Murujuga Rock Art Monitoring Program: Interim Environmental Quality Criteria

Interim Environmental Quality Criteria 2025.

Prepared for the Murujuga Aboriginal Corporation and the Department of Water and Environmental Regulation.

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1 Overview

1.1 Introduction

The Murujuga Rock Art Monitoring Program (**MRAMP**, the Program) is the most extensive scientific study to date to examine the impact of industrial air emissions on the rock art engravings of Murujuga, an area covering the Burrup Peninsula and Dampier Archipelago in Western Australia. The Program is overseen by the Department of Water and Environmental Regulation (**DWER**) in partnership with the Murujuga Aboriginal Corporation (**MAC**) and is a key component of the State Government's Murujuga Rock Art Strategy (**MRAS**, DWER, 2019b).

The Program incorporates extensive field measurements and laboratory (chamber) accelerated weathering studies on the five lithologies/rock types (granophyre, gabbro, granite, dolerite, basalt) which comprise the majority of petroglyph substrates. It consists of a detailed study design phase, followed by three to four years of detailed scientific studies, transitioning into ongoing monitoring and assessment against the Environmental Quality Criteria (**EQC**) established through the studies.

The MRAMP considers all potential atmospheric impacts on the geology/geochemistry, microbiome and visual appearance of the rock surface and rock art. These include anthropogenic and natural effects and sources. Previous research has focused on air emissions with a potential to form acidic or basic compounds which may react with the rock surface, principally nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ammonia (NH_3). These emissions have been considered in some detail, however all natural and anthropogenic air contaminants are the focus of the program. For example, natural and anthropogenic particulate matter (**PM**, dust/soot) is also abundant in the region. Components in environmental dust are an important building block in the formation of the rock surface patina, which has more complex interactions, including with microbes which cement the minerals to the rock surface. These interactions remain an area of ongoing study, both for the overall research project and for EQC development.

Chamber studies to date have focused on combustion emissions from various sources, as well as gaseous NH_3. Field studies have examined any and all relationships which may exist between field observations, together with current or historic emission levels and their spatial patterns.

1.2 Purpose of this document

This document sets out the Interim EQC based on the data collection and analysis from the first two years of monitoring studies and laboratory investigations. It is intended to be read in conjunction with the *Murujuga Rock Art Strategy* (DWER, 2019b), *Murujuga Rock Art Monitoring Program: Conceptual Model* (DWER, 2021), *Murujuga Rock Art Monitoring Program: Data Collection and Analysis Plan* (Curtin University, 2022), *Murujuga Rock Art Monitoring Program: Monitoring Studies Report 2023* (Curtin University, 2023) and *Murujuga Rock Art Monitoring Program: Monitoring Studies Report 2024* (Year 2 Report) (Curtin University, 2024) as well as relevant methodology statements.

A primary outcome of MRAMP will be a series of EQC which are designed to ensure environmental values and environmental quality objectives of the Murujuga Rock Art can be maintained. The EQC will complete the Environmental Quality Management Framework (**EQMF**), to ensure the long-term protection of the Murujuga rock art from undesirable anthropogenic effects (DWER, 2019a; DWER, 2019b).

1.3 EQC concept

The EQMF model for MRAMP is shown in Figure 1 (DWER, 2019b). The concept of the EQMF is intended to ensure that environmental values can be maintained and environmental quality objectives can be achieved (DWER, 2019a). This is achieved in part through the appropriate application of EQC. EQC are the scientifically based limits of ‘acceptable’ change. The criteria are the benchmarks against which environmental monitoring data are compared in order to determine the extent to which environmental quality objectives have been met, and if not, whether a management response is required. Criteria should be clear, readily measurable and auditable, and standardised approaches given for measuring indicators and for comparison of monitoring data against the criteria.

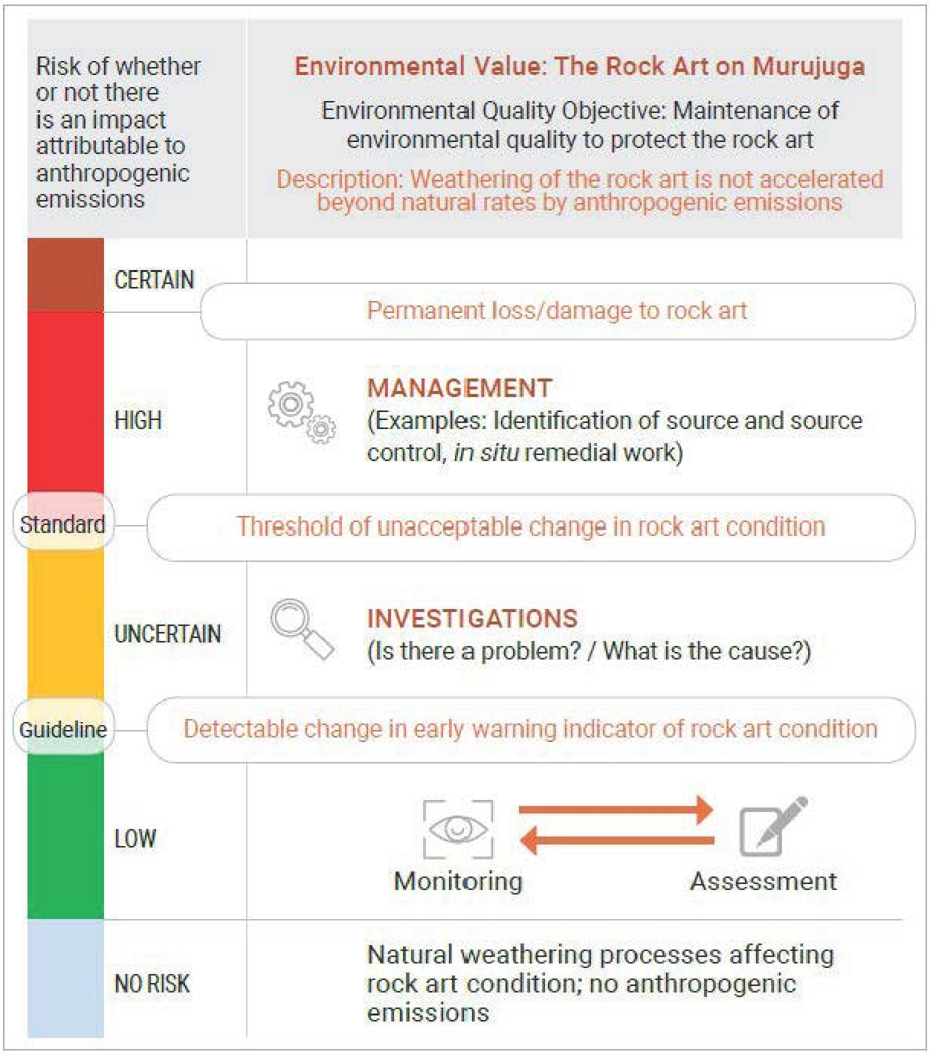

Figure 1: The Environmental Quality Management Framework for Murujuga, including Guideline and Standard EQC concepts (DWER 2019b).

Standard EQC levels, denoted by the threshold to the high (red) region on the risk scale in Figure 1, represent limits above which sufficient evidence exists that impacts are likely to occur, within appropriate levels of confidence. **Guideline** EQC levels are set lower using appropriate uncertainty factors to determine the minimum level where any possible effects could theoretically occur. These levels are denoted as the threshold from low (green) to the uncertain (amber) regions of risk in Figure 1.

EQC are generally developed based on the determination of nil or minimal effect levels or concentrations from environmental or experimental/clinical dose-response curves. A wide range of terminology is used to refer to the no-effect or minimal effect level in dose-response studies; in this document, the terms No Observed Effect Concentration (**NOEC**) or Lowest Observed Effect Concentration (**LOEC**) will be utilised for MRAMP, as they are the most widely used terminology in the field of ecotoxicology. NOEL or LOEL (refer glossary, where L denotes Level instead of concentration) may be included later if EQC are developed for parameters which are not a pollutant concentration.

MRAMP includes a multi-year research program to determine appropriate EQC parameters. Two years of the planned studies (see Curtin University (2022)) are now complete. The work to date has established a mechanism by which accelerated weathering may occur, and has developed a sufficient dataset of laboratory testing to permit Interim EQC values to be established for NO_2, SO_2, and NH_3, as these are the key gaseous pollutants. Field observations of accelerated weathering in granophyre samples have also been utilised (in conjunction with historic emissions estimates) to develop a comparable Guideline EQC for NO_2 as well as Standard EQC for NO_2.

These Interim EQC values are published in conjunction with the *Monitoring Studies Report 2024* (Curtin University, 2024) which explains the science underpinning the Interim EQC in detail. These Interim EQC are shown in Table 1.

Table 1: Interim EQC.

Air pollutant	Annual average concentration ($\mu g/m^3$)	EQC type	Application
Nitrogen dioxide (NO_2)	5.5_c	Interim Guideline	combined (NO_2 & SO_2)
Nitrogen dioxide (NO_2)	45.6_f	Interim Standard	single species
Sulfur dioxide (SO_2)	4.3_c	Interim Guideline	combined (NO_2 & SO_2)
Ammonia (NH_3)	5.2_c	Interim Guideline	single species

Subscripts $_c$ and $_f$ denote Interim EQC developed from chamber and field data, respectively.

The Interim EQC established in this report will continue to be reviewed and refined as research work progresses. It is anticipated that future revisions of the EQC (incorporating research currently in progress) will include additional pollutant species as well as refining the Guideline and Standard values in Table 1. The EQC values will remain as Interim EQC until the final year of MRAMP research is complete. As per the specifications in the MRAS, the Final EQC from the current research program will be subject to periodic review and revision as further monitoring data is collected over time (DWER, 2019b). These reviews are likely to be based on analysis of rock art and sample rock condition monitoring. Final EQC will encompass both Guideline and Standard levels for each pollutant as shown schematically in Figure 1 and will be applied as per the EQMF specification to ensure the environmental values of Murujuga are protected (DWER, 2019a).

It is important to note that:

- Owing to the complex nature of the rock surface weathering processes taking place at Murujuga and the prolonged timescale over which (non-anthropogenic) weathering occurs, it may not be possible to develop EQC values for all gaseous species present in the Murujuga airshed that would typically be considered criteria air pollutants (CAP). This is because CAP have been selected largely based on human health effects. Some of these pollutants are (a) unlikely to impact the rock/microbiome, (b) not present above trace levels at Murujuga or (c) naturally occurring in the rock/mineral structure (e.g. lead (Pb)).
- Future iterations of the EQC may include short term (peak) and long-term average concentration values as it may be possible to identify both peak responses from the chamber study data and long term/cumulative responses from the field data.

This report summarises the development of the Interim EQC to date, a conceptual method for monitoring against these Interim EQC, and further work required to finalise the EQC over the course of the MRAMP research.

1.4 Glossary

Table 2: Glossary.

Term	Definition
Airshed	A geographical region with a common flow of air or over which air pollutants are dispersed.
Anthropogenic	From human activity. In the context of this research anthropogenic includes human impact, including industrial, transport, tourism, site management, and all other impact that can be attributed to human activity. It can also be considered to include distal or global human activity which may impact the natural environment through changes in climate.
Biofilm	A biofilm growing on a surface typically comprises a syntrophic (feeding together) consortium of microbial cells that are embedded in a slimy extracellular matrix that is composed of extracellular polymeric substances (EPSs). The organisms that live close together can “communicate” with each other (share nutrients, exchange genes to make them immune to antibiotics etc.). In some cases a biofilm can comprise a single species of microbial cells, however biofilms in environmental contexts typically involve multiple microbial species.
Biomarkers	Organic compounds produced from natural degradation of biochemicals produced by living organisms. The structure of a biomarker can sometimes be linked to a biochemical produced by a specific organism or group of organisms, while others are more general. They are known as “molecular fossils” as they can be used to infer the presence of certain organisms in ancient environments.

Term	Definition
Bioweathering	The degradation of mineral/rock surfaces through biological mechanisms. Some examples include organic/inorganic acid production, physical alterations from hyphae growing into rock surfaces and metabolic processes resulting in the release of metals from the rock, and/or formation of new minerals.
Criteria Air Pollutant	Criteria air pollutants are six common air pollutants which statutory or regulatory authorities in most regions are generally required to monitor - primarily for human health considerations. These are: ozone, particulate matter, carbon monoxide, lead, sulphur dioxide, and nitrogen dioxide.
Culturally Important Place or Site	A location that has been identified as having cultural significance to Traditional Owners and Custodians that may be due to the existence of archaeological, ethnographic, historic, natural or social values. This includes values that may or may not be tied to a specific feature or geographic point in the landscape and may include tangible or intangible features tied to specific points in the landscape or a broader area or landform unit.
DPS	Dampier Power Station.
Dispersion	The spreading out of emissions from a localised source (e.g. industry stack, wildfire) over a wide area due to the effect of wind.
Eh-pH	A parameter which indicates the stability of mineral or chemical systems based on the activity of hydrogen ions (*pH*) and electrons (*Eh*). These are often compared using an *Eh-pH* diagram (Pourbaix diagram).
Environmental Quality Criteria (EQC)	EQC include both “Standard” and “Guideline” EQC (EPA, 2016; EPA, 2017). The former represent limits above which sufficient evidence exists that impacts are likely to occur (to appropriate levels of confidence), whereas the latter represents EQC which are set to level where effects could theoretically occur - so as to ensure appropriate early warning such that emissions can be reduced before Standards are reached. EQC may monitor dose (e.g. air pollutants) or response (rock/art) parameters.
Environmental Quality Management Framework (EQMF)	A framework to guide the assessment and management of activities related to a particular environmental value.
Fresher rock	Rock that does not show weathering alteration.
HFO	Heavy fuel oil.
Heterotrophs	Heterotrophic bacteria and fungi that derive energy from organic compounds.
LOEC	Lowest observed effect concentration (LOEC).
LOEL	Lowest observed effect level (LOEL).
LOR	Limit of reporting. The lowest concentration of a substance/chemical which can be reliably reported by a laboratory.
Microbiome	An integrated community of micro-organisms (bacteria, archaea, unicellular eukaryotes and fungi) occupying a particular habitat.
Microcolonial fungi	Colonies of fungi growing on rock surfaces. They are highly resistant against desiccation and ultraviolet damage.

Term	Definition
Mineral assemblages	Presence and abundance of mineral species in a given spatial region (either across the rock surface or from the rock surface to the “fresh” rock below the outer weathered rind).
MRAS	Murujuga Rock Art Strategy.
Murujuga	Traditional name for Burrup Peninsula and surrounding islands of the Dampier Archipelago.
Murujuga Rock Art Monitoring Program (MRAMP)	Overall program of work to be conducted to 2026. Includes initial studies to inform the design of the ongoing monitoring framework, as well as the development of EQC and the EQMF.
NOEC	No observed effect concentration (NOEC).
NOEL	No observed effect level (NOEL).
NO_x	Oxides of nitrogen ($NO + NO_2$).
Ongoing monitoring	The ongoing monitoring refers to the longer-term monitoring program to be jointly run by MAC and DWER once the current program of works is complete (expected to commence from 2026). Also referred to as “long-term monitoring”.
Organic geochemistry	The study of organic compounds in the environment, including in rocks, sediments, soils, petroleum, aquatic environments and the atmosphere. Organic geochemistry studies the origin of organic compounds, their transportation processes, and the alteration they undergo in the environment, over time scales ranging from the present day to hundreds of millions of years ago.
Patina	In the Murujuga context the texture and colour of the rock surface is referred to as a patina. This is a deliberately broad definition, which encompasses the full spectrum of rock surface characterisation, including rock varnish, desert varnish or biological matter. It also includes any other exposed, highly weathered rock surface and biota/biofilms/biological residue which may be present on the surface. The patina has been shown to form over a depletion zone, referred to as the crust or weathered rind. Weathered rind generally has a lighter appearance than both the patina and the underlying rock. An engraving is formed by breaking through the naturally formed patina to expose the lighter crust beneath. There may be cases where the engraving is deep enough to expose the underlying rock, which in this case may result in a darker engraved channel. There are many examples where a fully developed patina/varnish layer has regrown in engraved grooves. These examples are generally considered among the oldest petroglyphs for this reason.
Petroglyph	Literally “rock mark”, the term describes any cultural marking into a rock surface. The marks can be produced by a range of techniques, including pecking, pounding, incising, scratching or abrading, or a combination of two or more techniques. Techniques such as scratching can be very shallow (<1 mm), while pecking can be from 1 mm to more than 100 mm deep. All petroglyphs at Murujuga are Culturally Important.
Photoautotrophs	Photoautotrophs are organisms that can make their own energy using light and carbon dioxide via the process of photosynthesis. Examples are cyanobacteria and green algae, known to colonise rock surfaces. Photoautotrophs are considered primary producers since their biomass can be consumed by heterotrophs (defined above) as a source of carbon and energy.

Term	Definition
Photolysis	The process by which molecules are broken down into smaller molecules by exposure to sunlight (typically UV radiation).
PM	Particulate matter.
p-value	A statistical measure used in evaluating the strength of evidence. First a "null hypothesis" is formulated. After data are obtained, the *p*-value is defined as the probability of obtaining data at least as extreme as the data that were obtained, where this probability is calculated under the assumption (for the sake of argument) that the null hypothesis is true. A small *p*-value is interpreted as evidence against the null hypothesis, because if the *p*-value is very small, then "either something very unlikely has happened, or the null hypothesis is false". In this report, following standard conventions, a *p*-value <0.05 is deemed 'statistically significant' evidence against the null hypothesis.
Weathered rind	The portion of the rock between the surface (patina) layer and the fresher inner rock. This layer is sufficiently close to the surface to have interacted with oxygen or other environmental conditions. The weathered rind is significantly thicker than the surface patina layer and has different colouration to the underlying fresher rock (core).
Weathering	In the Murujuga context the concepts of weathering are differentiated as natural weathering and accelerated/anthropogenic weathering, which may be termed "degradation" to distinguish it from natural weathering. However, these effects may be difficult to decouple. • Natural weathering: the alteration of a rock surface through natural agents such as the impacts of temperature cycles, microbial activity, and interactions with water and aerosols/gases released by the surrounding (natural) terrestrial and marine environments. Weathering may be subtractive (erosion) or additive (mineralisation or accretion). • Accelerated weathering: degradation due to anthropogenic activity over and above the rate of natural weathering.

2 Methodology for EQC development

The Interim EQC in Table 1 have been developed based on chamber studies and field studies that demonstrated clear dose-response relationships (see Figure 2 for an example dose-response curve). LOECs have been determined from experiments or field observations, based on the transition to the no-effect range. These values have been utilised to develop the first Interim EQC for Murujuga. Interim EQC are presented separately for chamber studies and field studies. Given the findings from field-collected rock samples of increased porosity in the region with the highest historic NO_2 exposure (see Section 7.6 of Curtin University (2024)), an Interim EQC Standard for NO_2 has also been developed based on historic emissions estimates.

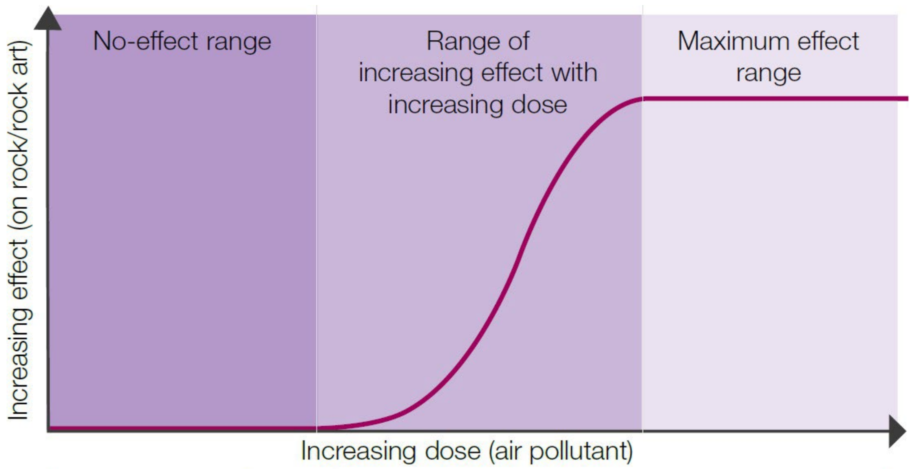

Figure 2: Example dose-response relationship.

Considerable attention has been given in recent literature to developing improved methods for estimating NOEC or equivalent (Piegorsch, 2014; Piegorsch et al., 2014; Pires et al., 2002; Hothorn, 2014; Van Der Hoeven, 1997; Van Straalen, 1997; Das, 2018; Jensen et al., 2019; Heringa et al., 2020; Fisher and Fox, 2023; Ritz et al., 2015; Fox and Landis, 2016; De Bruijn and Hof, 1997; Negri et al., 2021; Mebane et al., 2008; Green et al., 2013; Iwasaki et al., 2015). There exist a wide range of frequentist techniques as well as Bayesian statistical approaches that are becoming more commonly used (Shao, 2012; Shao and Gift, 2014; Fox, 2010; Fang et al., 2015; Krull, 2020).

A detailed investigation of these more sophisticated statistical approaches will be conducted in subsequent years as they will be vitally important to generate rigorous EQC combining complex datasets such as geochemical, microbial, field and chamber exposures. A dominant approach is to develop a suite of dose-response curves for each response variable, which permits both a robust determination of NOEC and LOEC as well as the combination of disparate response variables such as those mentioned above. This is planned for the third year of studies and associated reports.

The current Interim EQC can be considered an appropriate starting point. The similarity of the Interim Guideline EQC developed for NO_2, using completely separate approaches and datasets, points to the robustness of the methods used and the Interim EQC values determined. It was envisaged that multiple lines of evidence/inquiry would ideally be used for the development and assessment of EQC so the development of two Guideline values from different datasets for one pollutant appears to align with this approach. Given the uncertainty around such Interim Guidelines at this stage, it is appropriate to select the higher of two Guideline values until further refinement is possible.

2.1 Chamber studies (accelerated weathering)

The *Monitoring Studies Data Collection and Analysis Plan* (MSDCA Plan) (Curtin University, 2022) includes a series of laboratory based chamber exposure experiments. These experiments have been designed to promote accelerated weathering for the purposes of developing dose-response curves for pollutants and exposure scenarios relevant to the Murujuga airshed.

A detailed discussion of the chamber studies results and analysis to date is given in the *Monitoring Studies Report 2024* (refer Sections 4.4 and 7.1 in Curtin University (2024)). Key points are summarised here.

The agents utilised for experiments leading to current Interim EQC have been doses of:

- gaseous NH_3
- combustion emissions from a mixture of natural gas condensate and diesel combustion, leading to a dose comprised predominantly of NO_2 and SO_2.

The response to each dose was defined as a combined measure of detectable elemental leaching of specified chemical elements from any of the rock samples of the five lithologies being studied (basalt, dolerite, gabbro, granite, granophyre). These response agents were measured experimentally from pre- and post- exposure samples by the ChemCentre at the highest resolution (lowest detection limit) possible for the technique applied.

The design of these experiments was informed by observations of spatial gradients in porosity, which are presented in extensive detail in the *Monitoring Studies Report 2024* (Curtin University, 2024).

Aluminium (Al), Calcium (Ca), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), and Sodium (Na) were measured via inductively coupled plasma-atomic emission spectroscopy (ICP-AES), which is a relatively sensitive technique with detection limits that range from:

- 0.001 mg/L for Mn
- 0.005 mg/L for Fe and Al
- 0.1 mg/L for Ca, Na, Mg and K.

Four elements (Ca, Na, Mg, and K) exhibited a clear dose-response relationship and were selected as the most appropriate analytes for the development of EQC, at this stage as a combined (peak normalised) response variable of Ca+Na+Mg+K concentration in pre- and post-experiment paired data. The concentration of Mn was either very low or below the limit of reporting (**LOR**) for rocks without patina, and the concentration of Fe was consistently below LOR in all samples. The concentration of Al showed variability that may be attributable to contamination by Al-bearing components in the experimental apparatus, so this element is not discussed further here. Blanks consisting of 25 mm quartz-fibre filters were utilised in the chamber and did not return detectable Al, however this element did not present a consistent trend so was omitted. This decision may be revisited in future.

Elements released into solution during the experiments were initially hosted by minerals in the rock samples prior to the experiments. The experiments used cubes of fresher rock (i.e. samples without a surface patina), so the minerals within the fresher rock are the likely sources of the elements measured by ICP-AES. The five different lithologies contain different minerals in different proportions, but Ca is likely to be released from clinopyroxene and plagioclase in the mafic (silica- poor) lithologies (basalt, gabbro, dolerite), and from plagioclase in the felsic (silica-rich) lithologies (granite, granophyre). The main Na-bearing mineral and likely source of most of the Na for all lithologies is albite, which is an Na-rich feldspar, or plagioclase, which is an Na- and Ca-bearing feldspar, although minor Na may be released from amphiboles in the mafic lithologies. The most likely source of Mg is chlorite in all lithologies, and orthopyroxene, clinopyroxene, and amphiboles in the mafic lithologies. Alkali feldspar, as orthoclase, microcline, or sanidine, is the most likely source of K, although K may be held within the rock as part of clay minerals, such as illite, that form by alteration of alkali feldspar. Some proportion of all the elements that are released by breakdown of the minerals present in the fresher rock at the start of the experiment may transfer to secondary clay minerals that form as part of the mineral breakdown, and this process reduces the amount of the element that is released and measured in the experimental solutions.

The LOEC was determined as the exposed dose which produced a measurable response in 30-50% of rock samples. Conversely, 50-70% of samples (rock type groups or individual sample rocks) were below LOR. Although some differences in the response were found between different rock types and mineral grain sizes (coarse vs fine), it is important to develop EQC based on the most sensitive receptor (most vulnerable rock type), therefore the combined response/effect for all replicate rock samples across all rock types were grouped for analysis (refer Section 7.1 in Curtin University (2024)).

As discussed in Section 2, the determination of NOEC or LOEC is the subject of much debate in the scientific literature. For the purposes of developing Interim EQC at this point in MRAMP studies, the LOEC value as derived above was utilised without further estimation. This is because the 95% confidence interval for the mean response, in the lowest dose experiment, reached an effect level at or below zero (represented by the grey band in Figures 3 to 5 in Section 3). However, a precautionary approach corresponding to a reduction by a factor of approximately 61 has been applied. This factor represents the extrapolation of a 6-day accelerated weathering experiment to a year of real world exposure. This extrapolation also accounts for experimental uncertainty, detection limits and the precautionary principle.

The LOEC from experiments was converted to an annual dose, via the expression:

$$\text{Interim EQC} = \overline{\text{LOEC}_x} . \frac{t_c}{t_a} \quad (1)$$

where

$\overline{\text{LOEC}_x}$ is the mean pollutant dose concentration Cx for the experiment with the lowest observed effect concentration (LOEC),

t_c is the total duration of the (accelerated) chamber studies test, and

t_a the recalculation to a realistic field interval (one year in this case).

This conversion inherently incorporates a factor of ~61 reduction (60.875 for a year length of 365.25 days) as it averages a six day dose over 12 months. It assumes a cumulative reaction process between rock and atmosphere in dry periods, the products of which are flushed during significant rainfall events. Such events are irregular, however, it can be expected that rainfall greater than 20 mm in 24 hours occurs at least every year based on long term climate data (Curtin University, 2023). This assumption may change as further data is collected, however at this stage it is considered reasonable given a sufficient variation from the (approximately neutral) pH provided by rainfall is required for any thermodynamic effect on the mineral assemblage (Curtin University, 2024).

2.2 Field studies

Development of EQC based on field observations is generally preferred as it accounts for “real world” conditions, rather than simplified scenarios required for model or chamber exposure experiments.

Lateral spatial gradients have been observed in the near-surface porosity of granophyre rock on Murujuga from samples collected from the field. This has prompted a hypothesis by which surface weathering may be predominantly caused by abiotic processes. This is supported by the results of chamber experiments, both chemical and physical, as determined through microscopy. The variation in porosity found in the field represents a change in the order of ~3-5% across the spatial gradient of the study region (Curtin University, 2024). This near-surface porosity is statistically significantly elevated in a region centred slightly north of the town of Dampier.

If the variation in porosity is the result of anthropogenic activity, it likely represents a cumulative effect over 57 years since the bulk of industrial activity in the vicinity of Murujuga commenced around 1966 (Hamersley News, 1969). Detailed statistical analysis (Curtin University, 2024) cannot explain this elevated porosity through natural environmental conditions or location variables. Based on detailed statistical analysis of spatial gradients in porosity compared to current and historic spatial gradients in air pollutants, the variation in porosity is most closely related to NO_2 rather than other compounds or resultant acids such as HNO_3. SO_2 is slightly more complicated, as historic models show SO_2 gradients largely coincident with NO_2, however MRAMP measurements show average SO_2 concentrations are highest on the outer islands, likely due to reductions in fuel sulphur, especially in non-marine fuels, and closure of the Dampier Power Station (**DPS**). Furthermore, atmospheric measurements of HNO_3 are substantially lower in concentration in the environment than predicted by chemical transport models (relative to NO_2).

These observations and the neutral rainfall pH recorded during MRAMP support a formation associated with drier periods, rather than the previously proposed “acid rain” hypothesis, namely direct reaction between compounds such as NO_2 and the rock surface or geogenic dust particles (Curtin University, 2023). In light of this, a decision was made to undertake the accelerated weathering chamber studies primarily as a “dry” exposure process, interspersed by neutral “rainfall” to leach weathering by- products. This does not preclude an acid dissolution type mechanism, as sufficient moisture may be present during otherwise dry periods to react with gaseous air pollutants on the rock directly. Nor does it preclude historic “acid rain” events, given sparse but acidic rainfall measurements reported previously (Curtin University, 2024). There is also the potential for historically elevated emissions which may explain both the historic rainfall pH and current porosity measurements.

For this reason, an estimation of historic annual average air emissions into the Murujuga airshed is needed in order to calculate cumulative pollutant dose if Interim EQC are to be developed from spatial gradients of both pollutants and rock porosity. The Ramboll CAMx model of the Murujuga airshed (Ramboll Australia, 2020) is considered to be the best source of these data. The Ramboll model averages chemical species concentrations across 1.33 km spatial regions (grid squares). Historic SO_2 levels (in particular) were likely higher than estimated by the Ramboll model due to the use of more efficient vehicle and combustion technologies and reductions in sulphur in transport fuels over time. While the Ramboll model includes emissions from the relatively new Yurrali Maya gas fired power station (south of Murujuga and west of Karratha), it does not include emissions from the original (multi-stage) DPS which operated from 1966 to 2010. For some of the period between 1966 and 1985 it operated predominantly or entirely on heavy fuel oil (**HFO**) (Hamersley News, 1985b,a). NO_2 and NO_x emissions during this period appear to have peaked at a value at least twice the Ramboll 2014 modelled annual average and over three times the values measured during the current MRAMP field studies (Curtin University, 2024).

A detailed determination of these emissions is given in the Monitoring Studies Report 2024 (Curtin University, 2024). These cumulative emissions have been utilised, together with the porosity observed in the granophyre field samples, to determine a Guideline EQC for NO_2 based on this relationship.

A provisional calculation of the Interim Guideline EQC threshold was performed from the field observations of elevated porosity in granophyre, as follows:

The calculation utilised porosity measured from collected granophyre samples as the response variable. For air pollutant dose, the best (lower) estimate of cumulative (historic) emissions into the airshed was determined; calculated using the lower DPS estimate (growth model) summed with the Ramboll model until 2010 when DPS was decommissioned, thereafter using Ramboll estimates from 2010 until the removal of the granophyre rock samples for porosity measurement in 2022 (Curtin University, 2024). This method calculated a cumulative and/or long-term average dose of air pollutants from 1966 until removal for measurement.

From the results of the hypothesis test of elevated porosity (depicted in Figure 7.6-7 of the Monitoring Studies Report 2024 (Curtin University, 2024)), the region of land where there was statistically significant evidence of elevated porosity was identified. The threshold for statistical significance was fixed at the conventional threshold of 0.05. That is, a geographic location belongs to this designated region if the pointwise test of elevated porosity at that location has a p-value which is strictly less than 0.05. The resulting region is the orange labelled region in Figure 7.6-7(b) of the Monitoring Studies Report 2024 (Curtin University, 2024). The analysis was also repeated using the stricter threshold of 0.01.

The spatially-varying estimate of annual average concentration of NO_2 based on observations from the passive samplers was calculated; this is an average of the monthly estimates depicted in Figure 7.11-14 in the Monitoring Studies Report 2024 (Curtin University, 2024). The minimum value of average NO_2 concentration within the designated region of elevated porosity was found. This minimum value was 2.450 and 2.696 μg/m^3, respectively, for the significance thresholds $p < 0.05$ and $p < 0.01$.

As discussed in Appendix E of the Monitoring Studies Report 2024 (Curtin University, 2024), levels of NO_2 on Murujuga were probably greater in the 1960s and 1970s than they are at present. The total mass of NO_2 introduced annually into the airshed from 1966 to 2023 was calculated following the "growth model" described in that appendix. By this calculation, the total mass of NO_2 introduced annually was, on average over this period, approximately 1.18 times the annual rate modelled by Ramboll for 2014 and approximately 2 times the current emission level measured by MRAMP (Nov 2022 to April 2024). It should be noted this is a lower estimate than the 2 to 3 times higher peak estimate obtained by using the DPS full utilisation model (Curtin University, 2024). The lower growth model estimates were used for the purposes of Interim Guideline EQC determination, while the peak annual average emissions from the full utilisation model were used for the determination of the Interim Standard EQC.

The site of the former Dampier Power Station lies within the area between the monitoring sites EX09 and EX02, which are the sites where the highest levels of NO_2 are currently observed by MRAMP. It is therefore plausible that the spatial pattern of NO_2 concentration in past years was similar to the current spatial pattern observed by MRAMP except for the higher average level. This would imply that a location that is currently experiencing an annual average NO_2 concentration of 2.450 or 2.696 $\mu g/m^3$, has experienced a long-term average NO_2 concentration of 1.18 × 2.450 = 2.888 or 1.18 × 2.696 = 3.178 $\mu g/m^3$, respectively.

Accordingly, the provisional thresholds for NO_2 concentration are 2.888 μg/m3 ($p < 0.05$) and 3.178 μg/m3 ($p < 0.01$). This higher value is then taken as the Interim guideline EQC.

Given the observations from field-collected samples, it is also appropriate to select the estimated (historic) peak in annual average NO_2 as an Interim Standard EQC. This value was determined as 45.6 μg/m3 at both the EX02 and EX09 air quality monitoring station location squares. This represents the estimated historic peak annual average emission which is expected to have occurred around 1985 in the area around Dampier due to the operation of the DPS (refer Curtin University (2024)), calculated by combining the Ramboll 2014 estimates for those sites and estimates derived from the peak annual average in the DPS full utilisation model.

3 Interim EQC

Guideline Interim EQC values determined as part of the research work reported in the Monitoring Studies Report 2024 (Curtin University, 2024) have been developed based on experimental chamber studies of accelerated weathering. Guideline and Standard Interim EQC values have also been separately determined based on field observation of rock (art) surface condition and estimated cumulative and peak emissions of NO_2 into the airshed.

3.1 Interim EQC based on chamber studies

Table 3 shows the Interim EQC developed to date using the methods described previously. Figures 3 to 5 show the dose-response curves for NO_x (as NO_2), SO_2 and NO_2+SO_2. The y-axis in the figures shows a cumulative peak-normalised leaching response for each experiment, therefore the values are dimensionless. NH_3 experiments to date constitute a single set of exposures, so a dose response curve cannot be shown, however the single experiment undertaken appears to have been serendipitously conducted at the LOEC as only about 50% of the rock types exhibited a response above the detection limit. This is comparable with the LOEC response for other experiments.

Table 3: Guideline Interim EQC based on chamber studies.

Air pollutant	**Annual average concentration** (μg/m^3)	**EQC type**	**Application**
NO_2	5.5	Interim Guideline	combined (NO_2 & SO_2)
SO_2	4.3	Interim Guideline	combined (NO_2 & SO_2)
NH_3	5.2	Interim Guideline	single species

Figure 5 shows a more classical dose-response relationship for combined NO_x + SO_2 than the curve for NO_x alone, which suggests interaction effects between these two pollutants (and possibly others) may be occurring. For this reason, it is proposed that the Interim EQC for NO_2 and SO_2 should be applied together rather than separately as per Table 3. That is, an annual exceedance of the Guideline level(s) should be considered to have occurred when the respective levels for both NO_2 and SO_2 occur for the same monitoring location. This is because NO_2 and SO_2 can be expected to exhibit relatively similar types of interactions or effects in contact with the rock surface.

Preliminary experiments with other hydrocarbon fuel combustion such as HFO suggest a more complex relationship between combustion emissions, which will be explored in further work.

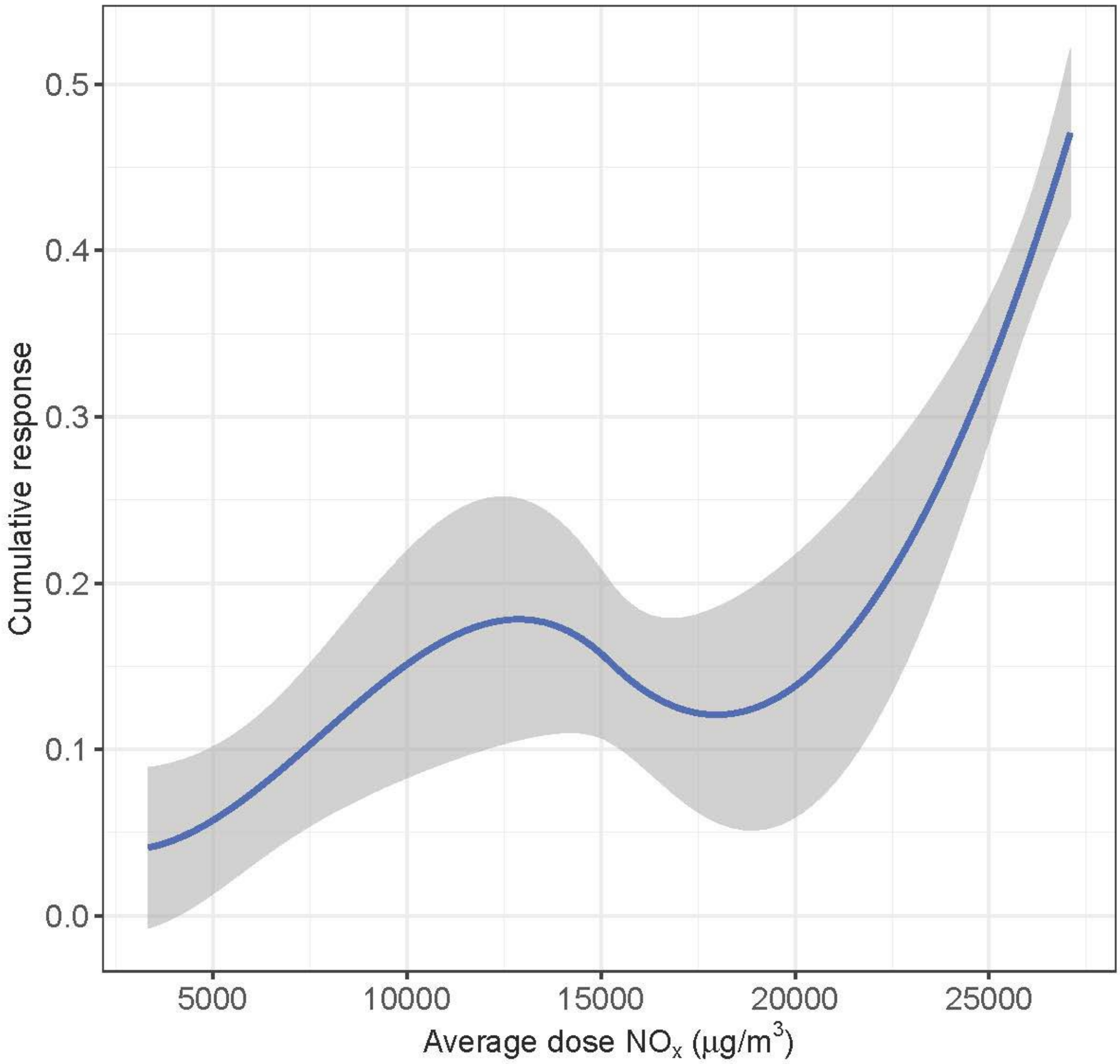

Figure 3: Cumulative peak-normalised response to NO_x dose. The blue curve is the smoothed conditional mean and the grey band represents the 95% confidence level.

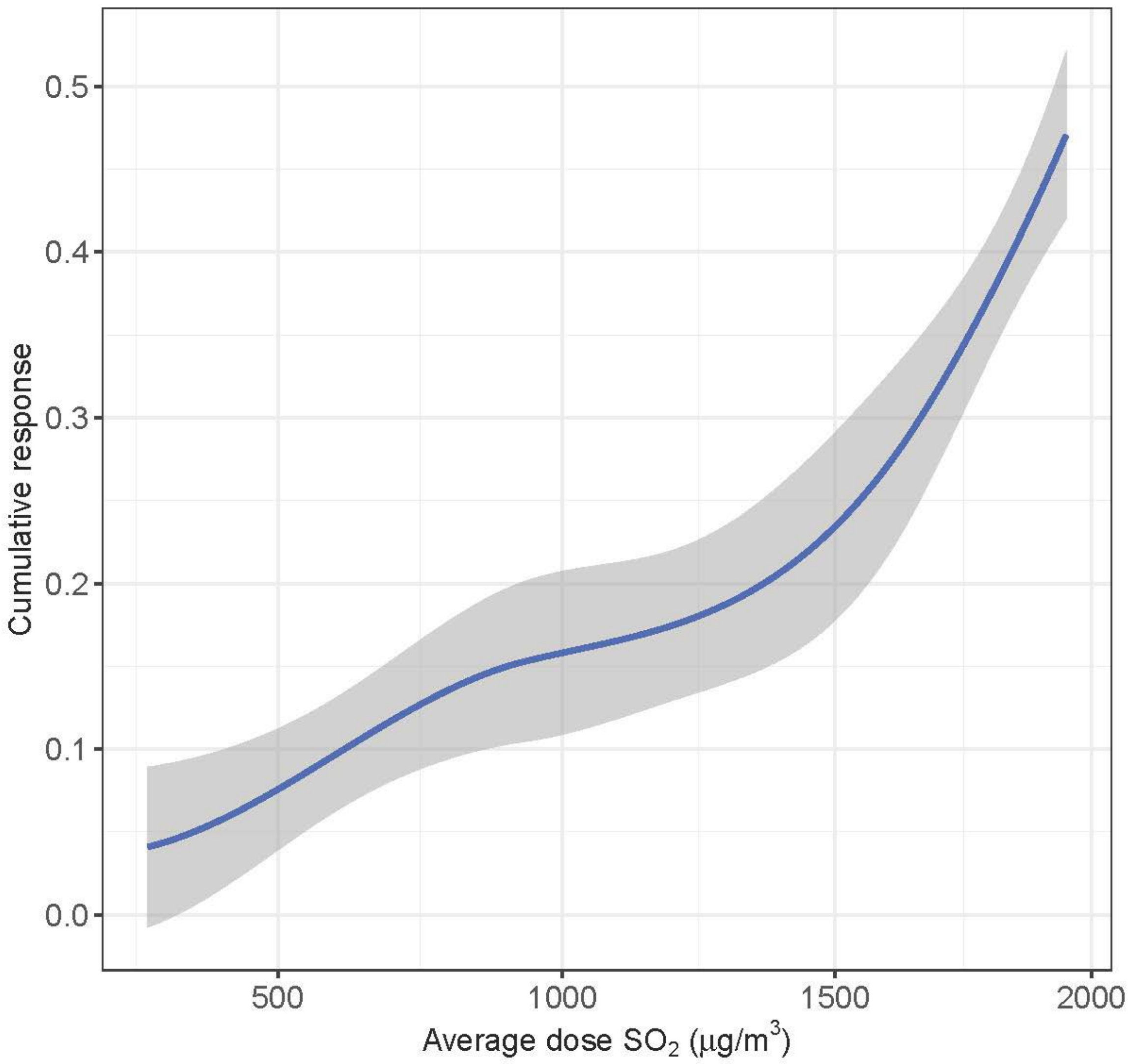

Figure 4: Cumulative peak-normalised response to SO_2 dose. The blue curve is the smoothed conditional mean and the grey band represents the 95% confidence level.

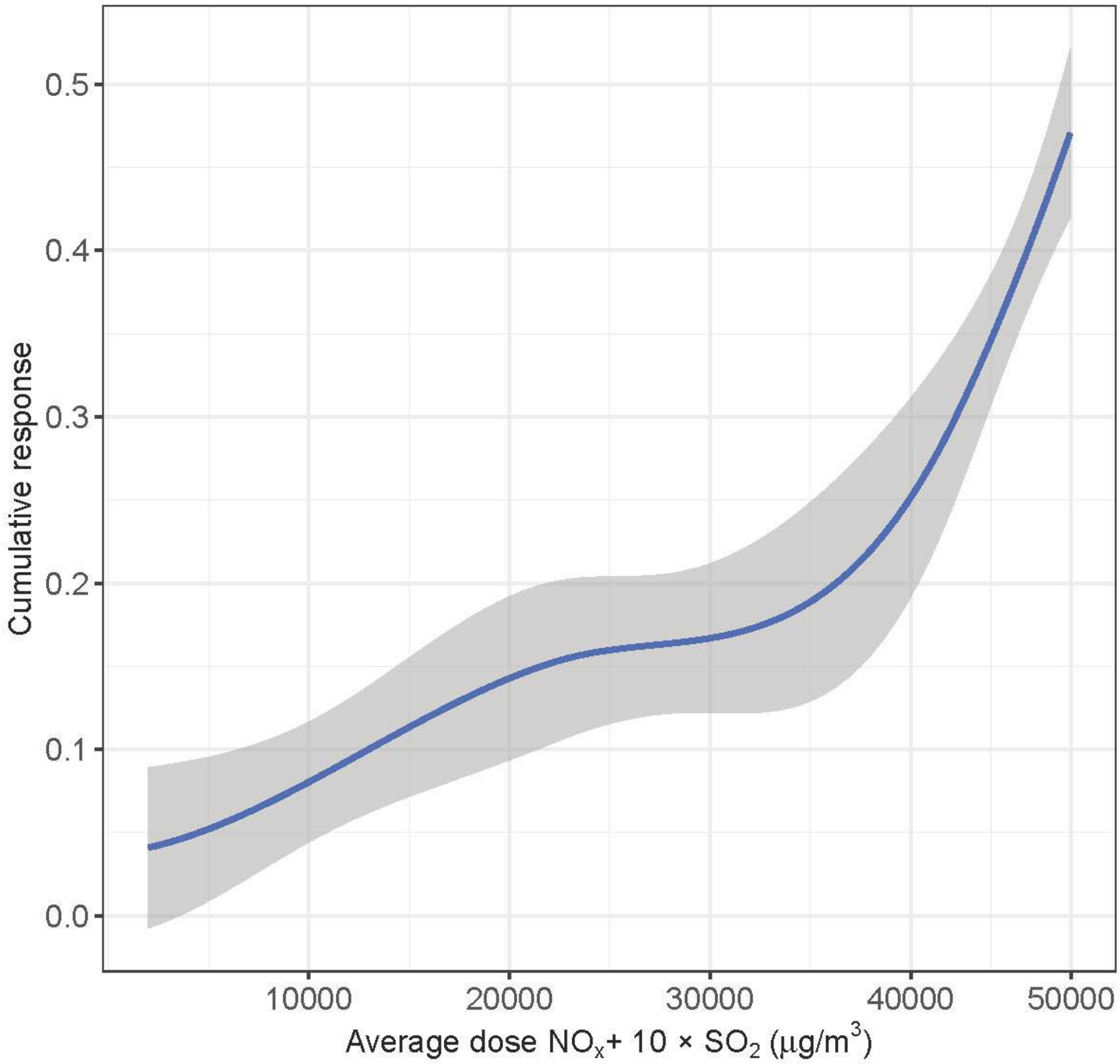

Figure 5: Cumulative peak-normalised response to dose of NO_x and SO_2. The blue curve is the smoothed conditional mean and the grey band represents the 95% confidence level.

3.2 Interim EQC based on field observations

From the field observations of elevated porosity in granophyre, a provisional calculation of the EQC threshold was performed using available data as described in Section 2.2.

Table 4 shows the Interim EQC values determined using this method. The Interim Standard EQC is based on the calculated historic peak annual average NO_2 value.

Table 4: Guideline Interim EQC based on field observations.

Air pollutant	**Annual average concentration** (μg/m^3)	**EQC type**	**Application**
NO_2	3.2	Interim Guideline	single species
NO_2	45.6	Interim Standard	single species

The Interim Standard for NO_2 developed above utilise data from a complex airshed and mix of pollutants (dose) and a single response variable (porosity). It is likely the Interim EQC variables will be revised as interactions and relative contributions from air pollutants are better understood and improved response data or data from multiple response variables are incorporated. A relatively simple methodology has been used to set the Interim Standard at the estimated peak annual average emission level. More sophisticated approaches will be utilised in the future based on findings of the MRAMP studies work currently in progress and will likely include interpolated historic emissions levels from the entire region where significantly elevated porosity have been found, combined with Standards derived from chamber studies.

3.3 Selection of Interim EQC for monitoring

The Interim Guideline EQC values determined from both chamber studies and field observation methodologies are low compared to existing human health standards set by the WHO. Owing to inevitable synergistic interactions between multiple air pollutant species in the data utilised to date, it is prudent to select the chamber studies based values and combined (NO_2+SO_2) exceedance for the purposes of Interim Guideline EQC determination.

The single species Standard NO_2 value developed from field observations is however justified as it is (a) based on expected historic peak annual average emissions, and (b) calculations show that NO_2 has always been emitted and present in the air at much greater levels than SO_2. This rationale has been used to arrive at the Interim EQC values presented in Table 1.

4 Ongoing EQC development

It is important to develop Interim EQC as soon as appropriate levels of statistical confidence indicate a particular degradation mechanism affecting a specific pollutant or mechanistic pathway.

Based on the findings to date, it is expected that MRAMP research will lead to the development of Standard and Guideline EQC for NO_2, SO_2 and NH_3. It may be possible to develop EQC for PM, however the bulk of PM (by mass) is likely produced by natural sources and the second-most abundant portion is likely iron-ore dust. Evidence to date (Curtin University, 2024) is that clay minerals and other components in geogenic dust (which constitutes the bulk of PM mass) are an important building block in patina formation. Dust may also play an important role in moderating the pH of potentially acidic emissions. It is not yet known if “excess” dust can be detrimental - either to the microbiome or through mechanical abrasion in high wind. These considerations will be investigated as far as practicable. Secondary air pollutants such as ozone (O_3) are also an important consideration, however it may prove sufficient or preferable to reduce precursor species thus inhibiting secondary pollutant formation.

Final Guideline and Standard EQC could be adjusted as more dose-response data become available and field and microbial datasets are integrated, as a result of improved statistical power and improved knowledge of interactions. Synergistic and antagonistic effects between air pollutants must also be considered.

5 Monitoring against the Interim EQC

The monitoring program embedded in the MRAS EQMF model (Figure 1) requires each of the pollutants of concern to be measured in the field in such a way that an exceedance of an EQC Guideline or Standard level can be identified, and measures taken to manage the risk of accelerated weathering of the rock surface and damage to the rock art. Monitoring and reporting procedures are specified in detail in the Interim Monitoring Program Design Report (Curtin University, 2025), however the key principles are summarised here.

Figure 6 shows a map of the monitoring sites. These are AQ01–18, AQA1 (MAC office), EX02 (Dampier) and EX09 (Mt Wongama). This represents a network of 21 air quality monitoring sites encompassing the Burrup Peninsula and Dampier Archipelago.

It is recommended that the 4-weekly average levels of atmospheric NO_2, SO_2 and NH_3 be monitored using the passive gas samplers in the MRAMP air quality monitoring network as an early indicator for a quarterly assessment against Interim EQC concentrations based on these data. The Interim EQC should be assessed across all stations, and the design be such that any location where rock art exists could be a valid monitoring site for EQC purposes. For example, some existing industry monitoring sites with passive samplers may be recommended for inclusion in the monitoring network in future. These have not been included at this time due to timing of data delivery and cross validation (data fusion) issues between sampler types and deployment intervals.

The NO_2 Interim Standard EQC developed from field data is based on estimates of annual average emissions. Therefore it is most appropriate to assess it against rolling annual average values.

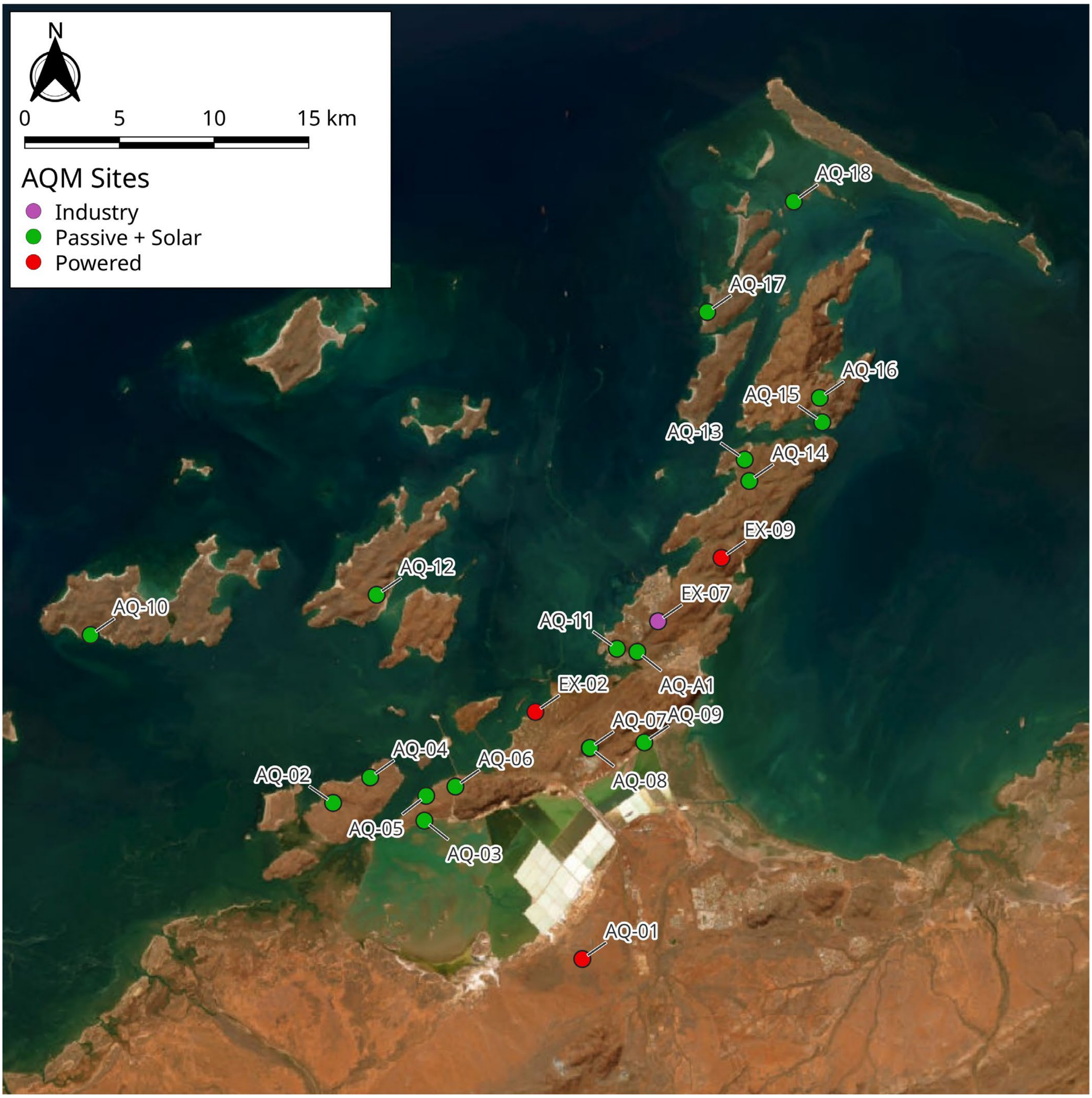

Figure 6: Map of monitoring sites used to develop Interim EQCs and proposed for ongoing monitoring and assessment.

5.1 Initial monitoring program design

Based on the points above, it would be most appropriate to assess whether an exceedance of the Interim EQC Guideline concentrations has occurred through comparison of annual average Interim EQC concentrations against monthly average passive sampler data for each of the pollutant species considered. This would be achieved using data collected from the passive gas samplers installed across the MRAMP air quality monitoring network. Furthermore, as the Interim Guideline EQC for NO_2 and SO_2 were developed from combined combustion experiments and are likely to have a similar mechanism of action, it is appropriate at this early stage of EQC development to assess these parameters together. That is, the Guideline level should only be considered to have been exceeded in the field if both NO_2 and SO_2 Guideline levels are both individually exceeded for a particular monitoring location.

A summary of the proposed reporting and assessment protocol is as follows:

Guideline EQC - Assessed quarterly based on a rolling 12-month average:

- NO_2 and SO_2 - Exceedance of respective NO_2 and SO_2 Guideline EQC at the same location over any 12-month interval.
- NH_3 - Exceedance of Guideline EQC at any location over any 12-month interval.

Standard EQC - Assessed quarterly based on a rolling 12-month average:

- NO_2 - Exceedance of NO_2 Standard EQC at any location over any 12-month interval.

The selection of quarterly reporting is to allow for delays in the return of passive sampler results from analytical laboratories. The analysis and reporting would however calculate the rolling 12 monthly average for each monthly (or more accurately 4-weekly) increment.

Figure 7 shows the Interim EQC plotted together with MRAMP measurements of atmospheric concentrations of the respective pollutants at each monitoring station. For each panel in the Figure, the dashed orange line represents the Interim Guideline EQC developed from chamber studies data. The black dots represent the rolling 12-month average values of passive sampler observations, for those sites where at least 12 months worth of data have been collected (nominally 18 months spanning 2023 to mid 2024). Thus, multiple black dots are typically shown for the same site; the vertical spread of dots for each site represents the observed variation in the 12-month rolling average values calculated from observations over the 18-month recording period. Note that the dots are close together for some sites, in particular NO_2, to help distinguish the individual dots, a small random offset (jitter) was applied along the x-axis.

For the powered monitoring sites, which were commissioned later, only 9 months worth of data were available at the time of preparation of this report; each grey dot in Figure 7 represents the average value of all data observed at a powered site. For the three pollutants, the relative spatial trend agrees with models (Ramboll Australia, 2020) and does not vary considerably if different averaging periods are used.

The green dashed line in the NO_2 plot (Figure 7b) represents the Interim Guideline EQC developed from the field porosity dataset and cumulative airshed emissions. The red dashed line indicates Interim Standard EQC developed from peak historic emissions and porosity data. The slightly higher Guideline value from the chamber studies will be used in the initial monitoring of NO_2.

By examining Figure 7, it can be seen that the individual Interim EQC Guideline levels are not exceeded by current (rolling 12-month averaged) atmospheric levels of gas species, with the exception of the two sites which have less than 12 months of data, so do not represent a true rolling annual average. The corresponding SO_2 average is relatively low at these two sites (compared to the other MRAMP sites), however the same caveat on the averaging interval applies. No exceedances are observed based on the current Interim EQC Guidelines and approach. Individual EQC for NO_2 and SO_2 will be developed in further EQC iterations.

While the graphical representations above are a useful visual comparison of EQC against current levels, for reporting purposes, a table format is proposed, as shown in Tables 5, 6 and 7. These tables show the same data as presented graphically; however, they simplify the identification and reporting of potential exceedances in accordance with EQMF. Months represent end months in 2023/2024 for the rolling 12 month average calculation.

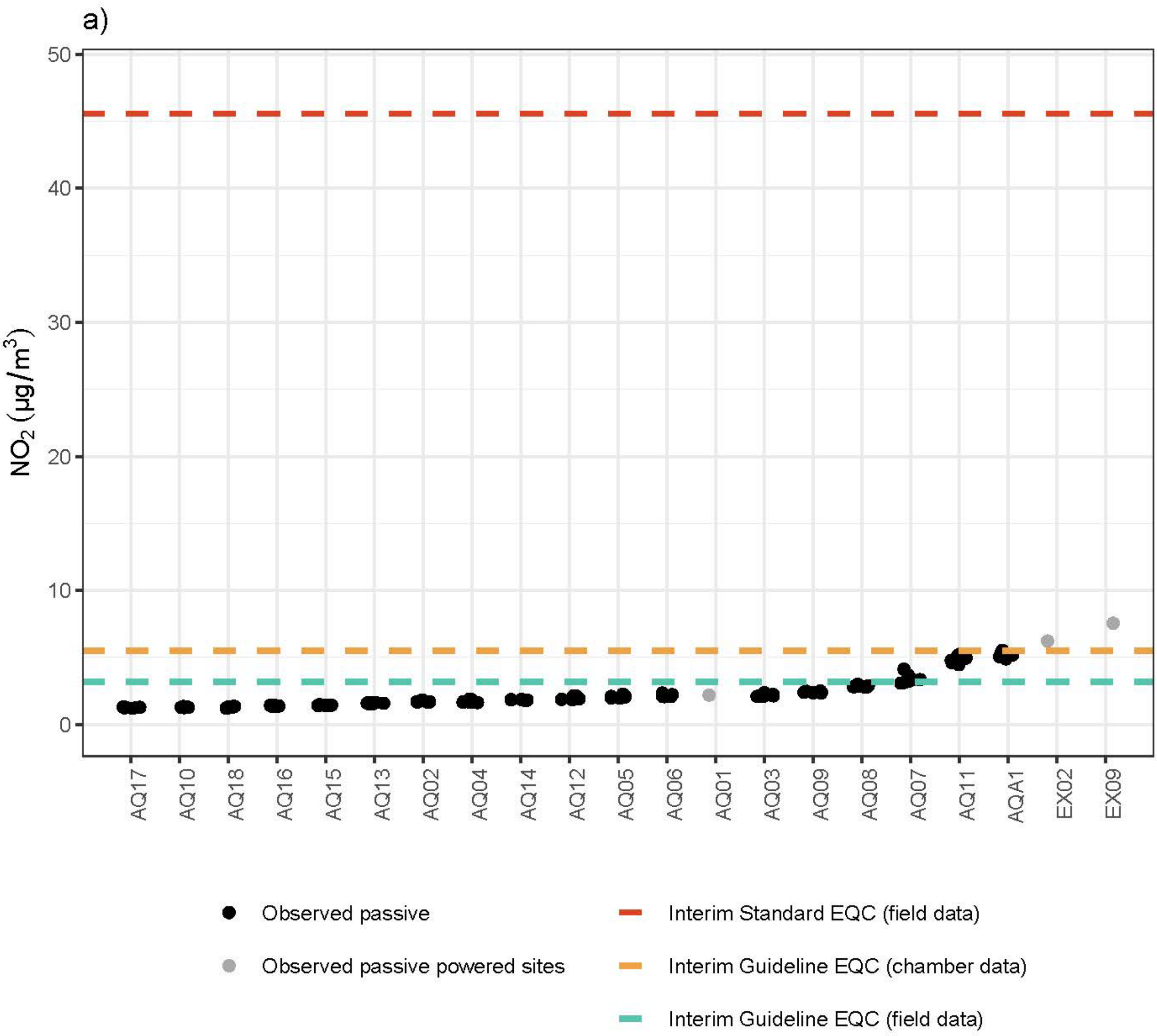

Figure 7: Interim EQC (dashed lines) and MRAMP (Nov 2022- April 2024) observed passive sampler average levels (•) at each MRAMP monitoring station. Powered air quality monitoring stations were commissioned later and have less than 12 months of passive sampler data available, so are shown in grey. In each plot, sites are ordered by their overall average concentration of NO_2. To make the individual • more distinguishable, a small random offset (jitter) has been applied along the x-axis. (a) NO_2.

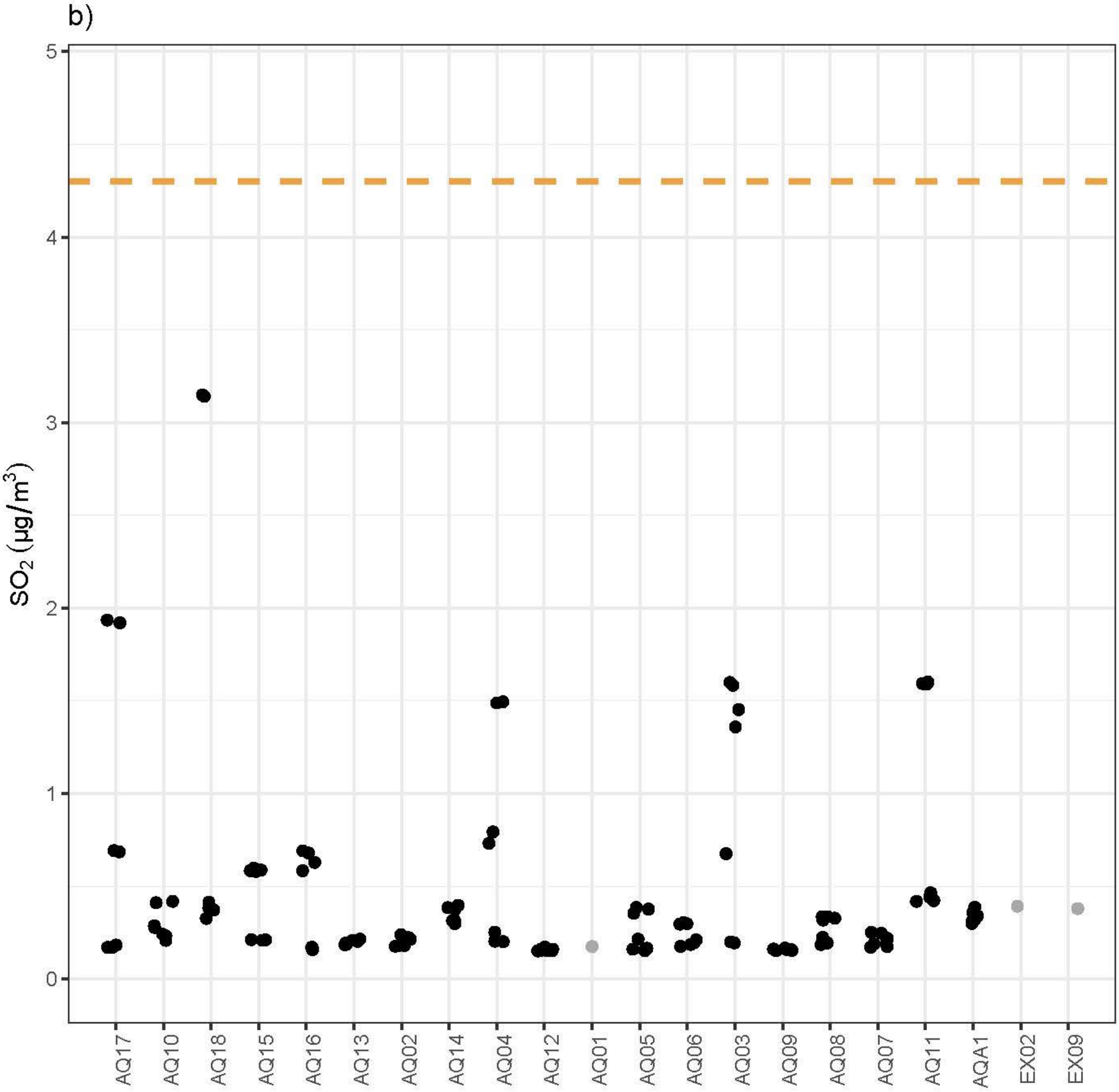

Figure 7b) SO_2 (Continued caption from Figure 7(a).)

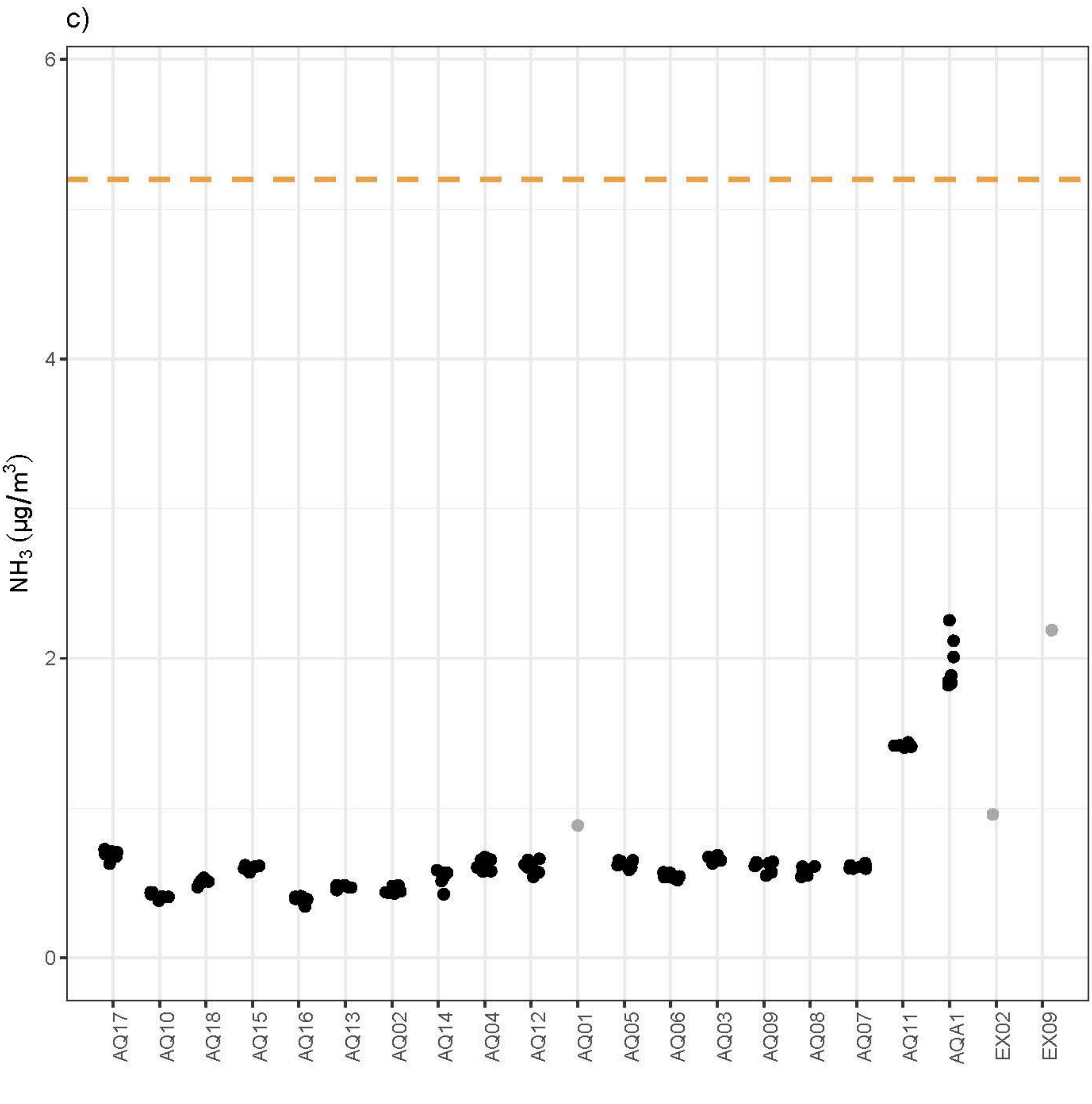

Figure 7c) NH_3 (Continued caption from Figure 7(a).)

Table 5: NO_2 rolling monthly average values for each AQM site, where the units are µg/m^3. Months represent end months in 2023/2024 for the rolling 12-month average calculation. Note that for the powered monitoring sites (AQ01, EX02 and EX09), the average value is only over 9 months.

Site	Nov 23	Dec 23	Jan 24	Feb 24	Mar 24	Apr 24	May 24
AQ01							2.19
AQ02	1.70	1.69	1.69	1.67	1.70	1.83	1.81
AQ03	2.24	2.21	2.10	2.09	2.14	2.22	2.37
AQ04	1.67	1.65	1.65	1.63	1.70	1.89	1.89
AQ05	2.13	2.09	1.97	1.96	2.05	2.14	2.26
AQ06	2.12	2.09	2.10	2.08	2.11	2.22	2.35
AQ07	4.12	3.68	3.35	3.35	3.09	3.14	3.25
AQ08	2.77	2.79	2.82	2.82	2.83	2.89	3.00
AQ09	2.50	2.48	2.39	2.40	2.35	2.37	2.40
AQ10	1.29	1.26	1.27	1.27	1.28	1.34	1.34
AQ11	4.46	4.62	4.61	4.78	4.96	5.18	5.24
AQ12	1.88	1.88	1.89	1.90	1.93	2.14	2.14
AQ13	1.55	1.55	1.58	1.58	1.60	1.62	1.64
AQ14	1.83	1.85	1.81	1.82	1.83	1.85	1.86
AQ15	1.40	1.42	1.43	1.48	1.45	1.44	1.42
AQ16	1.36	1.37	1.35	1.38	1.38	1.43	1.43
AQ17	1.21	1.24	1.27	1.29	1.30	1.28	1.29
AQ18	1.23	1.25	1.30	1.31	1.32	1.36	1.35
AQA1	5.25	5.20	5.08	4.90	5.05	5.42	5.54
EX02							6.23
EX09							7.55

Table 6: SO_2 rolling monthly average values for each AQM site, where the units are µg/m^3. Months represent end months in 2023/2024 for the rolling 12-month average calculation. Note that for the powered monitoring sites (AQ01, EX02 and EX09), the average value is only over 9 months.

Site	Nov 23	Dec 23	Jan 24	Feb 24	Mar 24	Apr 24	May 24
AQ01							0.17
AQ02	0.24	0.22	0.23	0.21	0.18	0.18	0.18
AQ03	1.60	1.58	1.45	1.36	0.68	0.20	0.19
AQ04	1.49	1.49	0.79	0.73	0.25	0.20	0.20
AQ05	0.39	0.38	0.35	0.22	0.16	0.17	0.15
AQ06	0.30	0.30	0.30	0.21	0.18	0.19	0.20
AQ07	0.20	0.17	0.19	0.18	0.22	0.25	0.25
AQ08	0.34	0.33	0.34	0.32	0.22	0.19	0.19
AQ09	0.16	0.15	0.16	0.15	0.16	0.16	0.17
AQ10	0.42	0.41	0.29	0.28	0.21	0.23	0.24
AQ11	1.60	1.59	1.59	0.42	0.42	0.44	0.46
AQ12	0.17	0.16	0.16	0.15	0.15	0.15	0.15
AQ13	0.21	0.21	0.20	0.19	0.18	0.19	0.19
AQ14	0.40	0.38	0.38	0.32	0.31	0.30	0.31
AQ15	0.60	0.58	0.59	0.58	0.21	0.21	0.21
AQ16	0.69	0.68	0.63	0.58	0.17	0.17	0.16
AQ17	1.94	1.92	0.69	0.69	0.17	0.18	0.17
AQ18	3.15	3.14	0.41	0.33	0.38	0.38	0.37
AQA1	0.36	0.34	0.34	0.32	0.39	0.30	0.31
EX02							0.39
EX09							0.38

Table 7: NH_3 rolling monthly average values for each AQM site, where the units are μg/m^3. Months represent end months in 2023/2024 for the rolling 12-month average calculation. Note that for the powered monitoring sites (AQ01, EX02 and EX09), the average value is only over 9 months.

Site	Nov 23	Dec 23	Jan 24	Feb 24	Mar 24	Apr 24	May 24
AQ01							0.88
AQ02	0.45	0.48	0.48	0.44	0.43	0.44	0.43
AQ03	0.63	0.67	0.65	0.68	0.67	0.66	0.65
AQ04	0.66	0.67	0.66	0.60	0.62	0.58	0.58
AQ05	0.64	0.65	0.65	0.62	0.62	0.60	0.59
AQ06	0.54	0.57	0.57	0.54	0.54	0.53	0.52
AQ07	0.63	0.60	0.60	0.60	0.62	0.62	0.61
AQ08	0.59	0.61	0.61	0.58	0.56	0.55	0.54
AQ09	0.61	0.64	0.64	0.63	0.63	0.57	0.55
AQ10	0.41	0.44	0.44	0.42	0.41	0.40	0.38
AQ11	1.42	1.40	1.42	1.41	1.42	1.42	1.44
AQ12	0.62	0.65	0.66	0.62	0.61	0.57	0.54
AQ13	0.47	0.49	0.47	0.47	0.48	0.45	0.47
AQ14	0.57	0.58	0.57	0.54	0.51	0.43	0.42
AQ15	0.58	0.60	0.61	0.57	0.61	0.62	0.61
AQ16	0.39	0.41	0.39	0.41	0.38	0.36	0.34
AQ17	0.73	0.71	0.71	0.68	0.69	0.67	0.63
AQ18	0.47	0.50	0.51	0.52	0.52	0.53	0.51
AQA1	2.25	2.12	2.01	1.89	1.83	1.82	1.85
EX02							0.96
EX09							2.19

5.2 Likely historic Interim EQC exceedance

As previously noted in the field studies discussion in Section 2.2, it is likely that historical average concentrations of atmospheric NO_2 peaked at 2 to 3 times current levels in the Murujuga airshed. Figure 8 examines the estimated historical atmospheric NO_2 concentrations relative to the proposed Interim EQC values for NO_2.

Four different measured or modelled air pollution levels are shown concurrently in Figure 8:

1. Black/grey dots: Recently measured average NO_2 concentrations determined from the MRAMP air quality monitoring network passive sampler data.
2. Light blue triangles: The predicted annual average NO_2 concentrations at each of the MRAMP monitoring sites from the Ramboll CAMx (2014) model estimates (Ramboll Australia, 2020). Note that the 2014 (current) scenario has been depicted from this model as the better estimate of recent historic emissions. The 2030 scenario is slightly lower.
3. Dark blue triangles: Estimated historical peak (1971-1985) annual average NO_2 concentrations due to emissions from the former Dampier Power Station in isolation. These levels have been predicted using the calculated power station NO_2 point source emissions, which have then been spatially dispersed through the airshed by scaling to the same concentration ratios predicted by the Ramboll model above (note that the historical and current NO_2 emission sources are in close enough proximity relative to the Ramboll model-grid granularity to permit this approximation). The values represent the approximate peak emissions period when DPS was operating on HFO (Curtin University, 2024).
4. Brown triangles: The summation of the estimated DPS NO_2 emissions (3) and current Ramboll NO_2 predictions (2) have been plotted. This data series is representative of the likely highest average annual NO_2 concentrations experienced in the airshed when the former power station was operating concurrently with other industrial emission sources.
5. The green, orange and red dashed lines are the same as depicted in Figure 7: green dashes representing proposed Guideline EQC developed from the field porosity dataset and cumulative airshed emissions; orange dashes represent the proposed Guideline EQC and red dashes represents the proposed Standard EQC.
6. For added context, the pink line represents the World Health Organisation Global Air Quality Guidelines annual average NO_2 concentration and the purple lines shows the 24-hr guideline (C40 Knowledge Hub, 2021). These are levels recommended from a human health/epidemiology perspective. It is not suggested that they are relevant for geochemical weathering processes, although they may have implications for microbiome health.

Figure 8 shows the MRAMP Interim EQC values and the passive sampler measurements only for clarity.

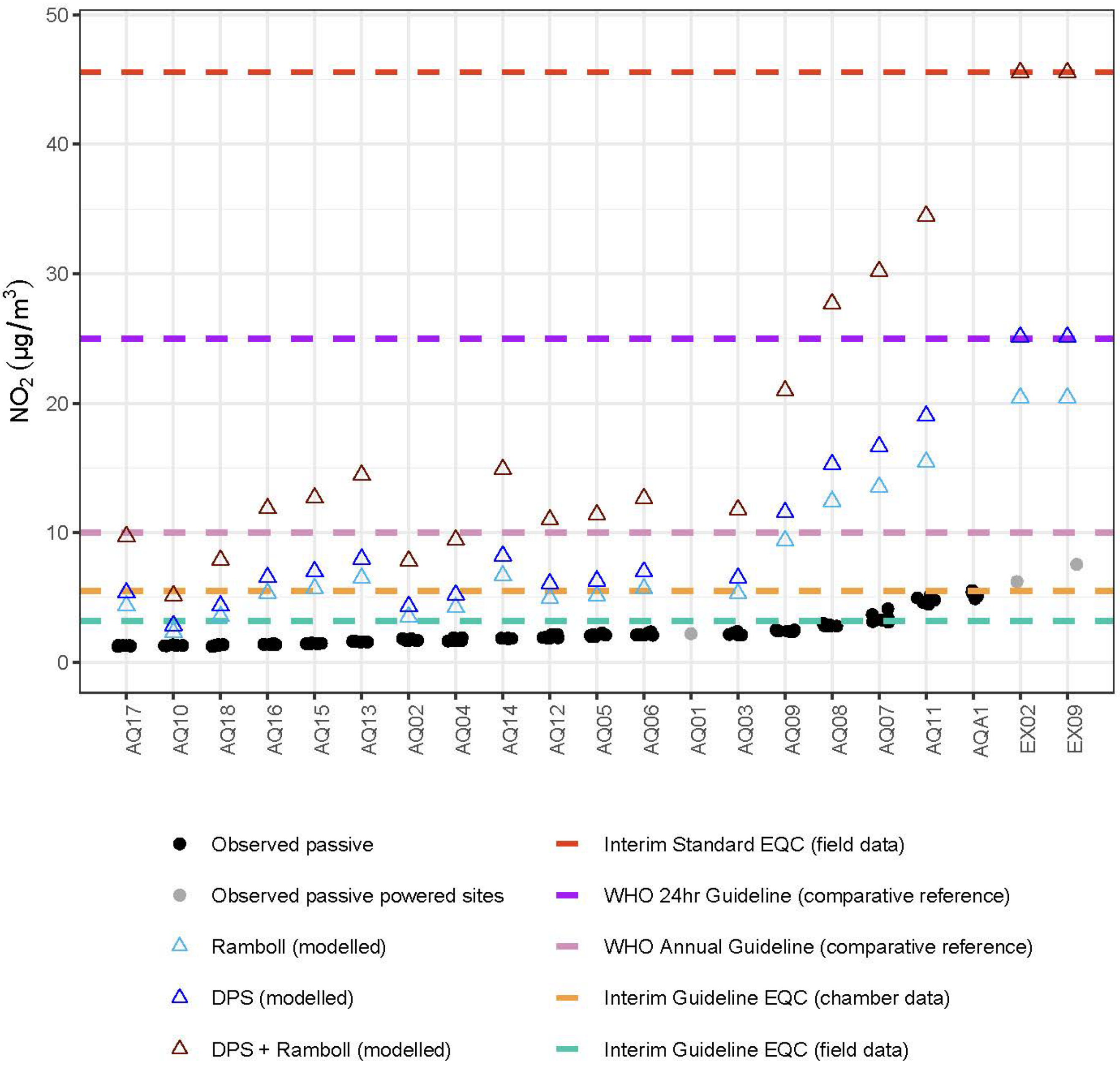

Figure 8: Guideline NO_2 Interim EQC (dashed lines), MRAMP (Nov 2022- April 2024) measured average NO_2 levels (•) and modelled or estimated historical average and peak (1971-1985) NO_2 levels (△). Powered air quality monitoring stations (sites) were commissioned later and have less than 12 months of data, so are shown in grey. WHO human health guideline levels are shown for comparative purposes only. Ramboll refers to a detailed chemical transport model for the airshed based on 2014 (post DPS decommissioning) emissions estimates (Ramboll Australia, 2020). The additional contribution from DPS has been modelled separately and the peak annual average emissions estimate added to the Ramboll model estimate.

It can be seen from Figure 8 that when the DPS was operational there was likely a uniform annual average exceedance of NO_2 concentrations compared to Interim EQC (both the Interim Guideline EQC level for a larger region, and the Interim Standard EQC level for a more localised area in Dampier). When considering this graph, it is important to note that some emission sources captured in the Ramboll airshed model (and depicted in data series (4) above) may have commenced operation too recently to be operating in parallel with the DPS emissions peak. However, other sources captured in the 2014 Ramboll model scenario would have lower emissions than earlier higher-emitting infrastructure. This summation includes both the former DPS and the current (lower emitting) Yurralyi Maya gas-fired power station near AQ01 that replaced it. This “over accounting” for emissions by including the current power station in the historical estimate has only a minor effect and probably compensates for some emissions reductions seen in long-term industrial operations since the 1980s due to the progressive introduction of emissions reduction measures.

This estimate of historical emissions may explain the spatial pattern of rock surface porosity found from the Murujuga field samples, which is most elevated in the samples from the sites encompassing AQ07–09, AQ11, AQA1, EX02 and EX09. This would therefore suggest that industrial emissions-induced acceleration of weathering (at least as expressed by the environmental indicator of rock surface porosity) may have occurred historically. Limited historic rainfall pH measurements from Bednarik (2007) suggest that rainfall pH may have been lower (more acidic) than the neutral levels measured in recent years (Curtin University, 2024). These observations may support a hypothesis of historic impact which may no longer be occurring under the current lower emissions scenario.

5.3 Summary

This document presents the first ever (Interim) EQC designed to help protect the petroglyphs of Murujuga. The determination of an Interim Guideline EQC for NO_2 from two completely separate datasets (field and chamber) has resulted in a very similar value, which is promising and supports the rigour of the methods being used.

The initial Interim EQC proposed in this report are preliminary Guideline and Standard values based on controlled exposure studies and field observations to date. Previous work in this area (prior to MRAMP) has suggested that a dominant mechanism for industrial emissions-induced weathering is acidic rainfall and as such previous laboratory-based studies have been focused on this area. Current research (Curtin University, 2024) has found neither acidic rainfall, nor any correlation between acids (such as HNO_3) and any response variables. Therefore, the concept for developing these Interim EQC is based on the assumption that dry (non-rainfall) exposure and associated weathering is the dominant mechanism/process and that sufficient (neutral pH) rainfall will occur on an annual basis as a minimum to “reset” the system. Hence the justification for assessment of EQC on an annual average basis at present.

More work will be undertaken to understand the relative contributions of NO_2 and SO_2 in isolation, as well as consider the microbiome and interactions with other species such as particulate matter. The interim EQC presented here are intended ultimately to be used as part of an ongoing monitoring program to ensure the environmental values are protected.

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