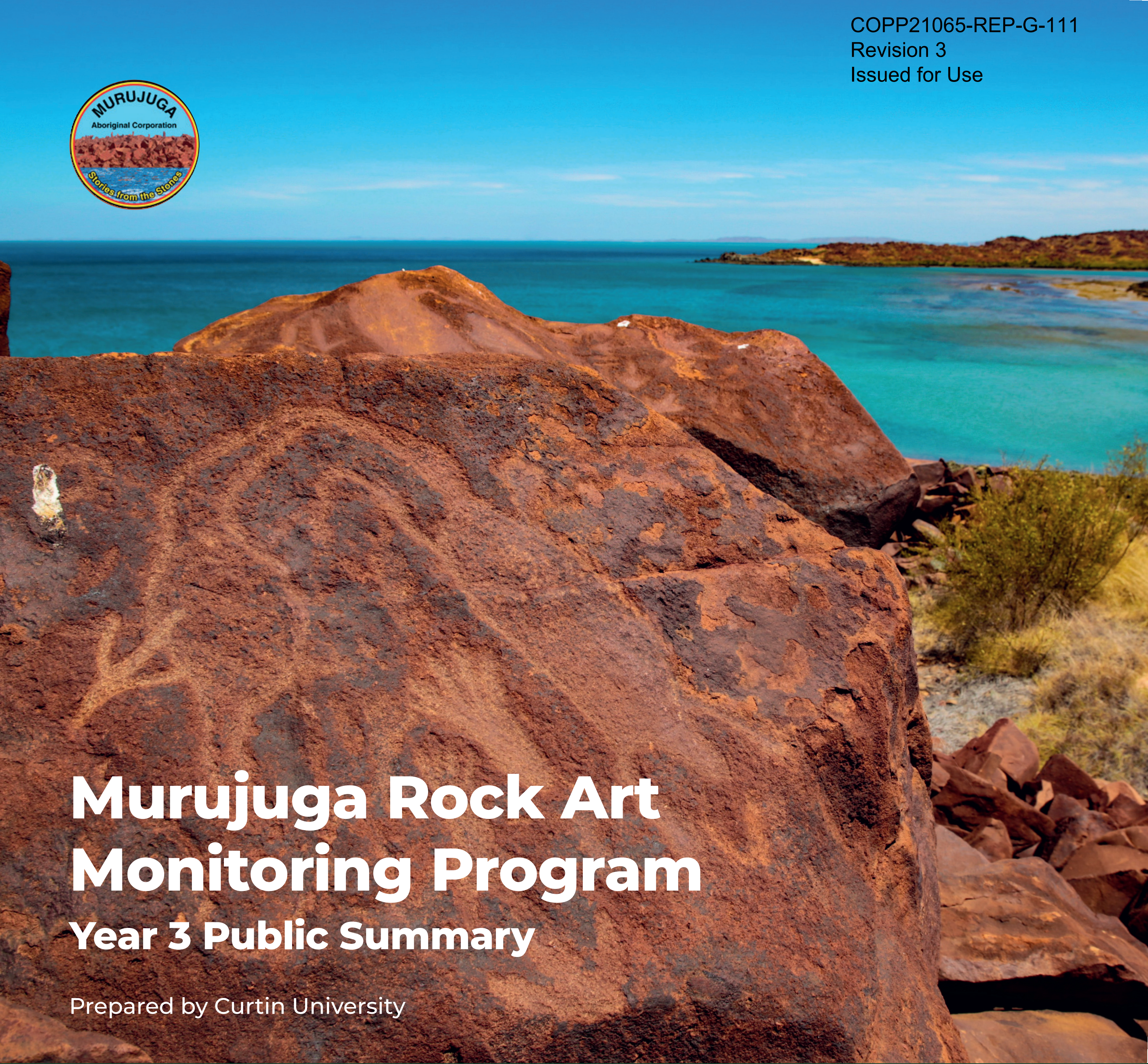
COPP21065-REP-G-111
Revision 3
Issued for Use



Murujuga Rock Art Monitoring Program

Year 3 Public Summary

Prepared by Curtin University

The Murujuga Rock Art Monitoring Program (MRAMP) is a partnership led by the Murujuga Aboriginal Corporation (MAC) and the Department of Water and Environmental Regulation (DWER). Scientific work is undertaken by Curtin University researchers and collaborators. The program monitors air emissions, rainfall chemistry, and other environmental factors that may affect Murujuga's rock art, and supports ongoing management and protection of the UNESCO World Heritage listed Murujuga Cultural Landscape (inscribed 2025).

MRAMP was designed as a staged program in which conclusions and protective criteria would be refined as additional field and laboratory evidence became available.

The progression from Year 2 to Year 3 reflects the program's planned shift from baseline monitoring to more targeted testing, strengthening the evidence base on how pollutants interact with rock surfaces.

Program progress

Three years of the planned four-year MRAMP research program have been completed. In Year 3, the team carried out three field trips totalling 12 weeks on Country, in addition to 19 weeks undertaking air sampling and maintenance (April 2024 to March 2025). 10 of the 11 planned monitoring campaigns are complete.

Across three years, MRAMP has recorded more than 186,000 measurements of rock art condition, supported by over 5,500 surface electrochemical tests and laboratory analysis of 87 rock samples. Year 3 also included a six-month LiDAR air-quality scanning campaign to better understand pollutant movement under varying atmospheric conditions. Figure 1 shows the study locations across Murujuga and extending to Karratha.

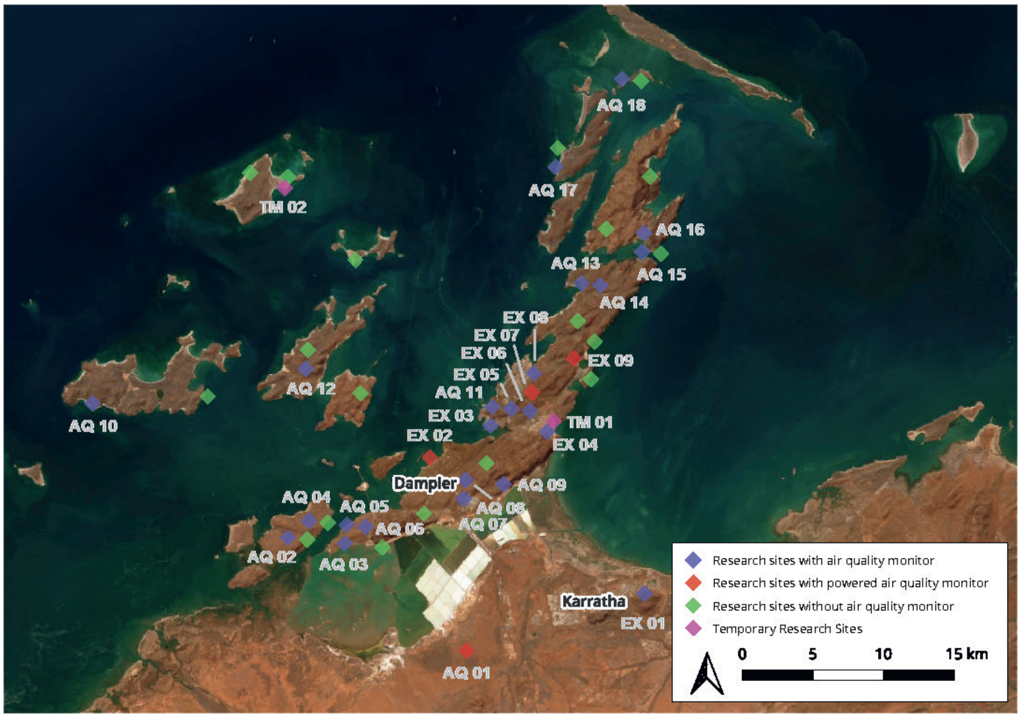


Figure 1. Study locations Source: MRAMP 2026 Report (Fig 1.1-1).

Year 3 highlights and key findings

- **Air quality is generally good.** Air quality measurements are mostly below MRAMP Environmental Quality Criteria (EQC) thresholds designed to protect rock art. Concentrations of the main reactive gases of concern (sulfur dioxide - SO_2, nitrogen dioxide - NO_2, ammonia - NH_3) are mostly well below the levels thought to cause damage to the rock art. Spikes of short duration were recorded but these were not sustained. Higher NH_3 concentrations were recorded near industrial and port areas, as expected given proximity. These were generally short-duration, localised peaks and were not sustained, apart from a peak near Dampier that was not replicated in passive samplers, so thought to be instrument error. Reactive gas levels nevertheless remained below MRAMP guideline thresholds and were not associated with measurable accelerated weathering. However, these observations highlight the value of laboratory experiments that investigate gases that increase, as well as decrease, pH (see below) and can account for both peak and average levels.
- **No acid rain observed during MRAMP monitoring.** Across three years of monitoring, rainfall and deposition pH values have consistently remained within the expected natural range from the average for unpolluted rain (pH 5.6) to slightly alkaline. No acid rain has been observed during the MRAMP monitoring period. Earlier studies (2005 to 2009) recorded lower pH values, indicating more acidic conditions in the past (Figure 2).

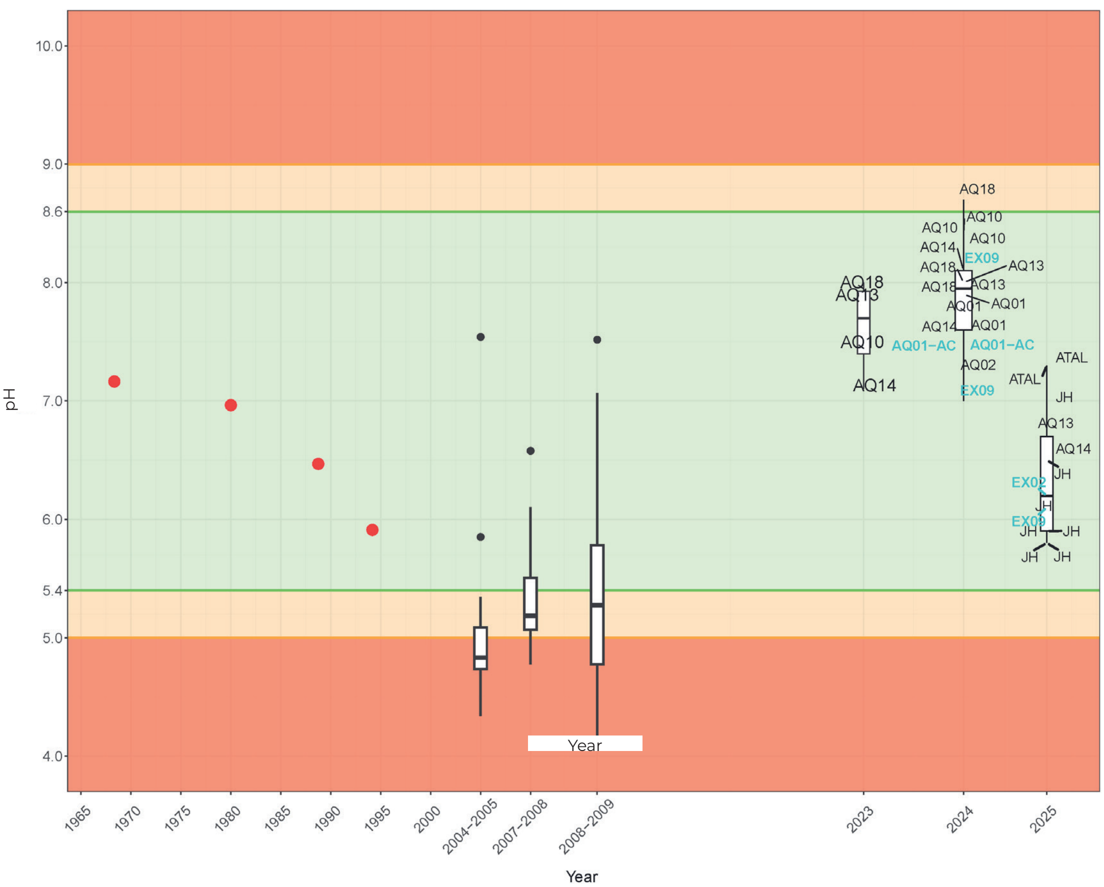


Figure 2. pH EQC applied to rainfall data. Source: MRAMP Interim EQC 2026 (Fig 2). Figure 7 (see page 7) provides a guide on interpreting box plots. The red dots represent single measurements.

- **Rock porosity pattern confirmed.** An area of elevated subsurface porosity in granophyre has been reconfirmed using additional data. The mapped extent differs from Year 2 due to a correction in the statistical significance level applied, rather than a change in underlying data or observed conditions. The most likely explanation for the elevated porosity is historic SO_2 emissions, because it is a more reactive gas than NO_2 and SO_2 emissions within the area of elevated porosity have decreased significantly over recent decades. There is no evidence that the area of increased porosity is expanding or that current air pollution is driving ongoing accelerated weathering.
- **Microbial research progressing.** Analysis of 484 samples is nearing completion, and the results will provide new insights into how microbes and pollutants interact on rock surfaces. Laboratory studies are examining how microbes interact with air pollutants.
- **Laboratory studies show no evidence of accelerated weathering from current pollution.** Laboratory studies have not detected accelerated weathering of rock surfaces in response to current pollutant levels.

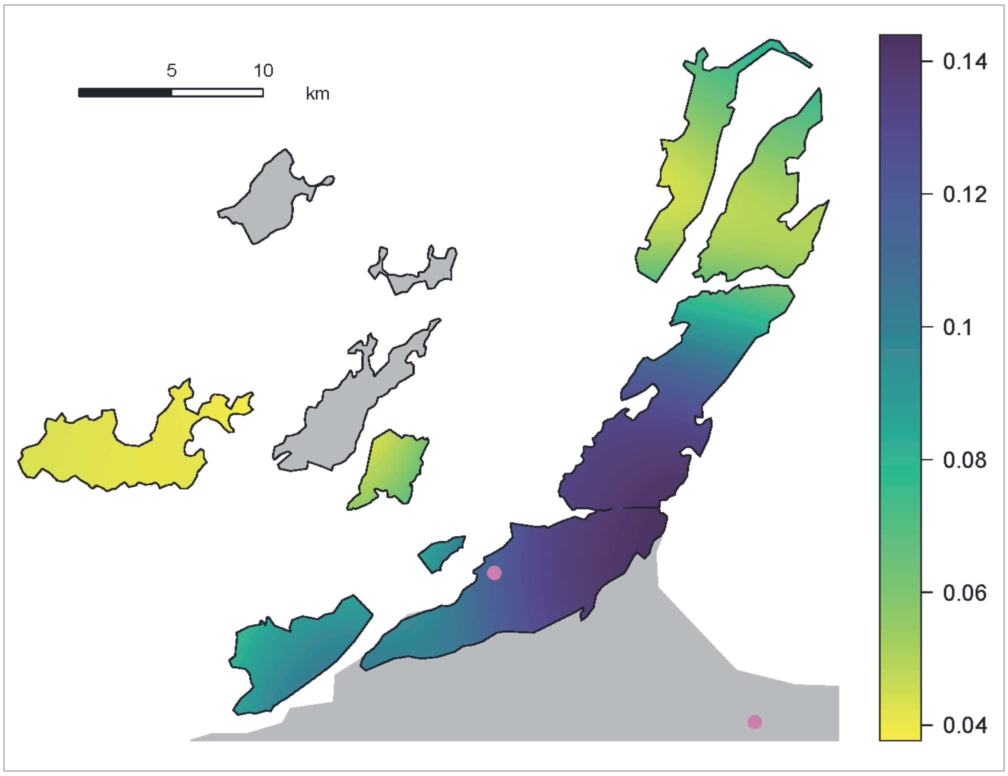


Figure 3. Granophyre surface porosity spatial map. Source: MRAMP 2026 Report (Fig 7.6-5).

Air quality results

Air monitoring across Murujuga used 18 solar/passive and four mains-powered stations. Results in Year 3 were broadly consistent with Year 2. The highest readings for NH_3 were near major industrial and port facilities. Concentrations remained below MRAMP guideline thresholds (as discussed below), designed to prevent accelerated weathering. Short peaks of NO_2, SO_2 and NH_3 were recorded near industrial areas and/or shipping routes, influenced by wind and vessel activity. Moderate levels of gases such as ozone and formaldehyde were detected; their relevance to microbial communities will continue to be investigated. Soot (black carbon) and dust samples were collected and are being analysed to understand their potential contribution to weathering.

A six-month LiDAR scanning campaign was undertaken in Year 3 to better understand pollutant movement across the landscape. Analysis of many terabytes of data from this study is ongoing.

Rainfall and deposition pH

Over the past three years, average rainfall and total deposition measurements have been neutral (pH 7) to slightly alkaline (pH > 7). During Tropical Cyclone Sean in early 2025, rainfall pH dipped to pH 5.6, which is not expected to be damaging. Occasional outliers were observed and these probably record natural contamination such as bird droppings or rust. Historic records of rainfall pH show pH values were sometimes below 5.5 from 2006 to 2009. These lower values support the view articulated in the Year 2 report that the impact of emissions was higher in the past.

Tests on rock surfaces showed near-neutral conditions on fresh rock and slightly more acidic conditions on patinated surfaces. These results can be explained by natural processes, and while a contribution from air emissions cannot be completely ruled out, there is no detectable link between rock surface pH and pollutant concentrations.

Porosity and patina

Granophyre rocks show a consistent spatial pattern of elevated subsurface porosity that includes Dampier and the Burrup industrial precincts. Year 3 data strengthen confidence in this pattern.

Historic emissions, particularly SO_2, were significantly higher than they are today and remain the most plausible explanation for this pattern. Current data show no evidence that porosity formation is accelerated by present-day air pollution.

However, while no ongoing damage has been detected, this does not rule out the possibility that current emissions may be increasing porosity at levels too low for current monitoring methods to detect.

Ongoing studies will continue to refine this understanding.

Rock art spectrometry and photogrammetry

Spectral imaging methods are now producing consistent, high-quality measurements suitable for detecting long-term change in rock art condition. A simplified photogrammetry approach has been validated and can detect sub-millimetre changes on the rock (art) surface. Temporal trend analyses will be completed after the final Year 4 campaign.

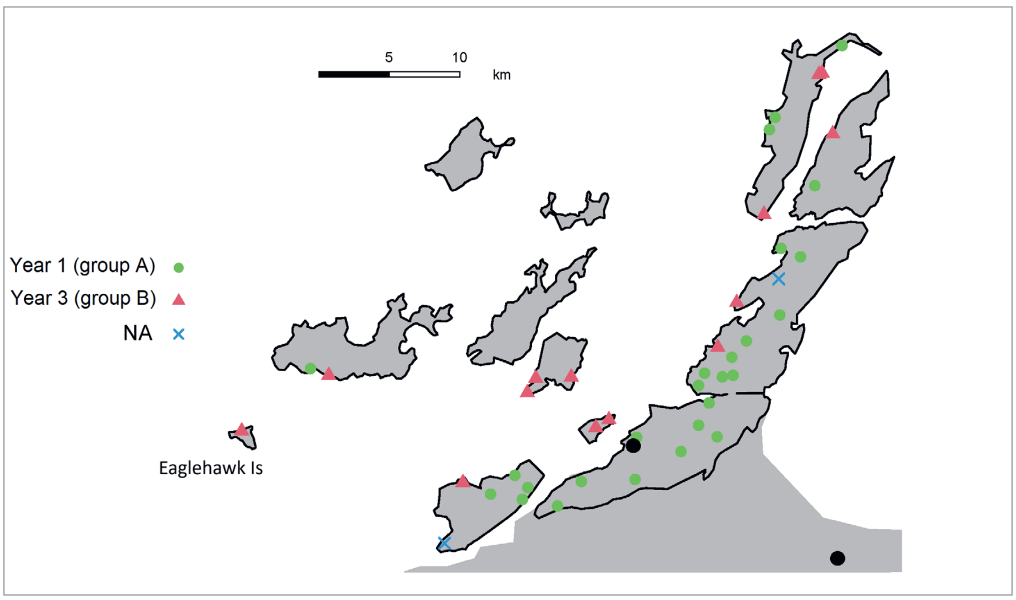


Figure 4. Granophyre surface porosity sample locations. Source: MRAMP 2026 Report (Fig 7.6-1).

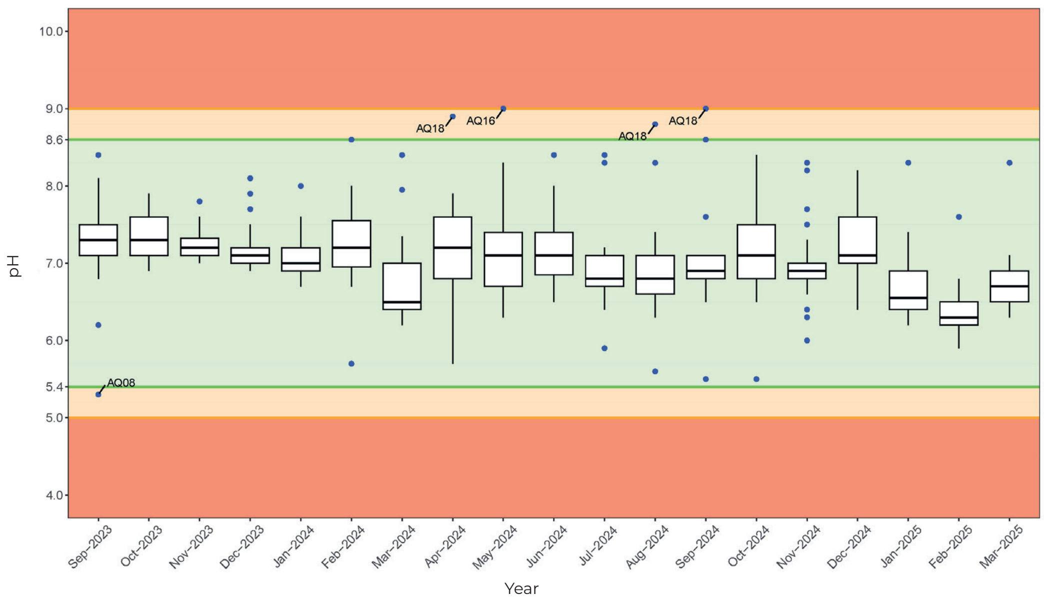


Figure 5. pH EQC applied to dust deposition sampler data.
Source: MRAMP Interim EQC 2026 (Fig A-1-2).

Updated Environmental Quality Criteria (EQC)

The EQC are MRAMP's practical thresholds for air quality and deposition that help flag when conditions may accelerate rock weathering. They form part of DWER's Environmental Quality Management Framework, which will provide mechanisms for regulatory response if thresholds are exceeded. Changes to the interim EQC have been introduced, based on Year 3 work:

- Year 3 laboratory testing found no measurable degradation of Murujuga granophyre from NO_2 at the range of levels measured over the past three years or even at levels many, many times higher than current peaks. For this reason, the previous combined EQC relating to the sum of NO_2 and SO_2 has been replaced with independent guidelines and standard values for each gas.
- The annual guideline value for NO_2 has been increased based on controlled laboratory testing showing no measurable rock surface response to NO_2 at the thresholds set in Year 2. This change is based on comprehensive observations of pollutant-rock interactions in the laboratory. This guideline replaces the previous EQCs derived from laboratory and field evidence (the yellow and teal lines, respectively, from the Year 2 report) with a single integrated EQC specific to NO_2, based on all available evidence.
- A new pH-based EQC has been introduced (Figures 2 and 5), recognising that very acidic (low pH) or very alkaline (high pH) conditions can speed up weathering. Monitoring ensures that rainfall and dry deposition pH remain within this range.

A weatherability index (Figure 6) that integrates natural and human influences is being explored for inclusion in the final set of EQC.

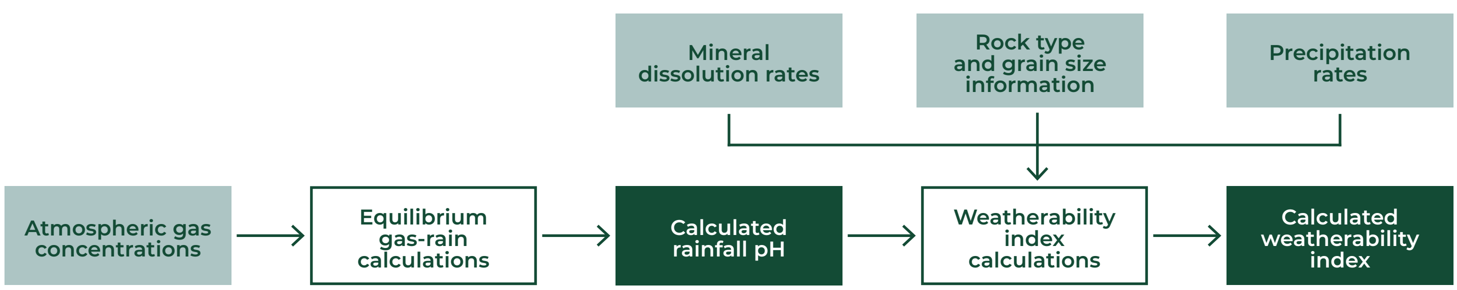


Figure 6. Weathering conceptual model. Source: MRAMP Interim EQC 2026 (Fig 5).

Interim EQC for gases

Air pollutant	Standard (24-hr avg) ppb	Standard (24-hr avg) µg/m3	Guideline (annual avg) ppb	Guideline (annual avg) µg/m3
NO_2	219	419	22	42
SO_2	47	125	5	13
NH_3	-	-	7.4	5.2

Interim EQC for deposition pH

Parameter	EQC type	Threshold	Application
Wet and/or dry deposition pH	Guideline	5.4 and/or 8.6	All deposition samplers
Wet and/or dry deposition pH	Standard	< 5.0 and/or > 9.0	All deposition samplers

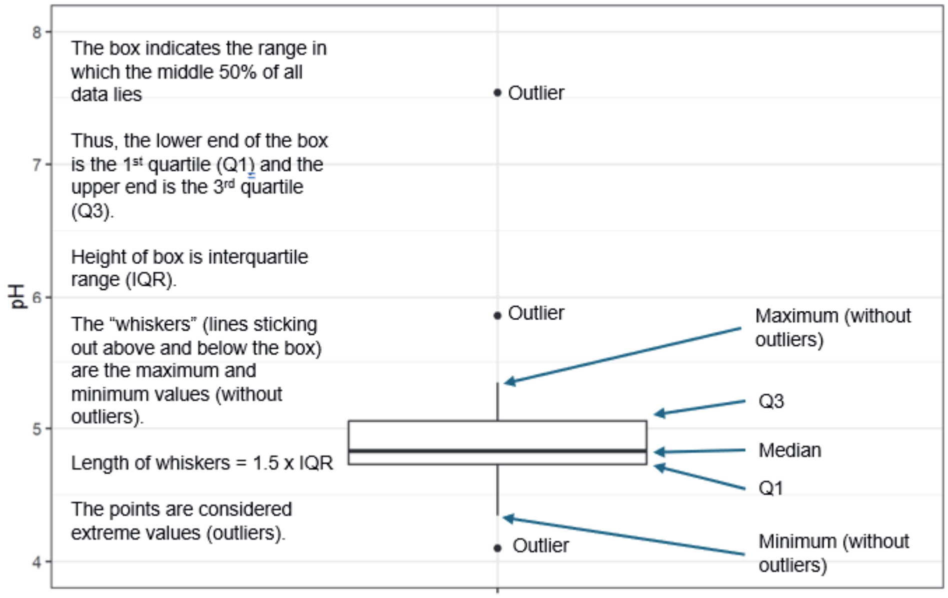


Figure 7. Explanation of box plot features in Figures 2 and 5.

How Year 3 Builds on Earlier Work

Area	What Year 3 Strengthened
Dataset size	Expanded monitoring dataset across three years, including additional laboratory exposure testing
Pollutant interpretation	Independent laboratory assessment of NO_2 and SO_2 rather than combined interpretation
Rainfall chemistry	Three-year trend dataset including cyclone capture and stability analysis
Porosity analysis	Refined spatial mapping and strengthened interpretation of historic emission legacy
Monitoring framework	Updated Environmental Quality Criteria based on controlled testing

Program Refinement Year 2 to Year 3

Year 2 established baseline monitoring patterns and interim criteria. Year 3 expanded both the field dataset and controlled exposure experiments to test those findings more directly.

Key points:

- Year 3 strengthens the conclusion that current measured pollutant concentrations are below levels demonstrated to accelerate rock weathering.
- Refinements to Environmental Quality Criteria reflect expanded laboratory evidence and improved scientific precision
- Independent laboratory testing of NO_2 and SO_2 replaced earlier combined interpretation, following controlled experiments clarifying their individual effects on granophyre.

The progression from Year 2 to Year 3 reflects the program's planned evolution from baseline monitoring to more focussed evidence-based testing of pollutant impacts.

Conclusion

Year 3 has strengthened the evidence base used to protect Murujuga's rock art. Air quality remains generally good; no acid rain was observed during MRAMP monitoring. A porosity pattern likely linked to historic emissions has been reconfirmed. There is no evidence of accelerated deterioration under current air pollution levels.

The updated EQC and improved methods provide a foundation for robust, long-term monitoring led by MAC and DWER. Monitoring provides an early-warning system, designed to detect potential risks before active damage occurs. Year 3 EQC incorporate real-time monitoring where possible, to ensure peaks in air pollutant concentrations, as well as average air quality measures, continue to remain within guideline thresholds.

While all natural rock surfaces weather over time, current monitoring and laboratory evidence show no measurable acceleration at Murujuga associated with present air pollution levels.

It is not possible to completely rule out impact on the rock art at current air quality levels. However, the results of laboratory studies and geochemical models have not revealed any such effects under current conditions on Murujuga. To increase confidence in the findings, a range of plausible biogeochemical scenarios that relate microbial activity to rock art impact are under investigation. The results of these studies will help MRAMP to develop environmental criteria that will protect the rock art from long term impacts.

These findings support Australia's ongoing World Heritage obligations for the Murujuga Cultural Landscape.

Next steps (Year 4)

The final year will integrate microbial chamber data, combine datasets into a weatherability index, complete temporal analyses of rock condition, and continue to validate the proposed EQC. These steps will provide the scientific basis for long-term monitoring and management.

Murujuga Aboriginal Corporation

Lot 501 Griffin Road
Burrup Peninsula WA 6713

08 9144 4112

admin@murujuga.org.au

murujuga.org.au

Publications related to the Murujuga Rock Art Monitoring Program are available from the Department of Water and Environmental Regulation and the Murujuga Aboriginal Corporation. View at www.wa.gov.au/murujuga

The Murujuga Rock Art Monitoring Program is a joint initiative of the Murujuga Aboriginal Corporation and the Department of Water and Environmental Regulation. It is being delivered by Curtin University, with the assistance of consultants from ArtCare, University of Wollongong, University of Melbourne, and L & K Engineering.

Curtin University