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Atmospheric corrosivity of the Bay of Plenty region

Zhengwei Li

BRANZ

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Preface

This is the first of a series of reports prepared during a research into the airborne contaminants in the Bay of Plenty region and their influences on the atmospheric corrosivity and degradation and performance of typical building materials.

Acknowledgements

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Author

Zhengwei Li

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Abstract

This study report summarises the key findings from a recent BRANZ investigation into the atmospheric corrosivity of the Bay of Plenty region including:

- a survey of major airborne pollutants, such as ammonia, hydrogen sulphide and sulphur dioxide
- information collected about the first-year atmospheric corrosion rates of mild steel, zinc and copper at representative exposure sites across the region
- an update of the region's atmospheric corrosivity map.

This study may help refine the New Zealand atmospheric corrosivity map. This map is a key component of the material specification scheme used by New Zealand Building Code Acceptable Solution E2/AS1 and NZS 3604:2011 *Timber-framed buildings*.

Keywords

Atmospheric corrosivity, geothermal, industrial, marine, hydrogen sulphide, sulphur dioxide, mild steel, copper, zinc, map.

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Executive summary

New Zealand Building Code Acceptable Solution E2/AS1 and relevant standards, such as NZS 3604:2011 *Timber-framed buildings*, use an atmospheric corrosivity zone micro-environment scheme to specify materials and protective measures for durability compliance. An atmospheric corrosivity map has been experimentally developed and incorporated into NZS 3604:2011 to support this practice. It is important that the credibility of this map is maintained, particularly when considering the potential influences of changes in climate, industrial emission and/or urban development.

The atmospheric environment of the Bay of Plenty region is influenced by human-related activity emissions and natural sources (such as geothermal, marine and volcanic). These may pose various challenges for the durability of materials, components, buildings and associated infrastructure assets in this region.

BRANZ has completed a study on atmospheric environmental conditions of the Bay of Plenty region. This involved:

- reviewing air monitoring results derived from previous studies carried out by Bay of Plenty Regional Council, BRANZ and other organisations
- conducting two runs of short-term monitoring of major air pollutants – ammonia, hydrogen sulphide and sulphur dioxide – at 31 sites across the region
- measuring the first-year atmospheric corrosion rates of mild steel, zinc and copper, at 31 sites across the region within two 1-year periods
- analysing and comparing the present and previous atmospheric corrosion rate data
- updating the region's atmospheric corrosivity map using the present air pollution and atmospheric corrosion rate data.

This experimental study found the following:

- Sulphur-containing gaseous species were detected with high concentrations in areas with geothermal and/or industrial emissions. The highest was 5.27 parts per billion (ppb) for hydrogen sulphide and 29.81 ppb for sulphur dioxide.
- Ammonia was detected with a typical average concentration of approximately 3–5 ppb in most areas. High concentrations (up to 26.28 ppb) were measured in areas very close to wastewater treatment plants.
- A large number of geothermal sources could combine to affect a much larger area than a single, isolated geothermal source, possibly through synergistic effects.
- Metallic materials showed varying atmospheric corrosion processes and responses when exposed to the diverse atmospheric environments in the region.
- At 11 sites, the newly measured metal atmospheric corrosion rates were higher than those measured in the 1980s. The percentage increase typically ranged from 17% to 377% for zinc and from 8% to 68% for mild steel.
- At 17 sites, the atmospheric corrosivity category determined by the present data was higher than that defined by the NZS 3604:2011 exposure zone map.

The following is then recommended:

- In areas from Waihī Beach to Te Puke, the zone C boundary would not be affected by the atmospheric corrosivity category defined by the present data.
- In areas from Te Puke to Whakatāne, the zone C boundary should be slightly widened inland. This is evident after consideration of the corrosion rate data

derived at Te Puke, Maketū, Edgecumbe and Whakatāne and the prevailing winds (northwesterly and southwesterly).

- In areas from Ōpōtiki to Waihau Bay, the zone C boundary should be slightly widened inland. This is necessary after consideration of the corrosion rate data derived at Ōpōtiki and Waihau Bay and the potential influences of the volcanic/geothermal emissions from Whakaari/White Island.
- In areas including Rotorua, Tikitere, Rotomā, Kawerau, Te Teko and Edgecumbe, the atmospheric corrosivity category should be increased from zone B to zone C after consideration of the following:
  - These areas have multiple active geothermal sources and also industrial activities that can emit various gases and/or particulate matter into the air.
  - Hydrogen sulphide and/or sulphur dioxide concentrations in these areas were higher than those in other non-geothermal, non-industrial, natural areas.
  - Winds from the south and west are common in these areas.
  - Relatively high rainfall levels were recorded in these areas.
  - First-year corrosion rates of mild steel, zinc and copper indicated a corrosivity category, zone C (C3 – Medium in ISO 9223:2012 *Corrosion of metals and alloys – Corrosivity of atmospheres – Classification, determination and estimation*) or even higher in some cases.
- Within those areas subject to geothermal influences, the microclimatic conditions defined by NZS 3604:2011 should still be applied. However, it would be appropriate to increase the current boundary from 50 m to 500 m. This is to align with SNZ TS 3404:2018 *Durability requirements for steel structures and components*.

Based on these, the atmospheric corrosivity map for the Bay of Plenty region has been updated and shown in Figure 1.
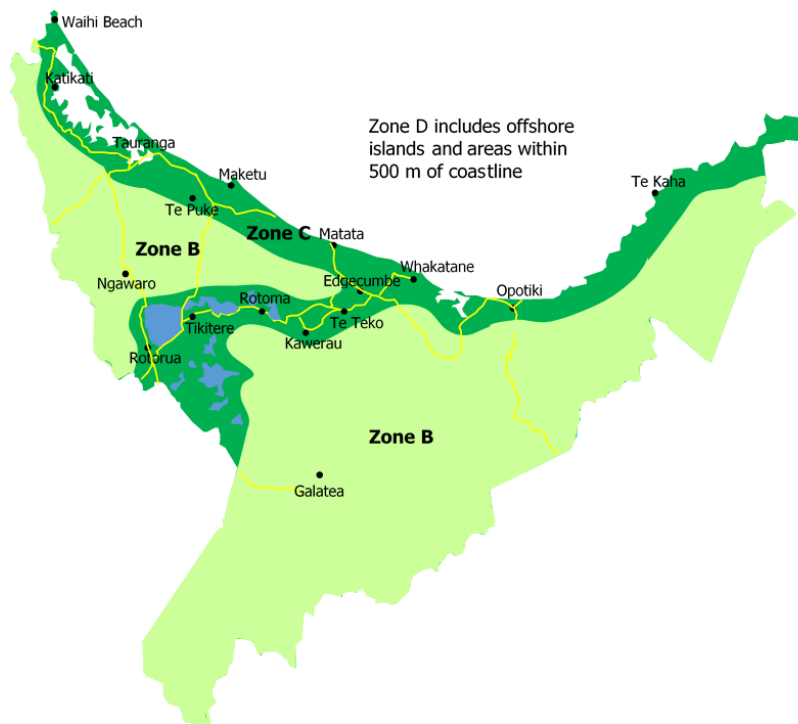
Figure 1. Atmospheric corrosivity map suggested for the Bay of Plenty region.

Key technical findings of this study may better support the specification of materials for buildings and associated infrastructure assets in the Bay of Plenty region. The updated regional map may help refine the atmospheric corrosivity map used in NZS 3604:2011.

1.   Introduction

Any functional building components, when chosen as Acceptable or Alternative Solutions, must meet or exceed the minimum durability requirements of the New Zealand Building Code, such as 5, 15 or 50 years. An atmospheric corrosivity zone micro-environment approach has been established and used to guide the specification of materials (particularly metals and alloys) and their protective measures (such as coatings and paints). These may include E2/AS1, NZS 3604:2011 and SNZ TS 3404:2018. It is necessary to accurately define the atmospheric corrosivity category of a specific geographic location for building using reliable approaches.

The atmospheric corrosivity map shown in NZS 3604:2011 can serve this purpose. This map was established by using metal atmospheric corrosion rate data experimentally derived by BRANZ in the 1980s and 1990s. The ongoing credibility of this map was evaluated by BRANZ in the early 2010s. This repeat study revealed significant changes in corrosion rates in some areas. Thorough analyses further indicated that, in some areas, the map has some limitations in its definition of atmospheric corrosivity zone boundaries.

BRANZ's interaction with the industry found that there was a need for information on atmospheric corrosivity and materials environmental degradation in fast-growing regions such as the Bay of Plenty.

The atmospheric environment of the Bay of Plenty region is affected by human-related activity emissions (such as agricultural, domestic heating, industry and vehicles) and natural sources (such as geothermal, marine and volcanic). Materials, buildings and associated infrastructure assets can be attacked simultaneously by sea salt, ammonia and/or sulphur-containing species in some areas. This complexity is not seen in other New Zealand regions as they normally have only one of those respective pollutants. This unique and challenging environment may lead to abnormal material degradation problems. BRANZ's previous inspection of small commercial buildings found that the premature deterioration of exterior claddings on commercial buildings was common and potentially serious in this region. However, the mechanisms behind these observations were not well understood.

A characterisation of the Bay of Plenty atmospheric environment and an update of its atmospheric corrosivity map is necessary. This is particularly evident when considering its fast population growth, strong demand for buildings and active infrastructure investments and development.

2. Bay of Plenty environment

2.1 Basic facts

The Bay of Plenty region is sheltered in the west, east and south and is one of the least windy areas in New Zealand (Chappell, 2013). It has two climate zones – Northern New Zealand and Central North Island, as defined by NIWA.[1]

- Northern New Zealand – this subtropical climate zone has warm humid summers and mild winters. Typical maximum daytime air temperatures are 22–26°C and 12–17°C for summer and winter respectively. Annual average sunshine hours are approximately 2,000, while Tauranga has more than 2,200 hours. Prevailing winds are from the southwest. Winter in this climate zone is usually unsettled and has more rain. Tropical storms may bring strong winds and heavy rainfall from the east or northeast during summer and autumn.
- Central North Island – this inland region, sheltered by high country to the south and east, has warm, dry and settled summers and cool, unsettled winters. Typical maximum daytime air temperatures are 21–26°C and 10–14°C for summer and winter respectively. Annual average sunshine hours are approximately 2,000–2,100 in most areas. Prevailing winds are from the southwest.

The atmospheric environment of the Bay of Plenty region is affected by agricultural, industrial, marine, geothermal and/or volcanic activities.

- It has a coastline approximately 260 km in length, extending east from Orokawa Bay (east of Waihī) towards East Cape ending near Lottin Point. It also has approximately 9,500 km² of coastal marine area (Bay of Plenty Regional Council, 2014).
- It has several areas with intensive industrial activities, such as primary and secondary timber processing in Rotorua, pulp and paper manufacturing and geothermal power generation in Kawerau and fertiliser manufacturing, speciality chemicals and asphalt processing in Tauranga.
- It has approximately 10 significant geothermal areas, including Kawerau, Rotorua, Tauranga and Waimangu.
- It has New Zealand's most active andesite stratovolcano, Whakaari/White Island. The island has been continuously releasing volcanic gases and has erupted in 2012, 2016 and 2019.

2.2 Geothermal/volcanic influences

Numerous geothermal systems with highly variable sizes and features have been identified in the Bay of Plenty region (Scott, 2010; Newson, 2010).

- Rotorua geothermal field (RGF) – this is at the southern margin of the Rotorua caldera in the active Taupō volcanic zone (TVZ). It underlies much of Rotorua city (Mroczek, Graham & Scott, 2011). This field has an area of approximately 18–28 km², and surface geothermal activity is mainly confined to three areas:
  - ○ Whakarewarewa/Arikikapakapa in the south.
  - ○ Kuirau Park/Ōhinemutu (on the shore of Lake Rotorua) to the northwest.

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[1] New Zealand's climate is complex and variable. NIWA has grouped selected locations into 12 broad climate zones based on statistical data of average rainfall and temperature – see https://niwa.co.nz/education-and-training/schools/resources/climate/overview

- o Government Gardens/Ngāpuna/Sulphur Bay to the northeast, which is also on the shore of Lake Rotorua (Gordon, Scott & Mroczek, 2005; Ratouis, O'Sullivan & O'Sullivan, 2014).

This field has approximately 1,200–1,500 known and recorded geothermal features. Reported surface expressions are highly variable and may include:
- o geysers
- o neutral to alkaline hot springs and pools
- o fumaroles
- o turbid acid pools and lakelets
- o mud pools and mud cones
- o warm or hot grounds and solfatara
- o dolines and craters (collapse and eruption).

Whakarewarewa has the largest concentration of geysers, which is recognised to be of regional, national and international significance.

- Kawerau – this geothermal field is near Kawerau township and located within eastern side of the TVZ. It is centred on the flood plains of the Tarawera River between Pūtauaki/Mount Edgecumbe and the Onepū Hills, covering an area of 19–35 km^2. It lies between the northeast-trending normal faults of the Taupō fault belt on its west and the northward-striking strike-slip faults of the North Island dextral fault belt to the east (Clarke, Townend, Savage & Bannister, 2009). Its basement surface is buried by volcanic materials and sediments to a depth of approximately 1 km and dips northward. The hydrothermal features in Kawerau are not as spectacular as those in Rotorua, but the temperature of geothermal fluids may still exceed 310°C (Milicich, Clark, Wong & Askari, 2016).
- Lake Tarawera – there are hot springs and warm seeps on the lake shore and fumaroles in the bush above.
- Lake Okataina Springs – several small warm seepages are identified on the lake shore.
- Lake Rotoiti – high heat flow has been recognised on the lake floor towards the eastern end.
- Tikitere (Hell's Gate) – it is approximately 16 km south of Rotorua and has an extensive area containing hot grounds, fumaroles, mud pools and springs.
- Taheke – this system features a moderate-size area of hot grounds, fumaroles and warm to hot springs.
- Lake Rotokawa – it has a few sinter-depositing springs and is the largest geothermal lake in New Zealand.
- Rotomā-Soda Springs – this area has warm-hot ground and springs, with lakeside seeps.[2]
- Waimangu-Rotomahana – it has large hot crater lakes, hot springs and grounds.
- Tauranga geothermal system – this system, extending approximately 60 km from Waihī Beach to Paengaroa, is a large-scale, low-temperature geothermal system (30–70°C).
- Whakaari/White Island – it lies approximately 48 km off the Bay of Plenty coastline and is an active andesitic stratovolcano with eruptions throughout the 20th century. It has active hot springs, steaming fumaroles and boiling muds. Yellow elemental sulphur precipitates could easily be found due to oxidation of H_2S gas expelled into the air from fumarole vents (composed of opaline silica).

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[2] A geothermal seep is any natural spring producing water that has been heated by geothermal processes to a temperature of more than 30°C (Keam, Luketina & Pipe, 2005).

These geothermal systems, particularly the high-temperature systems in the RGF, can emit large volumes of gases into the air. These may include (Lichti et al., 1996; Lee, Yang, Lan, Song & Tsao, 2005; Luketina, 2007):

- ammonia (NH_3)
- argon (Ar)
- carbon dioxide (CO_2)
- hydrogen (H_2)
- hydrogen chloride (HCl)
- hydrogen fluoride (HF)
- hydrogen sulphide (H_2S)
- methane (CH_4)
- nitrogen (N_2)
- steam (water vapour)
- sulphur dioxide (SO_2).

2.3 Air monitoring

Bay of Plenty Regional Council undertakes air monitoring activities as part of its statutory responsibilities. The current natural environmental regional monitoring network (NERMN) is a combination of a regional network of sites for environment monitoring, documentation and reporting and source-specific monitoring in targeted areas (Iremonger & Mackay, 2020). Meanwhile, other organisations, including ESR, the Ministry for the Environment and NIWA, have also performed monitoring activities in specific areas within the Bay of Plenty region.

2.3.1 Hydrogen sulphide concentrations

The RGF has numerous high-temperature geothermal systems that can emit high concentrations of sulphur-containing gases. These species, particularly H_2S, may have significant influences on human health and materials performance.

The Department of Health, in the 1970s, monitored H_2S levels within the Rotorua geothermal areas (Rolfe, 1980; Graham & Narsey, 1994). The highest concentration measured in the air was approximately 690 parts per billion (ppb) or above. A 3-month monitoring in 1978 gave a median concentration of approximately 20 ppb.

NIWA, in the 1990s, monitored H_2S concentrations within periods of 1–3 months at seven sites, including Whakarewarewa Village, Sunset Road, Te Ngae Road, Ōwhata, Jervis Street, Arawa Street and the lakefront. The highest H_2S concentration was found at the Te Ngae Road site close to Ti Street. The half-hour average concentration was approximately 72–108 ppb. H_2S concentrations measured at Whakarewarewa Village and Arawa Street were 66–100 ppb and 7–54 ppb respectively. At the other four sites, H_2S concentrations were 0.3–4 ppb (Iremonger, 2012a).

H_2S concentrations within short periods (10–60 minutes) along the shore of Lake Rotorua have been measured (Seigel, Penny, Seigel & Penny, 1986). The average concentration north of Ōhinemutu was approximately 5 ppb. H_2S concentrations at most sites from Ōhinemutu to the north tip of Sulphur Bay were 3–115 ppb. The lower Sulphur Bay sites had much higher concentrations of 1,200–2,700 ppb.

Bay of Plenty Regional Council performed long-term H_2S monitoring at Ti Street and Arawa Street sites from 1997/98 to 2005. The highest hourly concentration was approximately 2,800 ppb, while annual average concentrations were approximately

50–100 ppb. Monitoring at Te Ngae Road site showed that the annual average concentrations were approximately 90 ppb and 76 ppb in 2010 and 2011 respectively.

These previous studies revealed that high concentrations of airborne H_2S were normally found in the areas close to active, large-sized geothermal sources, such as Sulphur Bay in the central city.

These monitoring activities also revealed that H_2S concentration had a clear daily diurnal pattern. It started to increase during the late afternoon and early evening, remained high during the night, started to decrease during the morning and remained low during the day. In the yearly scale, H_2S concentrations during autumn and winter were higher than those during summer and spring. This pattern appeared to be related to meteorological factors such as wind speed and direction, atmospheric stability and rainfall (Iremonger, 2012a, 2012b).

However, these monitoring activities are not able to analyse the long-term trends of airborne H_2S concentration in Rotorua, such as whether there is an overall concentration increase or decrease with time. The data is not always comparable due to differences in monitoring instruments, location and period.

H_2S concentration maps had been developed for Rotorua using various techniques, roughly dividing the city into three regions (Horwell, Patterson, Gamble & Allen, 2005; Hinz, 2011). The central city (the corridor in the Mamaku ignimbrite to the east of the rhyolite domes following the northeast-southwest trending Ngāpuna and Roto-a-tamaheke faults) had high concentrations. West and east sides showed significantly lower concentrations. This agreed well with recent BRANZ measurements at six sites across the city (Li, Marston & Stokes, 2018).

In Kawerau, there are some paper and pulp manufacturing and geothermal power generation activities that can release H_2S from their processes and affect some areas nearby.

Ambient total reduced sulphur compounds (TRS) had been monitored at Kawerau, Edgecumbe and Te Teko by various organisations in the 1990s. Short-term (10–15 minute average) H_2S concentrations were approximately 640, 80, 50 and 20 ppb at the Tasman Mill site, the Kawerau site, the Edgecumbe site and the Te Teko site respectively. Annual H_2S average concentrations at these sites were approximately 4.8, 2.6, 0.6 and 0.2 ppb respectively (Iremonger, 2012a). These indicated a clear concentration dependence on the distance from the source.

In the period of August 2012 to June 2014, monitoring had been done to measure ambient H_2S in Kawerau and areas nearby. The highest hourly average H_2S concentration at Kawerau was approximately 210 ppb, which was approximately three times and six times higher than those at Edgecumbe and Te Teko respectively (Graham, 2014). This monitoring also found that H_2S concentrations had marked fluctuations from hour to hour, day to day and throughout the year due mainly to weather variations. In Edgecumbe and Te Teko, there was no obvious seasonal variations in H_2S concentrations. A small degree of seasonal variation was noticed in Kawerau during winter seasons. This is somewhat different to the observations in Rotorua.

Airborne H_2S concentrations had been monitored briefly at Rotomā in 1995 and ranged from approximately 5–15 ppb (Iremonger, 2012a).

Bay of Plenty Regional Council monitored airborne H_2S concentrations within Tauranga Harbour. The source may include industrial processes nearby and decomposing organic materials, such as sea lettuce. Extremely high H_2S concentrations (192,000 ppb peak concentration) were measured with organic decomposition in the early 2010s (Iremonger, 2012a). During the monitoring period of 2015–2020, the maximum hourly concentration was approximately 24 ppb (Iremonger & Mackay, 2020).

H_2S has a density of 1.36 kg/m^3 and is heavier than air. It tends to collect on the ground or in low-lying poorly ventilated areas. The dependence of airborne H_2S concentration on height above the ground has been investigated (Smid, Howe & Lynne, 2010). The concentration was found to be 0–100 parts per million (ppm), 0–57 ppm and 0–20 ppm at the feature entry at a height of 0.5 m above surface/entry and at 1 m above surface/entry respectively. This indicated an obvious decrease with height. BRANZ used passive tube sensors to measure airborne H_2S concentrations at three heights from the ground – 1 m, 2 m and 3 m – located next to a small-scale fumarole in Whakarewarewa. Average H_2S concentration in a 3-week period at 3 m was approximately 22 times lower than that at 1 m height (2.5 ppb versus 54.7 ppb) (Li, Marston & Stokes, 2018).

2.3.2   Sulphur dioxide concentrations

BRANZ measured airborne SO_2 concentrations at 10 sites in Rotorua (Li, Marston & Stokes, 2018). Monitoring was done within a 3-week period started on 21 June 2015 using passive tube sensors. At the six sites across the city from the west to the east, the highest concentration, approximately 37.8 ppb, was measured at the wastewater treatment plant site south of Sulphur Bay. Meanwhile, the west city area (Malfroy Road) appeared to have lower SO_2 concentrations than the east city area (Lynmore). Measurements taken within Scion's campus in Whakarewarewa showed that SO_2 concentration had an obvious dependence on the distance from the geothermal source. Concentrations measured at the two locations approximately 50–60 m away from a small-scale fumarole were approximately 3–4 times lower than those close to the source.

Ambient SO_2 has been monitored around the Mount Maunganui industrial area with fertiliser production, specialised chemicals and asphalt manufacturing and processing and shipping activities (Iremonger, 2010a).

ESR's short-term monitoring (from 14 October to 15 December 1994) in Totara Street, Tauranga showed that the 1-hour average and daily average SO_2 concentrations were approximately 86 ppb and 16 ppb respectively.

In the 2000s, three sites, including Totara Street, Maru Street and Chevron, were developed by Bay of Plenty Regional Council and Ballance Agri-Nutrients to map airborne SO_2 concentration and distribution. The highest maximum 1-hour SO_2 concentration was measured at the Totara Street site, approximately 260 ppb. The maximum 1-hour SO_2 concentrations at the Maru Street site and Chevron site were approximately 90 ppb and 100 ppb respectively. The maximum daily SO_2 concentrations were approximately 73 ppb, 24 ppb and 32 ppb at the Totara Street site, the Maru Street site and Chevron site respectively.

The data indicated that fertiliser manufacturing process and shipping activity had a dominating influence on the SO_2 profile within the southern Mount Maunganui area. Encouragingly, airborne SO_2 concentrations are showing reductions, probably due to

regulations with fuels and production process optimisation (Iremonger& Mackay, 2020).

As New Zealand's most active andesitic stratovolcano, Whakaari/White Island releases SO_2 with its activity (Wardell, Kyle, Dunbar & Christenson, 2001). The emission rate has been monitored since 2000s. It is estimated that approximately 162 tonnes of SO_2 are being released daily into the atmosphere (Iremonger, 2010a).

2.3.3   Particulate matter

Particulate matter is a type of air pollutant that is comprised of suspended particles in air with varying composition and size. It can arise from anthropogenic, industrial and/or natural activities. It can play an important role in eliciting health responses and effects (Anderson, Thundiyil & Stolbach, 2012; Kim, Kabir & Kabir, 2015). It can cause damage to building and construction materials, depending on the chemical composition and physical state. This is because it can be corrosive or it can absorb or interact with corrosive chemicals to accelerate degradation processes (Button & Simm, 1985; Ferm, Watt, O'Hanlon, De Santis & Varotsos, 2006; Saha, Pandya, Singh, Paswan & Singh., 2016).

The major sources for particulate matter in the Bay of Plenty region are domestic heating, transportation, shipping and industrial process. In certain periods, marine aerosols could also contribute. Particulate matter (PM_{10} and $PM_{2.5}$)[3] has been monitored by Bay of Plenty Regional Council continuously at a number of sites across the region from the 1990s (Iremonger, 2010b, 2012b; Iremonger & Mackay, 2020). These sites are mainly located in Mount Maunganui, Otūmoetai (Tauranga), Whakatāne and Rotorua.

High concentrations of particulate matter were observed at some sites. For example, in Rotorua, the maximum daily concentrations of PM_{10} were 162 μg/m^3 and 72 μg/m^3 at Edmund Road and Ngāpuna respectively (Iremonger, 2009, 2010b, 2012b). These were higher than the National Environmental Standards for Air Quality of 50 μg/m^3 for short-term exposure. Daily mean values of PM_{10} that closely approached or exceeded the standard value were observed in the Mount Maunganui industrial area (Iremonger & Mackay, 2020). These were supposedly related to anthropogenic and natural sources and overarching weather patterns. Encouragingly, long-term monitoring has shown a steady reduction both in number of exceedances and concentrations.

At most sites (for example, Edmund Road in Rotorua), there was a seasonal pattern with a wintertime increase observed, which was probably related to domestic heating (Iremonger & Mackay, 2020).

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[3] PM_{10} is particulate matter 10 micrometres or less in diameter. $PM_{2.5}$ is particulate matter 2.5 micrometres or less in diameter.

3. Objective

The Bay of Plenty region has various agricultural, geothermal and industrial activities. According to the results of previous air quality monitoring performed by different organisations, H_2S, SO_2 and particulate matter were present in the air. Their concentrations were highly location dependent. In particular, H_2S released from active geothermal sources within the TVZ and SO_2 from industrial activities can affect relatively large areas. These gaseous and solid species may have profound health effects on people living nearby. Therefore, they have been monitored by the regional council.

These airborne pollutant species are known to be corrosive and can significantly influence the environmental performance and durability of susceptible materials and components used for buildings and their associated infrastructure assets. Atmospheric corrosion rates of some metals had been experimentally measured at several sites within this region by BRANZ in the 1980s and 1990s. However, the effects of airborne pollution on regional atmospheric corrosivity have not been thoroughly investigated.

This study aimed to deliver a better understanding of the Bay of Plenty environment, particularly to map the corrosivity of the atmosphere in this region. This was achieved by undertaking:

- a survey of concentrations of major airborne pollutants, including H_2S, SO_2 and NH_3, across the Bay of Plenty region
- a collection of first-year corrosion rates of standard metals when exposed to the Bay of Plenty atmospheric environments
- an analysis and comparison of BRANZ's present and previous atmospheric corrosion rate data
- an update of the atmospheric corrosivity map for the Bay of Plenty region.

The findings will support the refinement of material specification schemes for design, construction and maintenance of new and existing buildings and infrastructure assets in the Bay of Plenty region. This region is demonstrating rapid economic and population growth and increasing spending in transportation.

4.   Experimental

4.1   Methodology

The presence, concentration and distribution of multiple airborne pollutants in the Bay of Plenty region are highly variable. They pose various risks to materials, buildings and infrastructure assets. Accordingly, this study had two interconnected research components to deliver its objectives: environmental condition characterisation and atmospheric corrosivity classification.

Effective state-of-the-art instruments such as passive diffusion tube sensors were deployed to monitor airborne pollutants. This was complemented by collecting meteorological data from the National Climate Database.

Atmospheric corrosivity categorisation was achieved by using internationally accepted methodologies to measure the first-year corrosion rates of standard metallic coupons at selected exposure sites (Knotkova, Boschek & Kreislova, 1995; Dong, Han & Ke, 2007). This method was used in BRANZ's studies in the 1980s and 2010s (Cordner, 1990; Duncan & Cordner, 1991; Li, Marston & Jones, 2013, 2015).

The environmental and corrosion rate data was reconciled to interpret environment-material interactions and to map the Bay of Plenty region's atmospheric corrosivity.

4.2   Exposure sites

In order to deliver representative environmental monitoring and atmospheric corrosion data, 31 exposure sites were established for the present study (Figure 2). Most of them were located within the wide Bay of Plenty region, and several were situated within the Taupō district (south end of the TVZ). Open and secure locations such as airports, farmland and wastewater treatment plants were chosen wherever possible. In some areas with geothermal, industrial or marine influences, a group of exposure sites (3–4 sites in close proximity to each other) were established. This was to investigate the effects of distance on atmospheric corrosivity and metal corrosion.

Two reference exposure sites have been established in the greater Wellington region (Figure 3). One is located within the BRANZ campus at Judgeford, Porirua, and the other at Oteranga Bay on the southwest coast of Wellington. The Judgeford site is in a sheltered semi-rural environment separated by approximately 3 km from the nearest saltwater, a tidal estuary, and further protected by gently rolling hills. It lies within zone C of the atmospheric corrosivity map in NZS 3604:2011. However, it is a fairly benign example of this classification as demonstrated by previous tests using mild steel and zinc (hot-dip galvanised steel and pure zinc). The Oteranga Bay site is approximately 60 m away from the sea, which passes through Cook Strait. It is a (very) severe marine environment with (very) strong westerly winds in some seasons. Its atmospheric corrosivity can be classified as ISO 9223:2012 C5 – Very high or C4 – High based on the first-year corrosion rates of mild steel and zinc.

A full list of the exposure sites is given in Table 1.

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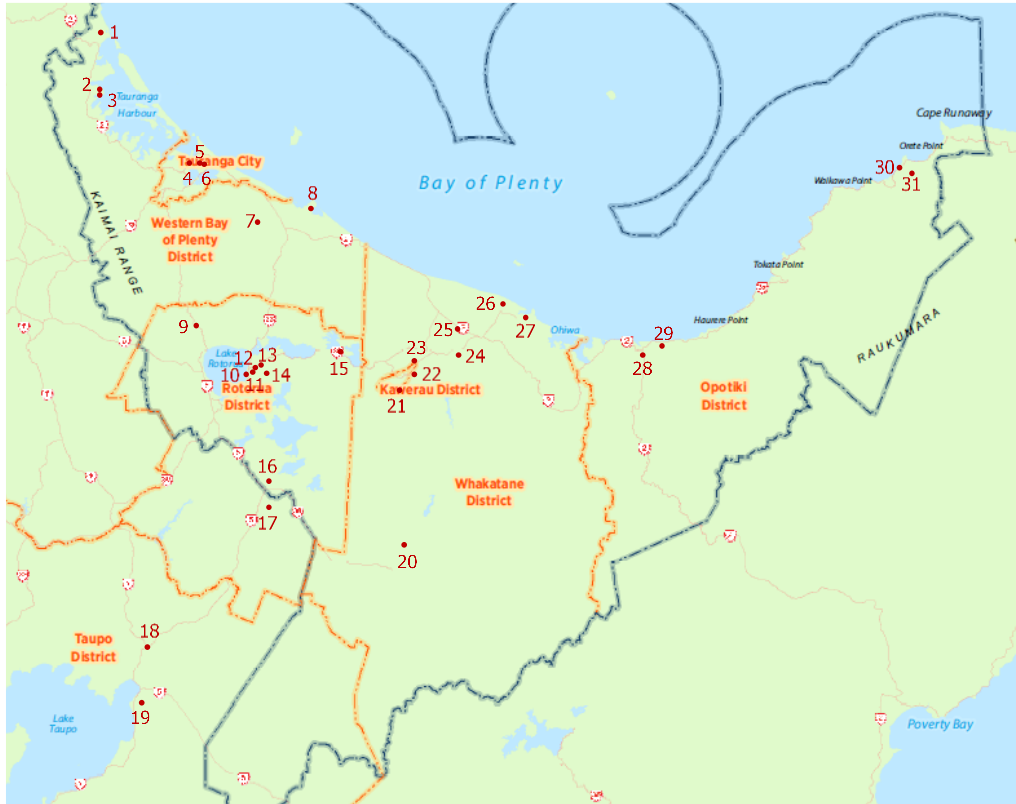
Map sourced from Bay of Plenty Local Council Boundaries Map Book.
https://maps.boprc.govt.nz/datasets/704c9b9594454c03ba615837167e0a01. Licensed under
the Creative Commons Attribution 3.0 New Zealand Licence.

Figure 2. Exposure sites established in the Bay of Plenty region and Taupō district.

Figure 3. Reference exposure sites established in the greater Wellington region.

Table 1. Location and characteristics of exposure sites established for this study.

No	Site	Location		Environmental characteristics
		Latitude	Longitude	
1	Waihī Beach	-37.43	175.94	Rural + marine Approximately 1.95 km west of the coastline
2	Pukakura Road, Katikati	-37.55	175.94	Rural + marine Approximately 0.22 km south of the coastline
3	Katikati	-37.56	175.93	Rural + marine + wastewater treatment Approximately 0.13 km north of the coastline
4	Chapel Street, Tauranga	-37.67	176.16	Urban + marine + wastewater treatment Approximately 0.02 km southeast of the coastline
5	Hewletts Road, Tauranga	-37.67	176.18	Industrial + marine Close to the port
6	Tauranga Airport	-37.67	176.20	Urban + industrial + air transportation Seawater relatively close at its west and south sides
7	Te Puke	-37.78	176.34	Rural + wastewater treatment Approximately 6.6 km southwest of the coastline
8	Maketū	-37.77	176.47	Rural + marine + wastewater treatment Approximately 0.3 km west of the Waihī Estuary
9	TECT All Terrain Park, Ngawaro	-37.95	176.15	Forest Approximately 22 km northwest of the RGF and approximately 31 km southwest of the coastline
10	Rotorua Airport	-38.11	176.32	Urban + air transportation + geothermal
11	2xx SH30, Tikitere	-38.07	176.35	Rural + geothermal Approximately 1.4 km southwest of the Hell's Gate geothermal field
12	3xx SH30, Tikitere	-38.07	176.36	Rural + strong geothermal Approximately 0.2 km southwest of the Hell's Gate geothermal park
13	Lake Rotokawau Road, Tikitere	-38.07	176.36	Rural + strong geothermal Approximately 0.12 km southeast of the Hell's Gate geothermal park
14	Lakes Ranch, Rotorua	-38.07	176.37	Rural + geothermal Approximately 1 km southeast of the Hell's Gate geothermal park
15	Rotomā	-38.04	176.55	Rural + geothermal Close to Lake Rotoehu and Lake Rotomā
16	Lake Okaro	-38.30	176.39	Rural + geothermal Approximately 1.3 km south of Waimangu volcanic valley
17	Wai-O-Tapu	-38.36	176.36	Rural + geothermal Approximately 0.7 km west of Wai-O-Tapu geothermal area
18	Wairākei	-38.62	176.10	Rural + geothermal Close to the Wairākei Power Station and Wairākei thermal valley
19	Taupō Airport	-38.74	176.08	Rural + air transportation + geothermal
20	Galatea	-38.41	176.74	Rural Inland

No	Site	Location		Environmental characteristics
		Latitude	Longitude	
21	Kawerau South	-38.10	176.70	Urban + geothermal Approximately 2.7 km southwest of industrial area (pulp and paper mill and geothermal power station)
22	Tamarangi Drive, Kawerau	-38.08	176.72	Industrial + geothermal + transportation
23	Onepu Spring Road, Kawerau	-38.06	176.73	Rural + industrial + geothermal Approximately 0.8 km northeast of industrial area (pulp and paper mill and geothermal power station)
24	Te Teko	-38.03	176.85	Rural
25	Edgecumbe	-37.98	176.83	Urban
26	Whakatāne Airport	-37.92	176.92	Marine + air transportation Approximately 1 km southwest of the coastline
27	Taroa Street, Whakatāne	-37.95	177.00	Urban Approximately 0.9 km southwest of the coastline and approximately 0.17 km southwest of Whakatāne River
28	Ōpōtiki	-38.01	177.28	Urban + marine Approximately 1.9 km south of the coastline
29	4xx SH35, Ōpōtiki	-37.99	177.32	Rural + marine Approximately 0.3 km south of the coastline
30	1xxxx SH35, Waihau Bay	-37.63	177.89	Marine Approximately 0.06 km east of the coastline
31	Orete Forest Road, Waihau Bay	-37.63	177.90	Rural Approximately 1.6 km southeast of the coastline
32	Oteranga Bay, Wellington	-41.29	174.63	Severe marine Approximately 0.06 km north of the coastline
33	Judgeford, Porirua	-41.11	174.95	Semi-rural Approximately 3.2 km southeast of Porirua Harbour

4.3   Environmental monitoring

Atmospheric environmental data, including ambient temperature, relative humidity, rainfall and wind speed, was downloaded directly from the National Climate Database, CliFlo, NIWA. Only some exposure sites established in the present study have meteorological stations nearby in operation. These include Rotorua Airport, Tauranga Airport, Whakatāne Airport, Taupō Airport, Te Puke and Galatea. However, not all atmospheric data needed for analysis was available for downloading.

Passive tube sensors were used to measure the concentrations of airborne H_2S, SO_2 and NH_3 at exposure sites. These sensors were supplied and analysed by Gradko Environmental, Hampshire, UK. They were installed approximately 2 m above ground level, and the typical monitoring period was 3–4 weeks. Airborne pollutants were chemically adsorbed and transformed into a stable compound in the tube. The concentrations were quantitatively determined by UV/visible spectrophotometry and/or ion chromatography with reference to calibration curves derived from the analysis of

standard solutions (UKAS accredited methods). This provided the averaged concentration of specific airborne pollutant during the exposure period.

4.4   Metallic coupons

Three types of metals – mild steel, copper and zinc – were used in the present study. They are commonly used for atmospheric corrosivity classification according to national and international standards. Zinc-based coatings, particularly hot-dip galvanised zinc coatings, are widely used in New Zealand for building and construction to protect steel-based components such as claddings and fastenings. Their chemical compositions are given in Table 2.

Table 2. Chemical compositions of metals (wt.%).

Metal	Element							
Mild steel	C	Al	Si	P	S	Ti	V	Nb
	0.08	0.039	0.02	0.016	0.024	<0.005	0.01	<0.0005
	Cr	Mn	Ni	Cu	Mo	B	Fe	
	0.02	0.60	0.02	0.01	<0.01	<0.0006	Bal.	
Zinc	Mg	Al	Cu	Sn	Pb	Fe	Cd	Ni
	<0.0005	0.002	0.127	<0.002	0.001	<0.002	<0.0005	<0.001
	Ti	Zn						
	0.103	Bal.						
Copper	Sn	Pb	Zn	Fe	Ni	P	S	Si
	0.006	0.010	≤0.0005	≤0.001	0.003	0.029	0.001	≤0.002
	Mn	Cd	Cr	Cu				
	≤0.0005	≤0.0005	≤0.0005	Bal.				

Considerable effort has been devoted to sample preparation (in terms of chemical composition, surface finish and field installation). This was to ensure the corrosion rates measured in BRANZ's previous and present studies are comparable for data interpretation and atmospheric corrosivity map updates.

Hot-dip galvanised (zinc) steel coupons were not used in the present study. Pure zinc was used instead. In the Bay of Plenty region, particularly within the TVZ, there are many high-temperature geothermal sources. They can discharge sulphur-containing gaseous species such as H_2S and SO_2 in high concentrations, as evidenced by air monitoring data shown in section 2.3. These can attack susceptible metals and lead to (very) high corrosion rates. Based on previous measurements, the hot-dip galvanised (zinc) steel coupons (Z300) would not last more than 1–2 years when exposed in some geothermally affected areas (Duncan & Cordner, 1991). To ensure the corrosion rate data collected at all exposure sites established by the present study is reliable and comparable, pure zinc coupons were then used.

Copper was not used in previous 1980s BRANZ studies. Copper is widely used in power distribution systems and does suffer atmospheric corrosion-related damage in some areas within the Bay of Plenty region, particularly in Rotorua. Previous BRANZ investigations revealed copper had a much higher sensitivity to the attack by (extremely) low concentrations of sulphur-containing geothermal species such as H_2S when compared with mild steel and zinc (Li, Marston & Stokes, 2018). It would be sensible to include copper to deliver reliable data that can be used to determine atmospheric corrosion risks of buildings and associated infrastructure assets.

Surface finish has an important role to play in atmospheric corrosion of metals (Hägg Mameng et al., 2016). In the present study, the surface finish of metallic coupons strictly followed BRANZ's previous practice. The surface of the mild steel coupon (~150 × 100 × 3 mm) was grit blasted to SA2.5 grade. The surfaces of copper (~150 × 100 × 3 mm) and zinc (~150 × 100 × 3 mm) were finished with 800 grit silicon carbon paper.

The coupons were numbered, and the dimensions of each coupon were measured. Prior to exposure, they were cleaned with acetone, dried with hot air and weighed to 0.001 g. The coupons were then sealed in separate plastic bags, shipped to exposure sites and mounted onto exposure racks using nylon fasteners immediately prior to rack installation.

4.5   Exposure racks

Exposure racks were fabricated with aluminium extrusions to support coupons and sensors (Figure 4).

Figure 4. A typical exposure rack with a selection of passive tube sensors.

Large separation distances were made between individual coupons to minimise potential cross-contamination and/or galvanic corrosion risk from corrosion products formed on mild steel, copper and zinc.

Nylon bolts, nuts and washers were used to fix the metallic coupons onto the racks to avoid potential galvanic corrosion risks between testing materials and aluminium extrusions. Washers of 12 mm thickness were also used to increase the gaps between the underside of the coupons and the aluminium supporting arms. This was to minimise water ponding and dirt accumulation in these sheltered areas and gaps.

The exposure racks were normally installed approximately 2 m above the ground and oriented towards north at an angle of 45°. At sites with (very) high levels of environmental pollution such as severe marine, the exposure racks were then positioned towards the pollution source.

4.6   Exposure scheme

Metallic coupons were exposed at selected sites according to the schedules below:

- November 2016 to November 2017: 1-year exposure (first exposure).
- November 2016 to November 2018: 2-year exposure.
- July 2017 to July 2018: 1-year exposure (second exposure).

A small number of coupons were also installed at additional sites (No. 15, 17 and 18 in Table 1) in November 2017 and retrieved in November 2018 (i.e. the third exposure).

4.7   Sample testing

After the designated exposure periods, metallic coupons were retrieved for lab analysis. Their surface morphology was examined visually and microscopically.

The corrosion products remaining on the coupon surface were then cleaned thoroughly following the procedures recommended by ASTM G1 *Standard practice for preparing, cleaning, and evaluating corrosion test specimens* to determine corrosion rates.

- Mild steel – 0.5 L/L hydrochloric acid (HCl, specific gravity = 1.19) + 3.5 g/L hexamethylenetetramine ($C_6H_{12}N_4$) at 20–25°C.
- Zinc – 100 g/L ammonium chloride (NH_4Cl) at 70°C.
- Copper – 0.1 L/L sulphuric acid (H_2SO_4, specific gravity: 1.84, 98%) at 20–25°C.

The chemically cleaned coupons were rinsed with flowing water, dried with hot air and reweighed to determine their mass losses due to atmospheric exposure. Several clean, unexposed metal coupons were also immersed into these chemical solutions for the same period as the cleaning process. Their mass losses were recorded for corrosion rate measurement correction.

4.8   Atmospheric corrosivity category

The classification of atmospheric corrosivity follows the definition of ISO 9223:2012 and uses the first-year metal corrosion rates (Table 3).

Table 3. Atmospheric corrosion classification based on 1-year corrosion rates.

ISO 9223:2012 category	Description	NZS 3604:2011 exposure zone	First-year corrosion rate (g/m²/year)		
			Mild steel	**Zinc**	**Copper**
C1	Very low		≤10	≤0.7	≤0.9
C2	Low	B	10–200	0.7–5	0.9–5
C3	Medium	C	200–400	5–15	5–12
C4	High	D	400–650	15–30	12–25
C5	Very high	E	650–1,500	30–60	25–50
CX	Extreme		1,500–5,500	60–180	50–90

Atmospheric corrosivity classification was mainly done using the first-year corrosion rates of mild steel and zinc. The corrosion rate of copper was used as a reference for classification in the present study. This was because previous BRANZ studies found that copper had a higher sensitivity to low concentrations of sulphur-containing geothermal emissions when compared to mild steel and zinc. Even in areas with trace quantities of sulphur-containing species, copper may still show a corrosion rate much higher than that in areas without geothermal influences.

5. Results and discussion

5.1 Climate

Climate data for selected exposure sites was directly downloaded from the National Climate Database, CliFlo. Climate factors analysed in the present study included ambient temperature, relative humidity (RH), rainfall and wind speed. Since field exposures were performed mainly within two periods (November 2016 to November 2017 and July 2017 to July 2018), weather data was also processed for these two periods separately. The 12-month average values are presented in Table 4.

Table 4. Weather at some exposure sites.

Climate factor	Period	Exposure site						
		Rotorua Airport	**Tauranga Airport**	**Whakatāne Airport**	**Taupō Airport**	**Te Puke**	**Edgecumbe**	**Galatea**
Temp (°C)	Nov 16–Nov 17	13.0	15.5	14.6	12.3	15.0	-	13.3
	Jul 17–Jul 18	13.5	16.0	15.1	12.7	~15.6*	-	13.7
RH (%)	Nov 16–Nov 17	85.6	80.5	85.1	84.2	-	-	81.2
	Jul 17–Jul 18	86.5	81.5	84.9	85.5	-	-	82.6
Rain (mm)	Nov 16–Nov 17	>1,712*	1,731	1,492	1,281	2,504	1,780	>1,235*
	Jul 17–Jul 18	>1,451*	1,466	>1,380*	>1074*	>1,841*	1,701	>577*
Wind speed (m/s)	Nov 16–Nov 17	3.7	3.9	3.4	3.7	1.5	-	2.2
	Jul 17–Jul 18	3.6	3.6	3.3	3.4	1.4	-	2.2

* Data was incomplete during the monitoring period.

These exposure sites had some differences in their climate.

- In general, those areas close to the coast, such as Tauranga, Whakatāne and Te Puke, had ambient temperatures higher than inland areas, such as Rotorua, Taupō and Galatea.
- Most areas in the Bay of Plenty region had relatively high annual rainfall. For example, Te Puke had an annual rainfall of approximately 2,500 mm.
- Wind speed was normally low as per NIWA's analysis.
- Tauranga Airport had the highest average ambient temperatures and wind speed but the lowest RH.
- Te Puke had a high average ambient temperature and the lowest wind speed.

5.2 Airborne pollution

Two airborne pollution monitorings were completed in the Bay of Plenty region. The BRANZ campus at Judgeford was used as the reference location.

- First monitoring – 28 November 2016 to 21 December 2016 – H_2S (25 sites), SO_2 (three sites) and NH_3 (seven sites).

- Second monitoring – 31 October 2017 to 28 November 2017 – H_2S (32 sites), SO_2 (32 sites) and NH_3 (31 sites).

The average concentrations of H_2S, SO_2 and NH_3 for an approximately 3-week exposure period are shown in Table 5.

Table 5. Airborne pollution monitoring results (ppb).

No	Site	H_2S		SO_2		NH_3	
		1st	2nd	1st	2nd	1st	2nd
1	Waihī Beach	0.07	<0.01		<0.69	5.15	3.45
2	Pukakura Road, Katikati		<0.01		<0.74		3.88
3	Katikati	0.08	<0.01		<0.69	26.28	24.76
4	Chapel Street, Tauranga	0.07	<0.01		1.17	3.75	3.37
5	Hewletts Road, Tauranga	0.05	0.01		7.74	4.36	4.60
6	Tauranga Airport	0.10	<0.01		1.03	4.25	2.81
7	Te Puke	0.11	<0.01		<0.69	6.65	4.07
8	Maketū	0.08	<0.01		0.83	10.24	7.95
9	TECT All Terrain Park, Ngawaro	0.04	0.12		9.73		x
10	Rotorua Airport	0.50	0.14	7.73	2.88		2.49
11	2xx SH30, Tikitere		1.32		10.23		4.22
12	3xx SH30, Tikitere		5.27		40.87		3.72
13	Lake Rotokawau Road, Tikitere	1.16	2.33	21.74	29.81		5.11
14	Lakes Ranch, Rotorua	0.39	0.18		3.25		2.61
15	Rotomā		0.01		<0.73		2.76
16	Lake Okaro	0.09	0.03		0.83		3.44
17	Wai-O-Tapu		0.14		3.55		5.26
18	Wairākei		0.02		0.74		3.53
19	Taupō Airport	0.10	<0.01	1.92	<0.72		2.72
20	Galatea	0.06	<0.01		<0.72		5.68
21	Kawerau South	0.22	0.02		1.14		4.66
22	Tamarangi Drive, Kawerau	0.15	0.10		2.70		5.51
23	Onepu Spring Road, Kawerau	0.21	0.12		2.49		6.77
24	Te Teko	0.11	<0.01		<0.72		5.13
25	Edgecumbe	0.05	<0.01		<0.72		5.23
26	Whakatāne Airport	0.08	<0.01		<0.72		4.83
27	Taroa Street, Whakatāne	0.05	<0.01		<0.72		2.29
28	Ōpōtiki	0.08	<0.01		0.87		3.95
29	4xx SH35, Ōpōtiki	0.30	<0.01		<0.72		2.88
30	1xxxx SH35, Waihau Bay	0.12	<0.01		<0.72		2.96
31	Orete Forest Road, Waihau Bay	0.09	0.01		2.73		2.57
32	Oteranga Bay, Wellington						
33	Judgeford, Porirua		<0.01		<0.63		1.73

x: Tube sensor for NH_3 was damaged during this monitoring.

5.2.1 Hydrogen sulphide

H_2S was detected with high concentrations at some exposure sites in or close to areas with known active geothermal sources, the RGF, Hell's Gate at Tikitere, Wai-O-Tapu and Kawerau. They included:

- Rotorua Airport
- 2xx SH30, Tikitere
- 3xx SH30, Tikitere
- Lake Rotokawau Road, Tikitere
- Lakes Ranch, Rotorua
- Wai-O-Tapu
- Kawerau South
- Tamarangi Drive, Kawerau
- Onepu Spring Road, Kawerau.

H_2S was detected in low concentrations at some sites that were relatively far away from active geothermal sources or where the geothermal sources nearby were not very active, particularly in gas emission. They included

- TECT All Terrain Park, Ngawaro – approximately 27 km northwest of Rotorua
- Rotomā, close to the Waitangi Soda Springs
- Lake Okaro – approximately 1.5 km south of the Waimangu volcanic valley which has numerous hot springs, steaming vents and geysers powered by a large magma dome (molten lava) approximately 2 km below the Earth's surface
- Wairākei – the exposure site is within the Wairākei geothermal field, which resides within volcanic strata of the TVZ, and the current surface features include steam-heated ground, thermal micro-climates (Hall of Fame Stream, Te Rautehia Stream, Wairākei Stream, Waipouwerawera) and thermal surface waters (Alum Lakes)
- Hewletts Road, Tauranga – the site is within the Mount Maunganui industrial area with shipping, fertiliser manufacturing and the airport.

At some exposure sites, the H_2S concentrations measured in the two monitoring periods were different, and it was difficult to determine the presence of H_2S in the air. These sites included:

- Waihī Beach
- Katikati
- Chapel Street, Tauranga
- Tauranga Airport
- Te Puke
- Maketū
- Taupō Airport
- Galatea
- Te Teko
- Edgecumbe
- Whakatāne Airport
- Taroa Street, Whakatāne
- Ōpōtiki
- 4xx SH35, Ōpōtiki
- 1xxxx SH35, Waihau Bay
- Orete Forest Road, Waihau Bay.

Special attention should be paid to the following sites:

- Taupō Airport – H_2S was detected with a concentration of approximately 0.10 ppb in the first monitoring period. Very low concentrations were measured in the second period. This exposure site is at the south end of the TVZ and is close to

Lake Taupō, a caldera volcano that is the most frequently active and productive rhyolite caldera in the world.

- Te Teko and Edgecumbe – these two exposure sites are northeast of Kawerau, which has a large timber, pulp and paper industrial complex and several geothermal power stations. Monitoring done by other organisations in 1992 and 2012–2014 indicated the presence of H_2S in the air (see section 2.3.1).
- Ōpōtiki and 4xx SH35, Ōpōtiki – these two exposure sites are approximately 55 km south of Whakaari/White Island, an active andesite stratovolcano. The island has been in a nearly continuous stage of releasing volcanic gas. H_2S and/or SO_2 could be included in these volcano gases.
- 1xxxx SH35 and Orete Forest Road, Waihau Bay – these two exposure sites are approximately 62 km southeast of White Island.

These seven sites might be subjected to weak and/or seasonal geothermal influences (i.e. a dependence on the monitoring period). The passive tube sensors used for monitoring have a typical sampling period of 4 weeks. Therefore, they could not continuously measure the concentrations of the airborne pollutants if replacements could not be deployed in a timely manner. Within the present study, it was impractical to deploy large numbers of passive sensors on a monthly basis to all exposure sites to deliver data covering the whole monitoring period (1–2 years). Consequently, airborne H_2S concentration data collected were not able to show the time-dependent variations across the whole monitoring period.

In those areas with strong geothermal influences, the concentration of H_2S decreased with the distance from a specific geothermal source. However, this monitoring indicated that sulphur-containing species could affect much larger areas due to the synergistic effects of a large number of geothermal sources, large or small, across the wider Bay of Plenty region.

5.2.2   Sulphur dioxide

SO_2 was detected in very high concentrations at two exposure sites in Tikitere – 3xx SH30 and Lake Rotokawau Road.

These two sites are very close to the Hell's Gate geothermal field. Concentrations of approximately 20–40 ppb were measured during two 3-week monitoring periods. These results were comparable to those measured by BRANZ at a site close to Sulphur Bay in Rotorua (Li, Marston & Stokes, 2018). However, it is currently unknown if the detected high concentrations of SO_2 in the air are directly released from the geothermal features or are an oxidation product of H_2S in the atmosphere under favourable transformation conditions (Cox & Sandalls, 1974; Spedding & Cope, 1984). Some monitoring results indicate that some geothermal features in the TVZ can release H_2S and SO_2 simultaneously while others might not have SO_2 present in their gaseous discharges (Luketina, 2007).

SO_2 was detected in relatively high concentrations at:

- 2xx SH30, Tikitere
- Rotorua Airport
- Hewletts Road, Tauranga
- TECT All Terrain Park, Ngawaro.

The site at 2xx SH30, Tikitere is approximately 1.4 km southwest of the Hell's Gate geothermal field. It could be influenced by geothermal emissions. However, this influence would be weaker when compared with the site at 3xx SH30, Tikitere.

The site at Rotorua Airport was influenced by the emissions from geothermal sources, predominantly Sulphur Bay in the central Rotorua city with winds from the west or southwest. However, due to its distance from the source, the concentrations of both H_2S and SO_2 measured were much lower, when compared with those at a site close to Sulphur Bay (Li, Marston & Stokes, 2018). This was another example of the distance effect on distribution and concentrations of geothermally sourced sulphur-containing species in the air.

The exposure site at Hewletts Road, Tauranga is within the Mount Maunganui industrial area. The air quality in this area is influenced by fertilisers, specialised chemicals and asphalt manufacturing and processing activities. Monitoring conducted by other organisations has detected high concentrations of SO_2 (see section 2.3.2).

It is difficult to understand why both H_2S and SO_2 were detected at the TECT All Terrain Park, Ngawaro. This site is approximately 27 km northwest of Rotorua.

SO_2 was detected in low concentrations at the following sites:

- Chapel Street, Tauranga – close to the Mount Maunganui industrial area.
- Tauranga Airport – close to the Mount Maunganui industrial area.
- Lakes Ranch, Rotorua – approximately 1 km southeast of the Hell's Gate geothermal field.
- Wai-O-Tapu – approximately 0.7 km west of Wai-O-Tapu geothermal area.
- Taupō Airport – approximately 30 km south of the Wairākei geothermal field and close to Lake Taupō, a caldera volcano.
- Kawerau South – approximately 2.7 km southwest of the industrial area (pulp and paper mill and geothermal station).
- Tamarangi Drive, Kawerau – close to the industrial area (pulp and paper mill and geothermal station). A variety of airborne sulphur-containing species have been detected by other organisations in Kawerau, including H_2S, dimethyl sulphide and dimethyl disulphide. It is not clear if the SO_2 detected in the present study was the primary species or the oxidation product of another species.
- Onepu Spring Road, Kawerau – approximately 0.8 km northeast of the industrial area (pulp and paper mill and geothermal power station).
- Orete Forest Road, Waihau Bay – a farming area with marine influences. It is approximately 62 km southeast of White Island, which can release SO_2 (see section 2.3.2). H_2S could be detected in the air in very low concentrations.

Airborne SO_2 could not be detected with high confidence at:

- Waihī Beach
- Pukakura Road, Katikati
- Katikati
- Te Puke
- Maketū
- Rotomā
- Lake Okaro
- Wairākei
- Galatea
- Te Teko

- Edgecumbe
- Whakatāne Airport
- Taroa Street, Whakatāne
- Ōpōtiki
- 4xx SH35, Ōpōtiki
- 1xxxx SH35, Waihau Bay.

5.2.3   Ammonia

There is very little information about ambient ammonia concentrations and emission rates in New Zealand. The most common source of ammonia within New Zealand is likely to be from productive farmland.

In the present study, ammonia (NH_3) was detected with a typical averaged concentration approximately 3–5 ppb at most exposure testing sites. A high ammonia concentration, approximately 26 ppb, was measured at Katikati wastewater treatment plant. This is approximately seven times higher than that measured in a rural area nearby (Pukakura Road, approximately 1 km north).

The discharge of ammonia from wastewater treatment plants has become a challenging issue. Ammonia is a critical nutrient in biological wastewater treatment. Free ammonia can pose inhibitory and/or biocidal effects on a variety of micro-organisms involved in different biological wastewater treatment processes and is widely seen at wastewater treatment plants due to the high levels of ammonium present in the systems.

5.2.4   Summary

It is relatively difficult to compare the present H_2S and SO_2 concentrations with those derived from previous monitoring activities. This is mainly due to the use of different measurement protocols.

For example, monitoring conducted by Bay of Plenty Regional Council normally gave 1-hour, daily and/or annual average values. Meanwhile, the present study only gave 3-week average values. However, at a small number of sites where monitoring has been done previously and currently, results showed some similarities. For example, the present study found that SO_2 concentrations in the industrial area of Tauranga were higher than those in other areas. This agreed well with the data derived from Bay of Plenty Regional Council.

5.3   Atmospheric corrosion morphology

Atmospheric environments in the Bay of Plenty region are diverse and can be polluted by emissions from geothermal, industrial, agricultural/farming activities and/or marine. These could affect atmospheric corrosion processes, and different metals may have varying responses to a specific pollutant in the air.

Mild steel, zinc and copper coupons after exposure were characterised visually. Figures 4–6 show their typical surface morphologies at representative environments.

Detailed characterisations were completed with electron microscopy (SEM/EDS) and X-ray diffraction (XRD) to investigate morphology, composition and phase structure of the corrosion products formed. (More in-depth results and investigation into the corrosion mechanisms and processes are available in other reports.)

Corrosion products formed on the metallic coupons exposed at Galatea, a rural environment, are adherent, compact and uniform (Figures 5a, 6a and 7a). They also seem to be thin. This is understandable as this inland environment is relatively benign due to the absence of corrosive pollutants in the air. The concentration of ammonia, approximately 5.68 ppb, is also comparable to that in other areas.

Figure 5. Mild steel coupons exposed for 1 year (July 2017 to July 2018) – a) Galatea – rural, b) Hewletts Road, Tauranga – industrial and marine, c) 3xx SH30, Tikitere – strong geothermal, d) Lakes Ranch, Rotorua – weak geothermal, e) Kawerau – geothermal and paper/pulp manufacturing, f) Waihau Bay – severe marine.

The surfaces of the metallic coupons exposed at Hewletts Road, Tauranga, an industrial area with marine influences, are relatively rough but still uniform (Figures 6b and 7b). They also collected and retained a reasonable amount of dust on their skyward surfaces. This was particularly evident on the zinc and copper coupons.

Figure 6. Zinc coupons exposed for 1 year (July 2017 to July 2018) – a) Galatea – rural, b) Hewletts Road, Tauranga – industrial and marine, c) 3xx, SH30, Tikitere – strong geothermal, d) Lakes Ranch, Rotorua – weak geothermal, e) Kawerau – geothermal and paper/pulp manufacturing, f) Waihau Bay – severe marine.

When exposed in an area with strong geothermal influence such as Tikitere (highest concentrations of H_2S and SO_2 among all exposure sites), severe corrosion took place on all metallic coupons. The mild steel coupons had very rough surfaces with very thick corrosion product layers formed on both skyward and groundward surfaces (Figure 5c). Frequently, a whole layer spalled off from their groundward surface and another layer with black corrosion products was revealed. A large number of physical defects, such as pores and cracks, were also observed. White powdery corrosion products were observed on zinc (Figure 6c). More powdery materials could be seen on the groundward surface. These could be easily removed to reveal another compact, dense and adherent layer. The dark blue corrosion products formed on copper were not adherent – some of them spalled off in small flakes (Figure 7c).

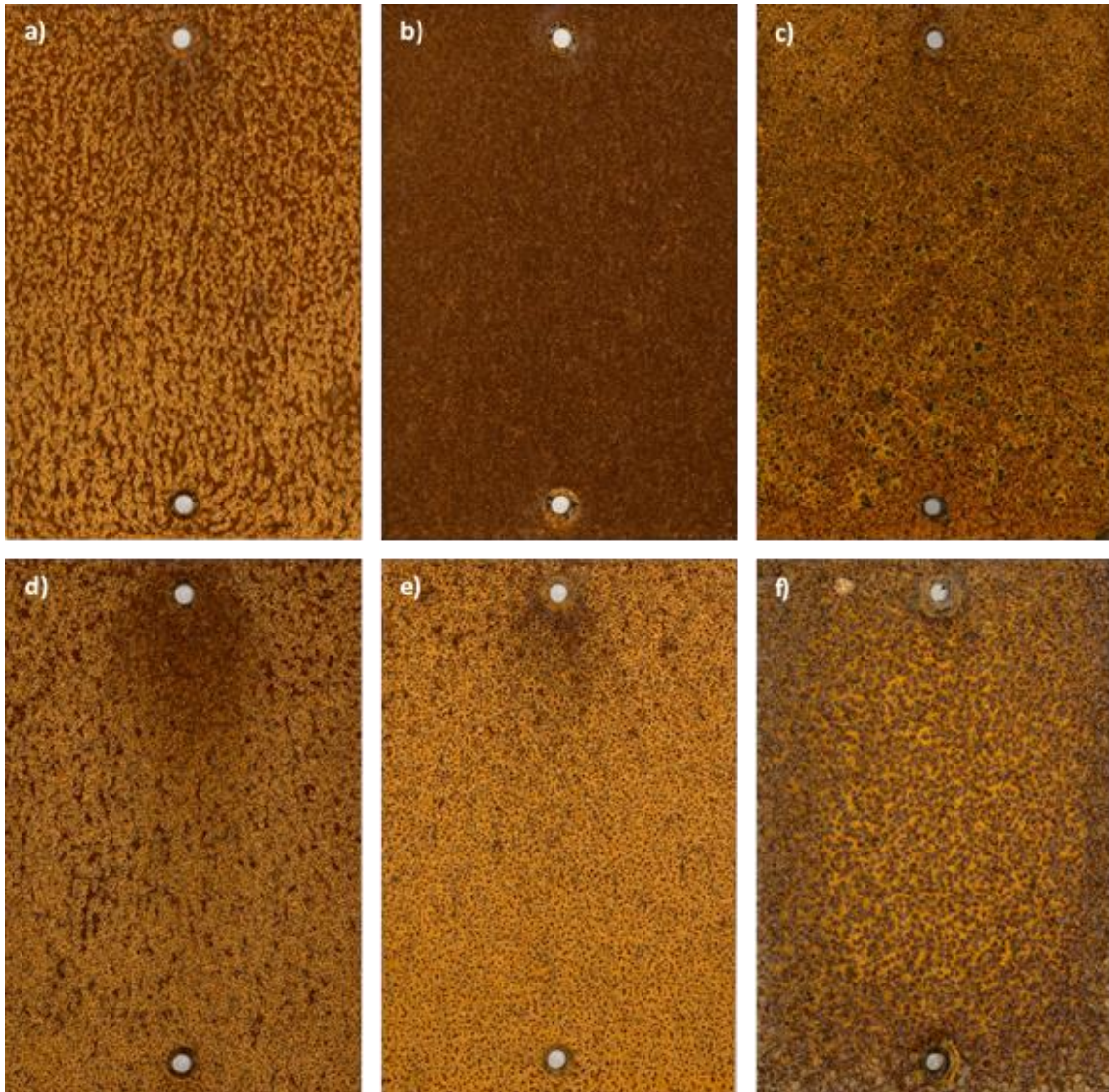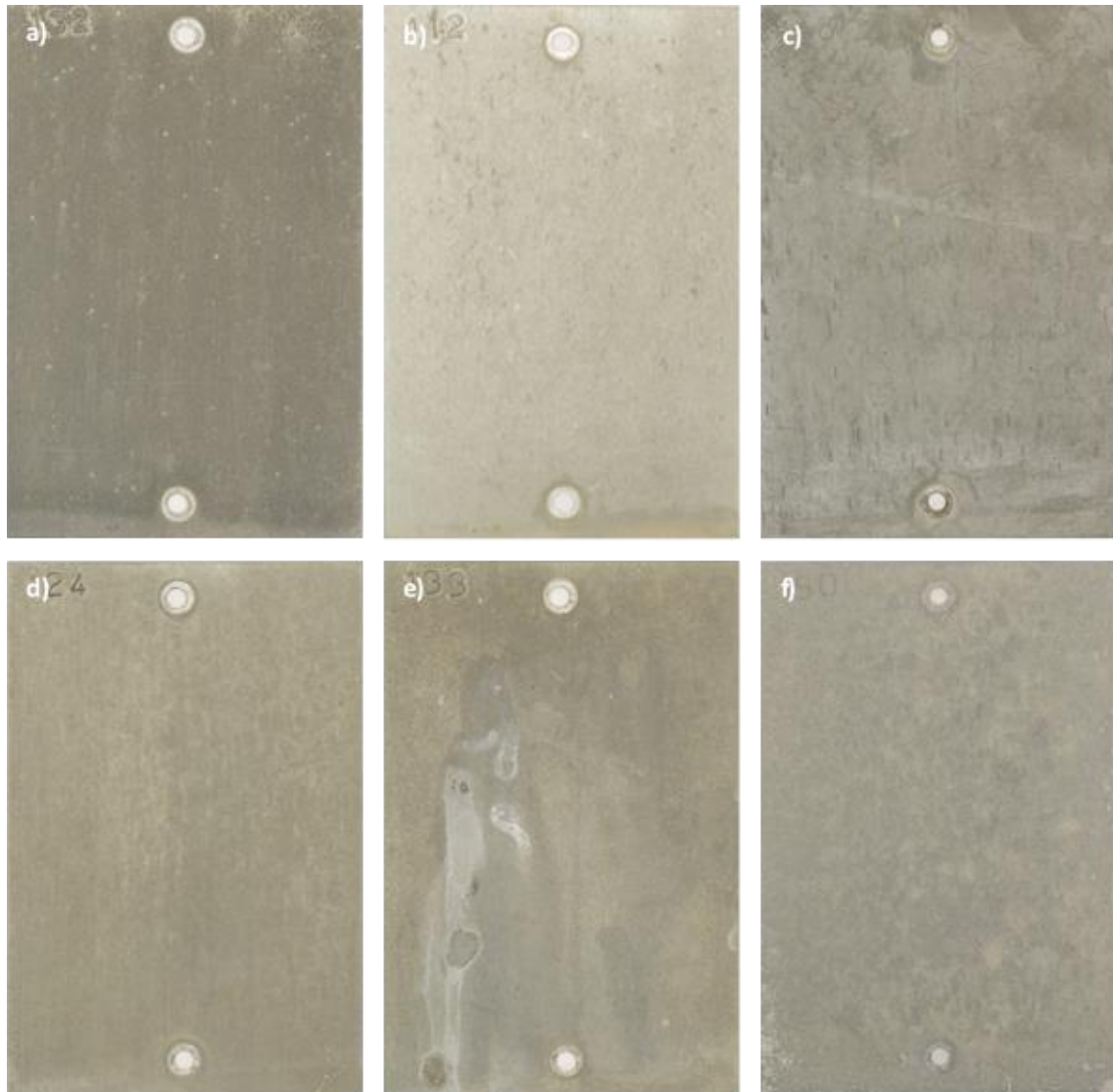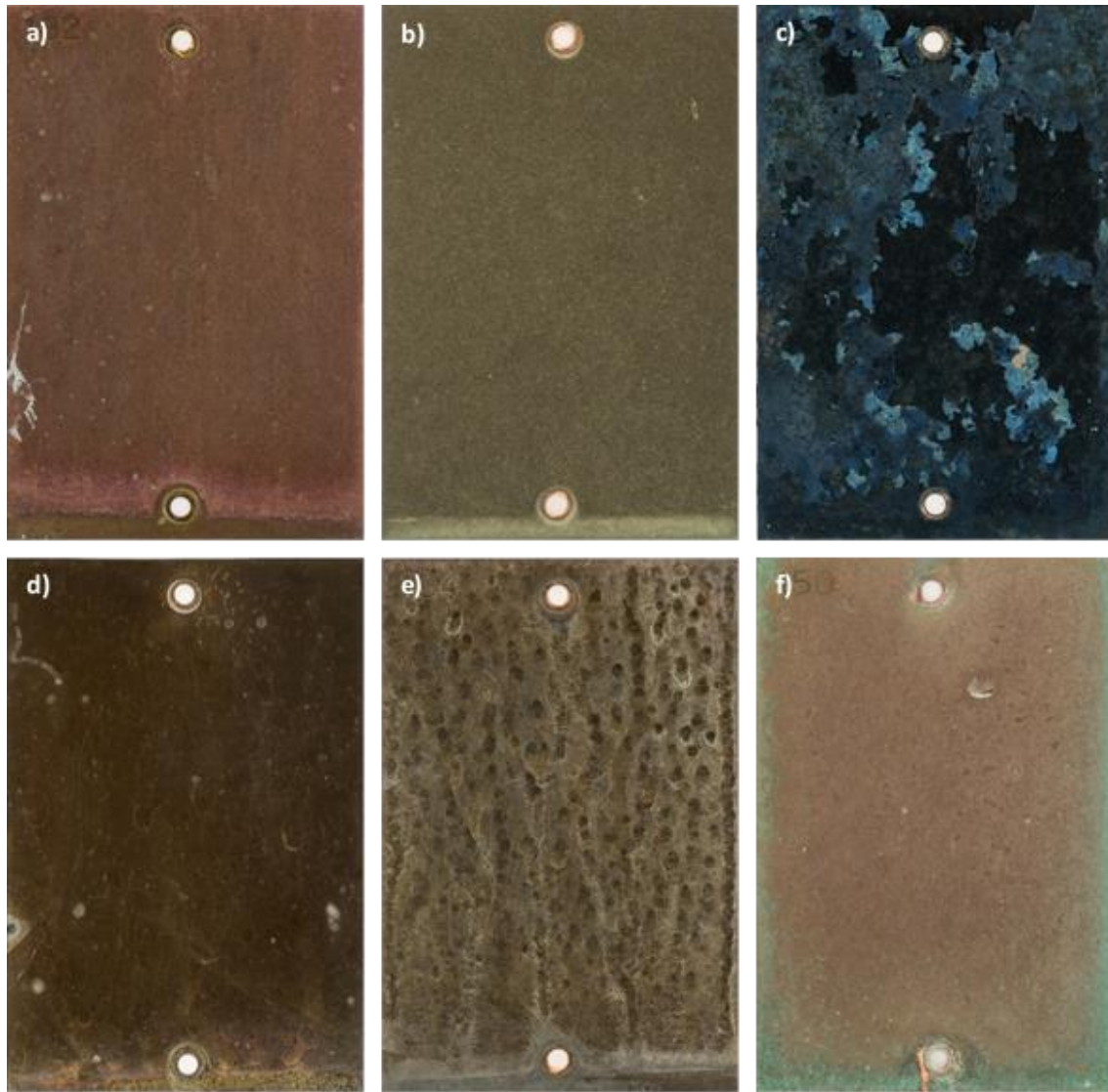**Figure 7. Copper coupons exposed for 1 year (July 2017 to July 2018) – a) Galatea – rural, b) Hewletts Road, Tauranga – industrial and marine, c) 3xx SH30, Tikitere – strong geothermal, d) Lakes Ranch, Rotorua – weak geothermal, e) Kawerau – geothermal and paper/pulp manufacturing, f) Waihau Bay – severe marine.**

The coupons exposed at Lakes Ranch, Rotorua were distant from the large-scale geothermal source Hell's Gate and corroded at lower rates. This was evidenced by the formation of corrosion products that were more compact and adherent to the underlying metal substrate. There was no corrosion product cracking or spallation on mild steel (Figure 5d) or copper (Figure 7d). The colour of the corroded copper was different from that of copper exposed to a strong geothermal environment (Figure 7c). Obviously, the lower concentrations of sulphur-containing species such as H_2S and SO_2 (as shown in Table 5) in this area contributed to this morphological and colour change.

At Onepu Spring Road, Kawerau, mild steel, zinc and copper coupons showed morphologies similar to those exposed at Lakes Ranch, Rotorua. The concentrations of airborne H_2S and SO_2 at these two exposure sites were also similar. There was a top layer with light-yellow powdery corrosion products on the dark brown base layer (Figure 7e). A high number of pit-like structures were also observed. This type of morphology was also observed with the copper samples exposed at another site close to the industrial area in Kawerau.

Kawerau has vast geothermal sources, particularly hot springs. It also has a pulp and paper mill and geothermal power station in operation. Emissions from these industrial activities are diverse and may include, in addition to H_2S, methyl mercaptan (MESH), dimethyl sulphide (DMS), dimethyl disulphide (DMDS), chlorine, chlorine dioxide, volatile organic compounds (VOCs) and particulates. These species were not monitored within the present study but may also contribute to the atmospheric corrosion of susceptible metals, either directly or indirectly. This may lead to further changes in corrosion mechanisms and processes and therefore changes in the micro-structure and composition of corrosion products and surface morphologies observed.

When exposed to severe marine environments, such as Waihau Bay in eastern Bay of Plenty and Oteranga Bay in Wellington, mild steel suffered severe corrosion. At Waihau Bay, a thin corrosion product layer detached from the skyward surface completely, and a rough surface with corrosion products of a slightly different colour was revealed (Figure 5f). This spallation phenomenon was similar to that observed with the mild steel coupons exposed in areas with strong geothermal influences (Figure 5c). However, the composition and phase structure of these corrosion product layers was quite different, evidenced in part by the presence of black sublayers on the coupons exposed at Tikitere. Furthermore, this spallation behaviour was different from that observed within another marine environment. At Oteranga Bay, some corrosion products were lost from the mild steel coupon surface as flakes, while others remained on the surface after 1-year exposure, leading to a very rough surface (Figure 8a).
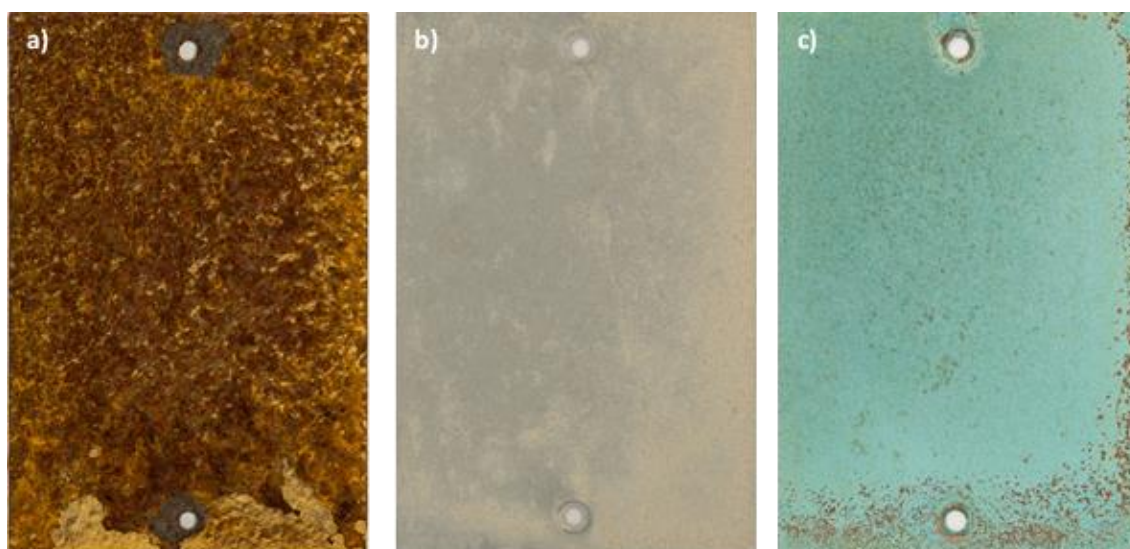
Figure 8. Coupons exposed for 1 year (July 2017 to July 2018) at Oteranga Bay, Wellington (severe marine) – a) mild steel, b) zinc, c) copper.

The surface morphologies of zinc coupons exposed at Waihau Bay and Oteranga Bay were similar, showing the formation of grey-white corrosion products (Figures 6f and 8b). However, it was evident that sand might interact with the growing corrosion products, leading to the formation of yellow patches on the skyward surfaces. Blue corrosion products covered the copper coupon exposed at Oteranga Bay (Figure 8c). Meanwhile, this blue layer was only observed in the edge areas of the copper coupon exposed at Waihau Bay (Figure 7f). Most of the surface was still brown – a colour typical in environments with no significant airborne chloride-containing or sulphur-containing pollutants.

The morphological differences between metal coupons exposed to these two severe marine environments could be a result of the following:

- Environmental condition variances – as shown in Table 5, sulphur-containing species such as H_2S and SO_2 could be detected during the exposure periods, although with relatively low concentrations at the site in Waihau Bay. This site is approximately 60 km southeast of White Island, which is an active cone volcano that has been in a nearly continuous stage of releasing volcanic gas. Therefore, the airborne aerosol contaminants in Waihau Bay could be more complex when compared with those from Oteranga Bay, an environment with marine aerosol effects only. The additional involvement of sulphur-containing species in the corrosion process could change corrosion product composition, micro-structure and surface morphology.
- Atmospheric corrosivity – the Oteranga Bay site is closer to the seawater and with (very) strong winds in some seasons, so the atmosphere is more corrosive with a higher contribution from marine-sourced salt particles. This would significantly change the growth rate of corrosion products. The colour comparison between Figure 7f and Figure 8c appeared to indicate that they were at different growth stages. It has been reported that the surface colour of copper changed from the initial salmon pink to reddish tones (cuprite) and subsequently to turquoise blue (basic copper chlorides on the cuprite) (Lopesino et al., 2018). The coverage of this blue layer normally increases with exposure time and is dependent on the chloride deposition rate and actual exposure conditions.

In this study, 1-year field exposure tests were mainly completed within two time periods – November 2016 to November 2017 and July 2017 to July 2018. This starting season difference seemed to have some impacts on the resulting surface morphologies.

An example cane be seen with the mild steel and zinc coupons exposed at Onepu Spring Road, Kawerau. The coupons exposed during the period November 2016 to November 2017 had a less-uniform corrosion product layer when compared with those exposed during the period July 2017 to July 2018. This morphological difference is quite obvious in Figures 5e and 6e and Figures 9a and 9b. Meanwhile, a large quantity of light-yellow powdery corrosion products was not observed on the copper coupon exposed during the November 2016 to November 2017 period (Figure 9c versus Figure 7e).

From Table 4, it can be observed that climatic conditions within these two periods showed some differences. When compared with November, July normally had a lower averaged ambient temperature, a higher rainfall and an increase in relative humidity. A higher rainfall and an increased humidity would result in a higher time of wetness. These would promote corrosion, particularly in the early stages, due mainly to the prolonged presence of moisture layers and increased dissolution of gaseous or solid corrosive media.
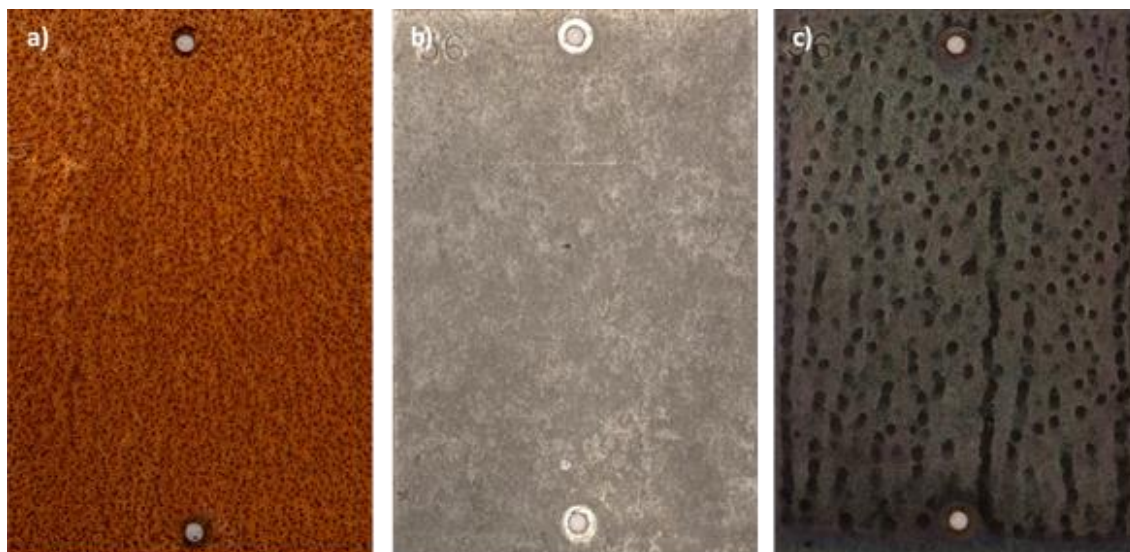
Figure 9. Coupons exposed for 1 year (November 2016 to November 2017) at Onepu Spring Road, Kawerau (geothermal and paper/pulp manufacturing) – a) mild steel, b) zinc, c) copper.

The surface colour of copper coupons varied largely, including reddish, brown, dark blue, green-blue and black in the present study. The surface colour of corroding copper is dependent on the phase composition of the growing corrosion products. Further, the phase composition is related to the atmospheric conditions (such as salinity and concentration of sulphur-containing species) and exposure time. Dark blue and/or black colours were mainly observed on the copper coupons exposed in areas with high concentrations of sulphur-containing geothermal emissions. In areas with relatively weak geothermal influences, a brown colour was normally seen. In addition, the colour can be affected by the morphology and micro-structure of the corrosion products formed (Li, Marston & Stokes, 2018).

5.4   Atmospheric corrosion rate

High corrosion rates were normally measured in areas with strong geothermal or marine influences, such as Tikitere and Waihau Bay (Table 6). For example, at 3xx SH30, the first-year corrosion rates of mild steel, zinc and copper were measured as 2,722 g/m^2/year, 71.1 g/m^2/year and 204.4 g/m^2/year respectively. This agreed very well with the morphological observations (Figures 5c, 6c and 7c,). However, the impacts of geothermal emissions reduced with distance. For example, at 2xx SH30, Tikitere, approximately 1.1 km southwest of 3xx SH30, Tikitere, the first-year corrosion rates of mild steel, zinc and copper were measured as 340 g/m^2/year, 15.4 g/m^2/year and 117.3 g/m^2/year respectively. This corresponded to a decrease of approximately 8.0, 4.6 and 1.7 times respectively. Table 5 shows that the concentrations of H_2S and SO_2 in the air were decreased by approximately four times with this distance.

In areas with relatively weak geothermal influences (low concentrations of H_2S and SO_2), such as Lakes Ranch, Rotorua and Rotorua Airport, relatively high corrosion rates have been observed with copper (35.6–49.9 g/m^2/year). This was similar to that observed in previous BRANZ studies (Li, Marston & Stokes, 2018). Again, this implied that copper had a higher sensitivity to the attack of airborne sulphur-containing species such as H_2S and SO_2 when compared with mild steel and zinc.

Table 6. First-year atmospheric corrosion rates of mild steel, zinc and copper.

No	Site	First-year atmospheric corrosion rate (g/m²/year)					
		Mild steel		Zinc		Copper	
		1st	2nd	1st	2nd	1st	2nd
1	Waihī Beach	193	215	6.5	5.6	11.5	13.4
2	Pukakura Road, Katikati		182		6.4		11.0
3	Katikati	190	227	7.9	11.8	8.0	11.7
4	Chapel Street, Tauranga	231	289	6.2	11.4	18.5	16.4
5	Hewletts Road, Tauranga	182	265	7.8	7.8	11.1	14.3
6	Tauranga Airport	261	298	10.5	9.9	12.6	16.3
7	Te Puke	201	259	8.5	8.7	13.8	15.4
8	Maketū	207	253	8.7	12.0	23.0	23.9
9	TECT All Terrain Park, Ngawaro	189	220	6.9	7.9	5.8	7.3
10	Rotorua Airport	202	223	7.2	8.8	43.0	35.6
11	2xx SH30, Tikitere		340		15.4		117.3
12	3xx SH30, Tikitere		2,722		71.1		204.4
13	Lake Rotokawau Road, Tikitere	1,477	1,315	13.6	18.8	98.6	111
14	Lakes Ranch, Rotorua	225	230	8.6	11.1	41.1	49.9
15	Rotomā	212[3rd]		9.8[3rd]		17.3[3rd]	
16	Lake Okaro	164	155	6.3	4.8	18.0	19.6
17	Wai-O-Tapu	180[3rd]		8.9[3rd]		47.5[3rd]	
18	Wairākei	141[3rd]		5.6[3rd]		19.1[3rd]	
19	Taupō Airport	135	144	4.9	5.9	13.8	14.8
20	Galatea	118	125	6.2	10.6	6.6	8.5
21	Kawerau South	199	224	8.1	9.7	20.0	21.3
22	Tamarangi Drive, Kawerau	204	249	6.7	7.0	26.6	31.7
23	Onepu Spring Road, Kawerau	248	259	9.6	12.2	31.3	39.1
24	Te Teko	196	221	7.5	7.3	10.0	10.1
25	Edgecumbe	205	206	7.7	10.5	13.1	11.7
26	Whakatāne Airport	273	325	8.1	9.5	19.3	16.3
27	Taroa Street, Whakatāne	206	221	8.4	5.9	16.1	17.7
28	Ōpōtiki	204	244	9.5	5.6	13.5	11.1
29	4xx SH35, Ōpōtiki	367	369	12.8	12.9	20.9	19.4
30	1xxxx SH35, Waihau Bay	583	799	15.5	17.5	35.6	37.9
31	Orete Forest Road, Waihau Bay	247	253	5.5	7.0	17.2	13.7
32	Oteranga Bay, Wellington		1,276		27.6		65.1
33	Judgeford, Porirua		221		6.9		15.5

1st – November 2016 to November 2017, 2nd – July 2017 to July 2018, 3rd – November 2017 to November 2018.

In Kawerau, with paper/pulp manufacturing and geothermal power generating activities, corrosion rates of mild steel and zinc were found to be comparable with those in other non-industrial, natural environments. However, the corrosion rates of copper were higher than those in other non-industrial, natural areas. Sulphur-containing species such as H_2S and SO_2 were detected in Kawerau with concentrations significantly lower than geothermal areas (such as Rotorua and Tikitere) but still higher than other non-industrial natural areas. As discussed, copper seems to have a higher

sensitivity towards sulphur-containing species, although the mechanisms behind these observations still remain poorly understood (Li, Marston & Stokes, 2018). This may explain why copper was observed to have higher corrosion rates in this mixed industrial-geothermal area. Additionally, sulphur in forms other than H_2S or SO_2 may be present in the Kawerau atmosphere and contribute to metal atmospheric corrosion. However, these species were beyond the experimental scope of the present study.

Dust and/or particulate matter were observed on the surfaces of coupons exposed at Hewletts Road, Tauranga. Meanwhile, SO_2 was detected in the air by the present study (approximately 7.74 ppb) and by Bay of Plenty Regional Council monitoring (daily maximum approximately 30 ppb). However, corrosion rates of mild steel (182–265 $g/m^2/year$), zinc (7.8 $g/m^2/year$) and copper (11.1–14.3 $g/m^2/year$) measured at this site were not exceptionally high. This implied that the solid deposits and airborne SO_2 did not appear to significantly affect the corrosion processes or the protective capability of the corrosion products formed on the metal surface.

Similarly, with morphological observations, the starting season seemed to have an influence on the first-year atmospheric corrosion rate. In general, the metallic coupons exposed during the July 2017 to July 2018 period corroded faster than those exposed during the 1-year period November 2016 to November 2017. However, the difference was not huge. These two periods had different atmospheric environmental conditions in terms of temperature, RH and/or rainfall, as shown in Table 4. Particularly, the winter start tended to deposit more rainfall or moisture onto the metal surface, therefore providing a larger time of wetness and a higher chance of collecting more solid or gaseous pollutants. This could affect the initial stages of metal corrosion and result in a higher corrosion rate than normal. However, this increasing effect appeared to attenuate with increasing exposure time. This phenomenon has been observed within a previous BRANZ study (Li, Marston & Jones, 2015).

The starting season effect was also more evident in the areas with relatively high concentrations of airborne pollutants such as Tikitere (geothermal), Kawerau (geothermal and industrial) and Waihau Bay (marine). In these areas, sea salt particles and/or sulphur-containing gaseous species may have a higher contribution to overall corrosion processes by dissolving into the water/moisture layers sitting on the metal surface.

The present study with two representative starts could produce a dataset that is capable of estimating atmospheric corrosion rates in areas of concern.

5.5   Atmospheric corrosion rate comparison

In the 1980s, BRANZ carried out a nationwide atmospheric corrosivity survey (Cordner, 1990; Duncan & Cordner, 1991). Some exposure sites were established within the Bay of Plenty region (and TVZ) to measure metal atmospheric corrosion rates. The present study established 31 exposure sites in the Bay of Plenty region. An analysis of exposure site location details indicated that 11 exposure sites were used for both the previous and present studies.

It is possible to compare the first-year metal atmospheric corrosion rates derived from these two studies. This comparison is presented as the percentage of increase or decrease in Table 7. Note that, if more than one corrosion rate is available, the highest is used for this analysis.

Table 7. Comparison of first-year metal atmospheric corrosion rates between previous and present BRANZ studies.

No	Site	Exposure	Mild steel		Zinc*		Present vs previous
			1st	2nd	1st	2nd	
1	Waihī Beach	Present	193	215	6.5	5.6	MS: 32% ↑
		1980s	163		4.4		Zn: 48% ↑
3	Katikati	Present	190	227	7.9	11.8	MS: 55% ↑
		1980s	146		3.8		Zn: 210% ↑
6	Tauranga Airport	Present	261	298	10.5	9.9	MS: 53% ↑
		1980s	195		4.4		Zn: 139% ↑
7	Te Puke	Present	201	259	8.5	8.7	MS: 68% ↑
		1980s	154		2.8		Zn: 211% ↑
10	Rotorua Airport	Present	202	223	7.2	8.8	MS: 8% ↑
		1980s	207		5.7		Zn: 54% ↑
11	2xx SH30, Tikitere	Present		340		15.4	MS: 40% ↑
		1980s	243		9.5		Zn: 62% ↑
18	Wairākei	Present	141[3rd]		5.6[3rd]		MS: 9% ↓
		1980s	155		4.8		Zn: 17% ↑
19	Taupō Airport	Present	135	144	4.9	5.9	MS: 38% ↑
		1980s	104		4.1		Zn: 44% ↑
21	Kawerau South	Present	199	224	8.1	9.7	MS: 12% ↓
22	Tamarangi Drive, Kawerau		204	249	6.7	7.0	
23	Onepu Spring Road, Kawerau		248	259	9.6	12.2	Zn: 28% ↑
		1980s	294		9.5		
25	Edgecumbe	Present	205	206	7.7	10.5	MS: 41% ↑
		1980s	146		2.2		Zn: 377% ↑
26	Whakatāne Airport	Present	273	325	8.1	9.5	MS: 66% ↑
		1980s	196		5.1		Zn: 86% ↑

1st – November 2016 to November 2017, 2nd – July 2017 to July 2018, 3rd – November 2017 to November 2018.
* Hot-dip galvanised zinc coated steel coupons were used for the test in the 1980s.
↑ increase, ↓ decrease.

At all 11 exposure sites, the first-year corrosion rate of zinc measured in the present study was higher than that measured in the 1980s. The percentage of increase was typically ranging from 17% to 377%. For example, the zinc corrosion rate increased significantly from 2.2 $g/m^2/year$ to 10.5 $g/m^2/year$ at Edgecumbe. The mild steel corrosion rate increased at nine sites. For example, it increased from 196 $g/m^2/year$ to 325 $g/m^2/year$ at Whakatāne Airport. However, the percentage of increase, typically ranging from 8% to 68%, was much lower than that of zinc. Meanwhile, a small decrease (approximately 9–12%) was observed at two sites – Wairākei and Kawerau.

Many factors can contribute to this atmospheric corrosion rate difference.

Climate

When exposed to the atmospheric environment, the metal atmospheric corrosion process is influenced by multiple climatic factors. These typically include ambient temperature, relative humidity, rainfall, wind (speed and direction) and solar irradiation. These factors can change over time and affect atmospheric corrosion measurement. Effort has been devoted to comparing the climate conditions in BRANZ's previous and present studies. However, essential data is not available for the specific period in the 1980s, and therefore, comparison cannot be made.

Air pollution

As shown in Table 1, these 11 exposure sites are located within areas with geothermal, industrial or marine influences. Chloride-containing sea salt particles or sulphur-containing gaseous species (as discussed in section 5.2) can play various roles in atmospheric corrosion processes occurring on the metals exposed at these sites. The concentration and distribution of these airborne pollutants can be affected by changes in climate and geothermal/industrial activities. However, as discussed in section 5.2.4, it is impossible to determine long-term air pollution variations based on the data available.

Material

It is arguable that different types of zinc coupons were used for these two studies. The 1980s BRANZ study used hot-dip galvanised steel coupons (Z300), while the present study used pure zinc. Hot-dip galvanised zinc coating may corrode differently from pure zinc, probably due to the differences in their chemical composition (alloying elements), micro-structure and/or phase structure. For example, the hot-dip galvanised zinc coating normally has a series of Zn-Fe phases and has a spangle structure on its top surface (Marder, 2000). However, BRANZ's tests completed at Judgeford indicated that the corrosion rates derived from pure zinc and hot-dip galvanised coupons were comparable. Furthermore, the corrosion rates measured at some exposure sites in the present study could be up to approximately five times higher than that in the 1980s. This difference cannot be explained when only considering the possible compositional and/or structural differences in the coupons used. Meanwhile, the mild steel coupons used in the present study have a very similar composition and surface finish to those used in the 1980s. This makes the data derived from different exposure tests comparable, as evidenced by previous BRANZ studies (Li, Marston & Jones, 2013, 2015).

5.6   Atmospheric corrosivity classification

The atmospheric corrosivity category of each exposure site was determined by the first-year corrosion rates of mild steel, zinc and copper individually, according to ISO 9223:2012 (Table 8).

The atmospheric corrosivity category defined by the map shown in NZS 3604:2011 section 4 *Durability* was also given. Note that atmospheric corrosivity categories were only estimated at some exposure sites, since the exact location of the exposure zone boundary, with regard to geographic coordinates, could not be well established on the current map scale.

Within the 31 exposure sites, the atmospheric corrosivity categories of 17 sites determined by the present first-year corrosion rates of mild steel and zinc are higher than those defined by the map. These are:

- TECT All Terrain Park, Ngawaro
- Rotorua Airport
- 2xx SH30, Tikitere
- 3xx SH30, Tikitere
- Lake Rotokawau Road, Tikitere
- Lakes Ranch, Rotorua
- Rotomā
- Wai-O-Tapu

- Wairākei
- Kawerau South
- Tamarangi Drive, Kawerau
- Onepu Spring Road, Kawerau
- Te Teko
- Edgecumbe
- Ōpōtiki
- Orete Forest Road, Waihau Bay
- Galatea.

Apart from Ōpōtiki, Orete Forest Road (Waihau Bay) and Galatea, these sites are subject to geothermal and/or industrial influences, either strong or weak. As discussed in section 5.2, H_2S and/or SO_2 were detected in their atmospheric environments.

At 14 exposure sites, the atmospheric corrosivity categories determined by the present first-year corrosion rates of mild steel and zinc are similar to or same as those defined by the map. These are:

- Waihī Beach
- Pukakura Road, Katikati
- Katikati
- Chapel Street, Tauranga
- Hewletts Road, Tauranga
- Tauranga Airport
- Te Puke
- Maketū
- Taupō Airport
- Whakatāne Airport
- Taroa Street, Whakatāne
- 4xx SH35, Ōpōtiki
- 1xxxx SH35, Waihau Bay
- Lake Okaro.

Apart from Lake Okaro, these sites are close to the coastline and therefore subject to marine influences, either strong or weak.

For 22 sites, the atmospheric corrosivity category determined by the first-year copper corrosion rate would be at least one level higher than that determined by the mild steel or zinc first-year corrosion rate. These are:

- Chapel Street, Tauranga
- Tauranga Airport
- Te Puke
- Maketū
- Rotorua Airport
- 2xx SH30, Tikitere
- Lake Rotokawau Road, Tikitere
- Lakes Ranch, Rotorua
- Rotomā
- Lake Okaro
- Wai-O-Tapu
- Wairākei
- Taupō Airport

- Galatea
- Kawerau South
- Tamarangi Drive, Kawerau
- Onepu Spring Road, Kawerau
- Whakatāne Airport
- Taroa Street, Whakatāne
- 4xx SH35, Ōpōtiki
- 1xxxx SH35, Waihau Bay
- Orete Forest Road, Waihau Bay.

The phenomenon of copper corrosion sensitivity was obvious at those exposure sites with strong or weak geothermal influences. Previous BRANZ studies have found that copper was more prone to geothermal attack than mild steel and zinc, particularly in areas with low concentrations of sulphur-containing species (Li, Marston & Stokes, 2018). Copper and its alloys are widely used in power distribution networks. Therefore, this increased atmospheric corrosion risk revealed in previous and present BRANZ studies should be carefully considered when assigning an atmospheric corrosivity category in areas with airborne sulphur-containing species.

Table 8. Atmospheric corrosivity category.

No	Site	Mild steel		Zinc		Copper		NZS 3604:2011 exposure zone
		1st	2nd	1st	2nd	1st	2nd	
1	Waihī Beach	C2	C3	C3	C3	C3	C3	C2/C3
2	Pukakura Road, Katikati		C2		C3		C3	C2/C3
3	Katikati	C2	C3	C3	C3	C3	C3	C2/C3
4	Chapel Street, Tauranga	C3	C3	C3	C3	C4	C4	C3
5	Hewletts Road, Tauranga	C2	C3	C3	C3	C3	C4	C3
6	Tauranga Airport	C3	C3	C3	C3	C4	C4	C3
7	Te Puke	C3	C3	C3	C3	C4	C4	C3/C2
8	Maketū	C3	C3	C3	C3	C4	C4	C3/C2
9	TECT All Terrain Park, Ngawaro	C2	C3	C3	C3	C3	C3	C2
10	Rotorua Airport	C3	C3	C3	C3	C5	C5	C2
11	2xx SH30, Tikitere		C3		C4		>CX*	C2
12	3xx SH30, Tikitere		CX		CX		>CX*	No specific definition
13	Lake Rotokawau Road, Tikitere	C5	C5	C3	C4	>CX*	>CX*	No specific definition
14	Lakes Ranch, Rotorua	C3	C3	C3	C3	C5	C5	C2
15	Rotoma	C3[3rd]		C3[3rd]		C4[3rd]		C2
16	Lake Okaro	C2	C2	C3	C2	C4	C4	C2
17	Wai-O-Tapu	C2[3rd]		C3[3rd]		C5[3rd]		C2
18	Wairākei	C2[3rd]		C3[3rd]		C4[3rd]		C2
19	Taupō Airport	C2	C2	C2	C3	C4	C4	C2
20	Galatea	C2	C2	C3	C3	C3	C3	C2
21	Kawerau South	C2	C3	C3	C3	C4	C4	C2
22	Tamarangi Drive, Kawerau	C3	C3	C3	C3	C5	C5	No specific definition
23	Onepu Spring Road, Kawerau	C3	C3	C3	C3	C5	C5	C2
24	Te Teko	C2	C3	C3	C3	C3	C3	C2
25	Edgecumbe	C3	C3	C3	C3	C4	C3	C2
26	Whakatāne Airport	C3	C3	C3	C3	C4	C4	C3
27	Taroa Street, Whakatāne	C3	C3	C3	C3	C4	C4	C3

No	Site	Mild steel		Zinc		Copper		NZS 3604:2011 exposure zone
		1st	2nd	1st	2nd	1st	2nd	
28	Ōpōtiki	C3	C3	C3	C3	C4	C3	C2
29	4xx SH35, Ōpōtiki	C3	C3	C3	C3	C4	C4	C3
30	1xxxx SH35, Waihau Bay	C4	C5	C4	C4	C5	C5	Sea spray
31	Orete Forest Road, Waihau Bay	C3	C3	C3	C3	C4	C4	C2
32	Oteranga Bay, Wellington		C5		C4		CX	Sea spray
33	Judgeford, Porirua		C3		C3		C4	C3

1st – November 2016 to November 2017, 2nd – July 2017 to July 2018, 3rd – November 2017 to November 2018.

* The upper limit of copper first-year corrosion rate in ISO 9223:2012 CX (Extreme) category is 90 g/m^2/year. In these areas, the first-year corrosion rates of copper measured in the present study could be much higher than 90 g/m^2/year.

6.   Updated regional atmospheric corrosivity map

The atmospheric corrosivity of the field exposure sites was determined by considering the corrosivity categories based on the first-year corrosion rates of mild steel, zinc and copper in the present study. When a difference was observed between previous and present definitions, a recommendation for zone boundary adjustment was given in consideration of the following:

- Environmental and/or geological characteristics of the exposure site – particularly the type and/or concentration of major airborne pollutants revealed by previous and present air monitoring activities performed by BRANZ and other organisations.
- Actual first-year atmospheric corrosion rates of metals – particularly their positions in the corrosion rate range of a specific atmospheric corrosivity category.
- Atmospheric corrosion categories of neighbouring exposure sites, if any.

Based on the findings and results reported in section 2 and section 5, the following is recommended:

- In areas from Waihī Beach to Te Puke, the zone C boundary would be slightly affected by the atmospheric corrosivity category defined by the present data and the prevailing southwest winds.
- In areas from Te Puke to Whakatāne, the zone C boundary should be slightly widened towards inland. This is evident after consideration of the corrosion rate data derived at Te Puke, Maketū, Edgecumbe and Whakatāne and the prevailing winds (northwesterly and southwesterly).
- In areas from Ōpōtiki to Waihau Bay, the zone C boundary should be slightly widened towards inland. This is necessary after consideration of the corrosion rate data derived at Ōpōtiki, 1xxxx SH35 and Orete Forest Road, Waihau Bay and the potential influences of the volcanic/geothermal emissions from Whakaari/White Island.
- In areas including mainly Rotorua, Tikitere, Rotomā, Kawerau, Te Teko and Edgecumbe, the atmospheric corrosivity category should be increased from zone B to zone C after consideration of the following:
  - At these sites, the first-year corrosion rates of mild steel, zinc and copper consistently indicated a corrosivity category, ISO 9223:2012 C3 – Medium (i.e. zone C) or even higher in some cases.
  - These areas within the TVZ have multiple active geothermal sources and also industrial activities that can emit various corrosive sulphur-containing gases and/or particulate matter into the air.
  - A large number of geothermal sources could combine to affect a much larger area than a single isolated geothermal source, possibly through synergistic effects.
  - Monitoring conducted by Bay of Plenty Regional Council, BRANZ and other organisations shows that airborne H_2S and/or SO_2 concentrations in these areas were higher than those in other non-geothermal natural areas.
  - Winds from the south and west are common in these areas.
  - Relatively high rainfall levels in these geothermally affect areas could promote the attack of H_2S and/or SO_2 on susceptible materials.

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A geothermal zone (zone 4) had been defined and used in the atmospheric corrosivity map of NZS 3604:1999. This zone, covering most of the TVZ, has since been dismissed and merged into zone B of the NZS 3604:2011 map.

NZS 3604:2011 considers geothermal emissions and industrial contaminants as micro-climatic effects that can convert a mildly corrosive atmosphere into an aggressive environment. It defines a 50 m boundary for separation from geothermal hot spots.

Previous BRANZ studies have found that, in areas within approximately 500 m of an active geothermal source, the atmospheric corrosivity is strongly influenced by many factors including

- geothermal source size
- emission capability and rate
- overall chemistry of the geothermal discharge
- weather conditions
- topographical factors.

The atmospheric corrosivity category could extend all the way up to ISO 9223:2012 CX – Extreme with considerable variations (Li, Marston & Stokes, 2018). Note that NZS 3604:2011 does not have an exposure zone that is equivalent to ISO 9223:2012 CX – Extreme. The highest exposure zone used in this standard is zone E, corresponding to ISO 9223:2012 C5 – Very high. However, this zone is not shown in the atmospheric corrosivity map since it has been incorporated into zone D.

This study suggests increasing the atmospheric corrosivity category from zone B to zone C for those areas with geothermal and/or industrial influences, including Rotorua, Tikitere, Rotomā, Kawerau, Te Teko and Edgecumbe. The micro-climatic conditions defined by NZS 3604:2011 should still be applied. However, it would be appropriate to increase the current 50 m boundary to 500 m in alignment with SNZ TS 3404:2018.

Based on the above results and discussion, the atmospheric corrosivity map for the Bay of Plenty region has been updated and is shown in Figure 10.

Note that this map may have some limitations:

- It is produced by translating metal atmospheric corrosion rates measured through 1-year field exposure at a number of specific sites in the Bay of Plenty region.
- Atmospheric corrosion is known to be influenced by a number of environmental factors such as meteorological parameters and airborne pollutants (type, concentration and distribution). These factors may show variations on different scales, hourly, monthly and yearly.
- Geothermal emissions may vary temporally and spatially and are affected by discharge rates and meteorological and topographical factors.
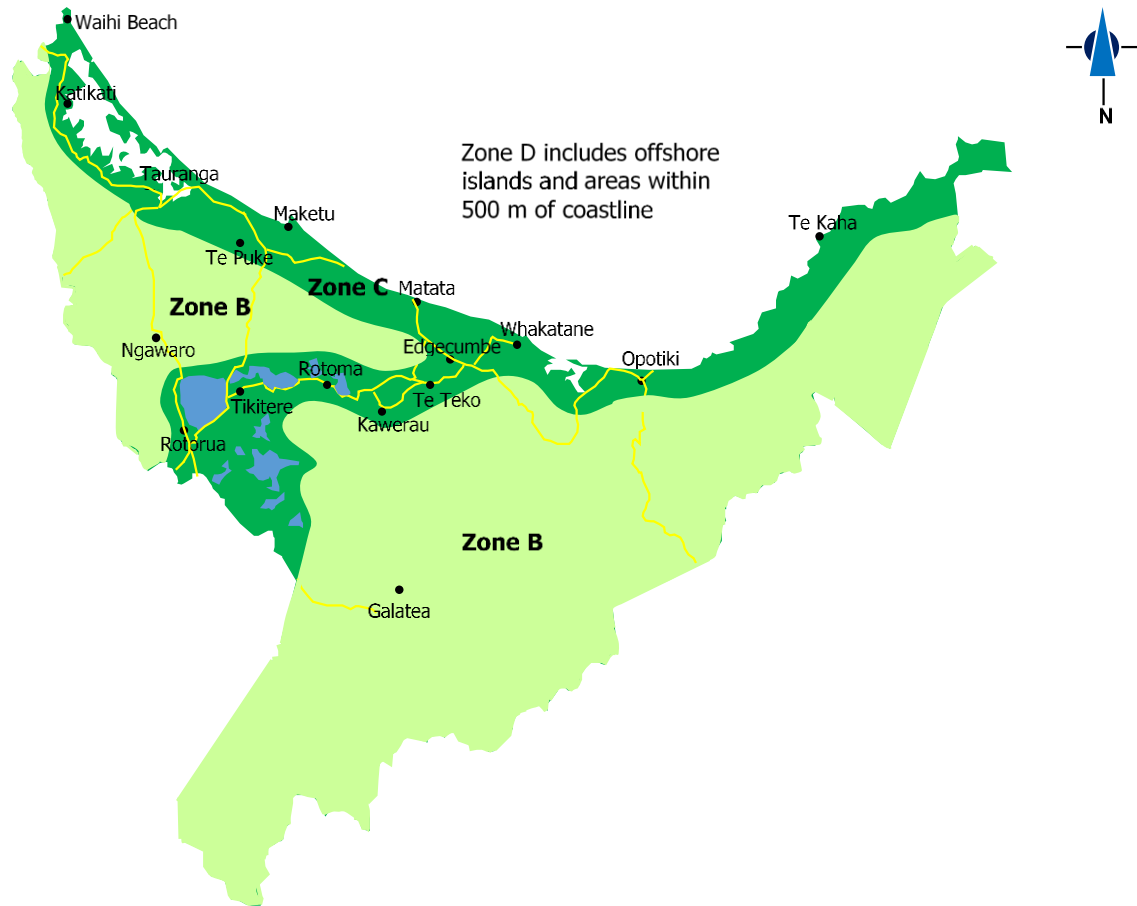
Figure 10. Atmospheric corrosivity map suggested for the Bay of Plenty region.

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