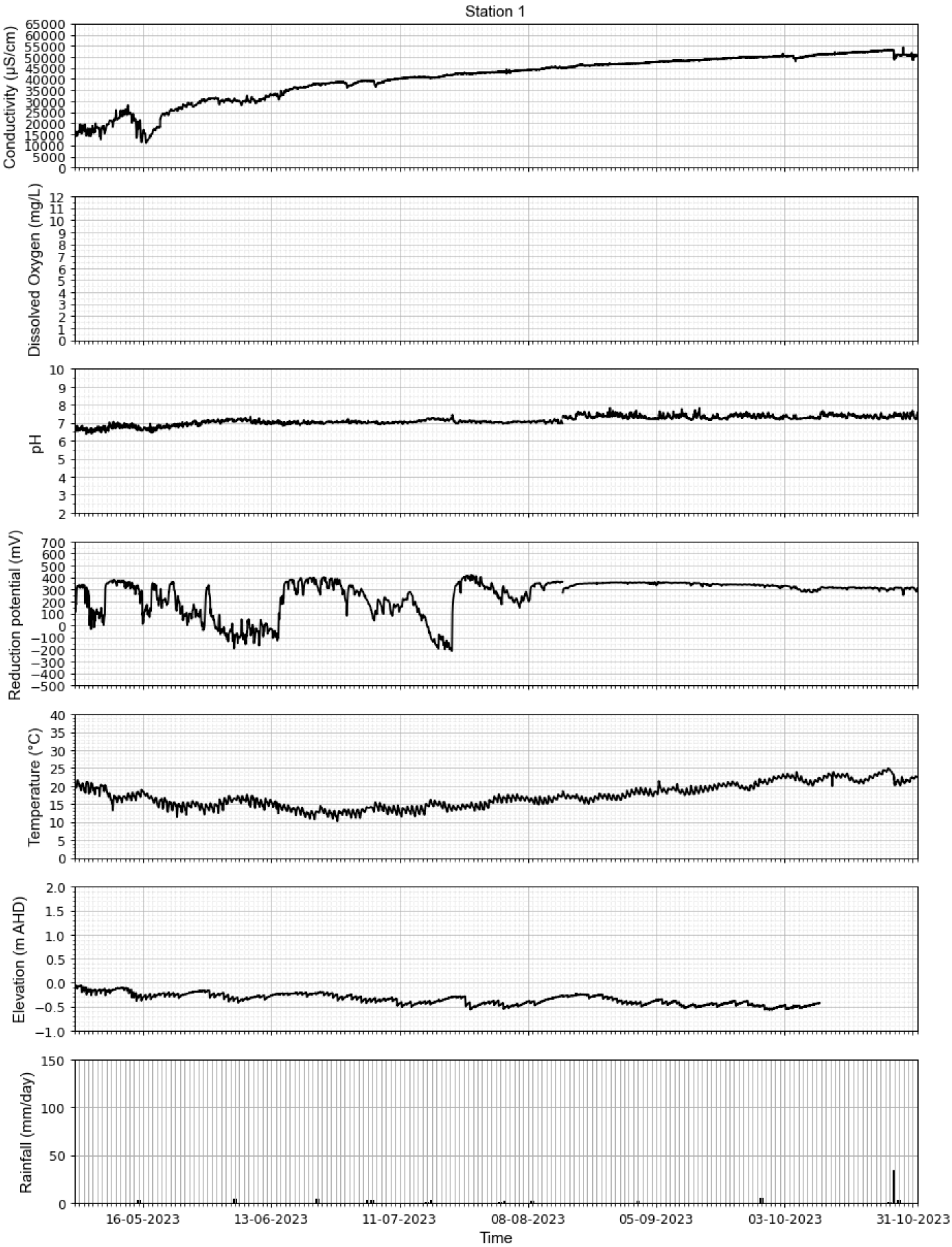

Figure A-4 Water quality data for Station 1 (May 2023 to October 2023)

Rainfall data from BOM (2025e)

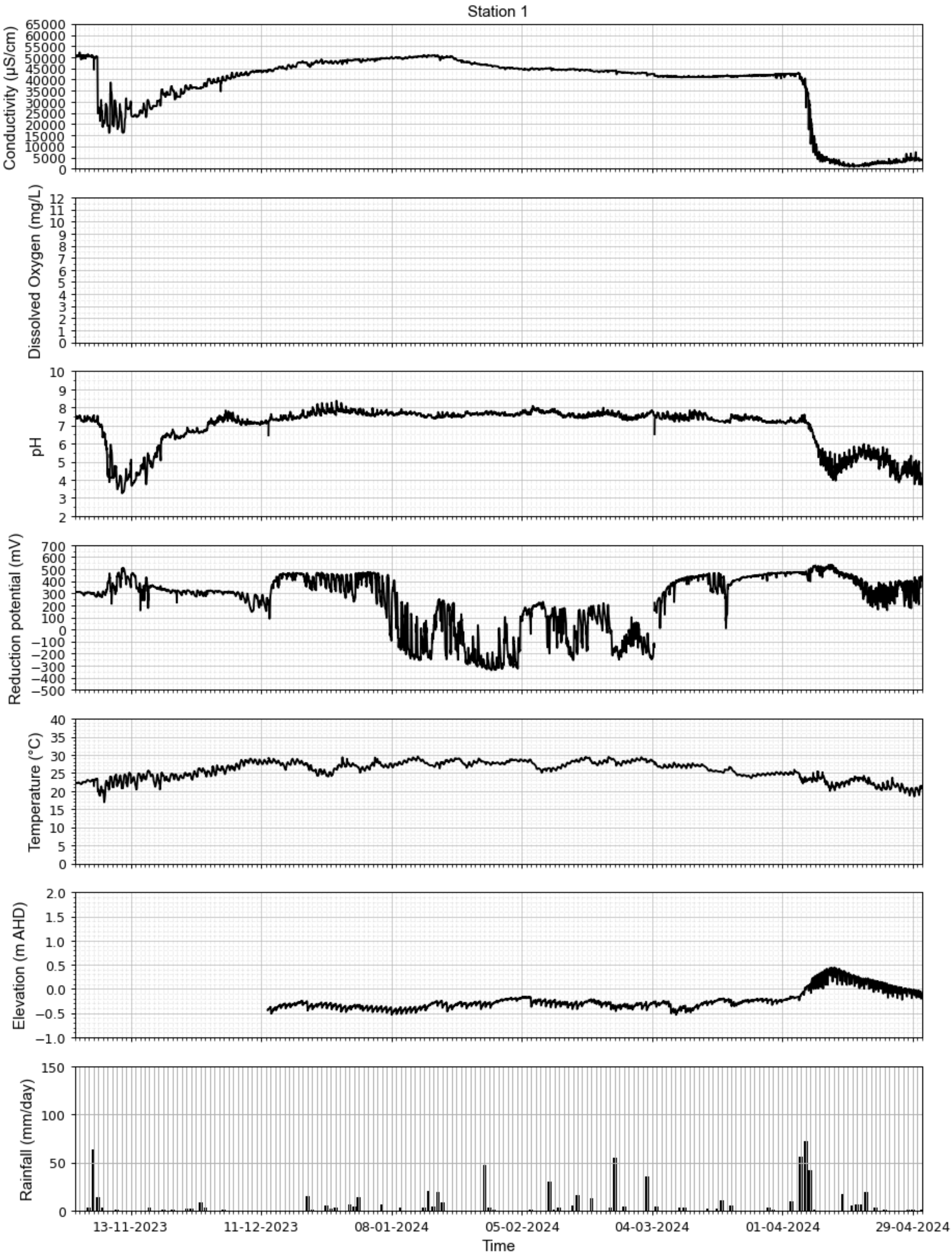

Figure A-5 Water quality data for Station 1 (November 2023 to April 2024)

Rainfall data from BOM (2025e)

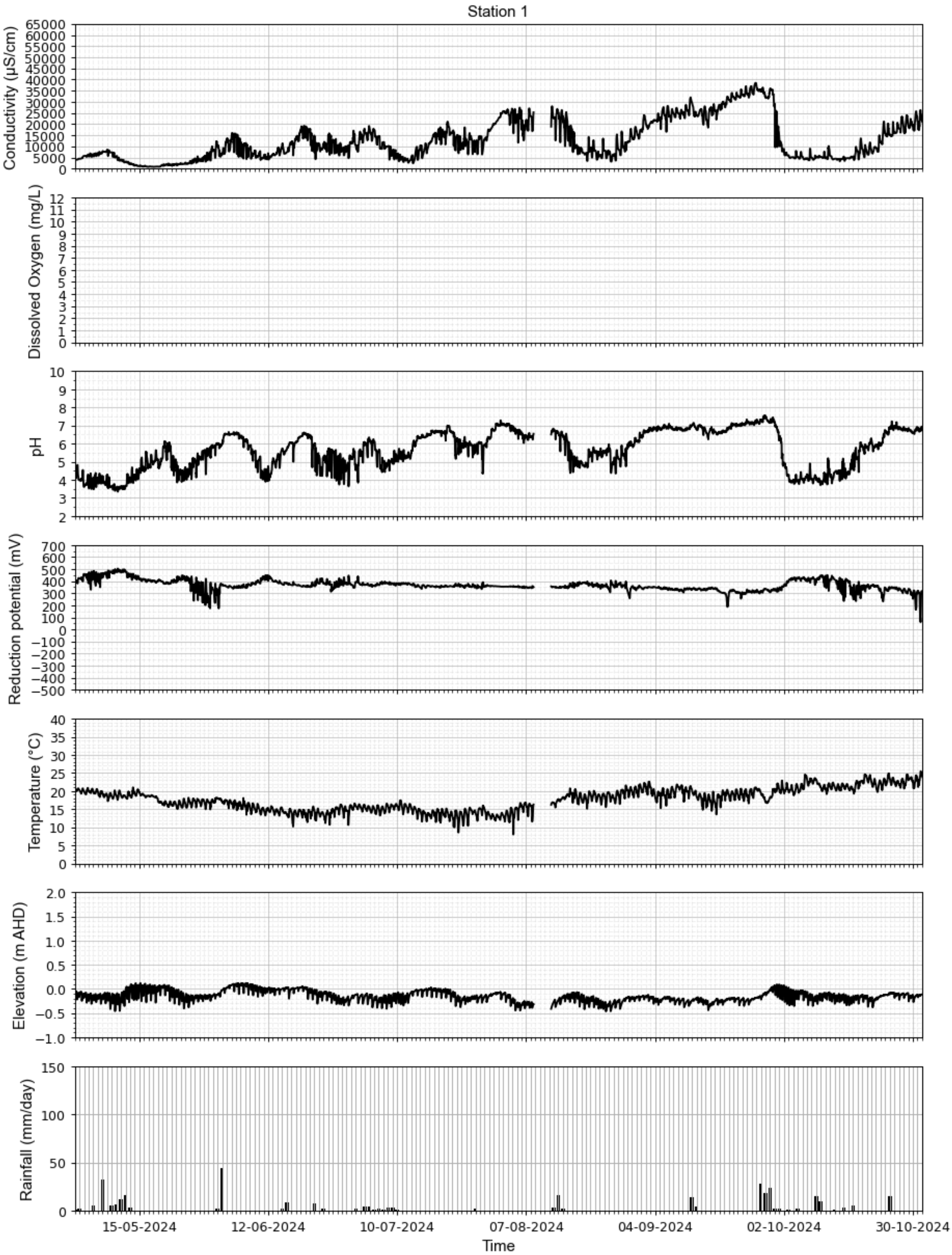

Figure A-6 Water quality data for Station 1 (May 2024 to October 2024)

Rainfall data from BOM (2025e)

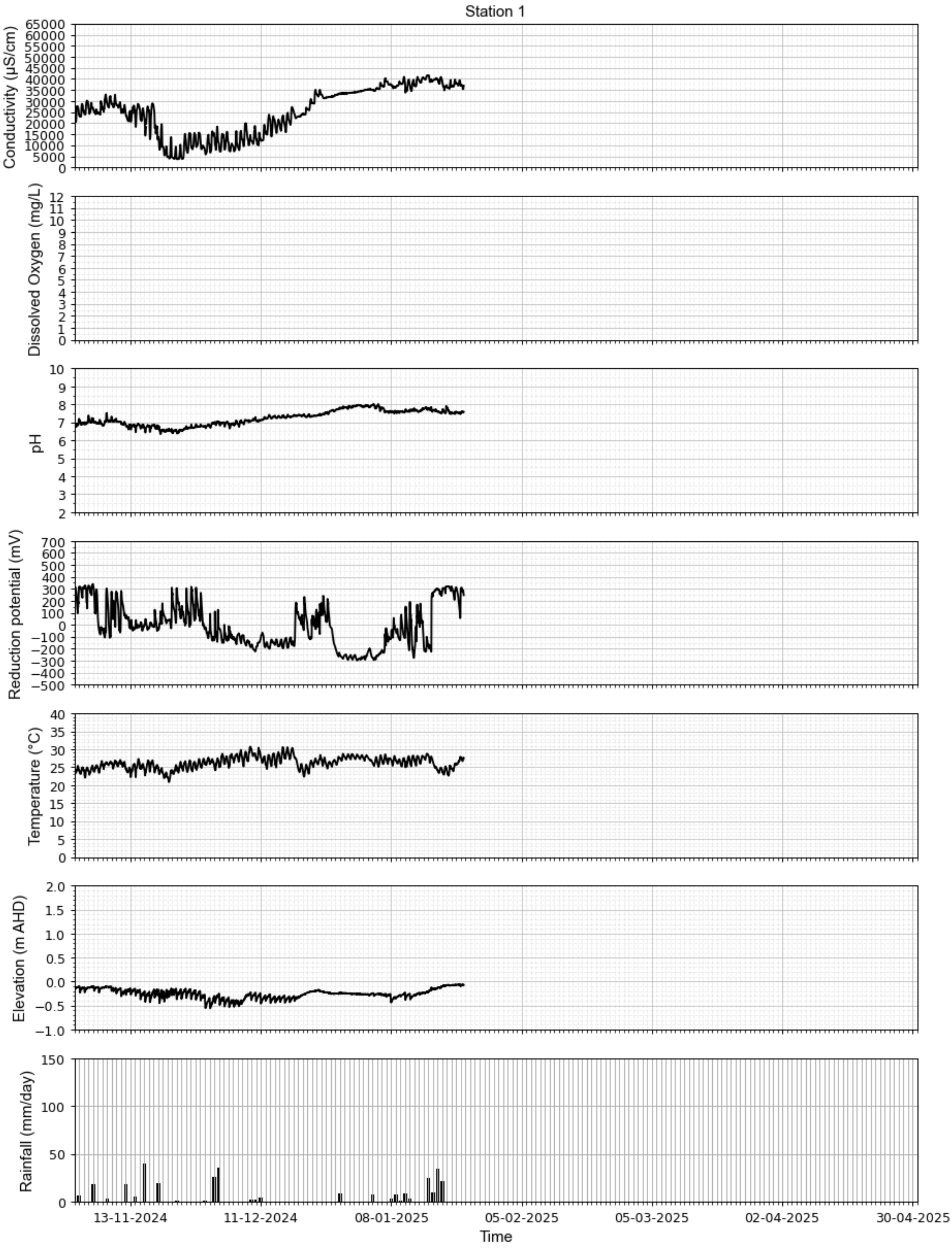

Figure A-7 Water quality data for Station 1 (November 2024 to January 2025)

Rainfall data from BOM (2025e)

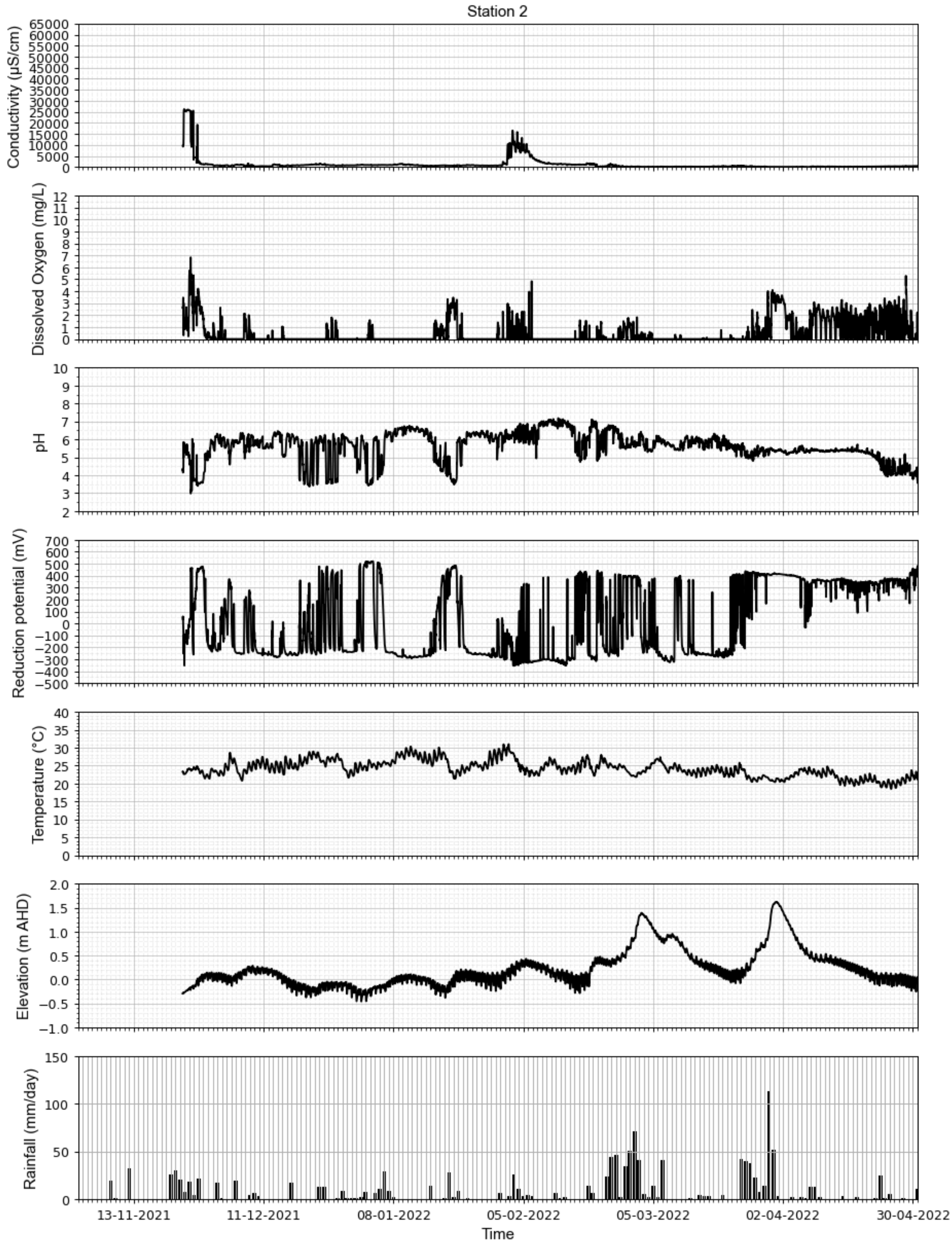

Figure A-8 Water quality data for Station 2 (November 2021 to April 2022)

Rainfall data from BOM (2025e)

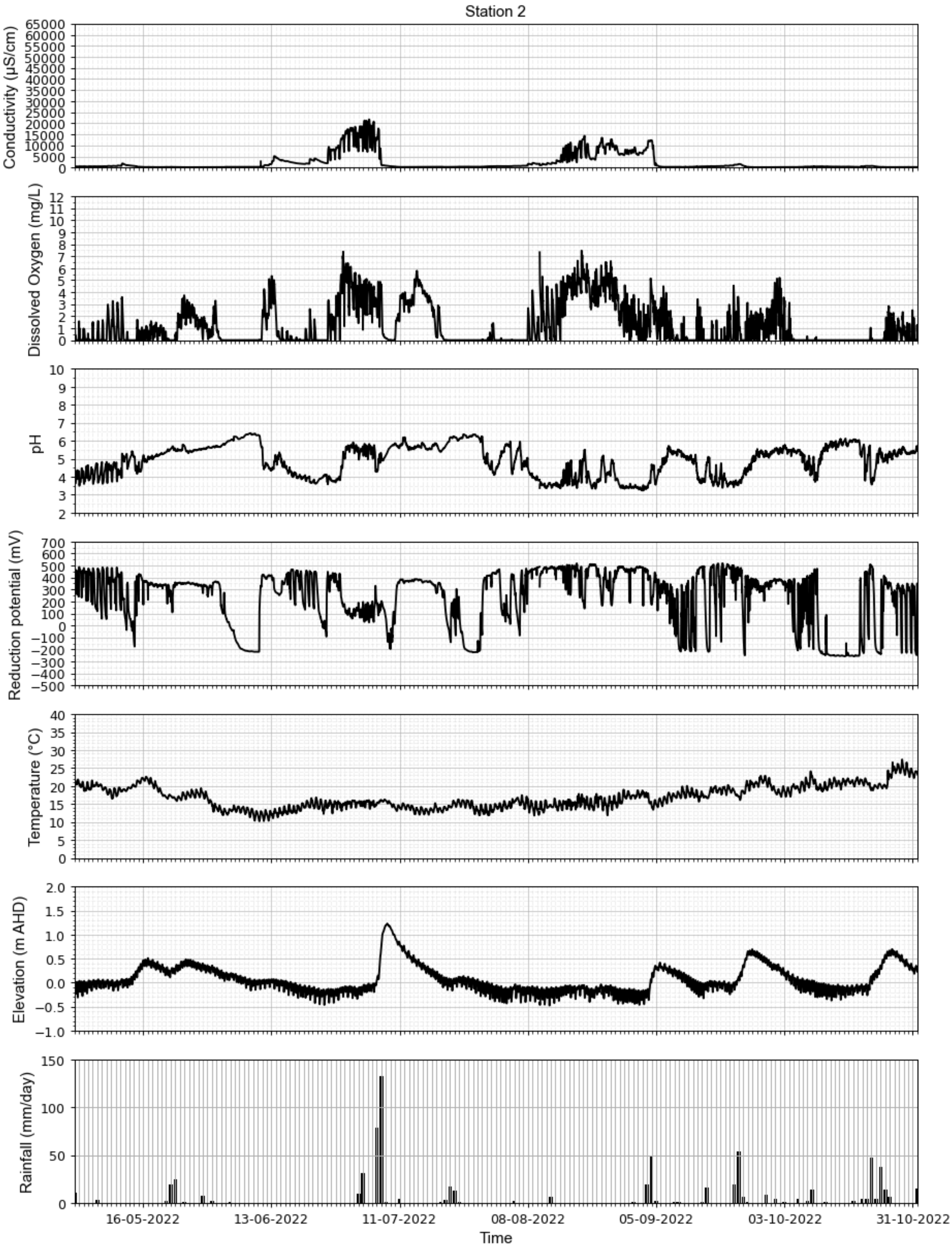

Figure A-9 Water quality data for Station 2 (May 2022 to October 2022)

Rainfall data from BOM (2025e)

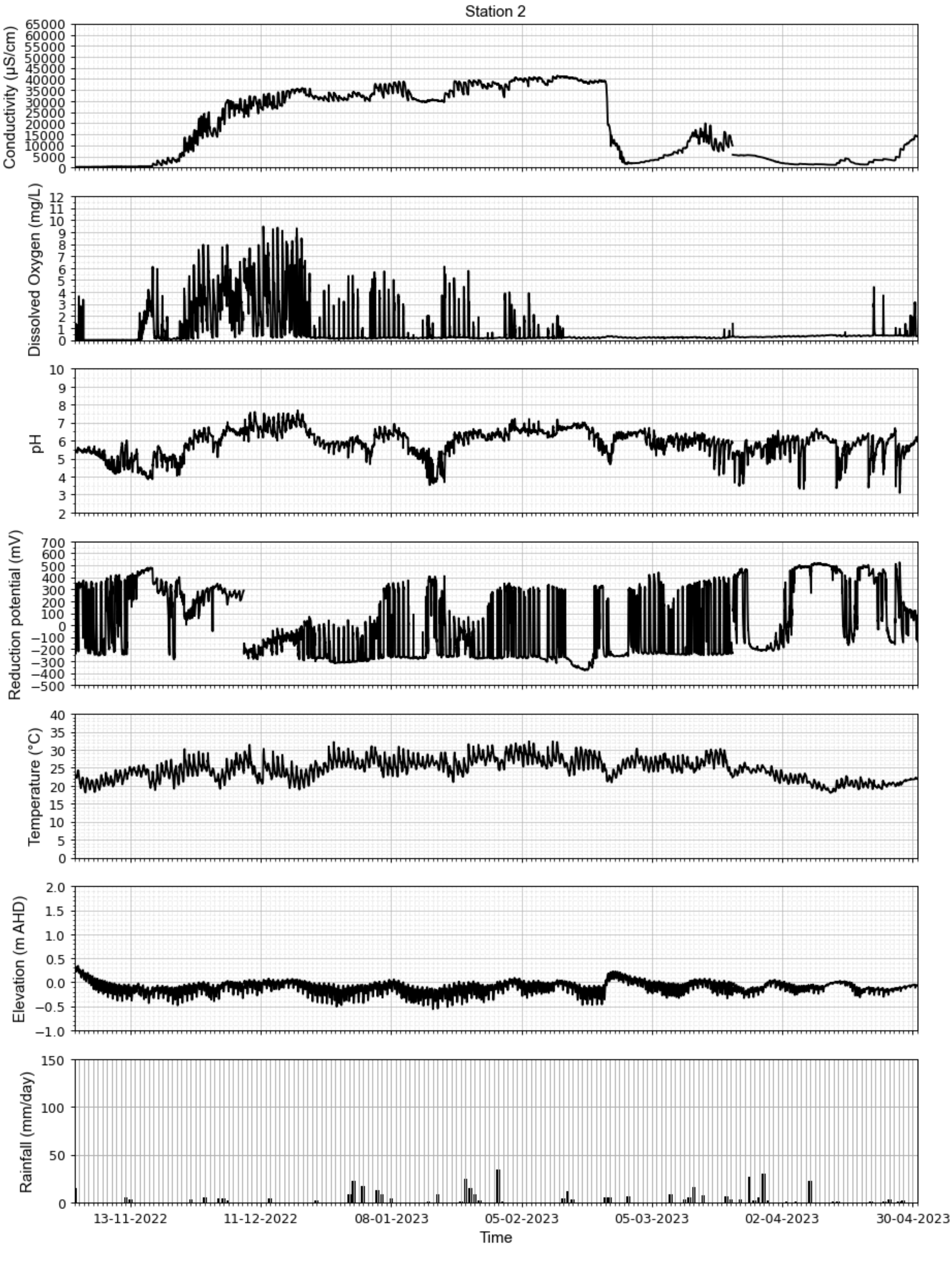

Figure A-10 Water quality data for Station 2 (November 2022 to April 2023)

Rainfall data from BOM (2025e)

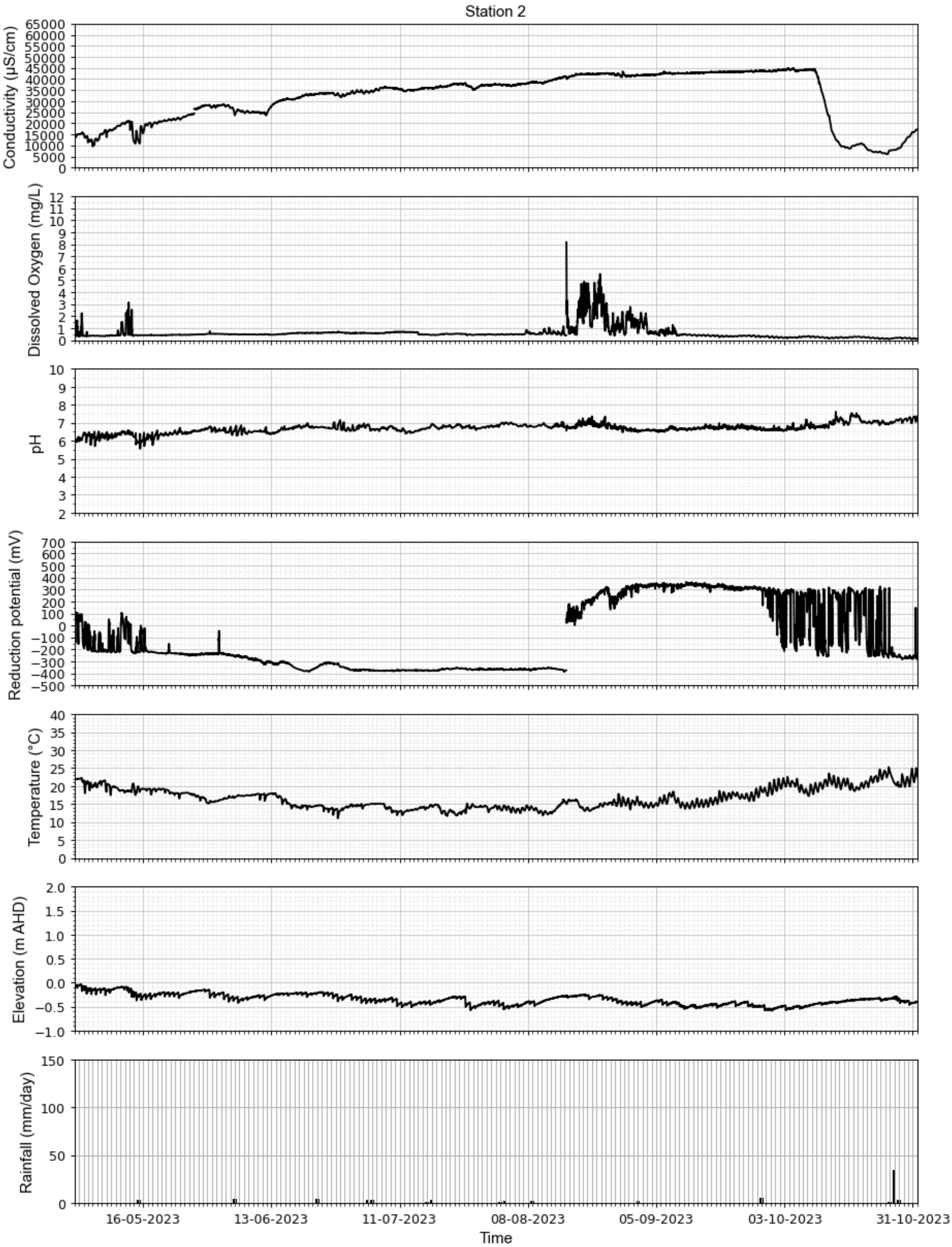

Figure A-11 Water quality data for Station 2 (May 2023 to October 2023)

Rainfall data from BOM (2025e)

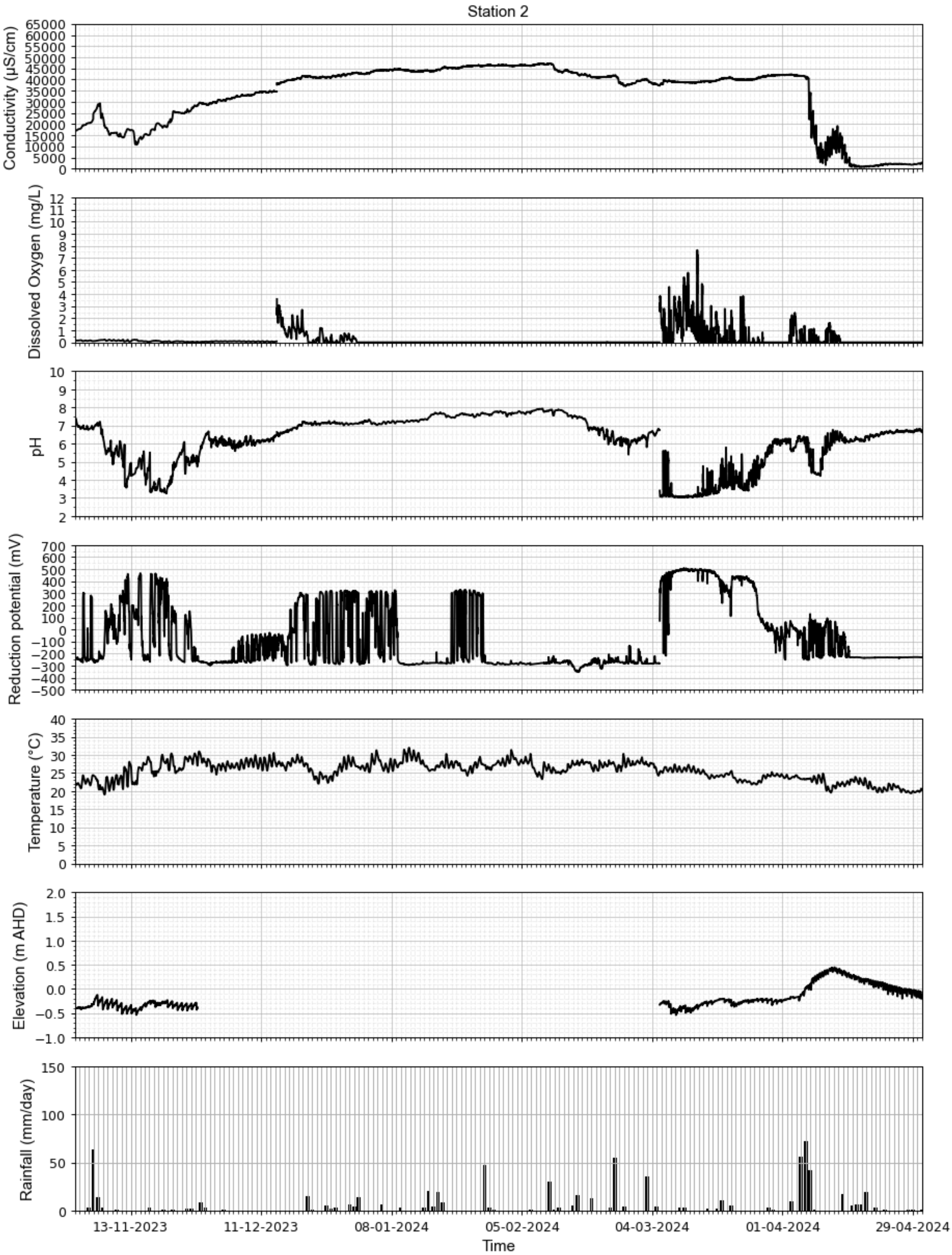

Figure A-12 Water quality data for Station 2 (November 2023 to April 2024)

Rainfall data from BOM (2025e)

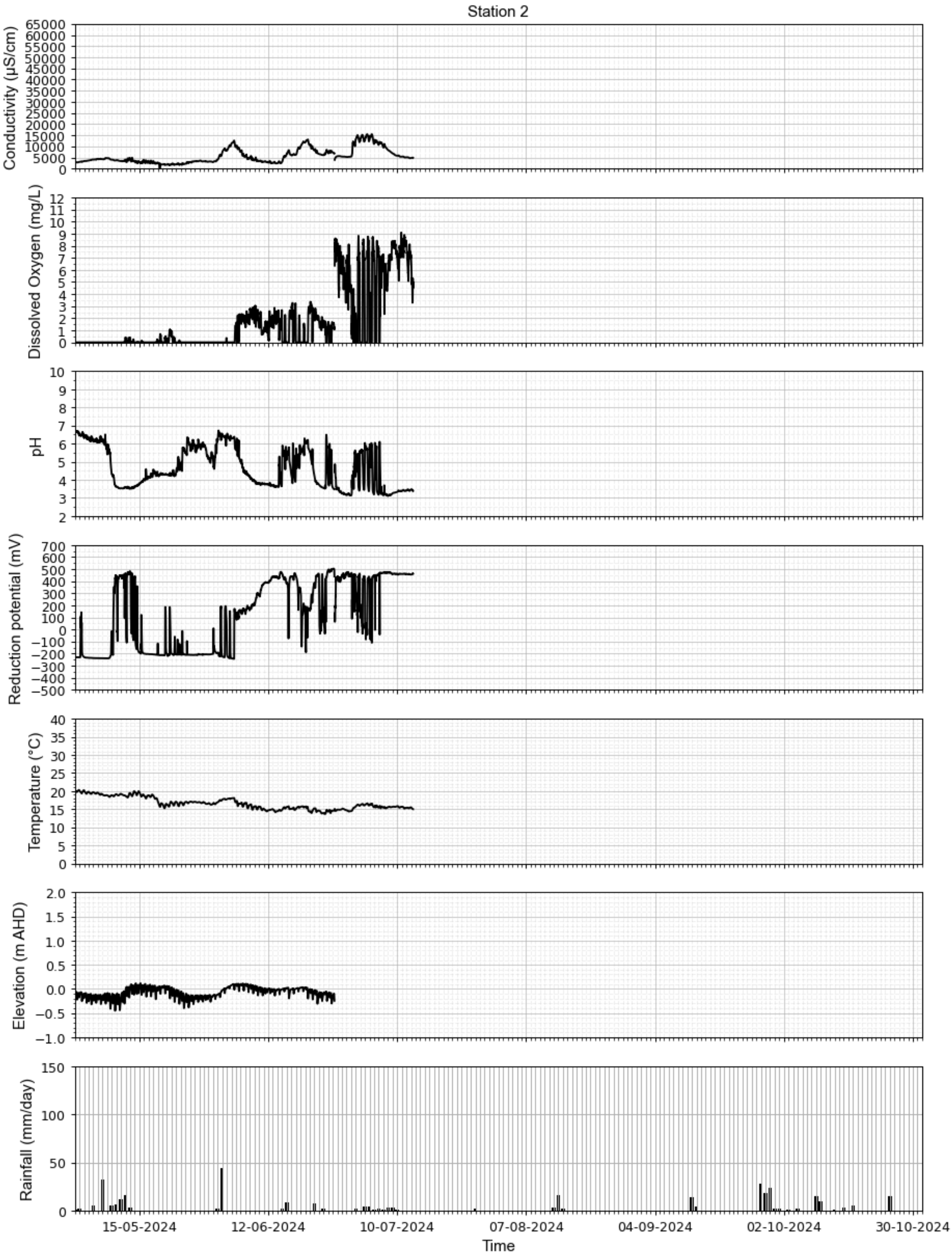

Figure A-13 Water quality data for Station 2 (May 2024 to July 2024)

Rainfall data from BOM (2025e)

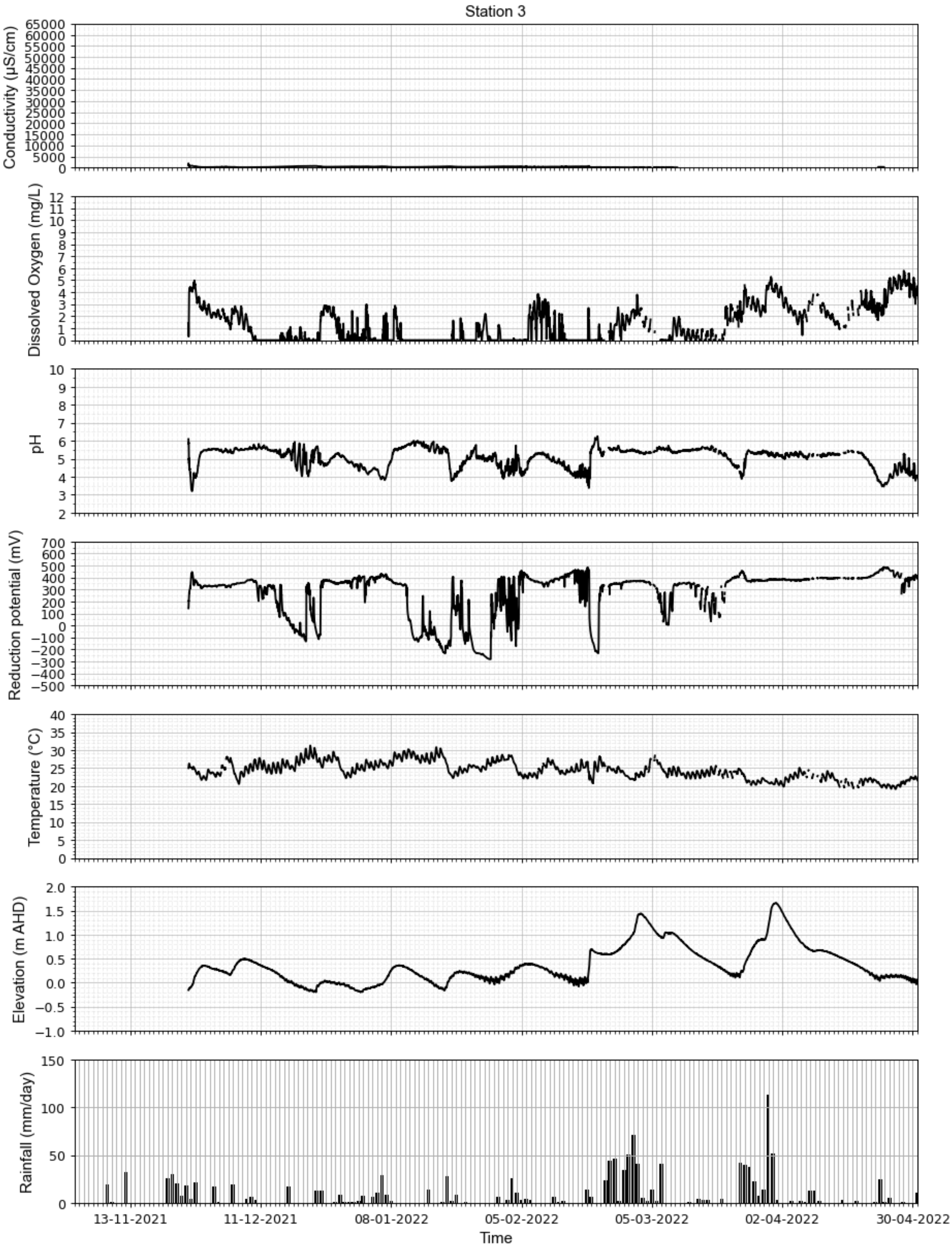

Figure A-14 Water quality data for Station 3 (November 2021 to April 2022)

Rainfall data from BOM (2025e)

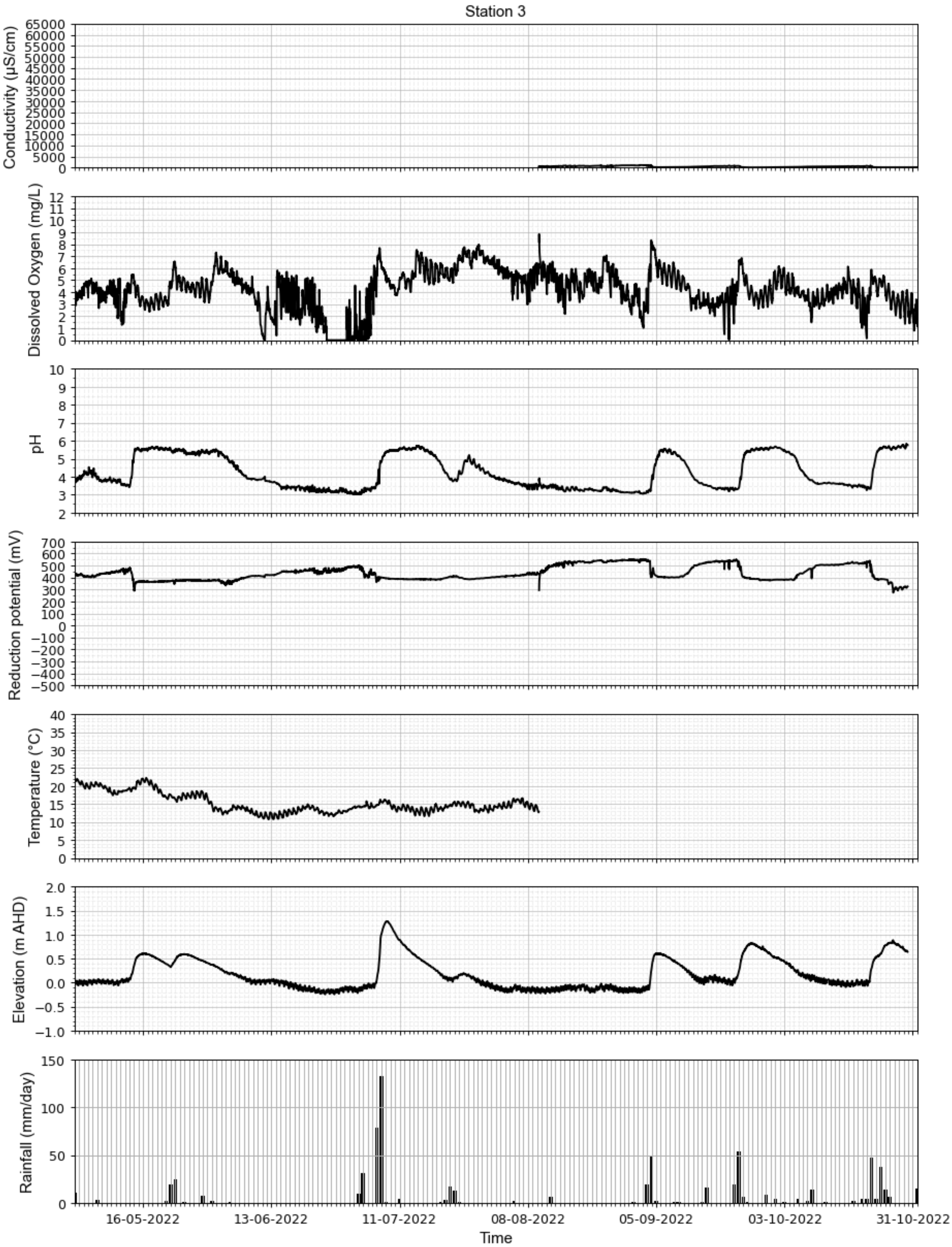

Figure A-15 Water quality data for Station 3 (May 2022 to October 2022)

Rainfall data from BOM (2025e)

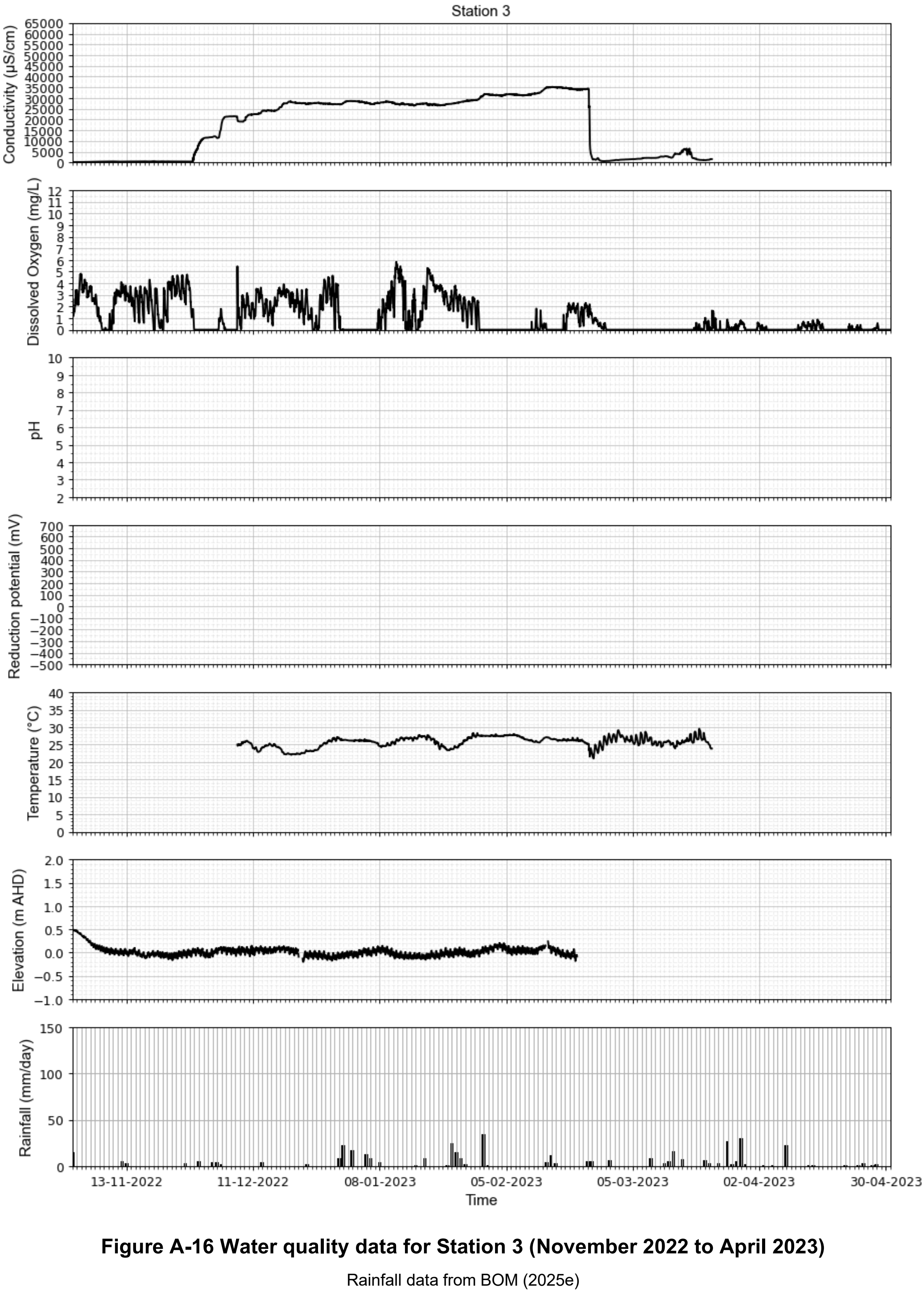

Figure A-16 Water quality data for Station 3 (November 2022 to April 2023)

Rainfall data from BOM (2025e)

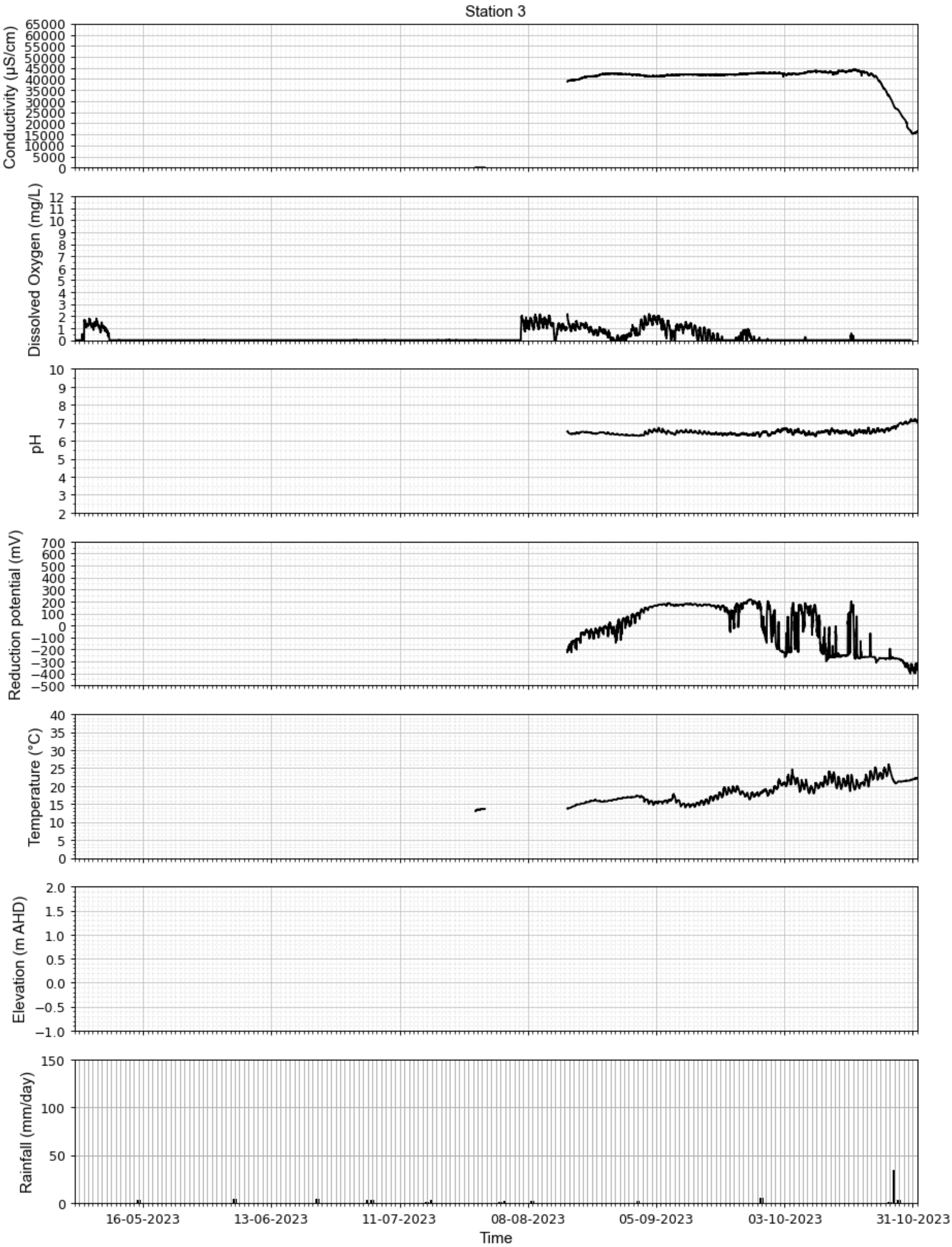

Figure A-17 Water quality data for Station 3 (May 2023 to October 2023)

Rainfall data from BOM (2025e)

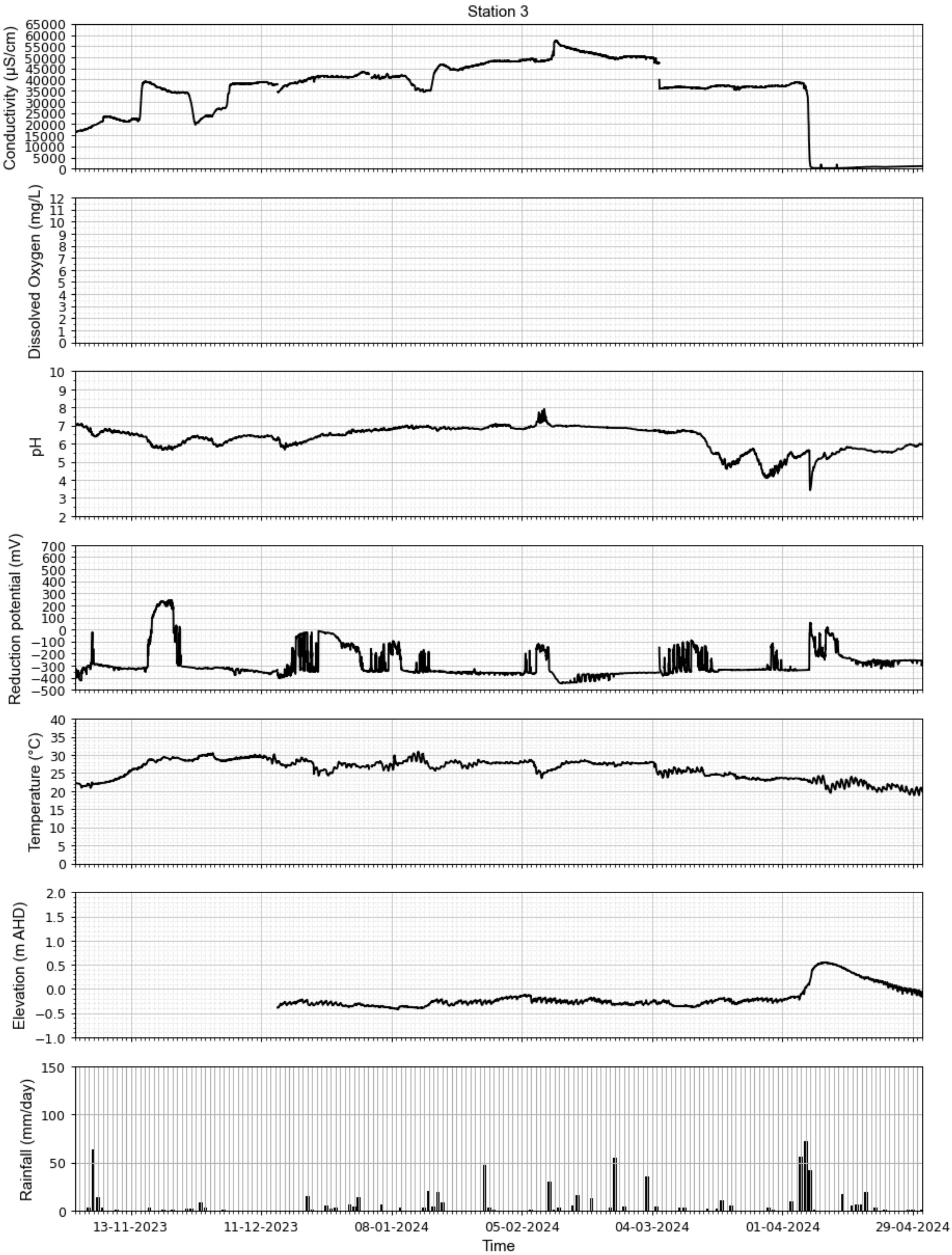

Figure A-18 Water quality data for Station 3 (November 2023 to April 2024)

Rainfall data from BOM (2025e)

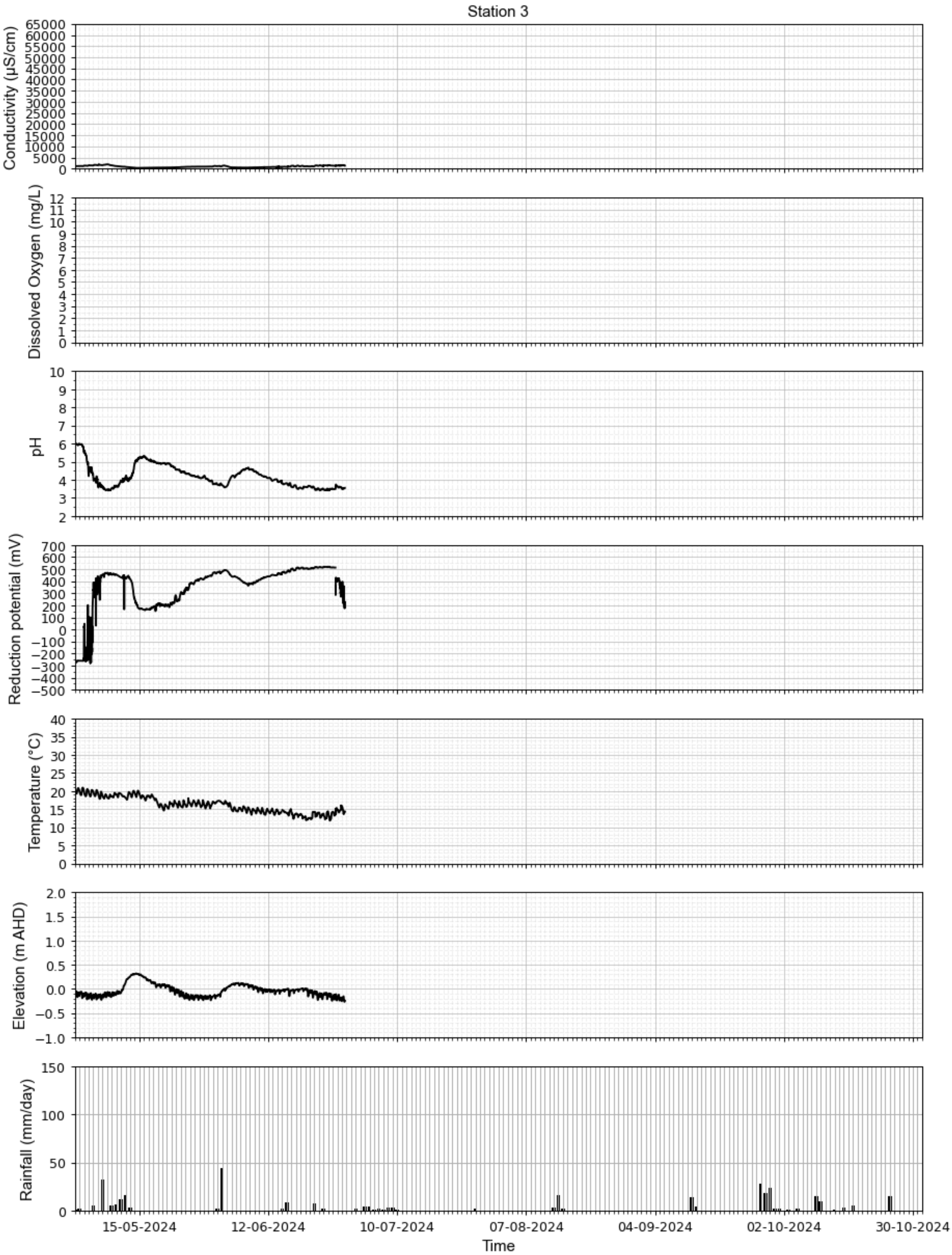

Figure A-19 Water quality data for Station 3 (May 2024 to June 2024)

Rainfall data from BOM (2025e)

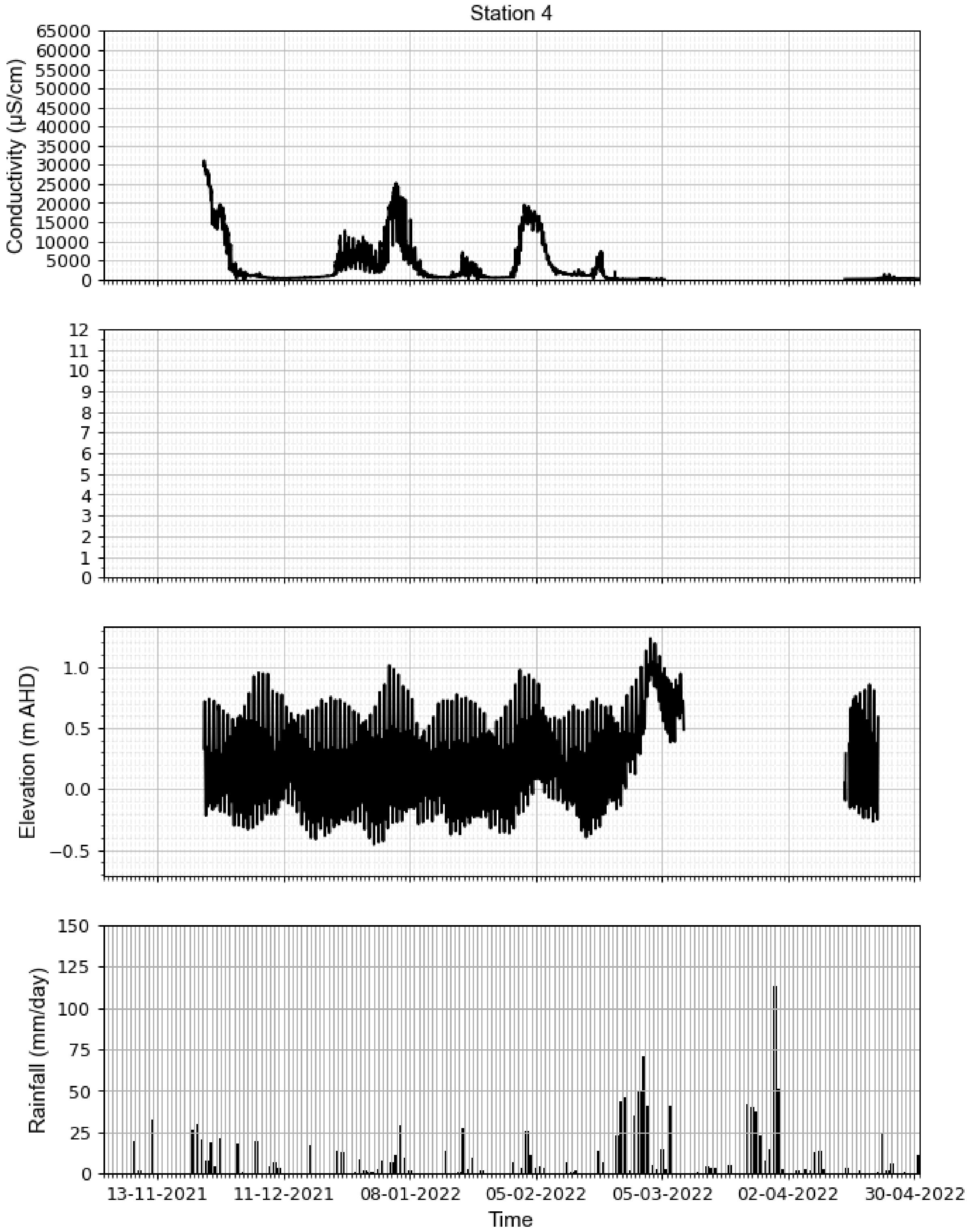

Figure A-20 Water quality data for Station 4 (November 2021 to April 2022)

Rainfall data from BOM (2025e)

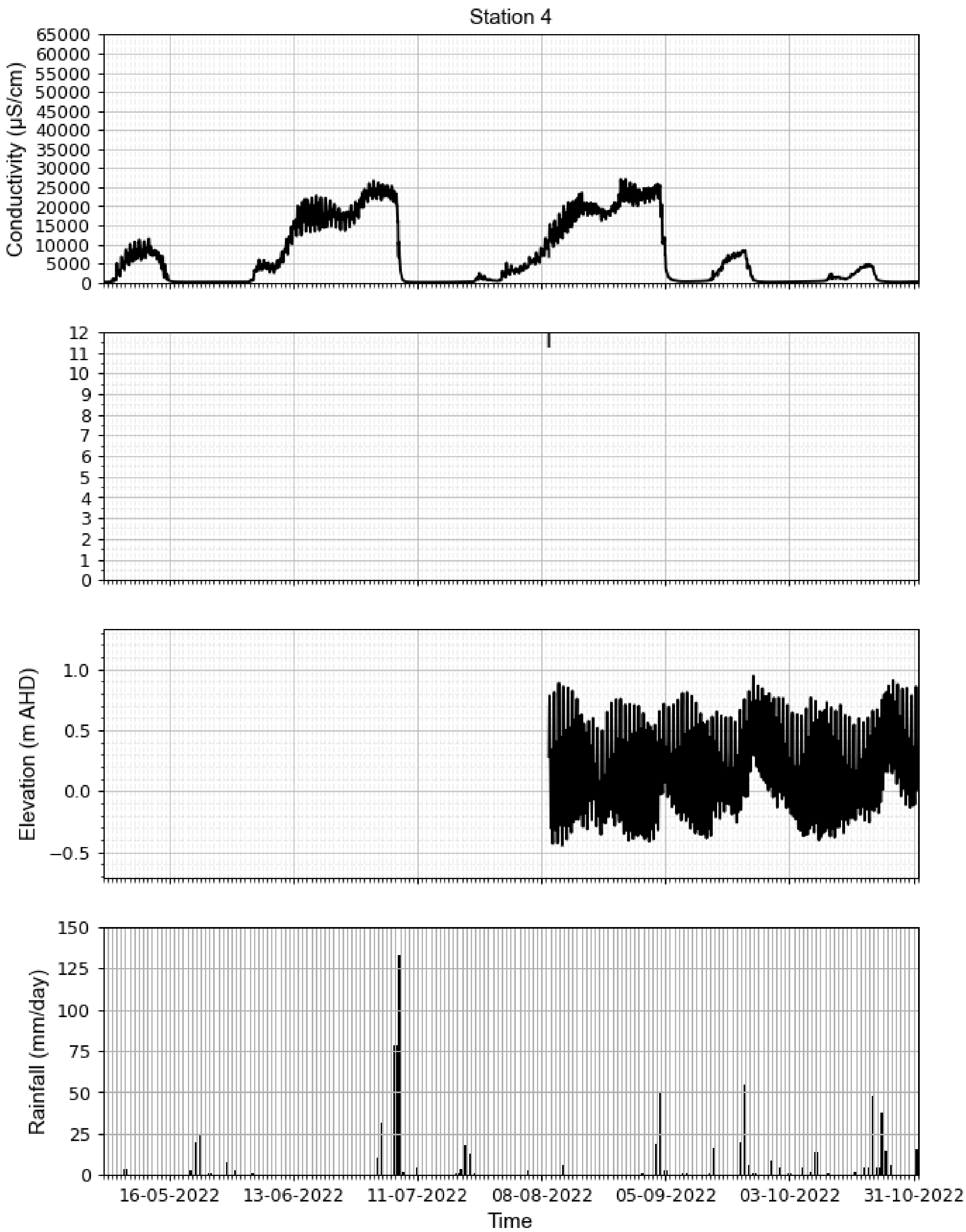

Figure A-21 Water quality data for Station 4 (May 2022 to October 2022)

Rainfall data from BOM (2025e)

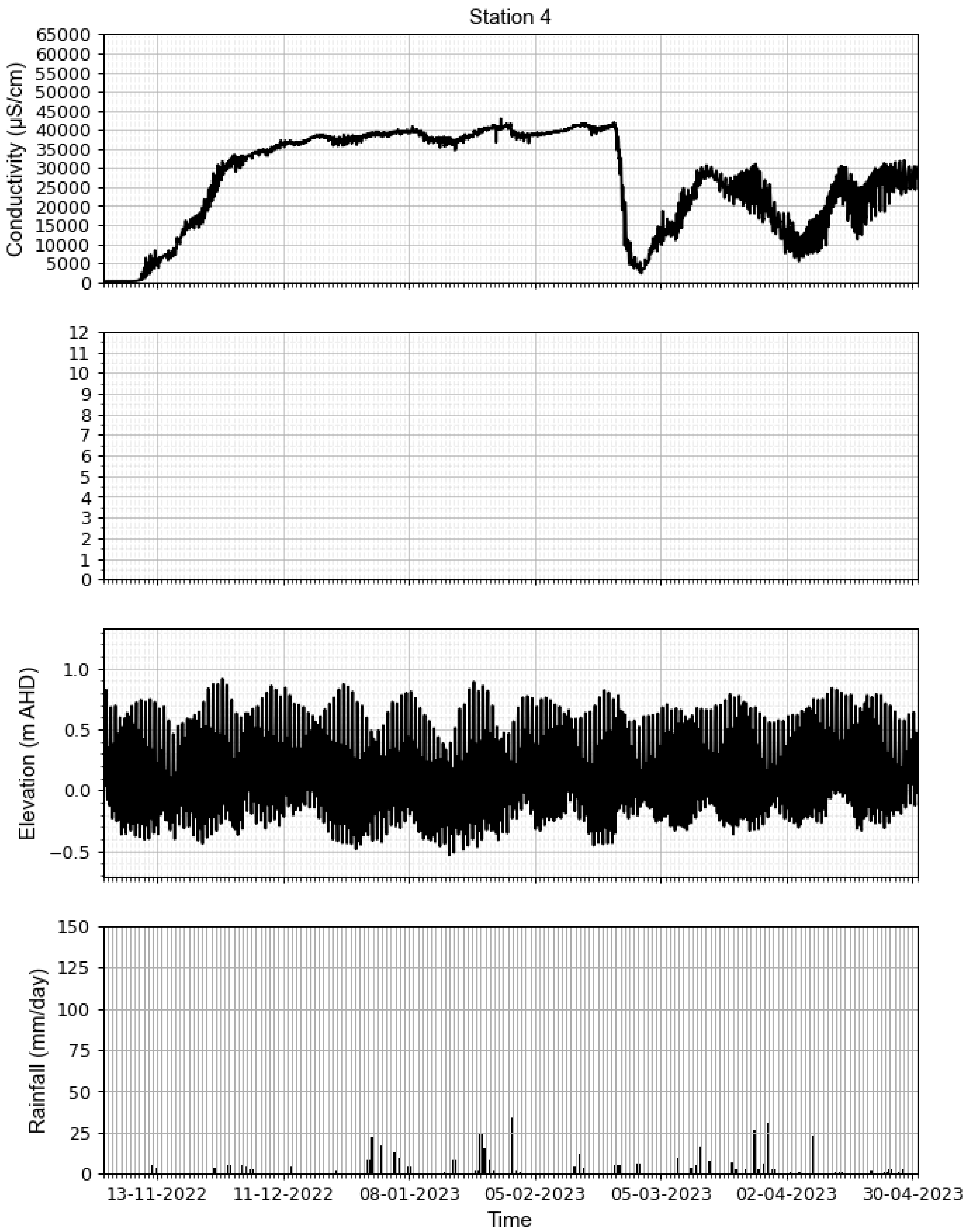

Figure A-22 Water quality data for Station 1 (November 2022 to April 2023)

Rainfall data from BOM (2025e)

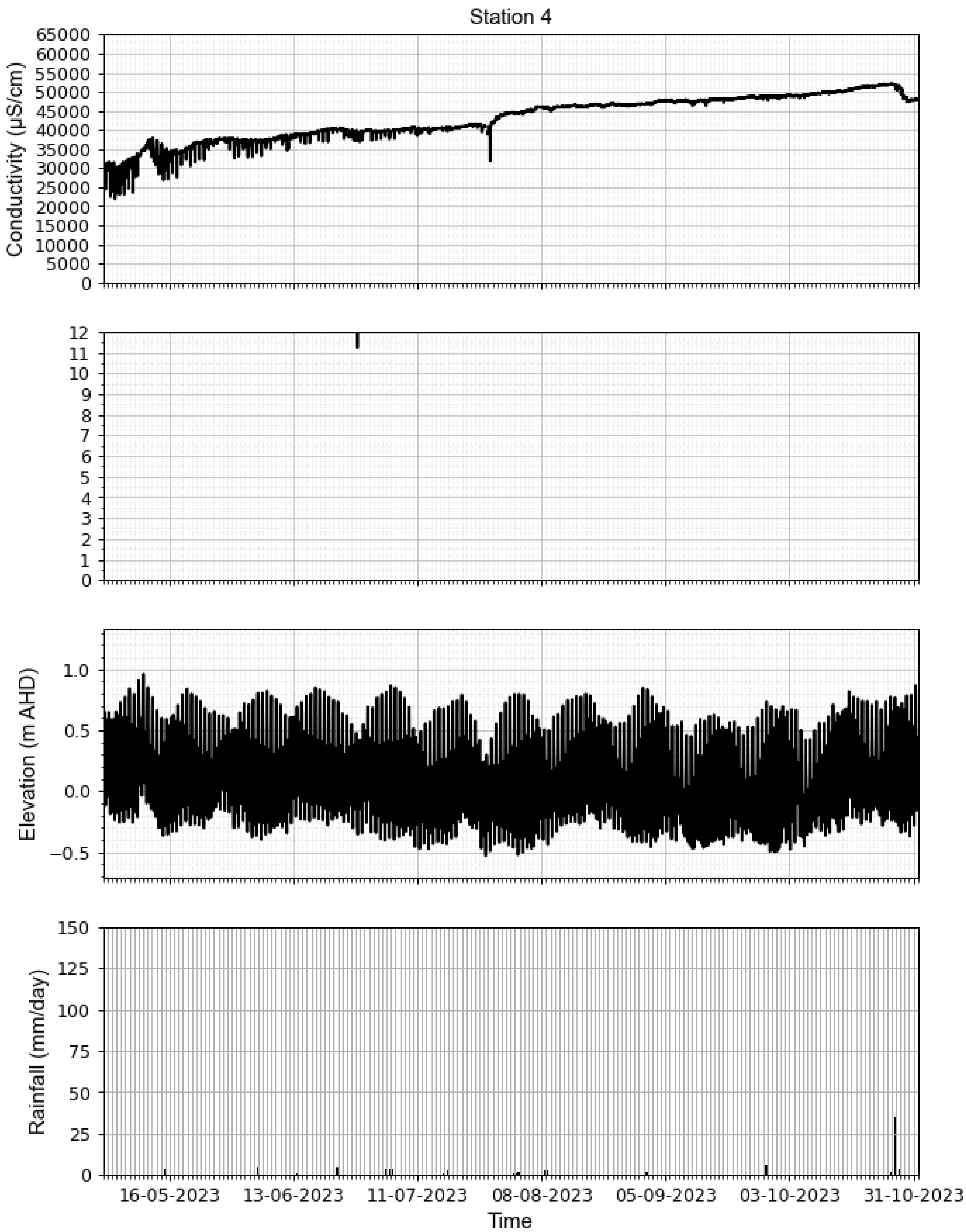

Figure A-23 Water quality data for Station 1 (May 2023 to October 2023)

Rainfall data from BOM (2025e)

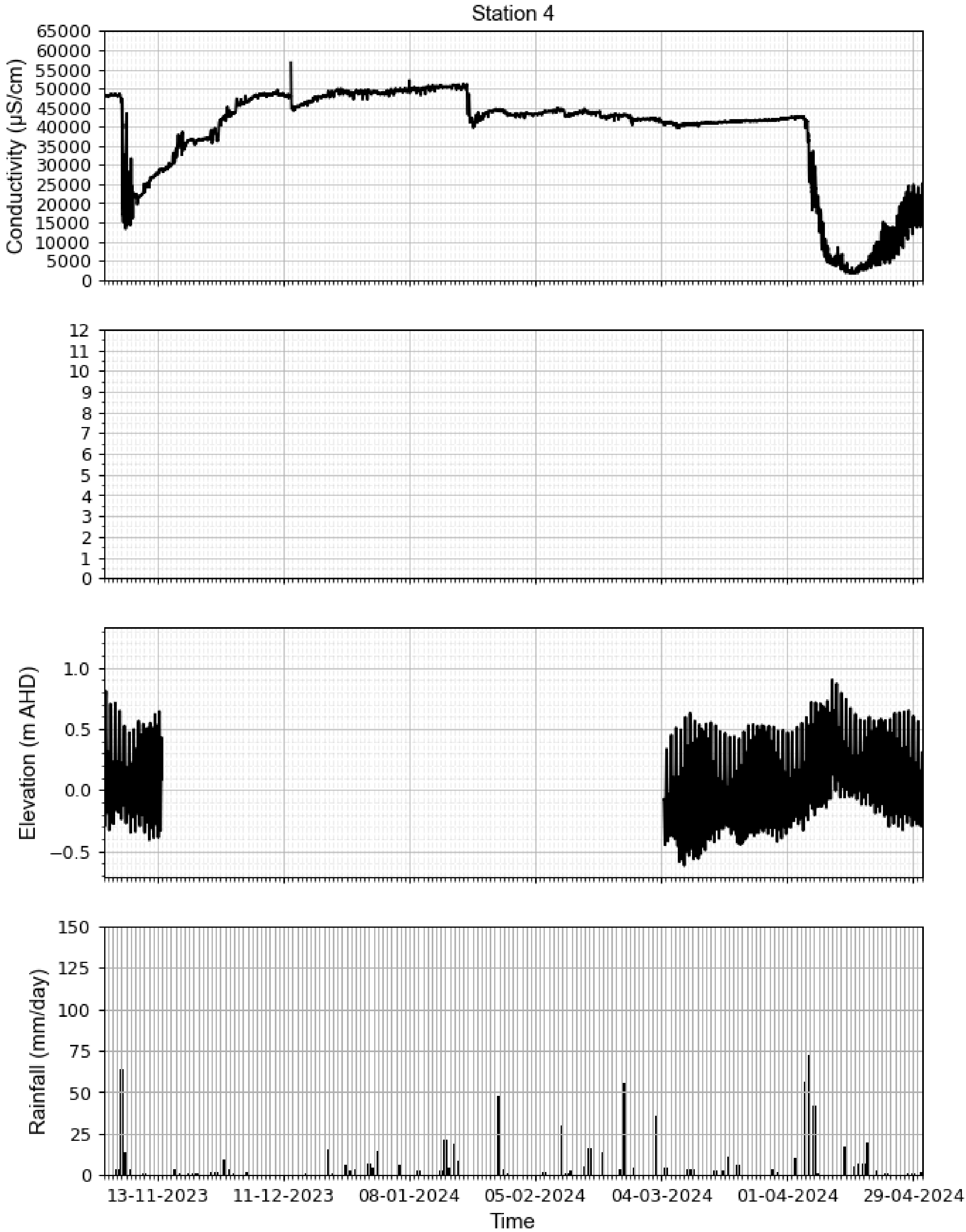

Figure A-24 Water quality data for Station 1 (November 2023 to April 2024)

Rainfall data from BOM (2025e)

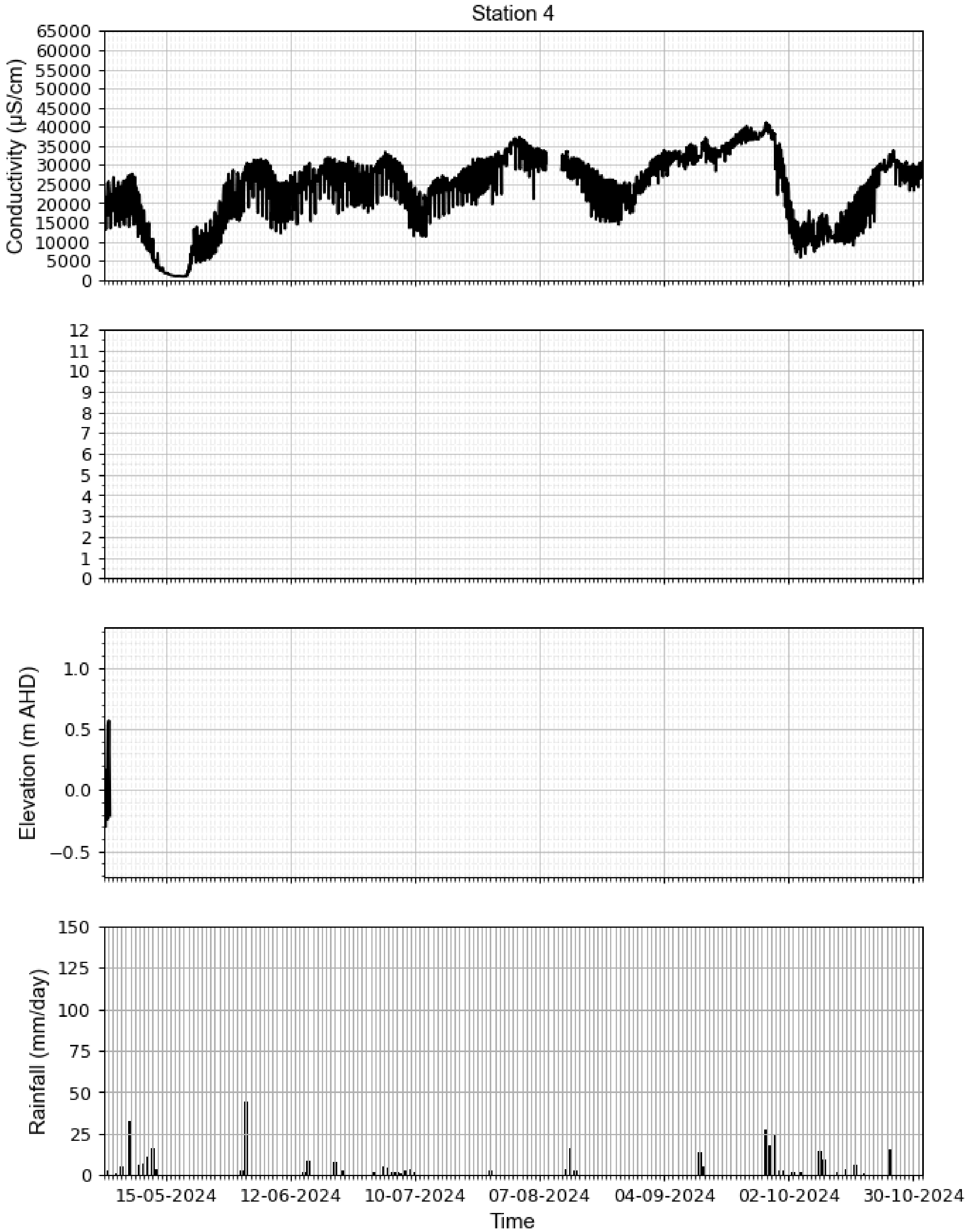

Figure A-25 Water quality data for Station 1 (May 2024 to October 2024)

Rainfall data from BOM (2025e)

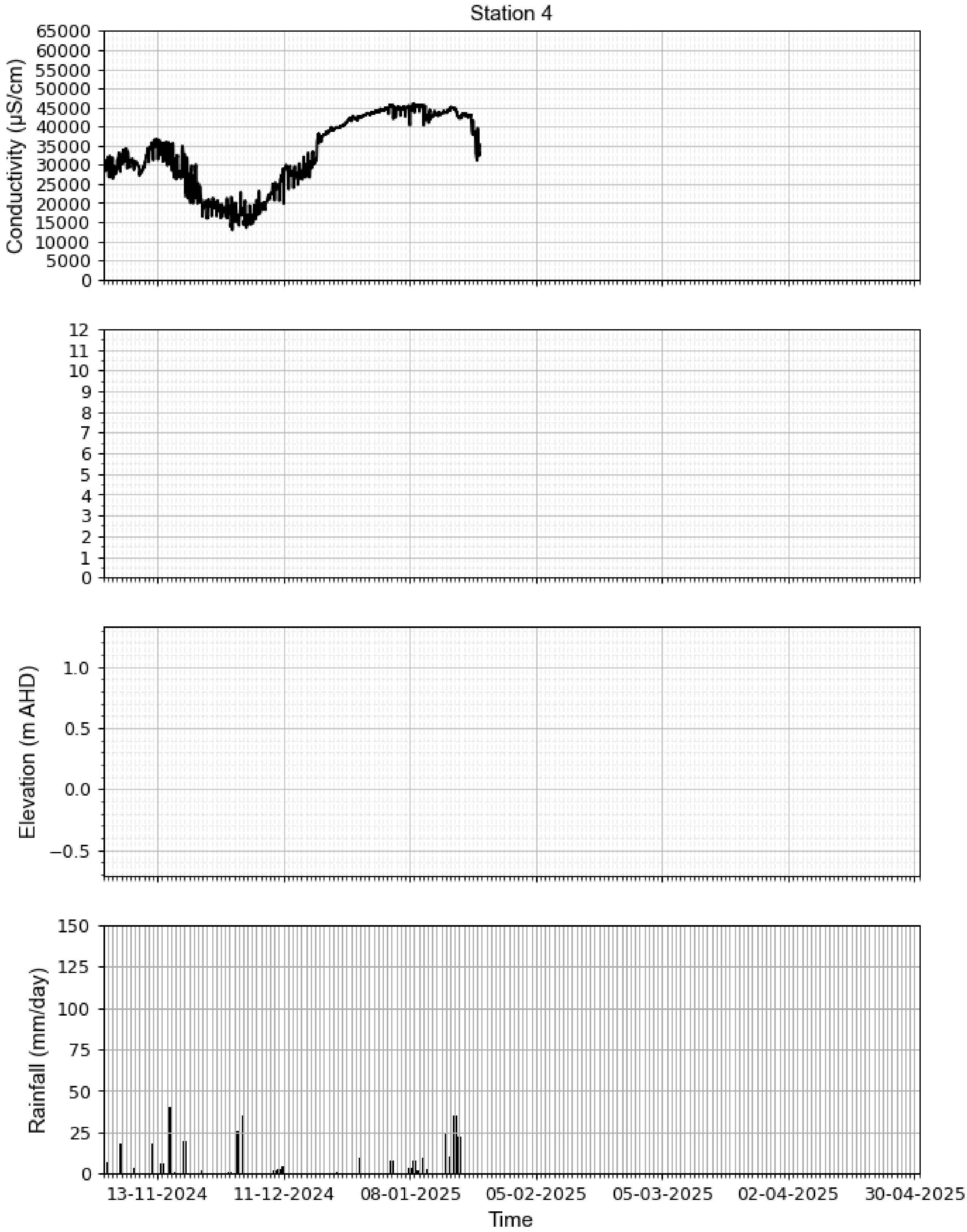

Figure A-26 Water quality data for Station 1 (November 2024 to January 2025)

Rainfall data from BOM (2025e)

Appendix B Seasonal data histograms

Figure B-1 shows the conductivity, pH and redox potential for different seasons. Based on historical rainfall data (shown previously in Figure 2-2), a wet season (January to March) and a dry season (July to September) were identified, with shoulder seasons in between. Data was also separated into individual stations to identify trends which may be occurring at different locations within the wetland. Note, dissolved oxygen data was only available during the first year of deployment and was considered unreliable for the identification of seasonal trends.

Observations (Figure B-1) showed that there was no clear seasonal trend for conductivity and pH data. This was likely related to the significant differences in climate which occurred across the 3 years of monitoring. Continued collection of water quality data is required to elucidate seasonal trends across a longer period.

Analysis of redox potential data showed a clear seasonal signal. Station 2 and 3 trended to have a low redox potential during the wet season (January to March) and a high redox potential during the dry season (July to September). Note, this trend was not observed at Station 1 and could indicate that increased tidal flushing acts to increase the redox potential. This trend could also be related to temperature which would have a significant influence on redox potential.

While not shown in Figure B-1, water temperature displayed a seasonal trend with higher temperatures (20°C to 35°C) in summer months, and lower temperatures (10°C to 20°C) in winter months. Temperature data is provided in Appendix A. There was minimal difference between the temperatures recorded at each of the three water quality stations. The temperatures behaved as expected increasing during summer where there are increased daylight hours and therefore increased solar radiation while decreasing during winter when daylight hours are reduced and there is less solar radiation.

Figure B-2, Figure B-3, and Figure B-4 provide the seasonal histograms for the conductivity, pH and redox potential data measured at Clybucca, respectively.

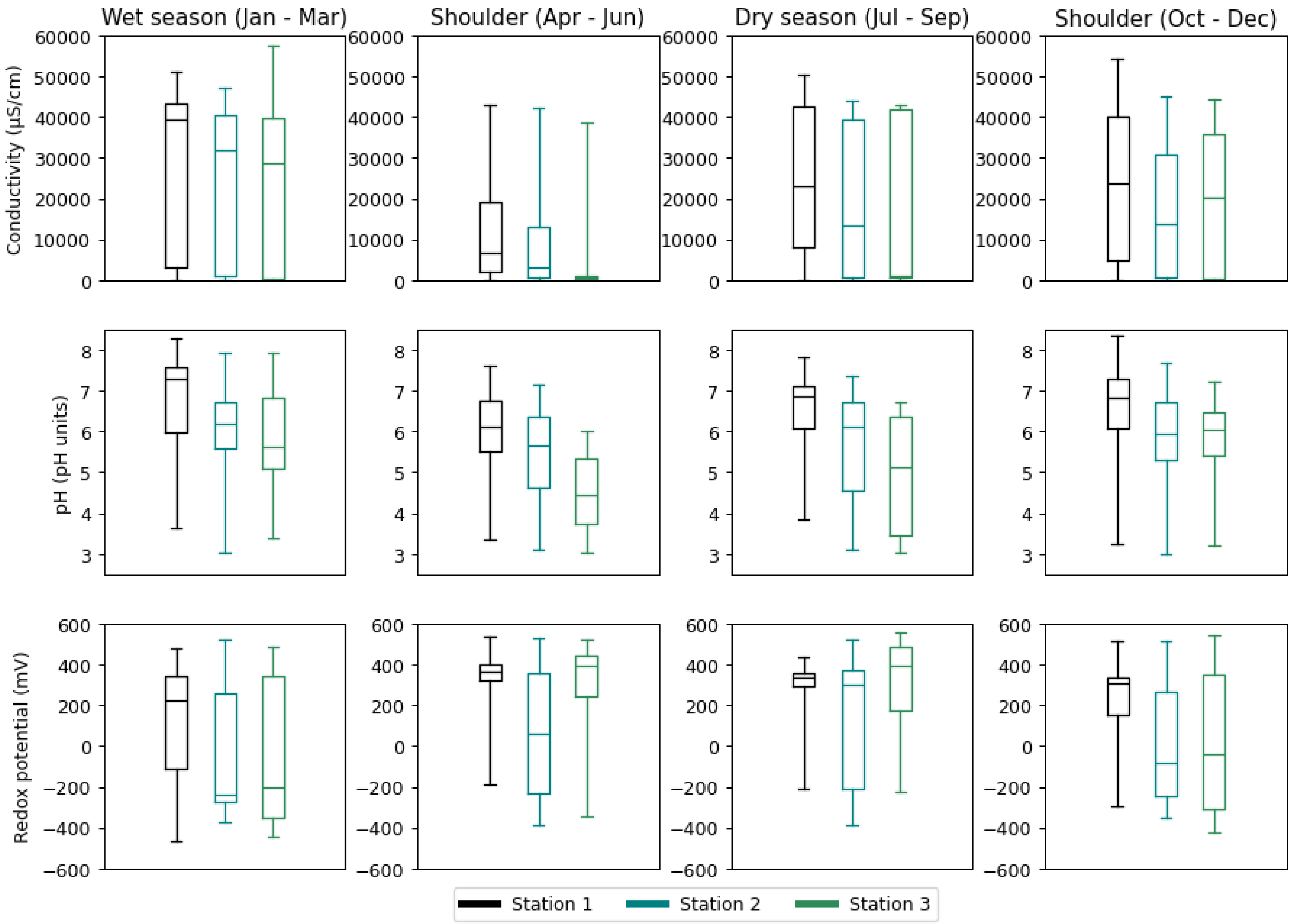

Figure B-1 Seasonal water quality observations for each monitoring station (box indicates 25th and 75th percentile with the median bar inside, whiskers indicate total data range)

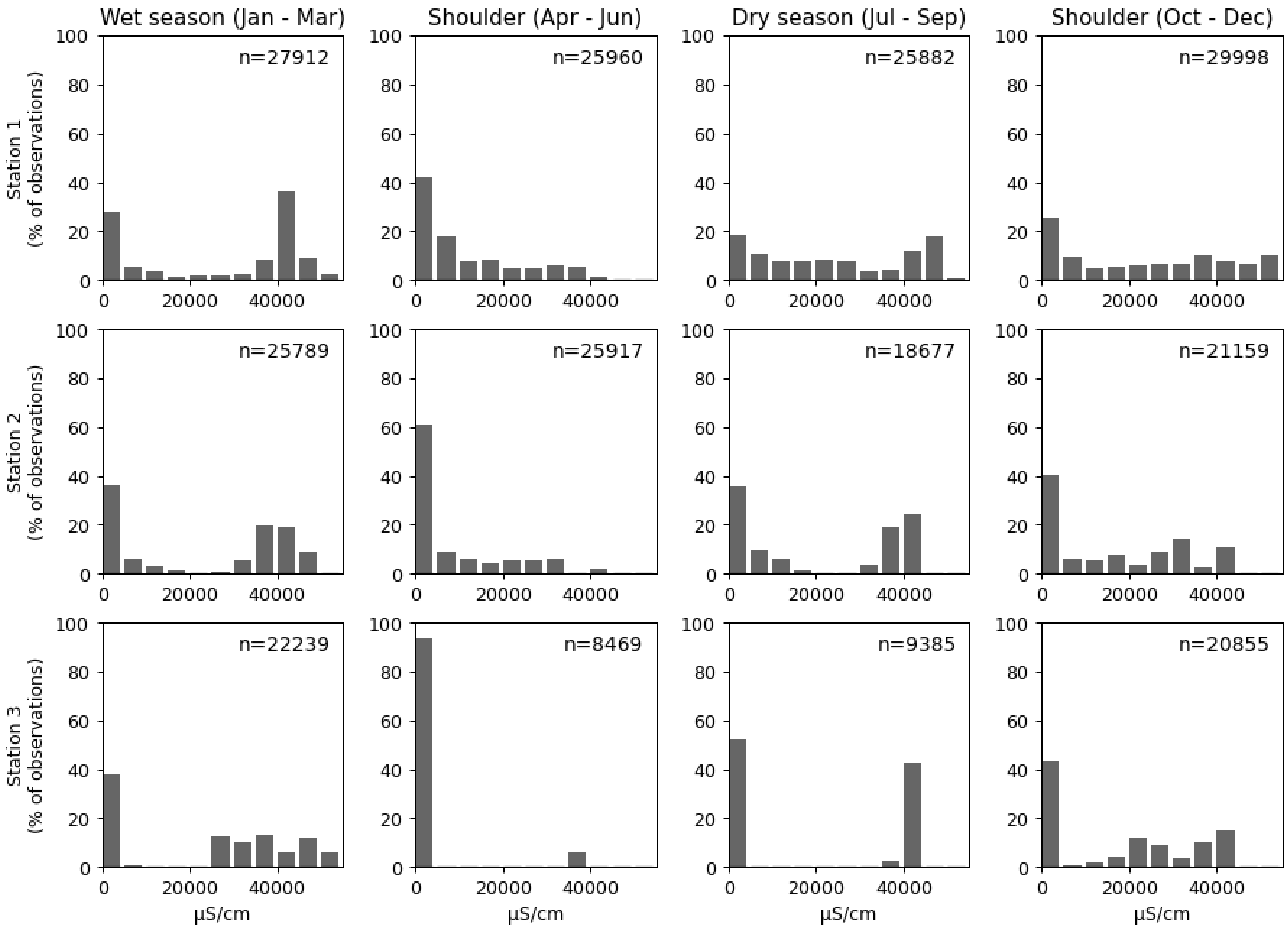

Figure B-2 Seasonal conductivity observations

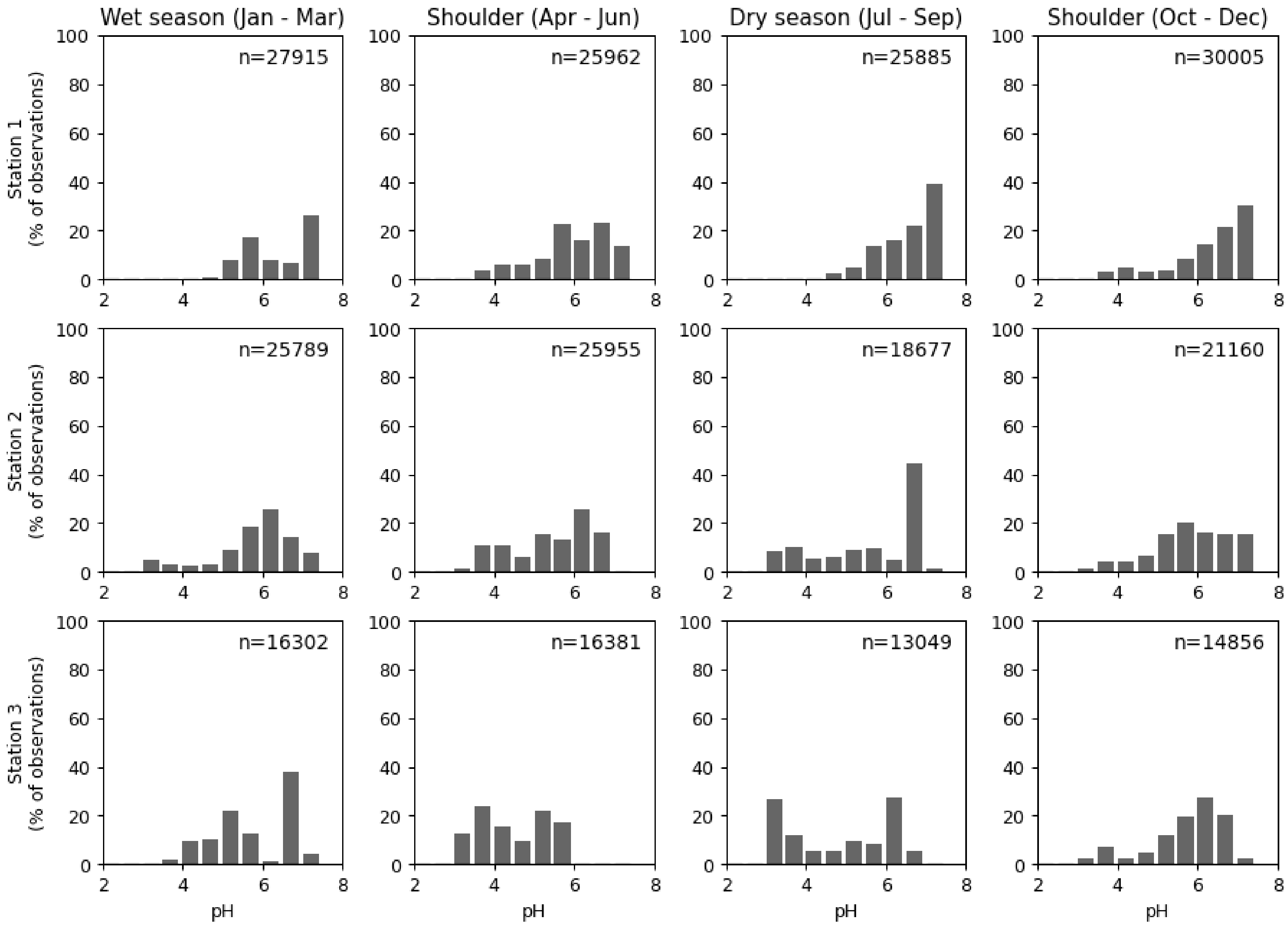

Figure B-3 Seasonal pH observations

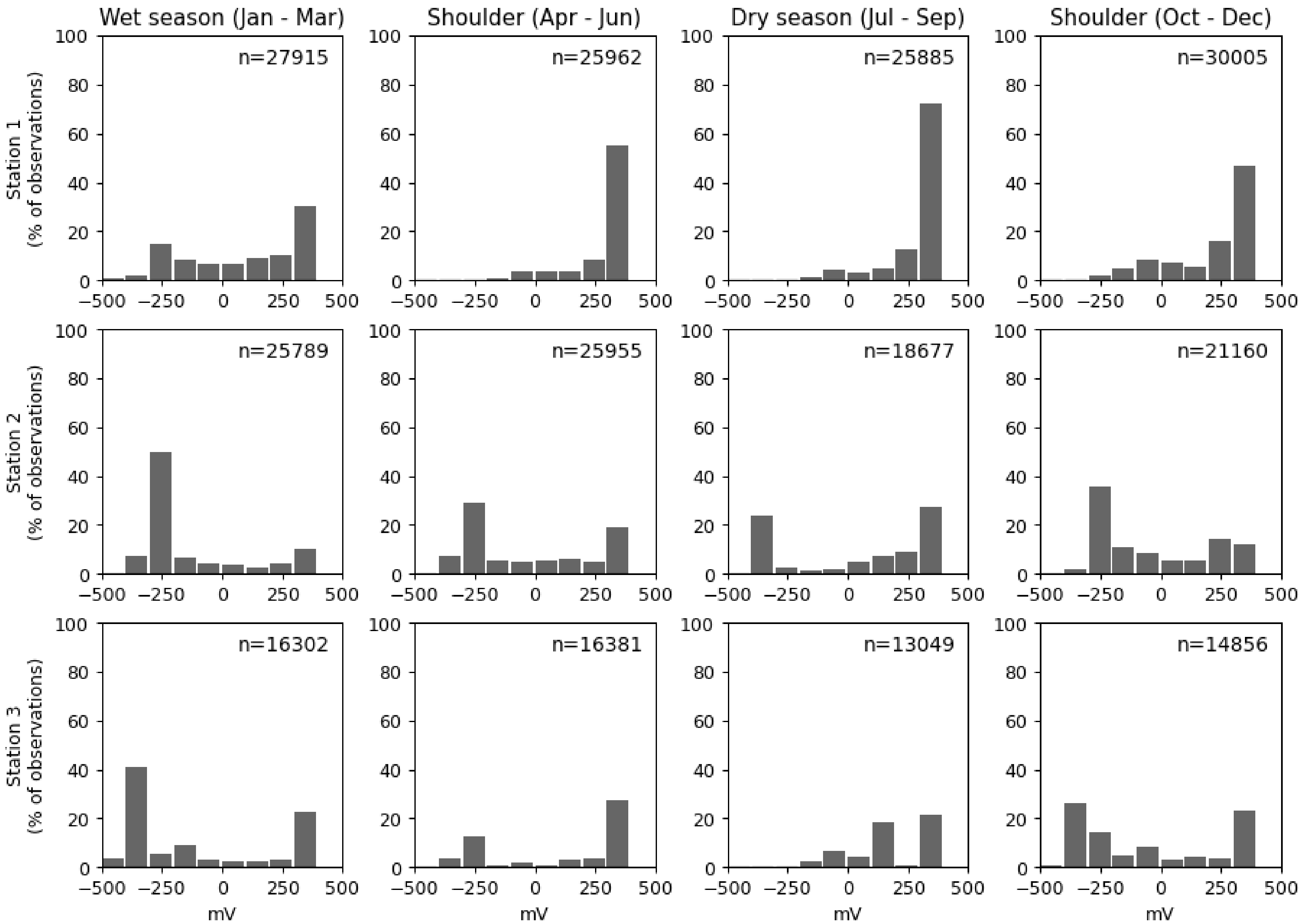

Figure B-4 Seasonal redox potential observations

Appendix C Event comparison

C1 Comparison of events

The following appendix provides a comparison between similar rainfall events that occurred during the monitoring period:

Comparison 1 (Figure C-1): Event 1 (21/11/2021) and event 9 (22/9/2022), both 3 EY events

- Following both events, conductivity levels remained fresh (~0 µS/cm), likely assisted by further rainfall in the days proceeding the events. Following event 9 conductivity levels began to rise after approximately 20 days, however, they remained low (<10,000 µS/cm).
- Following Event 1, the pH dropped at Station 1 from ~7 to ~4 over the course of the first week. Following Event 2, however, the pH at Station 1 remained neutral.
- At Stations 2 and 3, following both rainfall events, the pH initially rose to ~5.5 likely responding to the rainfall (which has a similar pH). Following event 1 the pH then declined from day 20 onwards to ~4 at all stations, likely due to the drainage of acid sulfate soils. Following event 9, the pH initially fell to ~4 at Stations 2 and 3 after 10 days.
- The redox potential had a high variability following each event.

Comparison 2 (Figure C-2): Event 1 (21/11/2021) and event 14 (22/9/2022), both 3 EY events

- The conductivity levels prior to both events were similar (20,000 µS/cm to 50,000 µS/cm), and both rainfall events resulted in a drop in conductivity. Conductivity levels dropped to and remained at ~0 µS/cm following event 1, while conductivity levels dropped following event 14 to ~20,000 µS/cm before increasing to 30,000 µS/cm to 40,000 µS/cm.
- Following event 1 there were a number of smaller rainfall events while event 14 had minimal rainfall proceeding it.
- Differing rainfall conditions likely resulted in different responses in the pH. While initially the pH increased following event 1 (likely due to rainfall), it then dropped towards ~4 with this trend continuing past 30 days. Conversely, following event 14, the pH dropped to ~4 almost straight away. Drier conditions and a higher conductivity then likely contributed to pH increasing to neutral by 30 days following event 14.
- The redox potential had a high variability following each event.

Comparison 3 (Figure C-3): Event 2 (31/12/2021) and event 21 (27/9/2024), both 6 EY events

- The antecedent conditions prior to event 2 were fresher (<10,000 µS/cm) than for event 21 (40,000 µS/cm). Both events showed a freshening response to rainfall, however, following event 21 the conductivity had recovered to 20,000 µS/cm by day 30 while the conductivity following event 2 at a similar time remained fresh.
- Following event 2 the pH at Station 1 remained between 5 and 6 (similar to the pH of rainfall). Contrastingly, the pH at Station 1 dropped from ~7.5 to ~4 over the course of 5 days before recovering to ~7 by day 30 following event 21. Due to data availability, pH was only comparable for Station 1.
- For event 2, Station 2 and Station 3 both observed a drop in pH to ~4 between days 15 and 20.
- The redox potential remained positive (~300 to 400 mV) at Station 1 following both events, potentially indicating a well-mixed/aerated water column following rainfall.

Comparison 4 (Figure C-4): Event 5 (20/5/2022) and event 22 (16/11/2024), both 12 EY events

- The antecedent conditions prior to event 5 was fresh (~0 µS/cm) compared to event 22 (20,000 to 30,000 µS/cm). While following event 5 the conductivity levels remained fresh, there was a drop in levels at Station 1 following event 22 to ~10,000 µS/cm before it increased to ~20,000 µS/cm at 30 days following the event.
- Following both events the pH at Station 1 remained relative neutral. This could be related to the increased conductivity that occurred at both stations from around day 15 and indicate buffering of acid. Due to data availability, pH was only comparable for Station 1.
- Interestingly, the pH dropped from day 29 and day 20 for Stations 3 and 2 respectively following event 5. This delay could be related to the site hydrology. It is potentially an indication of acid following the event from locations upstream of Station 3.
- The redox potential had a high variability following each event with no clear trend. A drop in redox potential at Station 2 following event 5 corresponded with a slight increase in pH at the same station. Redox then rose quickly as pH decreased around day 20 indicating that there may be complex chemical processes occurring that influence the networks water quality.

Comparison 5 (Figure C-5): Event 9 (22/9/2022) and event 14 (4/11/2023), both 3 EY events

- The antecedent conditions prior to event 9 was fresh (<10,000 µS/cm) compared to event 14 (~50,000 µS/cm). A drop in conductivity was observed following both events, however, the system remained mostly fresh (<10,000 µS/cm) following event 9 while the conductivity fluctuated between 10,000 µS/cm and 50,000 µS/cm (with an increasing trend) following event 14.
- As described previously, the pH at Station 1 did not respond to rainfall following event 9. Stations 2 and 3 responded to event 9 with an initial increase in pH (days 1 to 10) followed by a decline in pH following day 10. This is typical for an acid sulfate soil affected system.
- Following event 14, the pH dropped to ~4 over the first 10 days at station 1 and 2, before slowly recovering to neutral. The pH at Station 3 remained relatively neutral (~6) indicating that the Clybucca was a source of pH for this event.
- The redox potential had a high variability following each event.

Comparison 6 (Figure C-6): Event 16 (28/1/2024) and event 20 (1/6/2024), both 6 EY events

- Event 16 occurred following a relatively dry period as is shown by the high conductivity levels, even following the event (~50,000 µS/cm). Comparatively, the conductivity following event 20 was also relatively stable with a decreasing trend at locations further upstream.
- High conductivity levels following event 16 corresponded to neutral pH levels. It is likely that any acid generated was buffered by seawater during this period.
- Following event 20 there was already low pH levels at Station 3 which persisted for the 30 days following the event. Clear drops in pH were also observed at Stations 1 and 2. The pH at Station 2 was variable from about day 10 onwards following event 20 and could be due to buffering of acid during tidal inflow events.
- The redox potential had a high variability following each event.

Comparison 7 (Figure C-7): Event 17 (24/02/2024) and event 23 (1/12/2024), both 6 EY events

- Limited data availability meant that Events 17 and 23 were only comparable at Station 1.
- Following event 17 there were persistent high conductivity levels (~40,000 µS/cm). There is little evidence of the rainfall event preceding.
- Following event 20, conductivity slowly recovers from ~10,000 µS/cm to ~40,000 µS/cm.
- Following both events the pH at Station 1 remained neutral, likely due to buffering with seawater.
- pH levels at Station 2 and 3 indicated persistent low pH levels following event 17 despite high levels of conductivity potentially indicating either a) a source for conductivity other than

seawater, or b) bicarbonates within seawater could no longer buffer the low pH likely due to persistent acidic discharges.

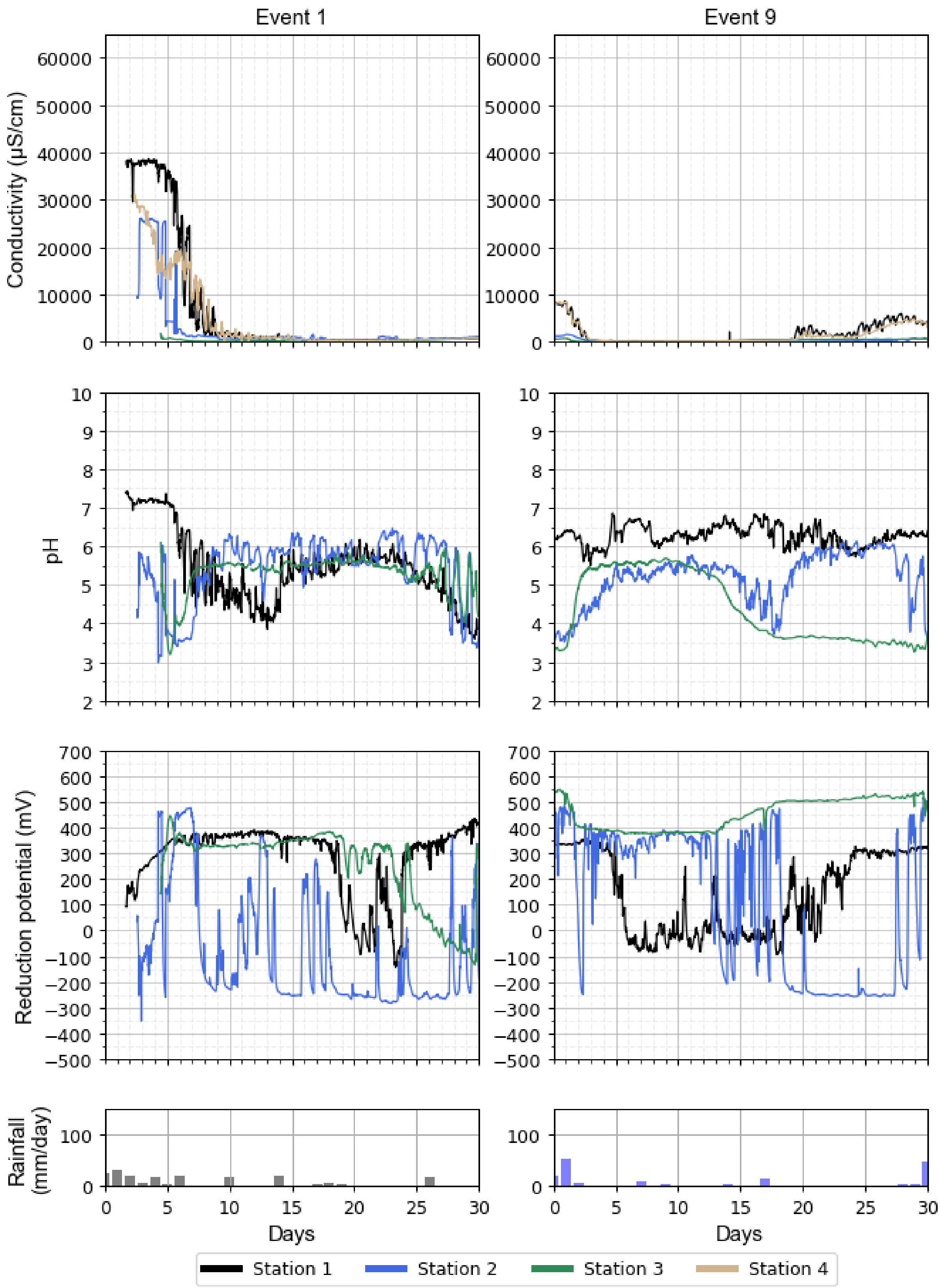

Figure C-1 Comparison of event 1 (21/11/2021) and event 9 (22/9/2022).

Rainfall data from BOM (2025b)

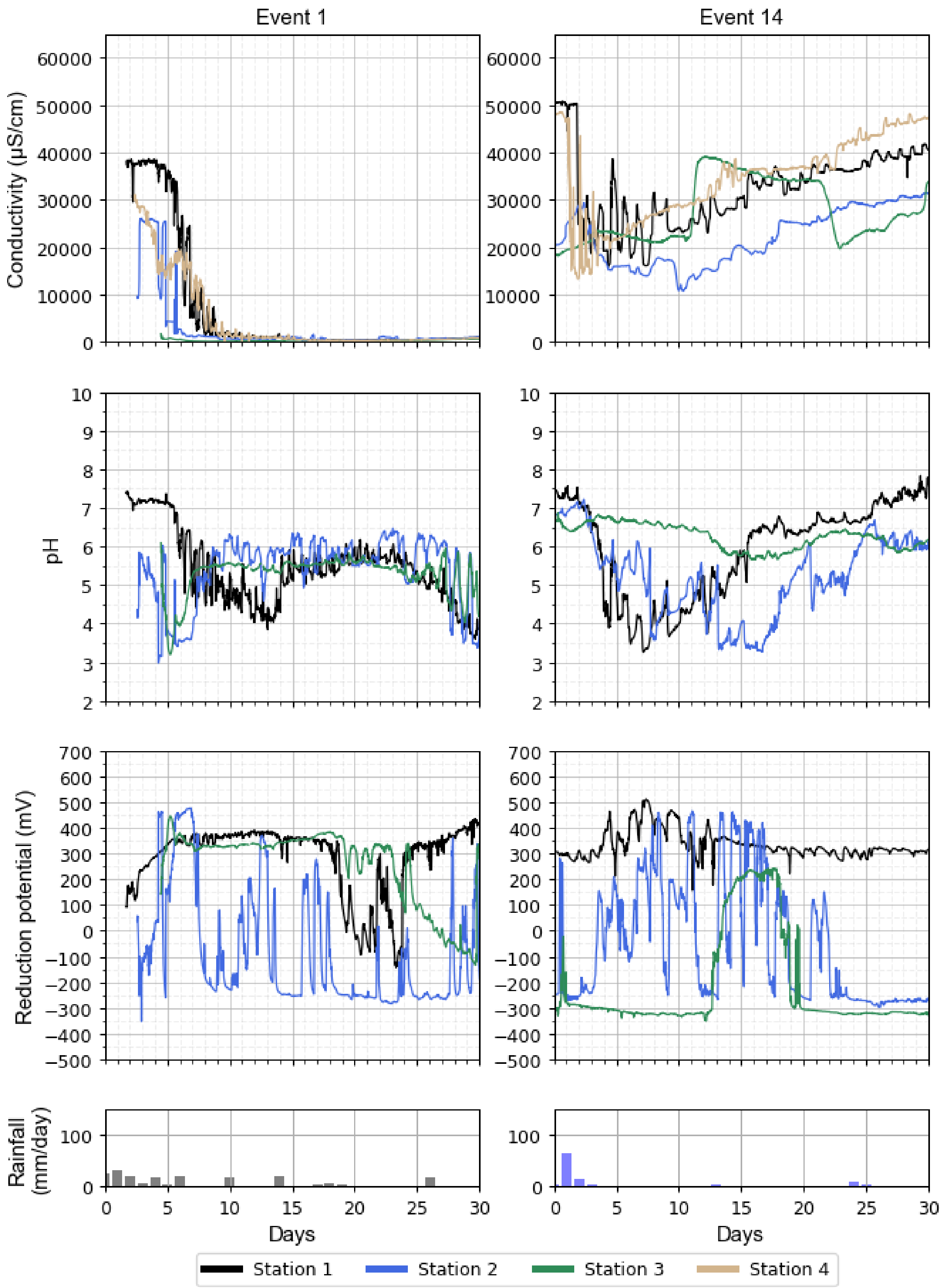

Figure C-2 Comparison of event 1 (21/11/2021) and event 14 (4/11/2023)

Rainfall data from BOM (2025b)

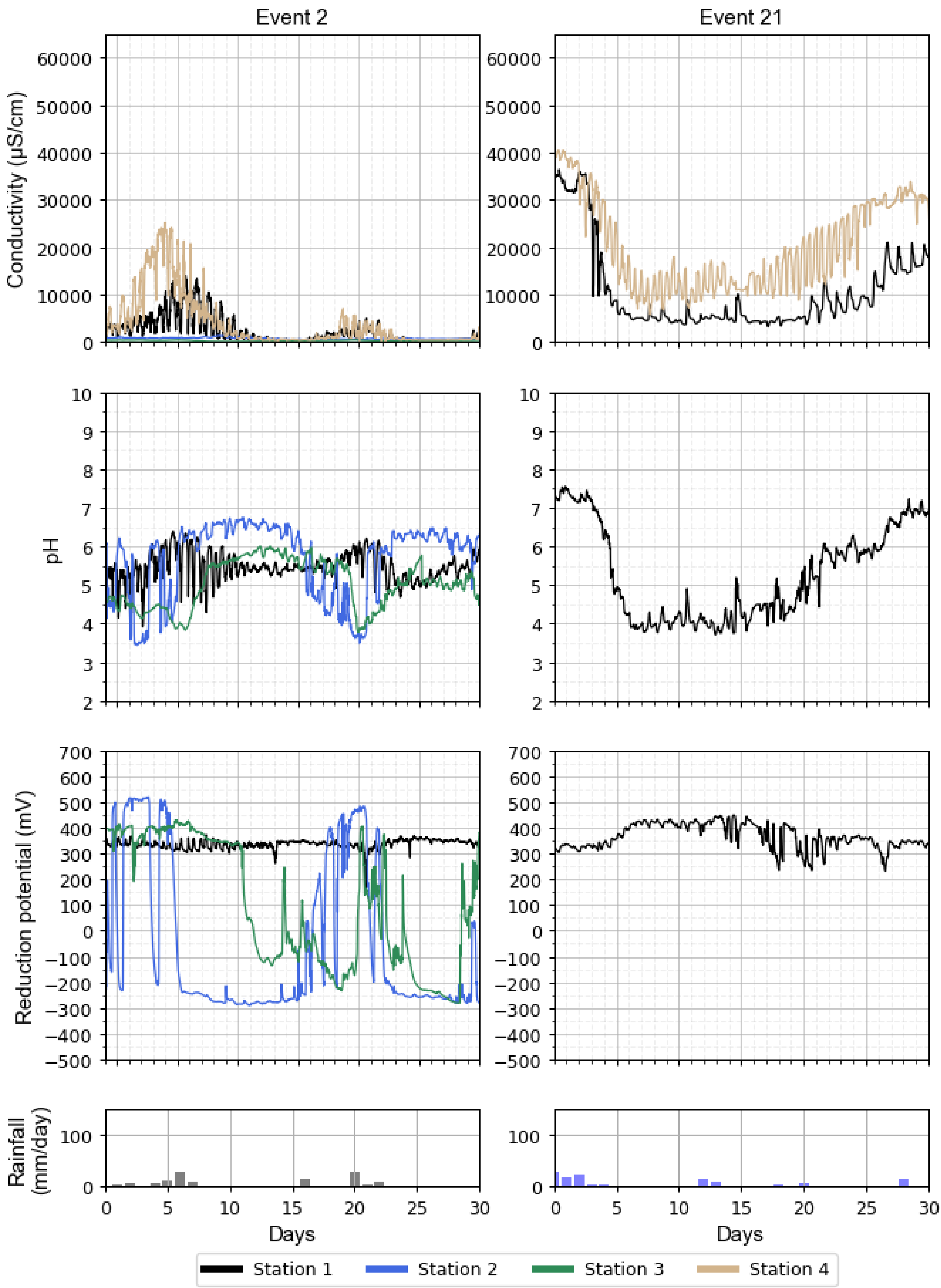

Figure C-3 Comparison of event 2 (31/12/2021) and event 21 (27/9/2024)

Rainfall data from BOM (2025b)

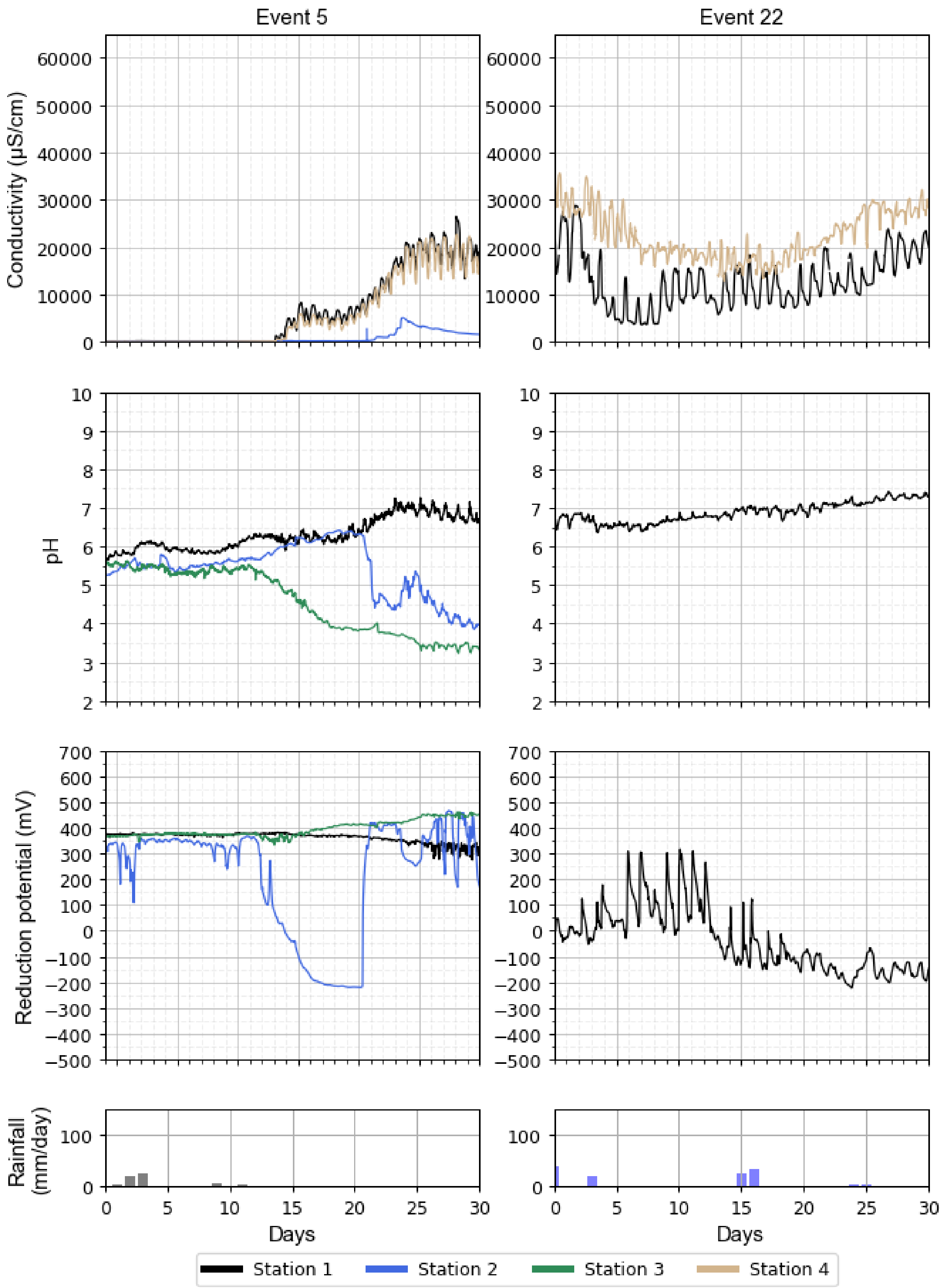

Figure C-4 Comparison of event 5 (20/5/2022) and event 22 (16/11/2024)

Rainfall data from BOM (2025b)

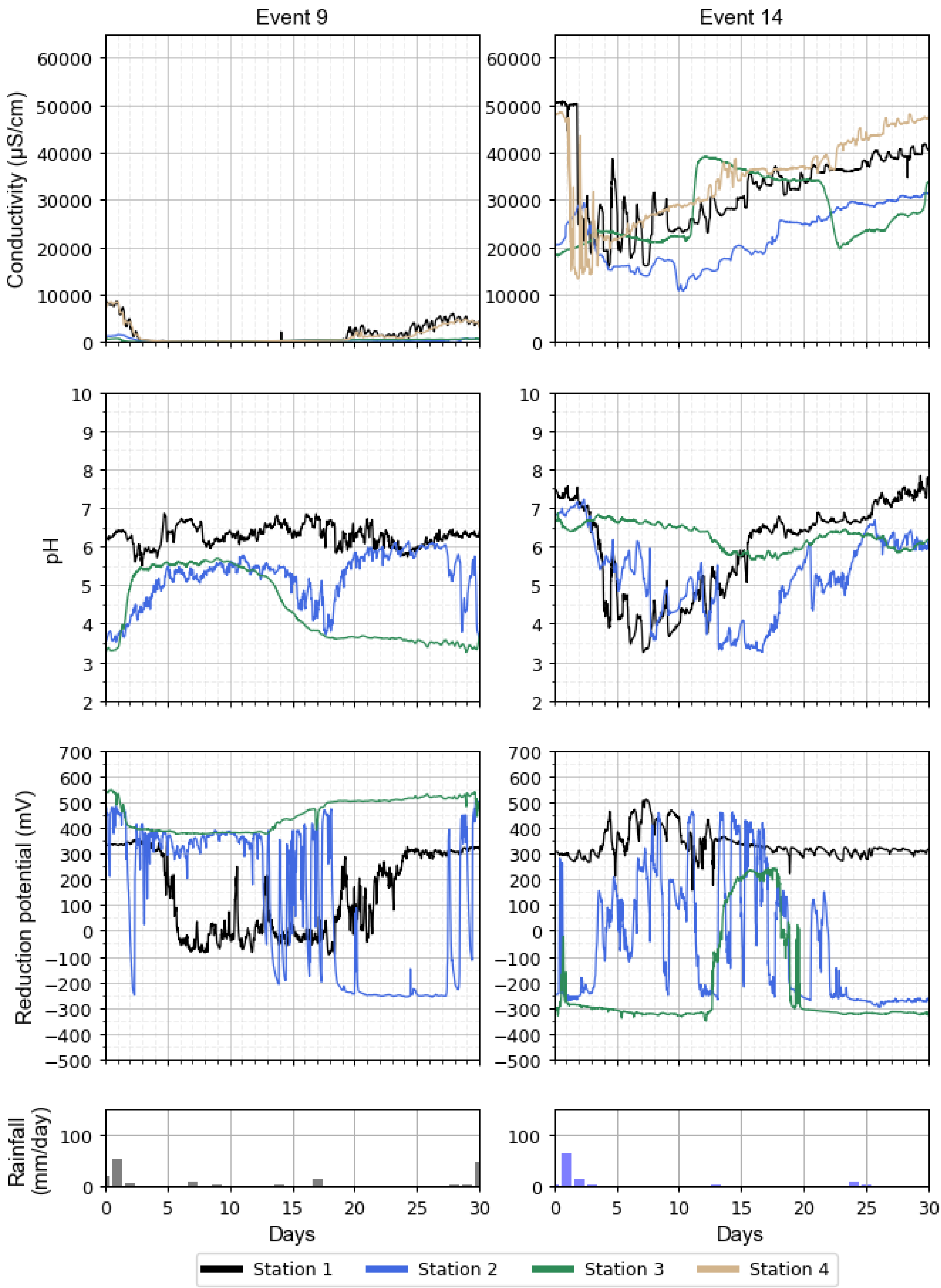

Figure C-5 Comparison of event 9 (22/9/2022) and event 14 (4/11/2023)

Rainfall data from BOM (2025b)

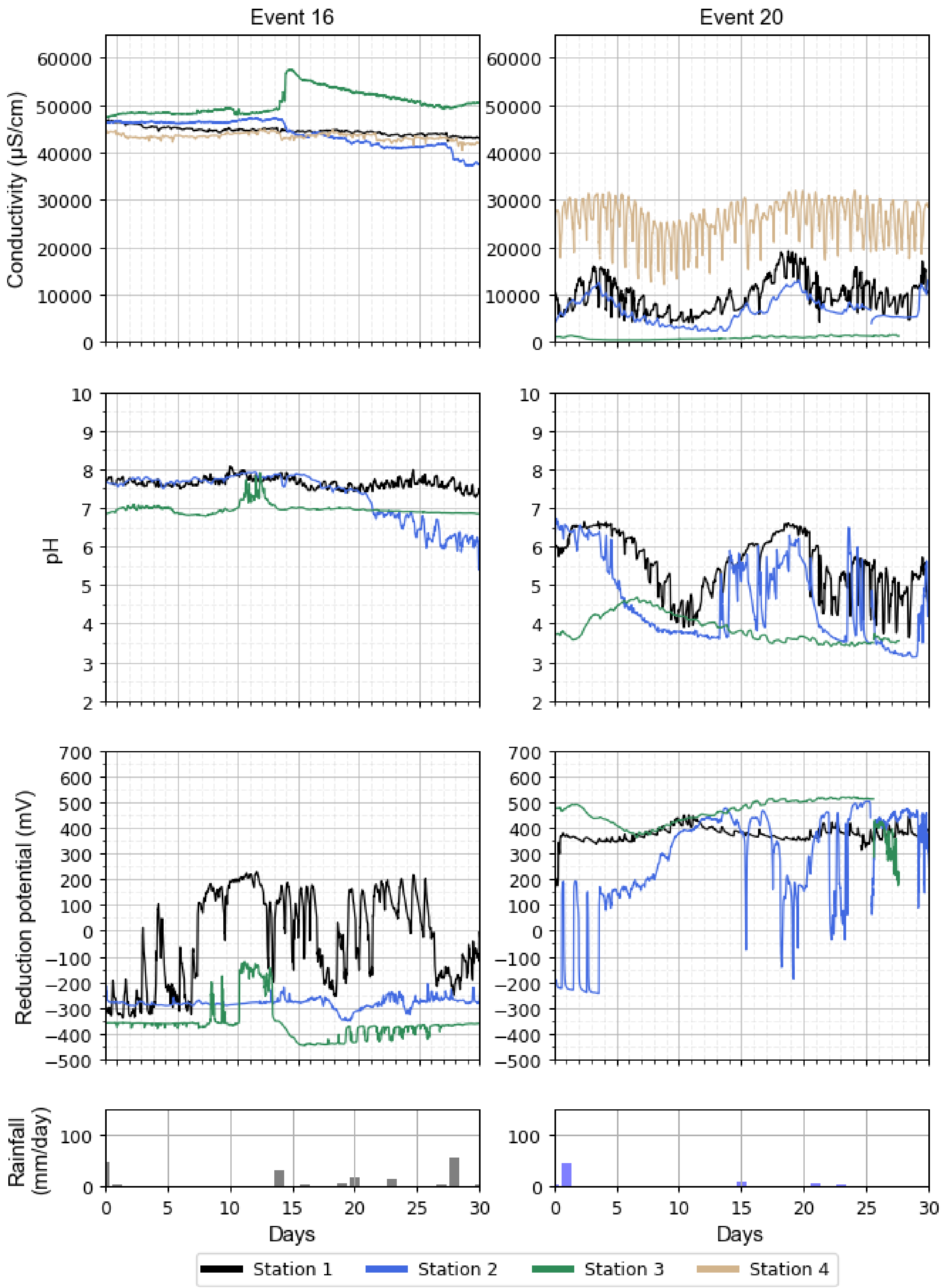

Figure C-6 Comparison of event 16 (28/1/2024) and event 20 (1/6/2024)

Rainfall data from BOM (2025b)

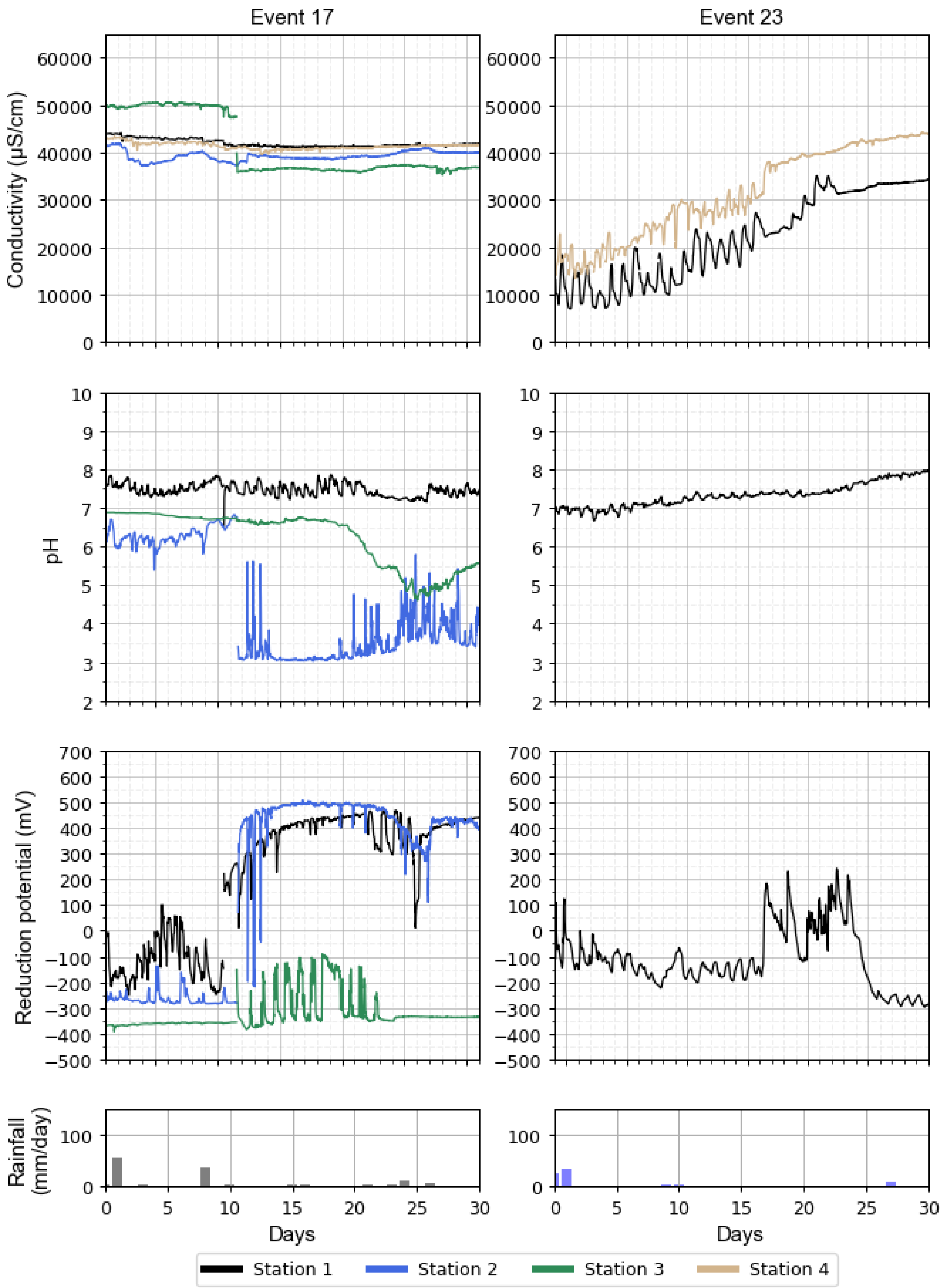

Figure C-7 Comparison of event 17 (24/02/2024) and event 23 (1/12/2024)

Rainfall data from BOM (2025b)

C2 List of significant rainfall events (2002 to 2004)

Table C-1 Significant rainfall events from 2002 to 2004*

#	Start date	End date	Total rainfall (mm)	Exceedance probability	Days of rain	Days since last event
25	19/11/2001	21/11/2001	51	6EY	3	192
26	31/01/2002	8/02/2002	124	2EY	9	70
27	27/03/2002	31/03/2002	179	50% AEP	5	46
28	25/12/2002	30/12/2002	72	6EY	6	268
29	17/02/2003	18/03/2003	45	6EY	2	48
30	200/2/2003	22/02/2003	62	6EY	3	1
31	24/02/2003	28/02/2003	94	3EY	5	1
32	10/03/2003	13/03/2003	112	2EY	4	9
33	21/03/2003	23/03/2003	43	12EY	3	7
34	14/05/2003	16/05/2003	90	2EY	3	51
35	27/05/2003	29/05/2003	60	6EY	3	10
36	25/10/2003	27/510/2003	57	6EY	3	148
37	22/11/2003	24/11/2003	43	12EY	3	25
38	5/12/2003	8/12/2003	56	6EY	4	10
39	13/12/2003	16/12/2003	47	12EY	4	4
40	11/01/2004	19/01/2004	70	6EY	9	25
41	23/01/2004	29/01/2004	57	12EY	7	3
42	24/02/2004	26/02/2004	82	3EY	3	25
43	4/03/2004	7/03/2004	47	12EY	4	6
44	14/03/2004	19/03/2004	74	4EY	6	6
45	22/03/2004	25/03/2004	99	2EY	4	2
46	17/10/2004	25/10/2004	216	50% AEP	9	205

*Exceedance probability presented is the maximum which occurred during the rainfall event. Event numbers continue from Table 3-2.
EY = Events per Year, AEP = Annual Exceedance Probability.
Rainfall data from BOM (2025b).

C3 Comparison of Greenspan and WRL pH events

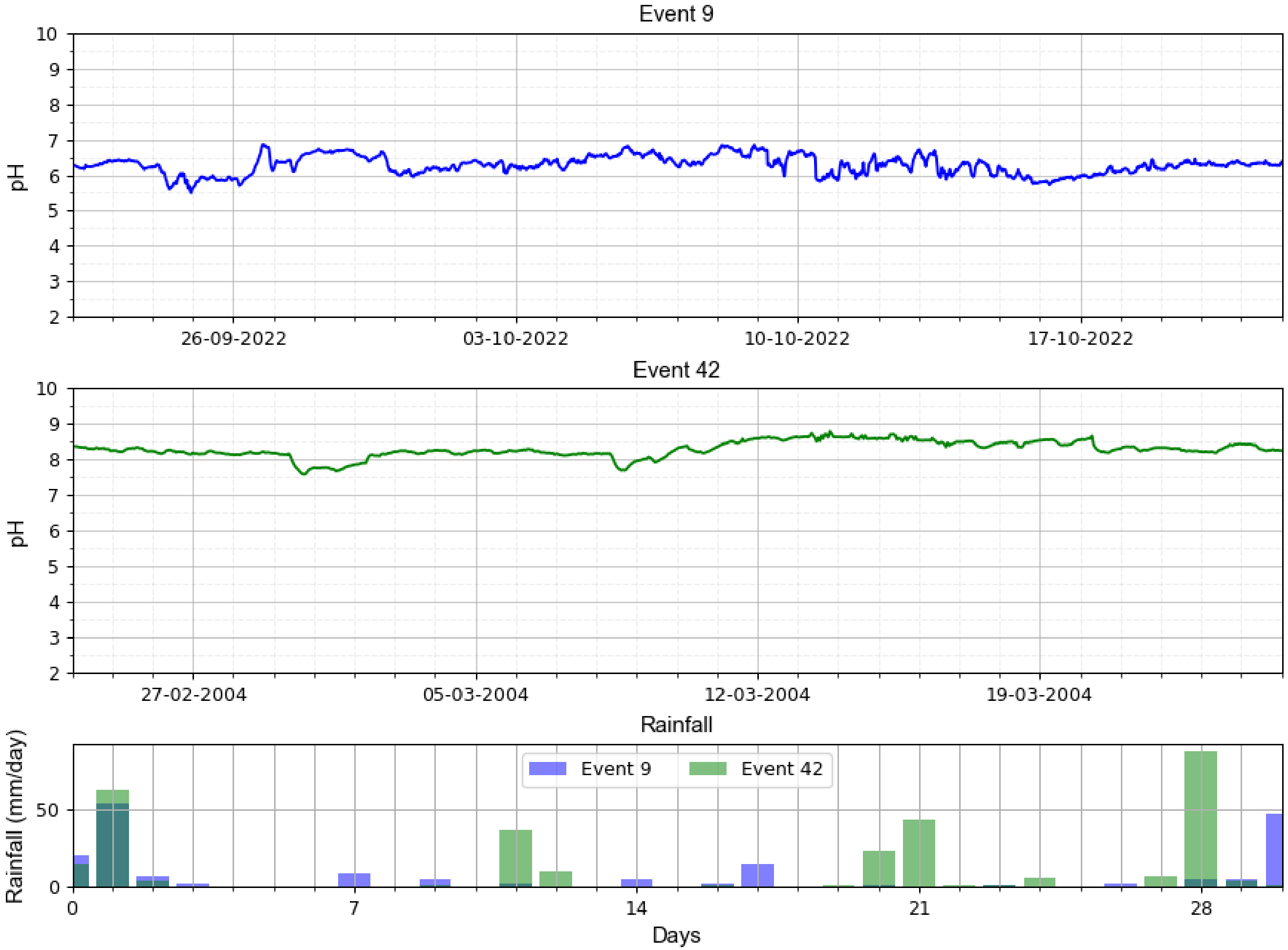

Figure C-8 Comparison of event 9 (22/09/2022) and event 42 (24/02/2004). Rainfall data from BOM (2025b)

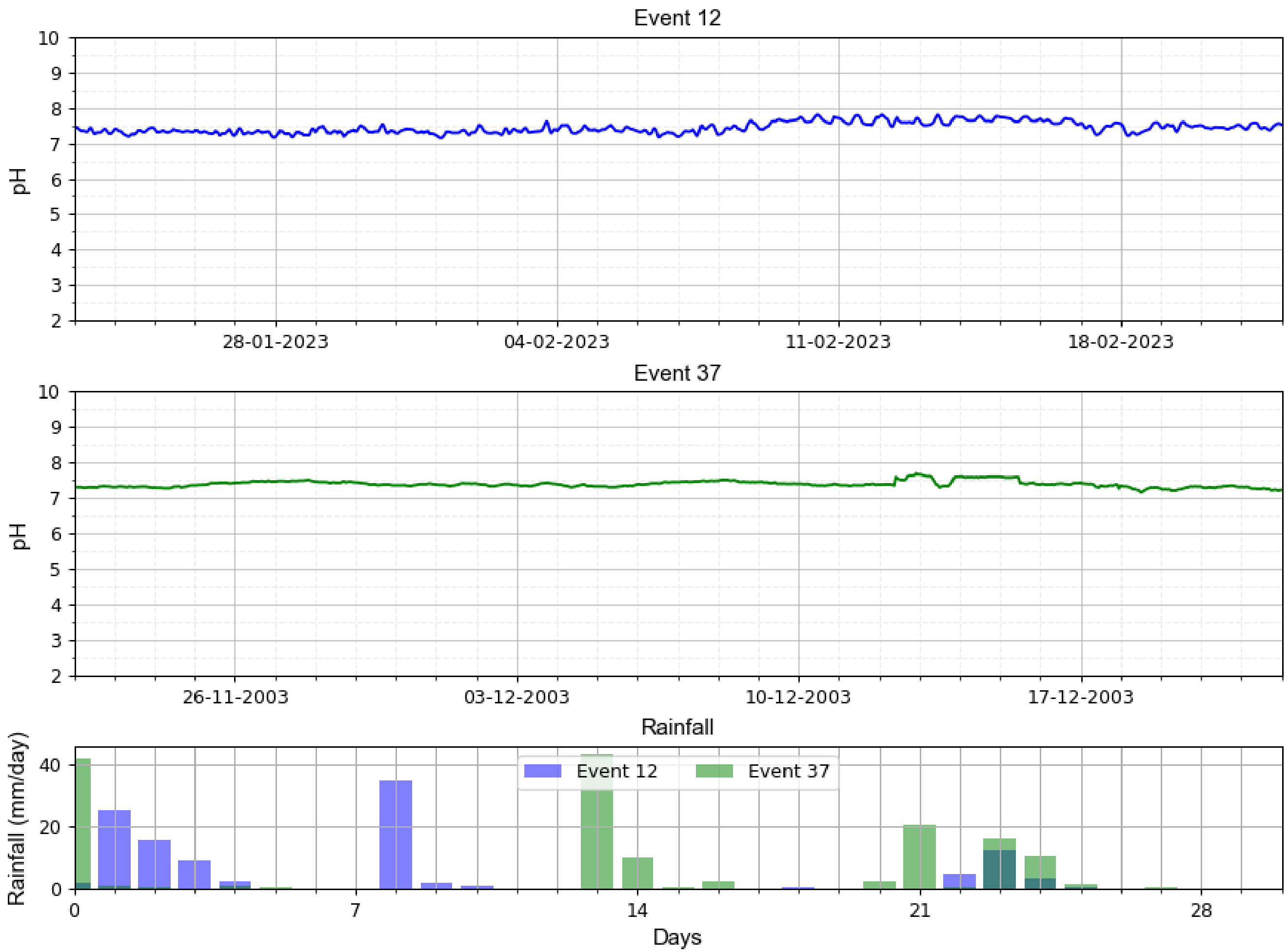

Figure C-9 Comparison of event 12 (23/01/2023) and event 37 (22/11/2003). Rainfall data from BOM (2025b)

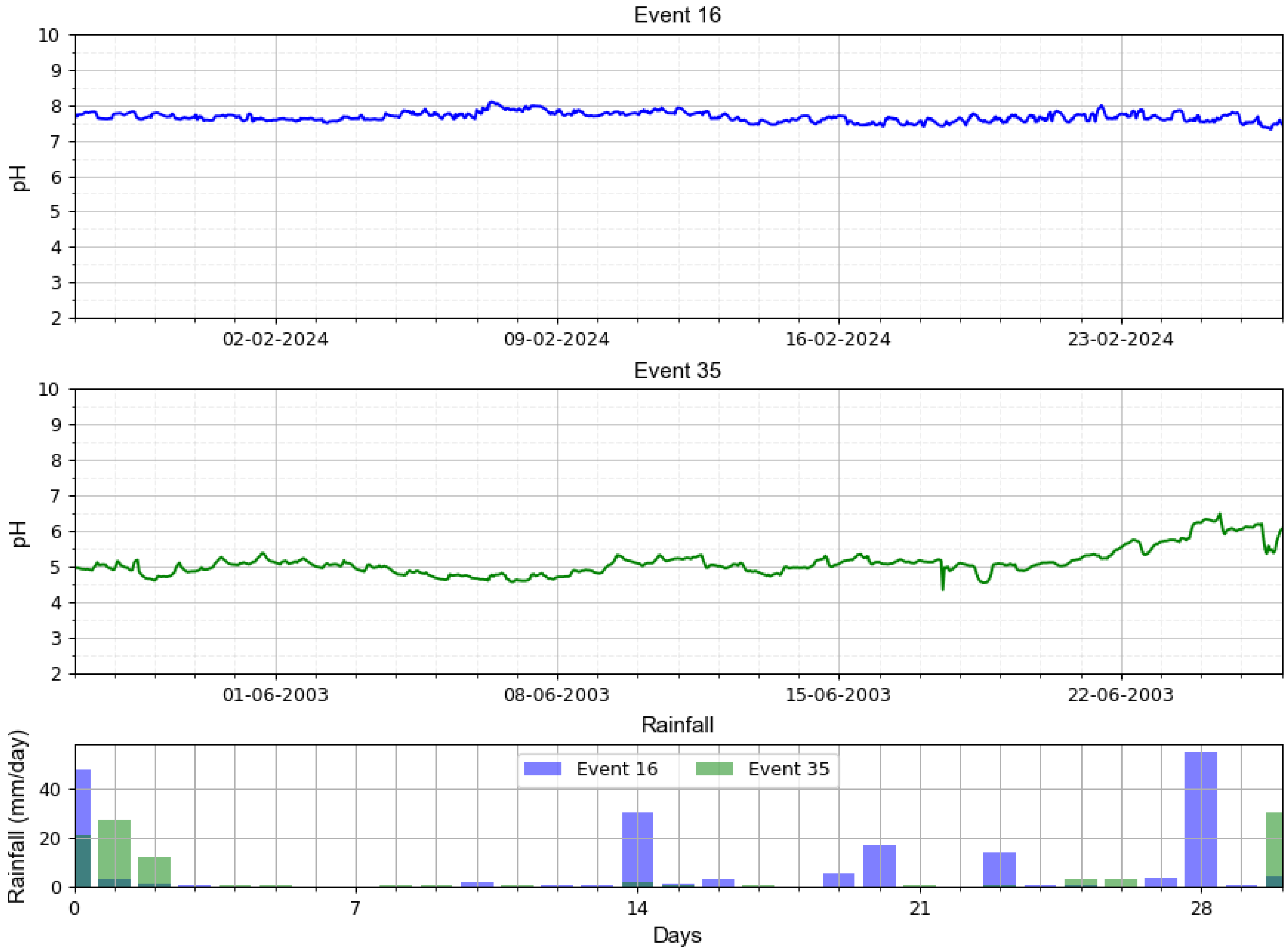

Figure C-10 Comparison of event 16 (28/01/2024) and event 35 (27/05/2003). Rainfall data from BOM (2025b)

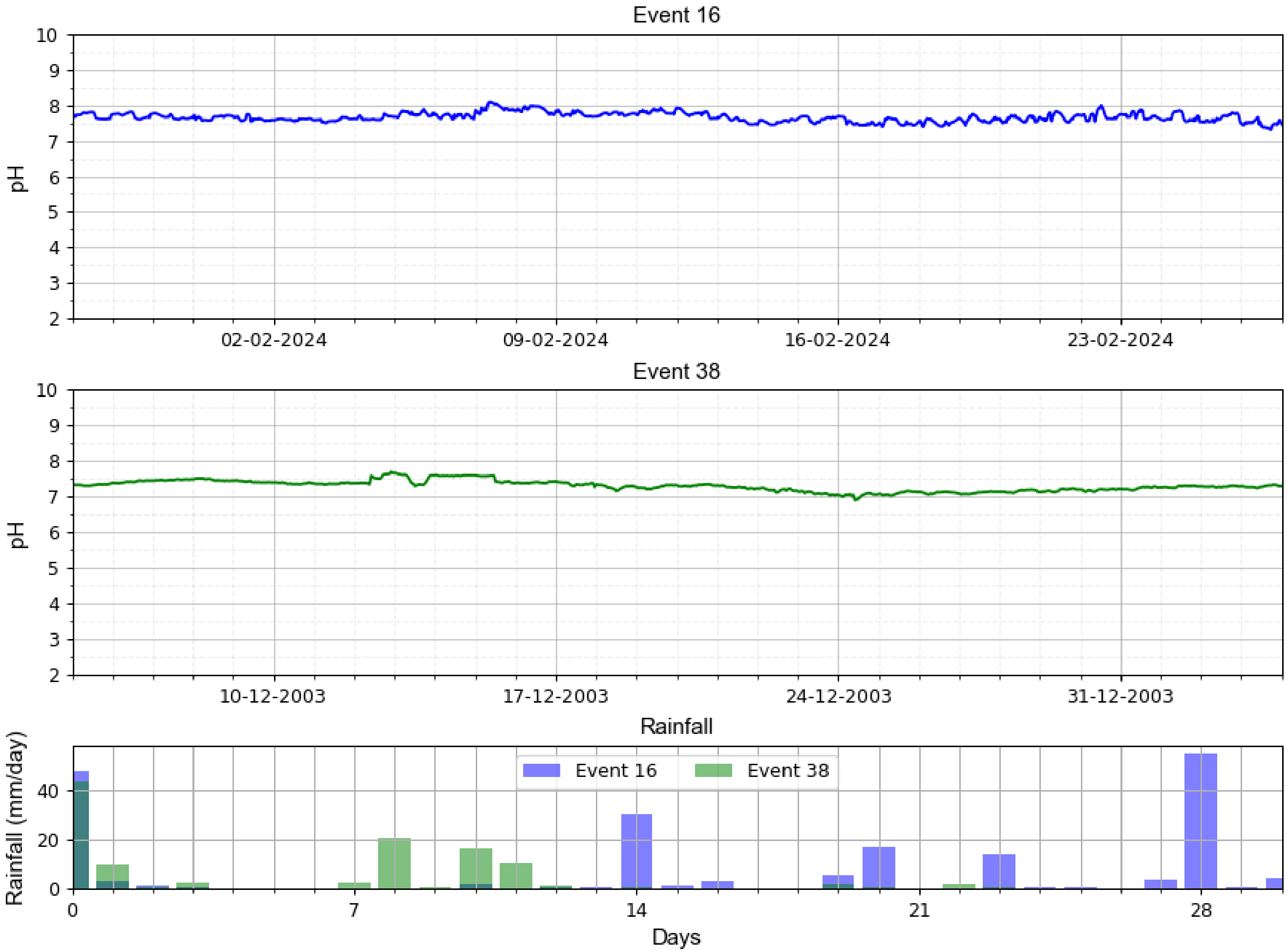

Figure C-11 Comparison of event 16 (28/01/2024) and event 38 (5/12/2003). Rainfall data from BOM (2025b)

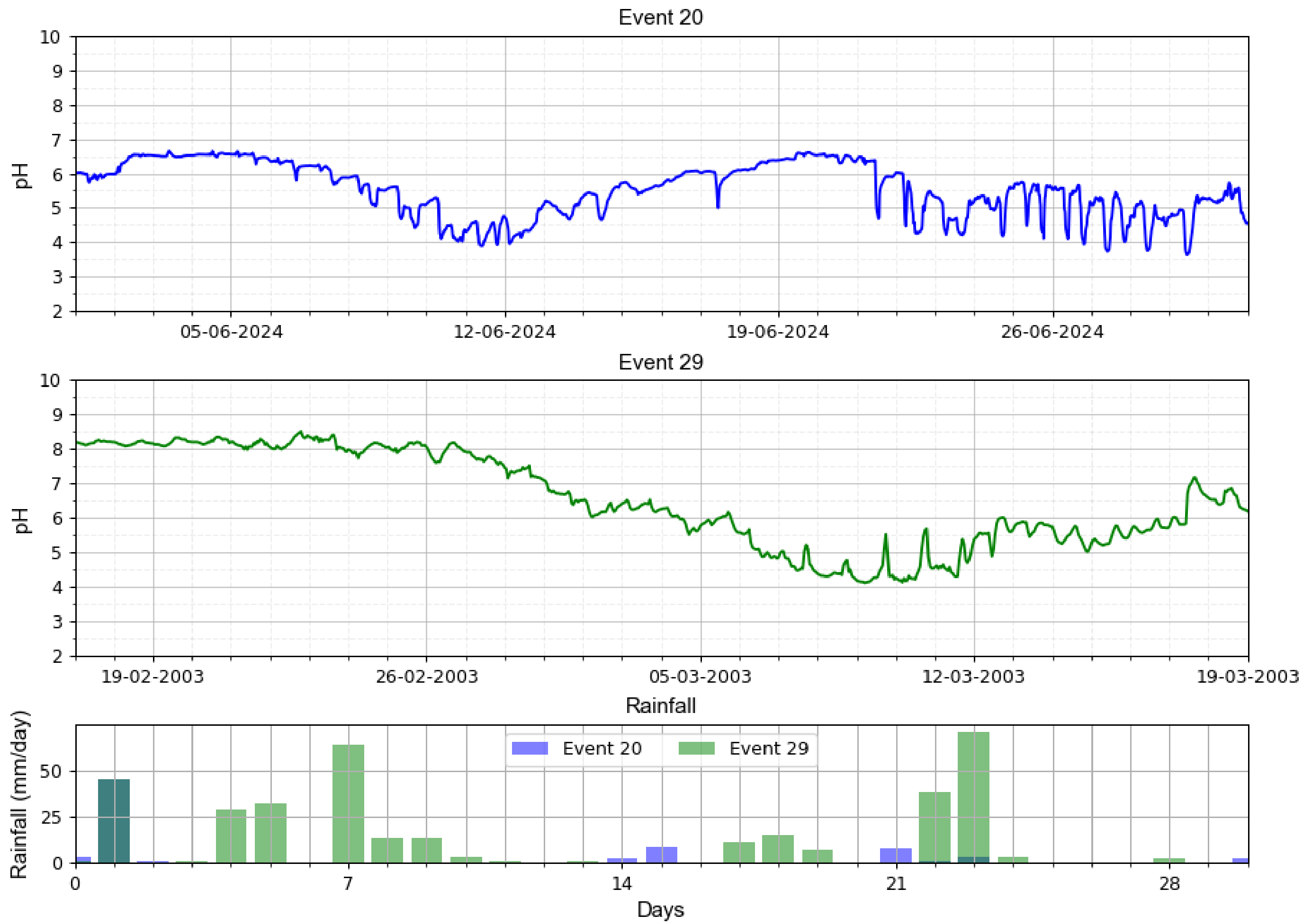

Figure C-12 Comparison of event 20 (1/06/2024) and event 29 (17/02/2003). Rainfall data from BOM (2025b)