

STUDY REPORT

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Update of New Zealand's Atmospheric Corrosivity Map (Part 2)

Z.W. Li, N.J. Marston, M.S. Jones



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Abstract

This study is the second part of the research project that aims to check and maintain the on-going validity of the experimentally derived New Zealand atmospheric corrosion rate dataset. This dataset underpins the New Zealand Atmospheric Corrosivity Map.

The first-year atmospheric corrosion rates of mild steel and hot dip galvanized (zinc) steel samples were measured at another twenty-five sites selected mainly in Auckland, Wellington, and Christchurch. Analysis supports the conclusion drawn in the first part of this research, i.e. at most testing sites the newly derived atmospheric corrosion data is comparable with the old data. Thus, a combination of the data collected by BRANZ in different periods (1987 – 1988, 2011 – 2012, and 2013 – 2014) will make the atmospheric corrosion rate dataset more complete and useful.

Comparisons were made between atmospheric corrosivity categories determined by the new data and by the current atmospheric corrosivity map. Results indicated that the New Zealand atmospheric corrosivity map shown in Section 4 – Durability of the NZS 3604:2011 has limitations in its zone boundary definition. Recommendations have been given for adjustments of boundaries in some areas within Auckland, Wellington, Christchurch, and Dunedin in this report. These exposure zone boundaries could be refined further, with more thorough analysis of the complex interactions between climate, environmental pollution, topographic condition, and material.

Efforts have also been made to investigate the influences of the starting season on metal atmospheric corrosion rate. These samples were exposed at BRANZ's campus at Judgeford, Wellington. The first-month corrosion rates of mild steel samples exposed in different seasons could be significantly different. However, their mass losses after one-year exposure were very similar. Analysis indicated that the large change in the first-month corrosion rate could be resulted from the variation in meteorological condition, particularly the first-month rainfall. This could be particularly true for areas where environmental moisture is the main contributor to atmospheric corrosion. However, the chemical and/or structural characteristics of the corrosion product layer would gradually approach a stable state governed mainly by the long-term atmospheric conditions of the exposure environment.

This research indicated that the widely accepted power function (the bi-logarithmic law equation) for long-term atmospheric corrosion kinetics fitting, $D = A \times t^n$, could be applied to short-term exposure under certain conditions. If its credibility could be checked in more atmospheric environments, an approach to classify environmental corrosivity using short exposures could be developed.

Keywords: Atmospheric corrosion; mild steel; zinc; mapping

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1. INTRODUCTION

The New Zealand Building Code (NZBC) requires that any functional components, when chosen as acceptable or alternative solutions for building and construction, must meet or exceed the minimum durability expectations. To achieve this, the NZBC and relevant standards use a framework based mainly on atmospheric corrosivity to guide the specification of metallic materials and protective coatings for buildings in specific geographic locations. This is further manifested as the development of the so-called New Zealand Atmospheric Corrosivity Maps.

One such map is currently shown in the New Zealand Standard, NZS 3604:2011 – Timber-framed buildings, and is widely used by the building industry. This map was established mainly from the metal atmospheric corrosion rate data experimentally derived by BRANZ from about 168 sites across New Zealand in the late 1980s. In this map, New Zealand is covered by several exposure zones, e.g. B (low), C (medium), D (high), and E (very high). One specific material will have different performance and/or durability expectation when used within different zones. To ensure that durable and also cost-effective materials and components are always specified and used for building and construction, the validity of the dataset and the map must be maintained.

This study is the second part of a BRANZ's research project that aims to:

- check and maintain the on-going validity of the metal atmospheric corrosion rate dataset for New Zealand,
- check the on-going validity of the New Zealand atmospheric corrosivity map shown in the NZS 3604:2011, and
- provide recommendations for exposure zone boundary adjustments.

This study measured the first-year atmospheric corrosion rates of mild steel and hot dip galvanized (zinc) steel samples exposed at another 25 sites located in Auckland, Wellington, and Christchurch.

Analysis of results from 61 testing sites indicated that the NZS 3604 map has some limitations in its definition of exposure zone boundaries. These are mainly shown as a relatively conservative estimation of the boundary of Zone C, particularly in areas with marine influences. This is probably a result of the small number of tests carried out in the regions concerned. Recommendations are given for zone boundary adjustments to atmospheric corrosivity maps for Auckland, Wellington, Christchurch, and Dunedin.

2. EXPERIMENTAL

2.1 Methodology

In this study, the corrosivity of the atmospheric environment concerned was determined by directly measuring the annual average mass loss of metallic samples. This method was used in BRANZ's study in the 1980s [Cordner 1990; Duncan and Cordner 1991] and the first part of this research [Li et al 2013]. This is also the simplest and most well-accepted method to characterise and classify the corrosivity of atmospheric environments [Knotkova et al 1995; Knotkova et al 2010; Dong et al 2007].

2.2 Sample

Considerable effort was devoted to sample preparation to ensure the corrosion rates measured in BRANZ's previous and present studies are comparable:

- Mild steel (~150 × 100 × 3 mm) and hot dip galvanized (zinc) steel (Z300, ~150 × 100 × 0.5 mm) samples used in this study were the retained, unused, samples

from BRANZ's testing in the 1980s. These samples were stored in a well-sealed cabinet, located in a room with constant temperature and humidity. Very limited corrosion (e.g. rust formation) was found on the mild steel samples after this prolonged storage. Chemical compositions of these materials are given in Table 1 [Cordner 1990; Duncan and Cordner 1991].

- The surface of the mild steel sample was grit blasted to ISO 8501-1 grade Sa3, the specified surface treatment for the 1980s testing. The hot dip galvanized steel samples were cleaned by immersing them into an ammonium chloride (NH₄Cl) solution to remove any corrosion products formed during this storage.

Table 1. Chemical composition of metallic samples used in this research (wt.%)

Metal	Element and Content							
	C	N	Al	Si	P	S	Ti	V
Mild Steel	0.18	0.003	0.007	0.04	0.027	0.014	0.005	0.002
	Cr	Mn	Ni	Cu	Mo	Sn	Nb	Fe
	0.03	0.69	0.02	0.03	<0.001	<0.001	<0.001	Bal.
Hot Dip Galvanized (Zinc) Steel	Mg	Al	Cu	Sn	Pb	Zn		
	<0.01	0.32	<0.01	<0.01	0.10	Bal.		

The dimensions of each sample were measured accurately to 0.01 mm. Prior to exposure, they were cleaned with acetone, dried with hot air, and weighed to 0.001 g. The numbered samples were then sealed in separate plastic bags, shipped to exposure sites, and mounted onto exposure racks using nylon fasteners.

2.3 Exposure Site

Twenty-five exposure sites were selected for this study. They were mainly within the Auckland and Christchurch regions. Several sites were also selected in Wellington and Greymouth to produce the data that had been missed in the first part of this research. Open locations were chosen, wherever possible, in order to make the atmospheric corrosion data representative. As such, most exposure racks were installed within climatological stations (operated by MetService or NIWA) and on farm land. The testing sites used in the first and second part of this research are shown in Figures 1 and 2.

2.4 Rack Installation

Exposure racks were fabricated from aluminium flat bars. Large gaps were made between supporting arms to minimise possible cross contamination of corrosion products formed on mild steel and zinc samples. These racks were erected by BRANZ, MetService, and/or NIWA during September and October of 2013. Typically, rack installation for any region was finished within one to two days. These racks were generally attached to existing, strong timber posts, placed approximately 1.8 m above the ground, and oriented towards the north at an angle of 45°.

2.5 Sample Assessment

After one year, samples were retrieved for lab analysis. Their surface morphology was examined visually and microscopically. The corrosion products were then cleaned thoroughly following the procedures recommended by ASTM G1:

- Mild steel: 0.5 L/L hydrochloric acid (HCl, specific gravity = 1.19) + 3.5 g/L hexamethylenetetramine (C₆H₁₂N₄) at 20-25°C; and

➤ Hot dip galvanized (zinc) steel: 100 g/L ammonium chloride (NH₄Cl) at 70°C.



Figure 1. Locations of atmospheric corrosion testing sites in the North Island

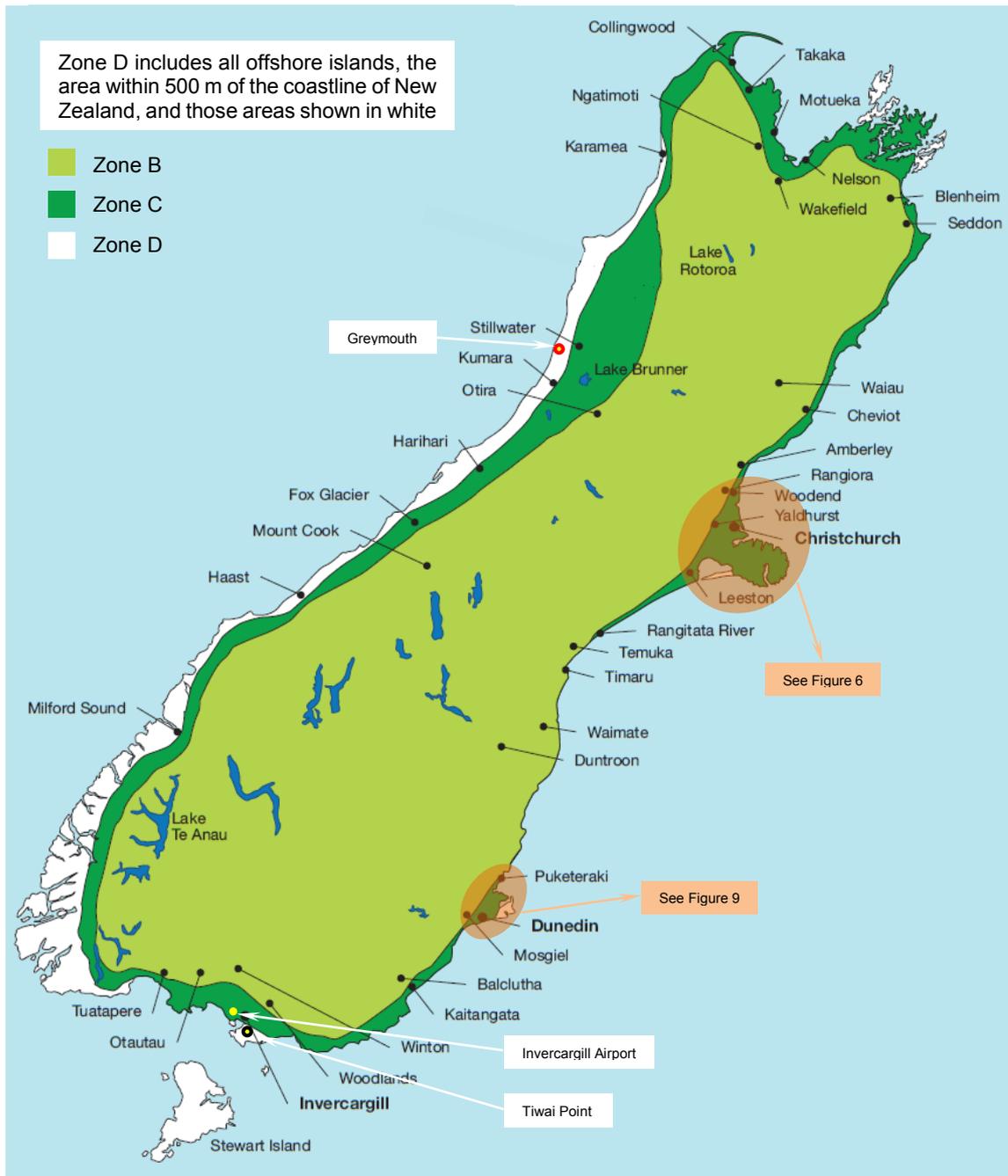


Figure 2. Locations of atmospheric corrosion testing sites in the South Island

The mild steel samples were pre-cleaned using a wooden spatula under flowing water to remove any loosely attached corrosion products. They were then immersed into the magnetically agitated chemical solution at ambient temperature. During this process, they were frequently taken out to manually remove the partially dissolved rust layer and to inspect the surface condition. This ensured that the samples were cleaned as quickly as possible, and not unnecessarily attacked by the cleaning solution. The cleaned samples were washed with flowing water, dried with hot air, and then re-weighed.

Several clean mild steel and hot dip galvanized steel samples were also immersed into the chemical solutions for the same period as the cleaning process. Their mass losses were recorded for corrosion rate correction.

2.6 Atmospheric Corrosivity Category

The classification of atmospheric corrosivity follows the definition of AS/NZS 2312 and ISO 9223, and uses the first-year metal corrosion rates (Table 2).

Table 2. ISO 9223 Atmospheric corrosivity classification based on first-year corrosion rates (g/m²/year)

ISO 9223 Category	Description	Mild Steel	Zinc	NZS 3604:2011 Exposure Zone
C1	Very low	CR≤10	CR≤0.7	
C2	Low	10<CR≤200	0.7<CR≤5	B
C3	Medium	200<CR≤400	5<CR≤15	C
C4	High	400<CR≤650	15<CR≤30	D
C5	Very high	650<CR≤1500	30<CR≤60	E
CX	Extreme	1500<CR≤5500	60<CR≤180	

Corrosion rates of hot dip galvanized (zinc) steel samples were measured, but not used for atmospheric corrosivity classification in this research. This is because the chemical composition of the zinc coating (as shown in Table 1) is not within the range required by Appendix B of AS 3566.2:2002. Thus, these samples were not suitable as standard materials for measuring atmospheric corrosion rate of zinc. However, hot dip galvanized (zinc) steel is commonly used for cladding and flashing applications in buildings and for structures in New Zealand. The corrosion rate derived from field exposure testing would be very useful for understanding material-environment interactions and material specification in natural environments.

3. RESULTS

3.1 Summary of Part 1 of This Research

Comparisons between the first-year metal atmospheric corrosion rates collected during the periods of 1987 – 1988 and 2011 – 2012 indicated that atmospheric corrosivity is changing. However, different sites exhibited different relative behaviours and there was no nationwide, universal trend derived from the results obtained. Significant changes in atmospheric corrosion rates of mild steel and/or hot dip galvanized (zinc) steel were observed at a very limited number of testing sites. These include Auckland Airport, Tiwai Point, and Greymouth. Overall, the corrosion rate data from most testing sites was still comparable with previous data of the 1980s.

Changes in climate over the period 1980 – 2010 were analysed. At most testing sites, the average annual ambient temperature increased slightly, whilst relative humidity and wind speed decreased slightly. The variations in rainfall and wet days were relatively complex. There was no uniform trends found with two climatic factors.

The potential effects of any individual climatic factor on atmospheric corrosion were discussed. It was not possible to confidently establish any correlations between the changing trends of a single climatic factor and the first-year mild steel corrosion rate. Therefore, there is no clear understanding of how variations in climate can affect atmospheric corrosion in the long term in New Zealand. However, significant changes and strong effects appear to be absent.

3.2 Changes in Climatic Factors – Sites for Part 2 of This Research

The differences in key climatic factors between the periods of 1987 – 1988 and 2013 – 2014 for several testing sites used in this part of research are summarised in Table 3.

Table 3. Summary of changes in climatic factors observed at several testing sites (two-year average difference, 2013/2014 minus 1987/1988)

Testing Site	Temp (°C)	RH (%)	Rainfall (mm)	Wet Days	Wind Speed (m/s)
Christchurch Airport	-0.3	3.6	8.2*	1*	-0.2
Greymouth	0.5*	3.0*	-60	-2*	×
Kelburn	0.3	-4.0	×	×	-0.7
Lincoln	-0.1	-3.1	19.0	1	×
Pukekohe	0.2	×	-12*	-2*	×
Rangiora	0.1	8.6	1.9	0	×
Warkworth	-0.2	-1.7	-25.2	-1	×
Wellington Airport	0	0.1	×	×	-0.3

Note:

- Climatic data retrieved from the National Climate Database (CliFlo, NIWA Science)
- Averaged monthly data in two-year period was used for comparison
- Wet days: number of days with 1 mm or more of rain
- ‘×’: Data not available or incomplete
- ‘*’: Monthly data in one-year period used

As with the first part of this research, significant variations in climatic factors between previous (1987 – 1988) and present (2013 – 2014) testing periods have not been found. Although the absolute differences of rainfall between these two periods appear to be large for Greymouth, Lincoln, and Warkworth, these changes are only with ~2-4 percent of the annual precipitations.

3.3 Atmospheric Corrosion Rates

The first-year atmospheric corrosion rates of mild steel and hot dip galvanized (zinc) steel samples are presented in Table 4. These represent data collected from 61 exposure sites during the periods 2011 – 2012 and 2013 – 2014.

In this table, the atmospheric corrosivity category of the selected exposure site, as defined by the map shown in the NZS 3604:2011, is also given. However, it should be noted that the atmospheric corrosivity category for some sites is only an estimation. This is because the exact locations of exposure zone boundaries with regard to geographic coordinates could not be well established with the current map scale.

The metal atmospheric corrosion rates derived from this part of the research were also compared, where possible, with those of the study carried out in the 1980s by BRANZ (Table 5). A large increase in atmospheric corrosion rate was observed for both mild steel and hot dip galvanized (zinc) steel samples at Kelburn, Wellington. At Greymouth, the first-year mild steel corrosion rate decreased 37% from 511 to 320 g/m²/year, while the zinc corrosion rate increased 20% to 10.9 g/m²/year. This observation is very similar to that derived from the 2011 – 2012 testing. In the Christchurch Airport and Lincoln areas, the atmospheric corrosion rate of hot dip galvanized (zinc) steel samples showed a very large increase, while the mild steel corrosion rate decreased slightly.

Table 4. First-year atmospheric corrosion rates of mild steel and hot dip galvanized (zinc) steel samples (g/m²/year)

No.	Testing Site	Exposure Zone (NZS 3604:2011)	Mild Steel	Hot Dip Galvanized (Zn) Steel	<i>Atmospheric Corrosivity Category by Current First-Year Mild Steel Corrosion Rate</i>
1	Warkworth (NIWA)	Zone C	228 (2011 – 2012)	4.3 (2011 – 2012)	<i>C</i>
2	Warkworth (Carran Rd)	Zone C	192 (2013 – 2014)	4.6 (2013 – 2014)	<i>B</i>
3	Waitoki	Zone C	194 (2011 – 2012)	3.0 (2011 – 2012)	<i>B</i>
4	Dairy Flat	Zone C	204 (2013 – 2014)	5.0 (2013 – 2014)	<i>C</i>
5	Sunnynook	Zone C	174 (2013 – 2014)	1.9 (2013 – 2014)	<i>B</i>
6	Muriwai Beach	Zone D	407 (2013 – 2014)	20.3 (2013 – 2014)	<i>D</i>
7	Ellerslie	Zone C	171 (2011 – 2012)	4.3 (2011 – 2012)	<i>B</i>
8	Auckland Airport	Zone D	491 (2011 – 2012)	33.3 (2011 – 2012)	<i>D</i>
9	Linwood (Karaka)	Zone C	188 (2013 – 2014)	4.3 (2013 – 2014)	<i>B</i>
10	Glenbrook (Karaka)	Zone C	196 (2013 – 2014)	5.7 (2013 – 2014)	<i>B</i>
11	Rogers Rd (Pukekohe)	Zone C	181 (2013 – 2014)	4.0 (2013 – 2014)	<i>B</i>
12	Paerata Rd (Pukekohe)	Zone C	171 (2013 – 2014)	4.6 (2013 – 2014)	<i>B</i>
13	Pukekohe (NIWA/PFR)	Zone C	173 (2011 – 2012)	5.3 (2011 – 2012)	<i>B</i>
14	Drury	Zone C	164 (2013 – 2014)	2.6 (2013 – 2014)	<i>B</i>
15	Hunua	Zone C	153 (2011 – 2012)	4.0 (2011 – 2012)	<i>B</i>
16	Ardmore Airport	Zone C	158 (2011 – 2012)	4.7 (2011 – 2012)	<i>B</i>
17	Tuakau	Zone C/B	136 (2011 – 2012)	2.6 (2011 – 2012)	<i>B</i>
18	Hamilton Airport	Zone B	169 (2011 – 2012)	3.3 (2011 – 2012)	<i>B</i>
19	Levin (MetService)	Zone C	189 (2011 – 2012)	5.3 (2011 – 2012)	<i>B</i>
20	Waikanae (WWTP)	Zone C	168 (2011 – 2012)	4.3 (2011 – 2012)	<i>B</i>
21	Paraparaumu Airport (MetService)	Zone C	191 (2011 – 2012)	6.7 (2011 – 2012)	<i>B</i>

No.	Testing Site	Exposure Zone (NZS 3604:2011)	Mild Steel	Hot Dip Galvanized (Zn) Steel	Atmospheric Corrosivity Category by Current First-Year Mild Steel Corrosion Rate
22	Pukerua Bay	Zone C	155 (2011 – 2012)	3.3 (2011 – 2012)	B
23	Titahi Bay (WWTP)	Zone C/D	223 (2011 – 2012)	8.6 (2011 – 2012)	C
24	Porirua/Tawa	Zone C	198 (2011 – 2012)	6.7 (2011 – 2012)	B
25	Tawa	Zone C	185 (2011 – 2012)	4.7 (2011 – 2012)	B
26	Johnsonville	Zone C	213 (2011 – 2012)	4.7 (2011 – 2012)	C
27	Gracefield	Zone C/B	159 (2011 – 2012)	5.3 (2011 – 2012)	B
28	Judgeford (BRANZ)	Zone C	171 (2011 – 2012)	4.7 (2011 – 2012)	B
			177 (2013 – 2014)	4.0 (2013 – 2014)	B
29	Wallaceville (NIWA)	Zone B	150 (2011 – 2012)	2.3 (2011 – 2012)	B
30	Wainuiomata (GWRC)	Zone C	168 (2011 – 2012)	3.3 (2011 – 2012)	B
31	Avalon	Zone C	155 (2011 – 2012)	2.3 (2011 – 2012)	B
32	Kelburn (MetService)	Zone C	203 (2013 – 2014)	5.8 (2013 – 2014)	C
33	Karori	Zone C	207 (2011 – 2012)	5.3 (2011 – 2012)	C
34	Wellington Airport	Zone D/C	343 (2013 – 2014)	13.6 (2013 – 2014)	C
35	Oteranga Bay (Transpower)	Zone D/E	>692 (2011 – 2012)	>33.1 (2011 – 2012)	E
36	Rangiora (WWTP)	Zone B/C	150 (2013 – 2014)	2.5 (2013 – 2014)	B
37	Woodend (WWTP)	Zone C	158 (2013 – 2014)	3.4 (2013 – 2014)	B
38	Belfast	Zone C	169 (2013 – 2014)	2.9 (2013 – 2014)	B
39	Yaldhurst	Zone C	151 (2013 – 2014)	7.4 (2013 – 2014)	B
40	Hornby	Zone C	219 (2013 – 2014)	2.8 (2013 – 2014)	C
41	Bromley	Zone C	153 (2013 – 2014)	3.0 (2013 – 2014)	B
42	South New Brighton	Zone D	303 (2013 – 2014)	14.1 (2013 – 2014)	C

No.	Testing Site	Exposure Zone (NZS 3604:2011)	Mild Steel	Hot Dip Galvanized (Zn) Steel	Atmospheric Corrosivity Category by Current First-Year Mild Steel Corrosion Rate
43	Cashmere	Zone C	125 (2013 – 2014)	2.3 (2013 – 2014)	<i>B</i>
44	Lincoln (PFR)	Zone C	169 (2013 – 2014)	11.6 (2013 – 2014)	<i>B</i>
45	Taitapu	Zone C	148 (2013 – 2014)	2.7 (2013 – 2014)	<i>B</i>
46	Leeston	Zone C	153 (2013 – 2014)	10.1 (2013 – 2014)	<i>B</i>
47	Banks Peninsula	Zone C	112 (2013 – 2014)	3.3 (2013 – 2014)	<i>B</i>
48	Warrington	Zone C/D	132 (2011 – 2012)	1.0 (2011 – 2012)	<i>B</i>
49	Port Chalmers	Zone C	178 (2011 – 2012)	4.3 (2011 – 2012)	<i>B</i>
50	Normanby	Zone C	155 (2011 – 2012)	4.7 (2011 – 2012)	<i>B</i>
51	Pigeon Flat	Zone C/B	153 (2011 – 2012)	2.0 (2011 – 2012)	<i>B</i>
52	Wakari	Zone C	146 (2011 – 2012)	1.6 (2011 – 2012)	<i>B</i>
53	Forbury	Zone C	162 (2011 – 2012)	3.0 (2011 – 2012)	<i>B</i>
54	Taiaroa Head	Zone D	312 (2011 – 2012)	5.0 (2011 – 2012)	<i>C</i>
55	Highcliff	Zone D	262 (2011 – 2012)	5.7 (2011 – 2012)	<i>C</i>
56	Fairfield	Zone C/B	128 (2011 – 2012)	0.6 (2011 – 2012)	<i>B</i>
57	Mosgiel	Zone B/C	120 (2011 – 2012)	3.6 (2011 – 2012)	<i>B</i>
58	Dunedin Airport	Zone B/C	135 (2011 – 2012)	1.3 (2011 – 2012)	<i>B</i>
59	Greymouth (NIWA)	Zone D	350 (2011 – 2012)	9.3 (2011 – 2012)	<i>C</i>
			320 (Jun 2013 – Jun 2014)	10.9 (Jun 2013 – Jun 2014)	<i>C</i>
			390 (Sept 2013 – Sept 2014)	13.0 (Sept 2013 – Sept 2014)	<i>C</i>
60	Invercargill Airport	Zone C	216 (2011 – 2012)	4.3 (2011 – 2012)	<i>C</i>
61	Tiwai Point (NIWA)	Zone D	300 (2011 – 2012)	4.7 (2011 – 2012)	<i>C</i>

Table 5. Changes in first-year atmospheric corrosion rate

Testing Site	Atmospheric Corrosion Rate				Relative Corrosion Rate Change (2013 – 2014 vs. 1987 – 1988)	
	1987 – 1988		2013 – 2014		MS	HDG
	MS	HDG (Zn)	MS	HDG (Zn)		
Warkworth (NIWA)	191	5.7	228	4.3	19%	-25%
Pukekohe (NIWA)	192	4.1	173	5.3	-10%	29%
Glenbrook	155	3.3	196	5.7	26%	73%
Kelburn (MetService)	128	2.5	203	5.8	59%	132%
Wellington Airport	268	18.3	343	13.6	28%	-26%
Greymouth (NIWA)	511	9.1	320	10.9	-37%	20%
Christchurch Airport	206	2.8	151	7.4	-27%	164%
Bromley	207	3.5	153	3.0	-26%	-14%
Lincoln (PFR)	175	2.4	169	11.6	-3%	383%

Note: The Christchurch airport testing site for the 2013 – 2014 period is very close to the southwest end of the runway but not within the airport

3.4 Impacts on Current Atmospheric Corrosivity Map

The atmospheric corrosivity of the exposure sites was categorised based on the first-year corrosion rates of mild steel samples measured in this research. When a difference was noticed between previous and present definitions, an analysis was performed of:

- environmental characteristics of the exposure site,
- changes in actual corrosion rates, and
- atmospheric corrosivity category of neighbouring exposure sites (if any).

3.4.1 Auckland

Currently, Auckland is in need of more residential houses due to strong economic and population growth. Development of new homes is likely to be in the north, west, and south regions, such as Warkworth, Silverdale, Dairy Flat, Kumeu, Huapai, Pukekohe, Drury, and Karaka. A limited number of exposure sites had been selected in these areas for atmospheric corrosion testing in the 1980s (BRANZ). To assist any possible development, this research aimed to collect some reliable data by recruiting seventeen exposure sites in these areas.

A significant proportion of the Auckland region is covered by Zone C as defined by the map of the NZS 3604:2011. The west coast was strongly influenced by marine generated salt particles and considered to be more corrosive than other areas. Muriwai Beach, within this zone, has been commonly used as a testing site for performance evaluation and product development by some manufacturers in New Zealand and Australia. The first-year corrosion rates of mild steel and hot dip galvanized (zinc) steel samples were measured as 440 and 22.8 g/m²/year, respectively, by BRANZ in the 1980s [Cordner and Brown 1990]. A significant part was then categorised as Zone D (including Zone E).

The Muriwai Beach exposure site used for current testing is not on the beach, but is about half way up the hill slope, facing towards the west. (Very) strong winds from the southwest, carrying large amount of sea salt can, in some seasons (June to September), rise up the hill to the top. After one year of exposure the mild steel sample lost a significant amount of its mass, 407 g/m²/year. Meanwhile, 20.3 g/m²/year was recorded

with the hot dip galvanized (zinc) steel sample. These numbers are very similar to previous BRANZ measurements and could easily put this site into corrosivity category D (high). Please note that locations for previous and present BRANZ testing are slightly different. This measurement then confirmed that the west coast region of Auckland is highly corrosive due to marine produced salts carried by the strong westerly. However, the corrosivity towards some western suburbs of Auckland city might not be very high. This is because the Auckland Centennial Park and Waitakere Ranges Regional Parkland could, to some extent, provide a barrier to the transport of airborne sea salt particles.

The corrosion rates derived from the exposure periods of 2011 – 2012 and 2013 – 2014 were added onto the Auckland part of the NZS 3604:2011 corrosivity map (Figure 3).



Figure 3. Schematic showing atmospheric corrosion rate of mild steel in Auckland region (Yellow dots: sites for the 1st part of this research; Red dots: sites for the 2nd part of this research; Blue dots: sites for other research during 2013 – 2014)

In the southeast of Auckland, the mild steel corrosion rates at Ardmore Airport and Hunua were measured to be 158 and 155 g/m²/year, respectively. At Drury, a similar corrosion rate, 164 g/m²/year, was obtained. All five locations in the southwest produced slightly higher values, ranging from 171 to 196 g/m²/year. These numbers are slightly higher than 155 g/m²/year that was previously measured by BRANZ at Glenbrook [Cordner and Brown 1990].

In the north of Auckland, the atmospheric corrosion rate of mild steel is around 200 g/m²/year at Warkworth, Dairy Flat, and Waitoki. In Albany, the first-year mild steel corrosion rate is slightly lower, 174 g/m²/year. The corrosion rate of hot dip galvanized zinc coating sample is also low, 1.9 g/m²/year. This site is about 2.7 km away from the east coast and has a large reserve and golf course to its east. Airborne sea salt particles from the east coast could be partially blocked by trees and other plants. Further, the wind from the east is generally weak. Some tropical storms coming from the east may occur in summer and autumn.

3.4.2 Wellington

Within the map shown in NZS 3604:2011, Wellington City is completely classified as Zone C. Parts of Porirua, Lower Hutt, and Upper Hutt are also classified into this atmospheric corrosivity category. In this research, atmospheric corrosion testing was carried out at 16 sites, including one in Paraparaumu and one in Waikanae.

The southwest coast of Wellington is extremely corrosive. For example, mild steel, after one-year exposure at Oteranga Bay, lost 692 g/m²/year of its mass. This number is not completely reliable as the exposure rack was broken due to strong winds during exposure. BRANZ's previous study at this site revealed a much higher number, ~1600 g/m²/year, for vertically installed mild steel facing towards the sea [Holcroft 1998; Haberecht and Kane 1999]. This mass loss rate is much higher than those obtained in other well-known corrosive areas, such as Muriwai Beach, Auckland (slightly higher than 400 g/m²/year). This is closely related to extremely high deposition rates of chloride-containing sea salts carried by the westerly winds that are funnelled through Cook Strait. Salt candle measurements according to ISO 9225 gave a 12-month average deposition rate of 1291 mg/m²/day [Haberecht and Kane 1999]. These salt particles can be brought a long way inland by strong northwest winds into the Wellington region. This is believed to contribute to the relatively high corrosion rates of around 200 g/m²/year measured for the region extending from Karori to Tawa (Figure 4). Slightly weaker prevailing winds from both north and south directions can contribute to the relatively high atmospheric corrosivity in this region as well.

At the Pukerua Bay site on the west coast of Porirua, mild steel had a first-year corrosion rate of 155 g/m²/year. This number can classify the atmospheric corrosivity as category B (low). This site, about 1 km south of the sea, has lots of trees in the surrounding area. These can capture some sea salt aerosols from the coast and partially block their movement further inland, therefore decreasing the corrosivity of the local environment.

The northeast side of Wellington harbour, i.e. Gracefield and Seaview, is an industrial area. It has light manufacturing and engineering workshops, a paint manufacturer, hazardous waste processor, freight storage, oil and fuel tank farms, and a wastewater treatment plant [Davy and Day 2001]. Heavy atmospheric emissions are probably absent in this area. Volatile organic compounds (VOCs), lead (Pb), and arsenic (As) were detected in the air. However their levels are likely to have decreased significantly since 2004 due to improvements in process control. Meanwhile, particulate matters (PM) identified in this area were soil, marine aerosol, road dust, and coarse sulphate [Mitchell 2012]. Some of these particles, for example, sea salt, sulphate, and dust, could contribute to material deterioration when deposited onto surfaces and wetted. The mild steel sample, exposed at a site close to one busy road and blocked from the sea by a large building, gave a corrosion rate of 159 g/m²/year, i.e. corrosivity category B. Classification based on the hot dip galvanized (zinc) steel corrosion rate, 5.3 g/m²/year, would just be C. However please note that the zinc coating sample might not be acceptable according to relevant standards.

Mild steel corrosion rates were around 160 g/m²/year in most Lower Hutt and Upper Hutt areas. Meanwhile, hot dip galvanized (zinc) steel samples also lost their mass slowly and their corrosion rates typically ranged from 2 to 3 g/m²/year.

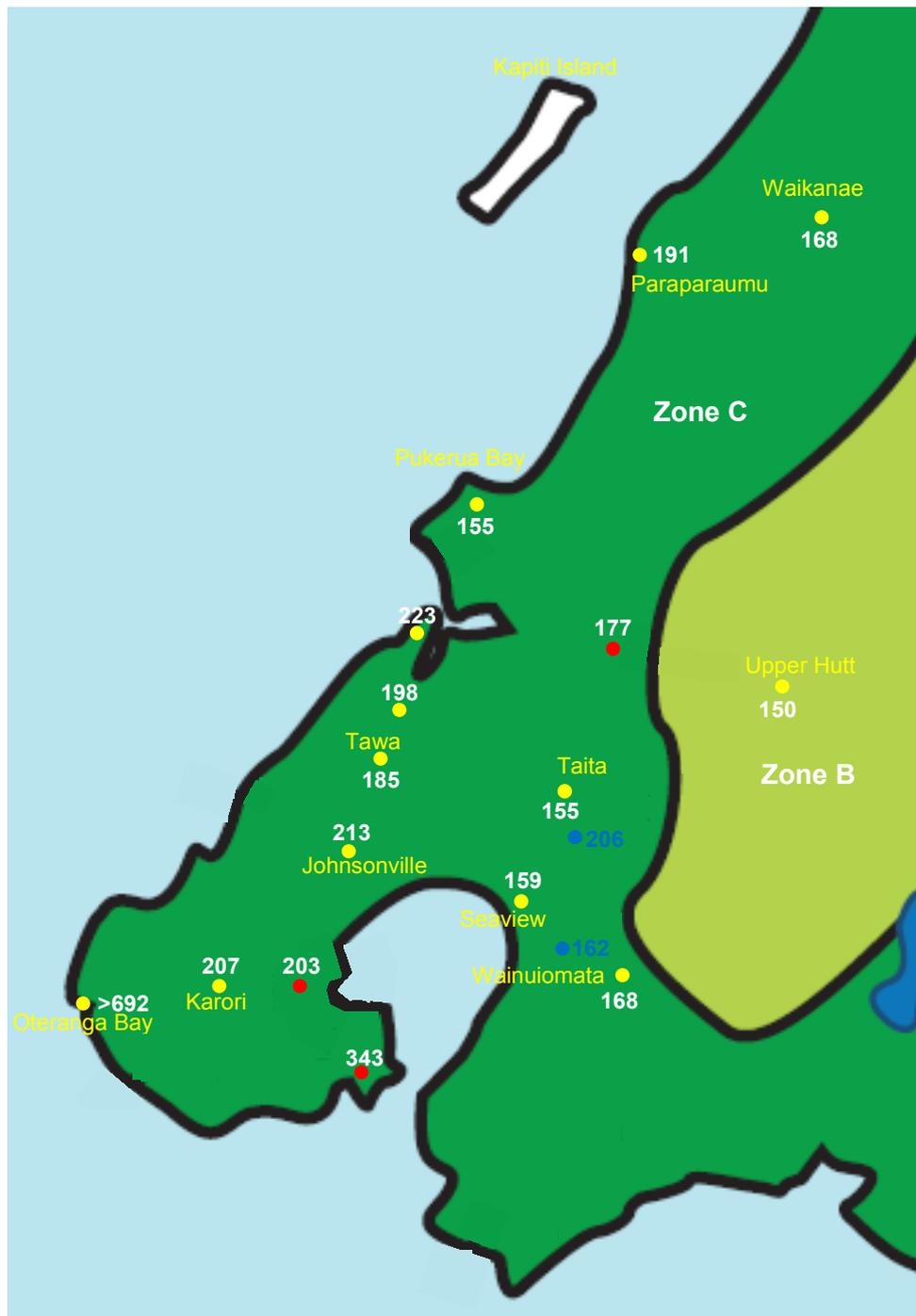


Figure 4. Schematic showing atmospheric corrosion rate of mild steel in Wellington region (Yellow dots: sites for the 1st part of this research; Red dots: sites for the 2nd part of this research; Blue dots: sites for other research during 2013 – 2014)

3.4.3 Christchurch

After the 2010 and 2011 earthquakes, the Christchurch City Council rezoned land in the Greater Christchurch region in order to provide sufficient land for rebuilding. It is estimated that more than 20,000 households will be developed in coming years. The majority of new residential sections will be in the southwest and Belfast areas as shown in Figure 5. Meanwhile, Wigram, Halswell, Lincoln, Rolleston, Rangiora, and Woodend were identified for long-term growth. In the map shown in the NZS 3604:2011, atmospheric corrosivity of most these areas is classified as category C (medium).

Atmospheric corrosion rate was measured at four sites in Christchurch region during BRANZ's survey in the 1980s. It appears that a relatively conservative approach was used to define the boundary between Zone C and Zone B, i.e. mainly based on geographic characteristics and prevailing winds. As a result, Zone C covers the whole of Banks Peninsula, Christchurch city, and some areas in the northeast and southwest.

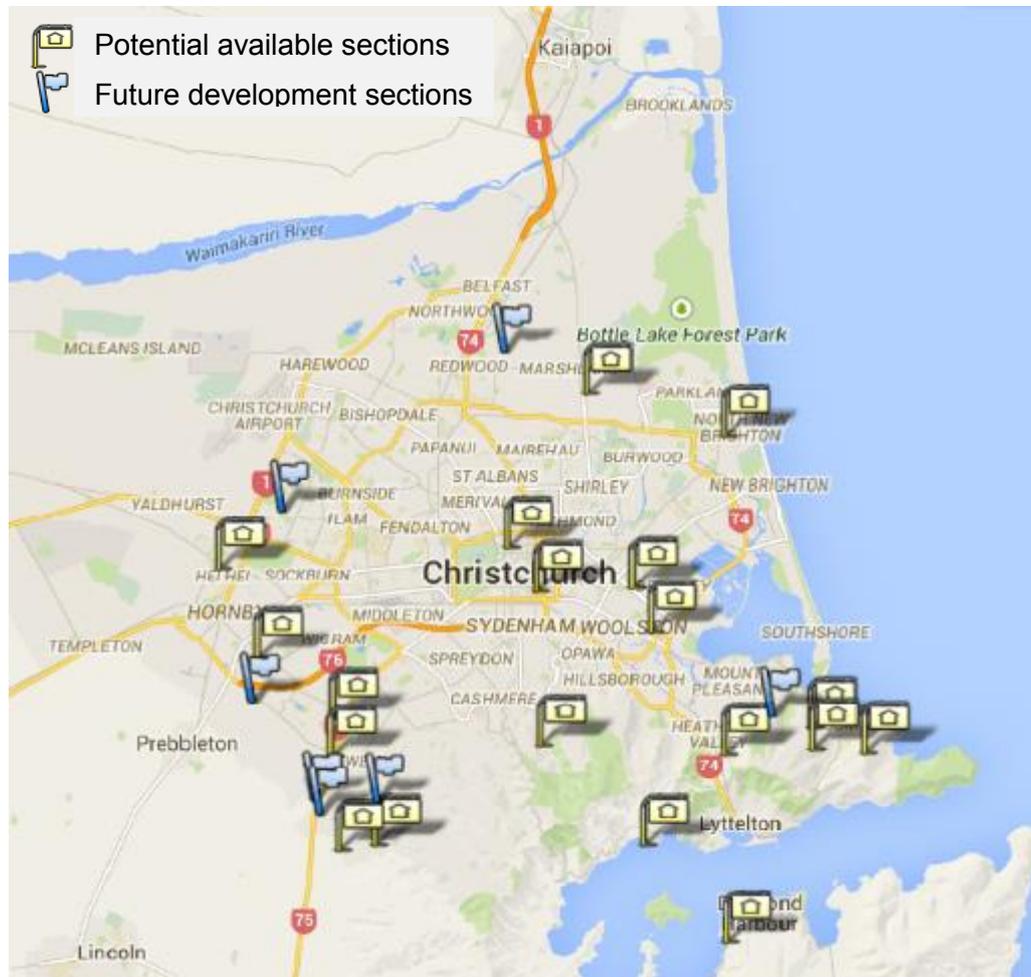


Figure 5. Land available for residential development in Christchurch [Christchurch City Council]

In this research, 12 exposure racks were erected in the Christchurch region. No rack was installed within the metropolitan region in consideration of:

- potential effects of dusts from demolition of earthquake damaged buildings on metal atmospheric corrosion, and
- main areas for new housing development.

The first-year atmospheric corrosion rate of mild steel is lower than 200 g/m²/year at most testing sites except at two locations: South New Brighton and Hornby (Figure 6).

- South New Brighton: The exposure rack was installed on the east side fence of a residential house. This property is among the first row of houses adjacent to the beach (about 150 meters away from the coastal line) and a main road. The rack was facing towards the sea (rather than north). Therefore the sample surface could receive sea spray driven by the wind from the northeast direction, and also collect dust from the road (Figure 7). Mild steel had a mass loss of 303 g/m²/year after one-year exposure. This value sits at the middle of corrosivity category C.

Meanwhile, the hot dip galvanized (zinc) steel sample lost 14.1 g/m²/year. This number could qualify this site as a high-end example of corrosivity category C. However, please note that the hot dip galvanized zinc sample might not be acceptable for atmospheric corrosivity category classification.

- Hornby: This suburb has a large fertiliser works operated by Ravensdown Fertiliser Ltd. The industrial estate of Sockburn also lies to its east. The superphosphate manufacturing process can release gaseous emissions (e.g. sulphur dioxide) and particulates. These can negatively influence the atmospheric corrosion performance of mild steel, cast iron, and reinforced concrete structure [Kear and Marston 2007]. In this research, the first-year corrosion rate was measured as 219 g/m²/year for mild steel, which was exposed about 550 meters southwest of the fertiliser factory. This could classify the atmosphere as category C. However, the galvanised steel sample recorded a mass loss of only 2.8 g/m²/year, which is in the range of atmospheric corrosivity category B. Mechanisms behind atmospheric corrosion of zinc and iron are somewhat different. It is believed that the concentration of specific emissions in the atmosphere is very important, as below a certain threshold, corrosive attack might not occur [Bawden and Ferguson 1989]. Unfortunately, there is no clear understanding of how and to what extent, the industrial emissions could affect material performance in this environment.



Figure 6. Schematic showing atmospheric corrosion rate of mild steel in Christchurch region

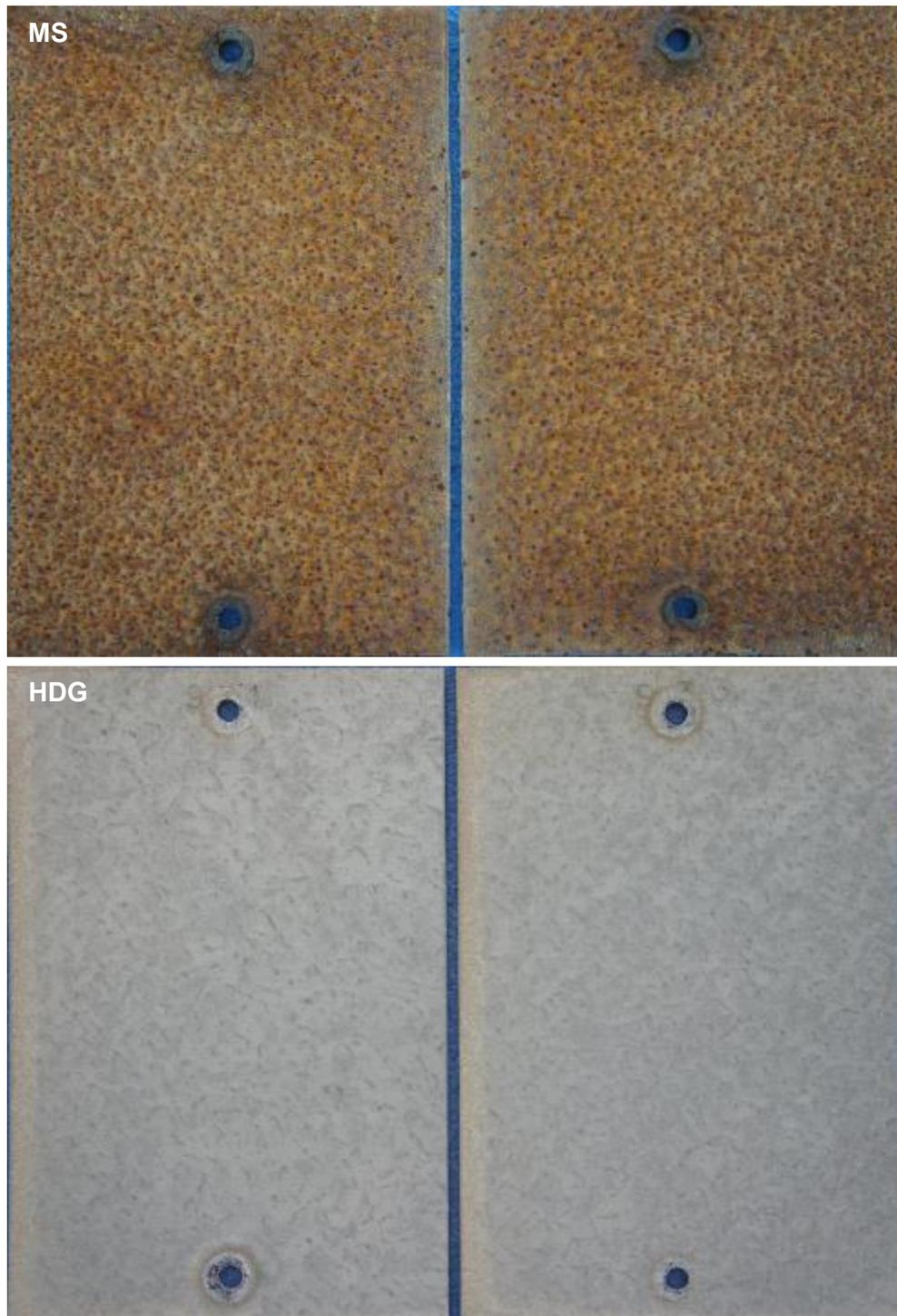


Figure 7. Skyward surface morphology of mild steel and hot dip galvanized (zinc) steel samples exposed at a test site at South New Brighton for one year

In Lincoln and Leeston, mild steel samples corroded relatively slowly, indicating an atmospheric corrosivity of B. However, considerably higher corrosion rates were measured with hot dip galvanized (zinc) steel samples, indicating a higher corrosivity category, C. A check of BRANZ's data from the 1980s showed that current and old mild steel corrosion rates at Lincoln were very similar. However, galvanised steel only lost 2.4 g/m²/year in the 1980s, much lower than the present result of 11.6 g/m²/year. Surface morphological characterisation revealed that corrosion products, white and/or light-

yellow particles and/or patches, covered a significant proportion of the surface, in particular, the skyward surface (Figure 8). This morphology is not commonly observed on samples exposed at other testing sites in this research.

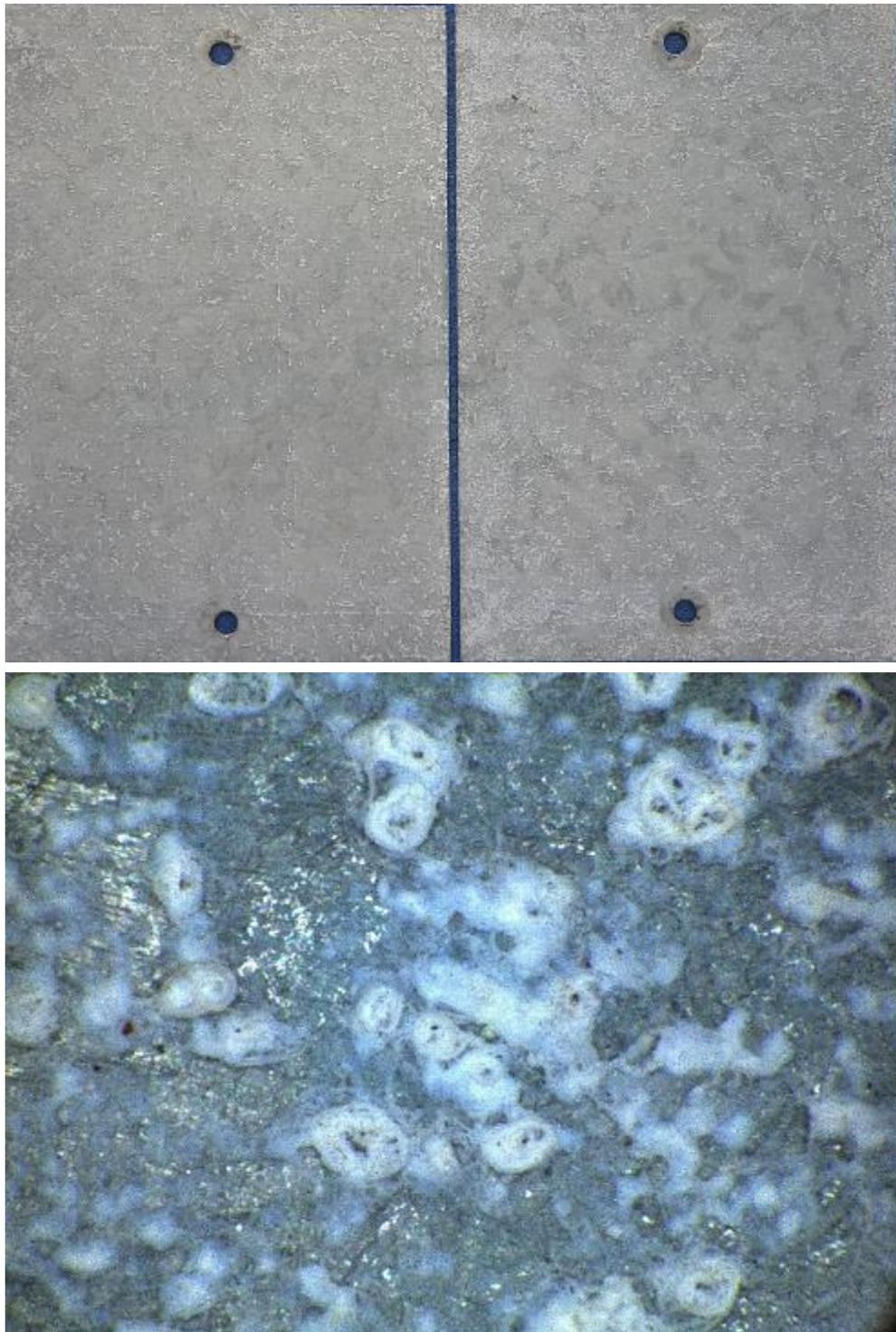


Figure 8. Surface morphology of hot dip galvanized (zinc) steel sample exposed at a test site in Lincoln for one year

Samples tested in Lincoln were installed within a large area of flat land, used for plant and food research. In Leeston, the samples were installed within the open yard of a steel structure manufacturing factory which was also surrounded by farm land. A variety of

chemicals are used in agriculture and farming, for example, fertilisers, grain and silage, preservatives, and chemicals for pest, disease and weed control. Some of these chemicals can attack metals directly, while others may exert negative influences on corrosion resistance when decomposing, or reacting to produce corrosive substances. Examples may include ammonia, hydrogen sulphide, and chloride [Eker and Yuksel 2005]. Some herbicides and pesticides, for example, copper-bearing Bordeaux mixture, can be quite corrosive to zinc through galvanic corrosion processes [Porter 1994]. However, there is no information about what chemicals had been used within these areas during this exposure period. Therefore, the mechanisms behind the significantly increased atmospheric corrosion rate of hot dip galvanised (zinc) steel are not clearly understood in this research.

3.4.4 Dunedin

In the 1980s, the first-year mild steel atmospheric corrosion rates were measured to be 239, 243, and 127 g/m²/year at Taiaroa Head (Otago Peninsula), Musselburgh, and Dunedin Airport, respectively. In the map shown in the NZS 3604:2011, the boundary between Zones B and C roughly followed the northeast – southwest direction (Figure 9). Meanwhile, the majority of the Otago Peninsula was covered by Zone D.

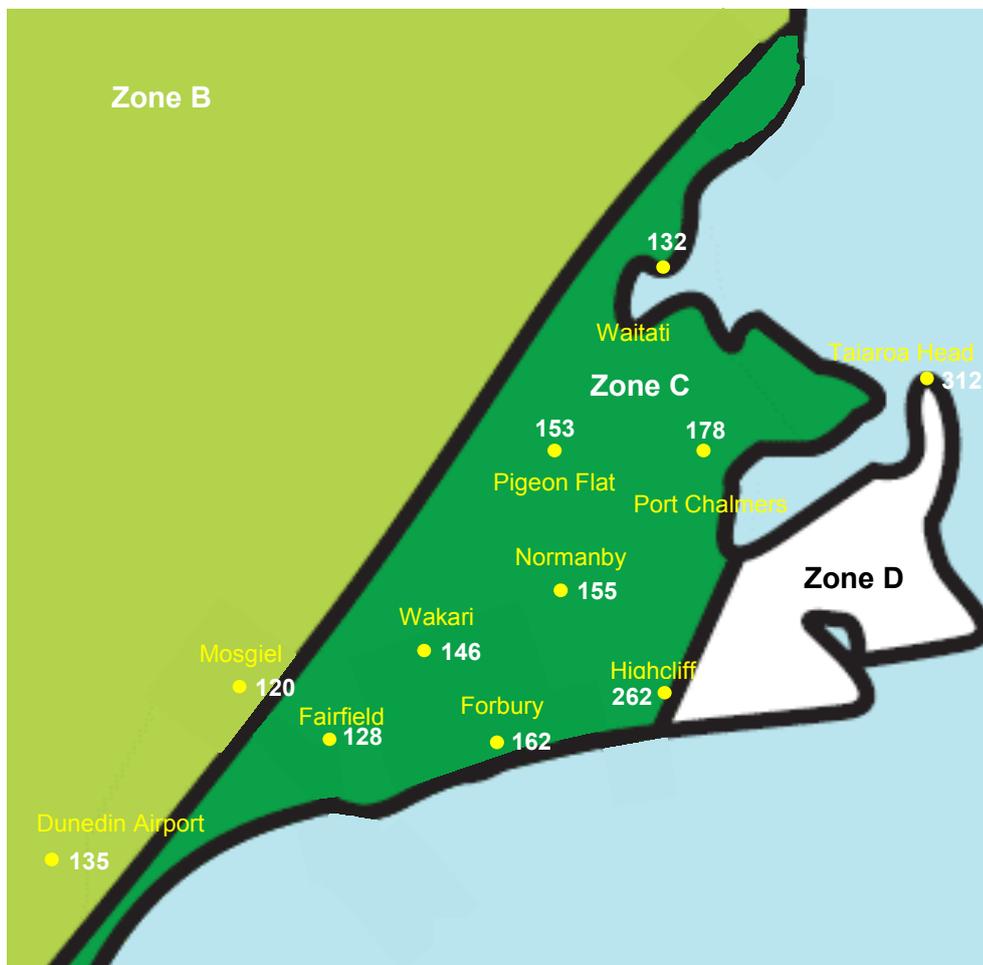


Figure 9. Schematic showing atmospheric corrosion rate of mild steel in Dunedin region

In this study, atmospheric corrosion testing sites were selected in areas:

- close to the current boundary between Zone C and Zone B,
- close to the coast, and

- where previous measurements had been performed.

The first-year corrosion rates of mild steel were measured during the period of 2011 – 2012. They are 153, 155, 146, 120, and 128 g/m²/year at Pigeon Flat, Normanby, Wakari, Mosgiel, and Fairfield, respectively. These numbers are within the range of category B, 10 – 200 g/m²/year. The hot dip galvanized (zinc) steel samples lost their masses slowly and their corrosion rates were 2.0, 4.7, 1.6, 3.6, and 0.6 g/m²/year, respectively.

The exposure site at Taiaroa Head was on a gentle slope on the north tip of the Otago Peninsula, facing towards the sea and wind, and without any obvious obstacles. After one year of exposure, mild steel had a mass loss of 312 g/m²/year. This is higher than the corrosion rate, 239 g/m²/year, measured in the 1980s, but, is still within the range of Zone C, 201 – 400 g/m²/year. The hot dip galvanized (zinc) steel sample only lost 5.0 g/m²/year of its mass during this period. The Highcliff site was facing the Otago harbour and was partially blocked from the sea to the south by gentle hills, with trees and vegetation. The first-year corrosion rates were 262 and 5.7 g/m²/year for mild steel and hot dip galvanized steel, respectively.

3.5 Recommended Adjustment to Regional Atmospheric Corrosivity Map

An analysis of the first-year mild steel corrosion rates measured in this research indicated that the atmospheric corrosivity map shown in the NZS 3604:2011 has limitations in its zone boundary definition. Suggestions are then given for potential modifications to atmospheric corrosivity maps for Auckland, Wellington, Christchurch (Canterbury), and Dunedin (Otago). These were made by taking account of:

- changes in metal atmospheric corrosion rates between previous and present BRANZ studies,
- geographic features, climate (e.g. prevailing winds and rainfall), and/or environmental pollution,
- atmospheric corrosion rate and corrosivity category of nearby sites (if any), and/or
- corrosivity zone definition in the map shown in the NZS 3404:2009.

3.5.1 Auckland

In the north of Auckland, atmospheric corrosion rate measurements in this research support the current exposure zone definition of the NZS 3604:2011 map. This area of land is relatively narrow in the west – east direction, westerly wind could pass over this land mass, influencing atmospheric corrosivity with marine sourced salt particles.

The west coast region of Auckland is highly corrosive, as evidenced by high metal mass loss rates measured at Muriwai Beach. That said, the atmospheric corrosivity in some western suburbs of Auckland city might not be very high due to the fact that:

- the Auckland Centennial Park and Waitakere Ranges Regional Parkland could provide barrier effects to the transport of airborne sea salt particles carried by the westerly, and
- the common wind from the east coast is not very strong.

The western area of the South Head of the Manukau harbour could be highly corrosive. The first-year atmospheric corrosion rates were measured to be 327 and 11.4 g/m²/year for mild steel and hot dip galvanized (zinc) steel samples at one site in the 1980s by BRANZ. Special attention might be necessary for material specification in this area. However, no update is recommended for current exposure zone defined by the map of NZS 3604:2011 as no measurement has been conducted in this research.

In the south of Auckland, Zone C could be narrowed from the east towards the centre, while its southern boundary could be moved towards the north, based on present

corrosion rate measurements. The Hunua Ranges are covered by dense native forests and vegetation so can, to some extent, reduce marine influences from the east coast.

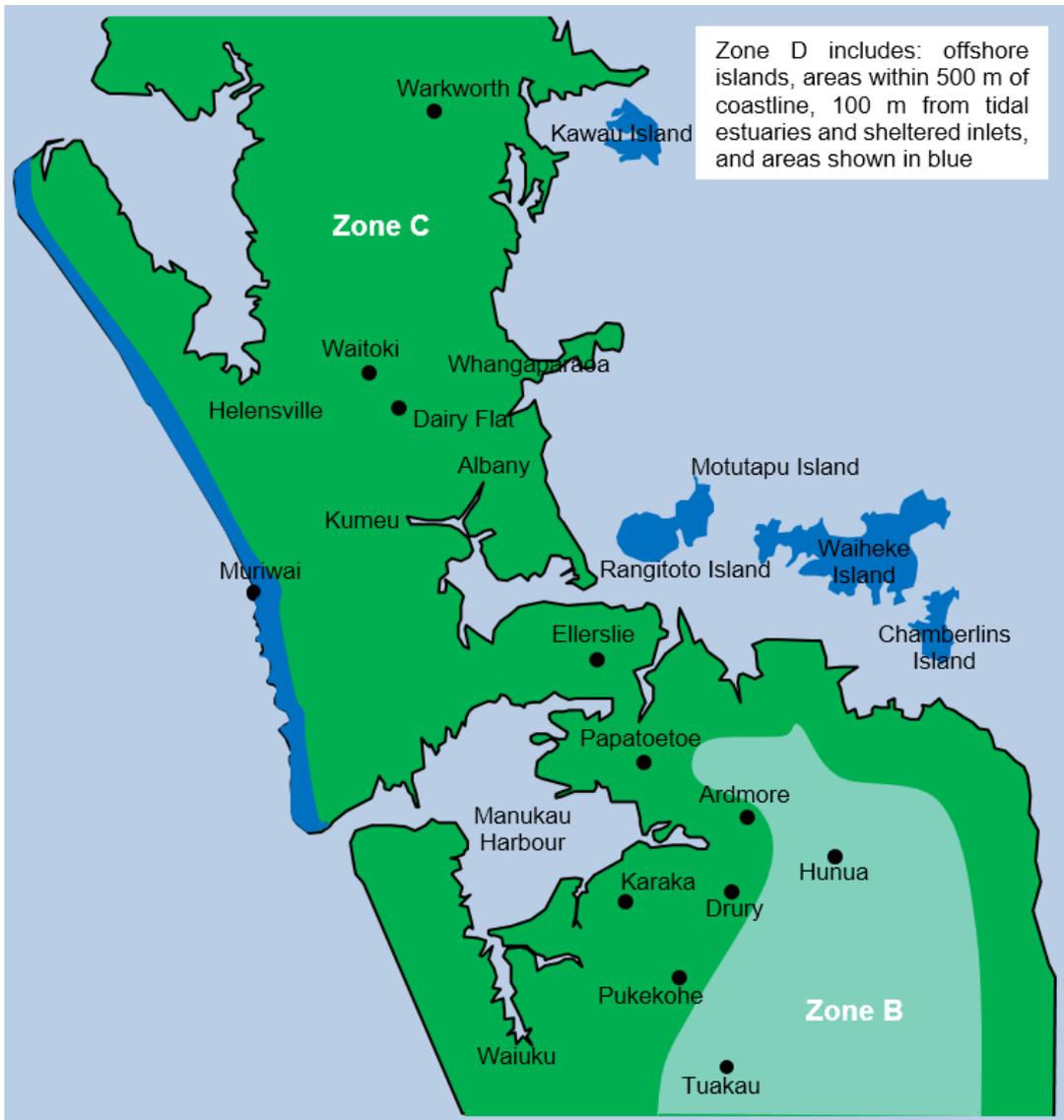


Figure 10. Atmospheric corrosivity map suggested for Auckland region

3.5.2 Wellington

The results derived from this research imply that the exposure zone definition in the map shown in the NZS 3604:2011 is still applicable to most metropolitan and urban areas of Wellington city. The west coast is highly corrosive, as evidenced by the extremely high metal mass loss rates derived from BRANZ studies at Oteranga Bay. This is probably due to the rough sea and (very) strong westerly wind, which can produce and carry large amounts of sea salt particles. It would be appropriate to widen Zone D in this area, similar to that done for the area around Muriwai Beach on the west coast of Auckland.

The boundary between Zone B and Zone C requires adjustment for some areas in Porirua, Lower Hutt, and Upper Hutt. The atmospheric environment of these areas is relatively benign due to:

- relatively low influence of airborne sea salts,
- absence of heavy industrial emissions, and

➤ protection by large forests and ranges on east and south sides.

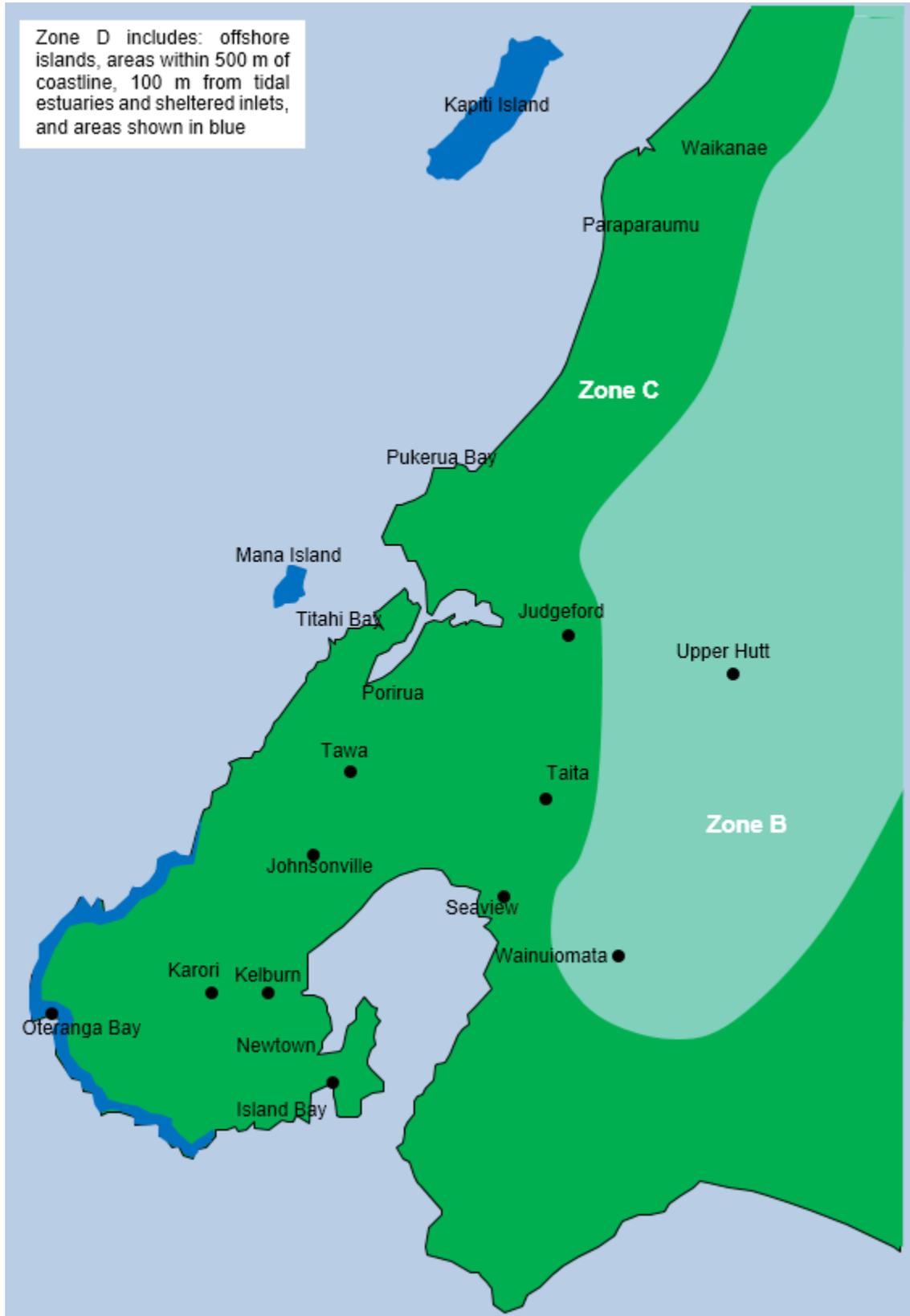


Figure 11. Atmospheric corrosivity map suggested for Wellington region

3.5.3 Christchurch

The measurement conducted at the site adjacent to the beach-front of South New Brighton proved that the east coast of Christchurch is more corrosive than inland areas, probably due to sea spray. However, the corrosivity of this coastal environment appears to be lower than that of New Zealand west coast, for example, Muriwai Beach in Auckland and Oteranga Bay in Wellington. This is probably a result of:

- weaker winds which produce less sea salt particles that travel for shorter distances, and
- lower rainfall and/or humidity.

The measurements and observations in the southern part of Christchurch and on Banks Peninsula indicated that the exposure zone definition of the NZS 3604:2011 map would require adjustments. The areas classified as Zone C could be narrowed down.

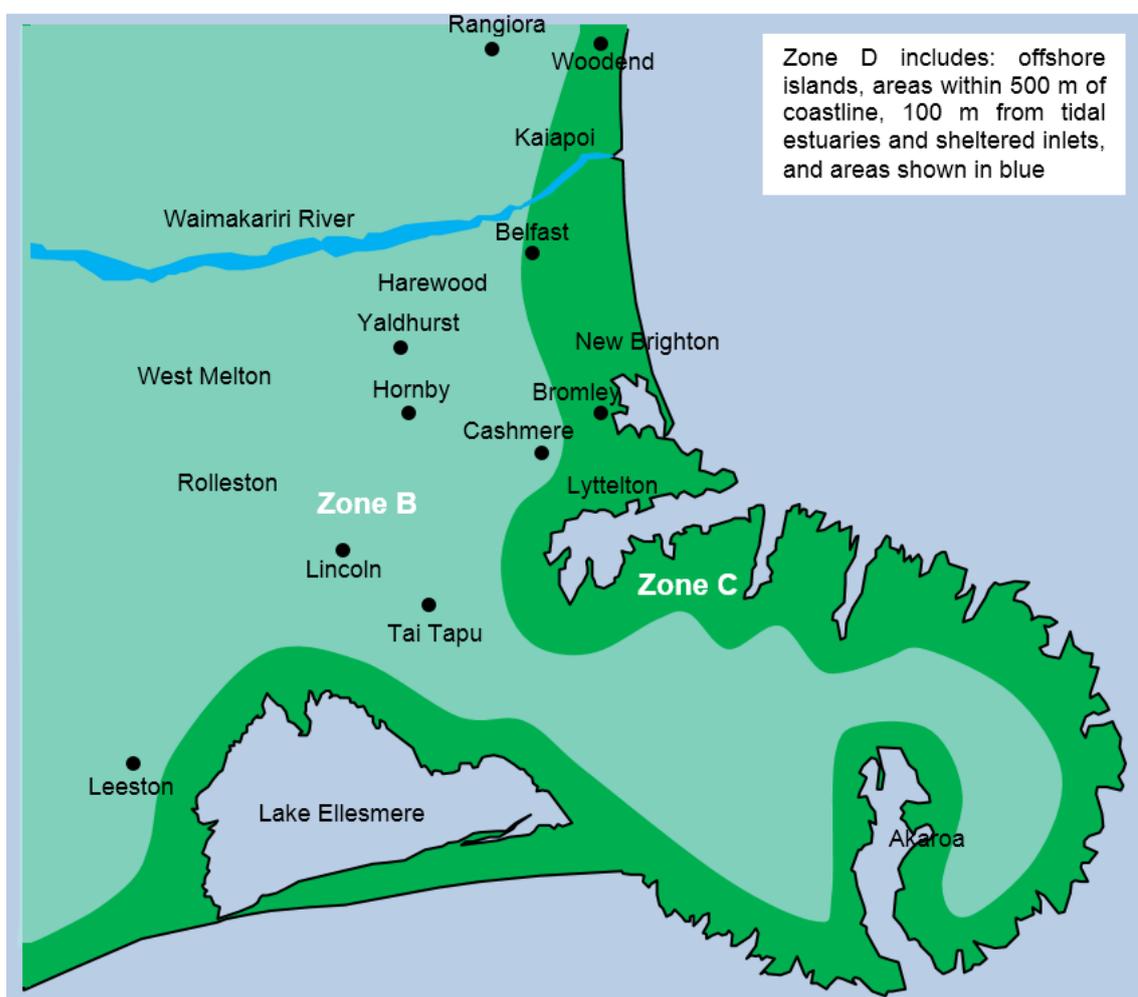


Figure 12. Atmospheric corrosivity map suggested for Christchurch region

Some discrete areas with a higher corrosivity category than their surroundings might be necessary for the modified map. This probably applies to:

- Hornby with emissions from fertiliser manufacturing processes,
- Yaldhurst with influences of airport operation and farming, and
- Lincoln with influences of agricultural chemicals.

However, the exact boundaries for these areas could not be explicitly defined based on current results. More detailed studies would be required to reveal the mechanisms behind the increased local environmental corrosivity towards zinc as observed in this research, and to define the exact region affected.

3.5.4 Dunedin

Dunedin is characterised by hilly topography and proximity to the sea. The city has major industrial and commercial activities on the harbour side, which can release pollutants of fine particles, oxides of carbon, nitrogen, and sulphur [Wilton 2005; Otago Regional Council 2005 & 2010].

Present and previous studies confirmed that the atmospheric environment of the Otago Peninsula was more corrosive than that of the west side of the Otago Harbour and the Dunedin urban area. This is probably due to the stronger influences of sea from the eastern and southern directions. However, to some extent, the Otago Peninsula could provide a barrier against sea salt transportation to the urban areas.

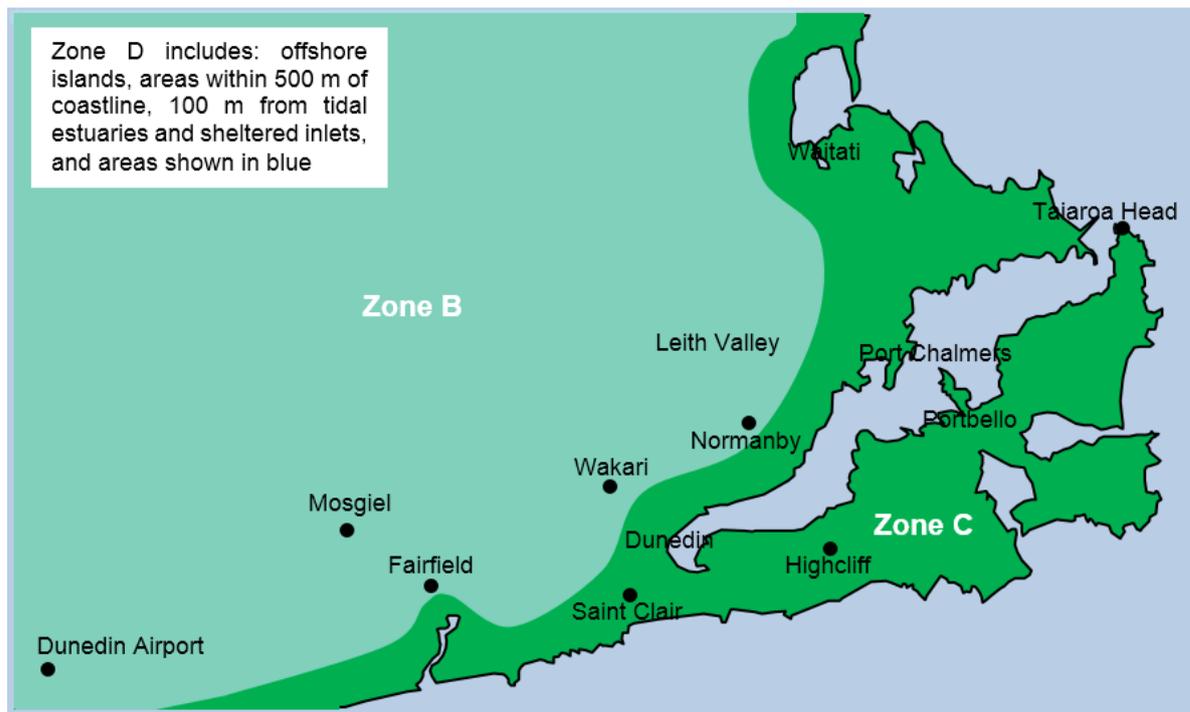


Figure 13. Atmospheric corrosivity map suggested for Dunedin region

The prevailing wind in the Dunedin region is along the southwest – northeast direction. No obvious change in the metal atmospheric corrosion rate with distance along this direction was found in the current measurements. This is probably a result of:

- the blocking effect offered by the ranges in the northeast region, and
- relatively weak winds.

Climatic records from weather stations at the Dunedin Airport and Musselburgh indicated that wind speed in Dunedin region is relatively low, typically around 4 m/s.

4. SUMMARY

First-year metal atmospheric corrosion rates were measured at sixty-one sites selected mainly in Auckland, Wellington, Christchurch, and Dunedin. These corrosion rates were compared with those measured by BRANZ in the 1980s. Obvious changes in corrosion

rates of mild steel and/or hot dip galvanized (zinc) steel were found at several sites. At Auckland Airport and Kelburn (Wellington), both mild steel and zinc corroded faster over the current testing period. A significant decrease in corrosion rate was found for mild steel at Greymouth and for zinc at Tiwai Point. At several sites in Christchurch, a significant increase in zinc coating corrosion rate was noticed, though the new corrosion rate data for mild steel was similar to the 1980s' data. At most exposure sites, although changes in corrosion rates were noticeable, the new data was still comparable with the old data. This indicates a relatively stable environmental corrosivity over a period of near thirty years. Thus, the data from this research updates the only experimentally derived metal atmospheric corrosion rate dataset for New Zealand and makes it more complete and useful.

Climatic parameters, including ambient temperature, rainfall, humidity, wind speed, and solar irradiation, were retrieved from the National Climate Database. Their trends over the period of 1980 – 2010 were analysed using linear regression method. At most testing sites, the average annual ambient temperature increased slightly, while relative humidity and wind speed decreased slightly. The variations in rainfall and wet days were complex and no uniform trend was found.

The differences of each individual climatic factor between the short periods of 1987 – 1988 and 2011 – 2012 (or 2013 – 2014) were calculated as well. Significant changes were not identified. In general, a single climatic factor seemed to exhibit variations that were unrelated to another.

It appears that the differences of a single climatic parameter between the two short periods could be correlated with the changes in the first-year mild steel corrosion rate. However, a clear understanding of the influences of climate change on atmospheric corrosion of metal in New Zealand was not achieved in this research. The main reasons are explained below:

- atmospheric corrosion is a result of extremely complicated interactions between material, climate, and/or environmental pollution,
- although key factors in atmospheric corrosion of metals and alloys have been specified, other factors, known or unknown, can still influence,
- the influences of one specific climatic factor on another, and on atmospheric corrosion has not been clearly understood, and
- climate change is a gradual, complicated, and slow process.

Atmospheric corrosivity zone boundaries, as defined by the map shown in the NZS 3604:2011, were checked against the first-year corrosion rate data of mild steel collected from this research. Some sensible changes have been identified, particularly for regions where atmospheric corrosion testing was limited in BRANZ's study in the 1980s. Recommendations to zone boundary adjustments have been given to regional atmospheric corrosivity maps for Auckland, Wellington, Christchurch, and Dunedin.

It should be noted that atmospheric corrosivity is heavily influenced by weather condition, environmental pollution, and topography of an area. Its determination is further influenced by material and methodology used. How these factors, intrinsic and extrinsic, relate to one another is extremely important. Thus, the exposure zone boundaries suggested in these maps are not set in stone. Testing, together with environmental characterisation, is highly recommended to ensure the correct specification of materials most suitable for the local climate.

5. APPENDIX

5.1 Effect of Starting Season on Atmospheric Corrosion

The starting condition (or commencing season) of field exposure tests is believed to play an important role in metal atmospheric corrosion process and also mass loss rate. This is because the composition and structure of corrosion products formed initially could change with variations in environmental conditions. Consequently, the protective capability of the growing layer(s) on the metal surface can be affected [Syed 2006; Parekh et al 2012]. However, it is impractical to keep the starting conditions of different exposure tests the same, since climatic parameters, such as temperature, rainfall, humidity, and/or wind speed vary frequently.

5.1.1 Exposures

A small part of this research was then focused on the influences of starting season on atmospheric corrosion rate measurement. Several sample racks carrying mild steel and hot dip galvanized (zinc) steel samples were erected at the outdoor exposure site within BRANZ's Judgeford campus. Field tests were started in March, June, September, and December 2013, and the total duration for each exposure was 12 months. First-month and first-year corrosion rates were measured with mild steel samples, while first-quarter and first-year corrosion rates were measured with hot dip galvanized (zinc) steel samples. For the sample set exposed in June 2013, mild steel corrosion rates were measured after 1, 3, 6, 9, and 12 months to investigate the evolution of atmospheric corrosion rate with exposure time.

The Judgeford exposure site is in a sheltered semi-rural environment. It is situated approximately 5 km from the nearest salt water, a tidal estuary, and further protected from the open sea by gently-rolling hills. It lies within Zone C (medium) of the atmospheric corrosivity map shown in the NZS 3604:2011, but is considered a fairly benign example of this category. Environmental moisture would, therefore, be the main contributor to metal corrosion. This largely minimises the complex influences of other factors, such as airborne pollutants.

5.1.2 Seasonal Corrosion Rates

The corrosion rates of mild steel and hot dip galvanized steel samples are presented in Table 6. The first-month corrosion rate of mild steel had varied greatly, from ~200 to ~1000 g/m²/year. Meanwhile, the first-quarter corrosion rates of galvanised steel samples showed much smaller variations. The clean, fresh, steel surface could react with environmental moisture and oxygen very quickly to form iron-rich corrosion products of low protective capability. Any change in atmospheric conditions during the initial exposure stage could lead to relatively large variations in corrosion process. By comparison, zinc corrosion products offer better protection in benign and moderate atmospheres. Therefore, they would grow at a slower rate and are less sensitive to changes in environmental conditions.

Rain is a very important climatic factor for atmospheric corrosion. Abundant rain will maintain environmental humidity above the critical relative humidity for corrosion initialisation and progress. Rain retained in pockets or crevices of the growing corrosion product layer will lead to continued moisture in these areas, which will sustain and/or accelerate corrosion [Cole and Ganther 2006; Cole and Paterson 2007]. Washing of the sample surface by flowing rainwater could also partially remove loose corrosion products. Consequently, the underlying metal substrate would be more easily exposed to environment with corrosive media.

Table 6. Corrosion rates (g/m²/year) of mild steel and hot dip galvanized (zinc) steel samples exposed at Judgeford

Starting Date	1 st -month Mild Steel Corrosion Rate	1 st -quarter HDG Corrosion Rate	1 st -year Corrosion Rate	
			Mild Steel	HDG
19/03/2013	206	6.5	209	3.6
19/06/2013	960	7.8	247	3.0
19/09/2013	596	7.3	196	2.9
19/12/2013	567	6.8	180	3.1

On the other hand, rain may have beneficial effects on corrosion resistance. Atmospheric corrosion has been observed to be more severe on surfaces that were not periodically washed by rain [Haberecht et al 1999]. This effect is particularly noticeable in environments with severe marine influence. The reason is that the flowing rainwater can, to some extent, remove accumulated salt particles, dust, and/or other corrosive deposits [Ganther et al 2011]. However, if the amount of rainfall is not sufficient, deposits may only redistribute on the metal surface, but their total load will remain the same. The amount of rainfall required for surface cleaning to begin was found to be between 0.8 and 1.2 mm, while 1.3 and 3.7 mm of rain could completely clean a surface. Pollutants could be reduced to 10% of their original concentrations after a rainfall of 1.5 mm [Cole and Paterson 2007].

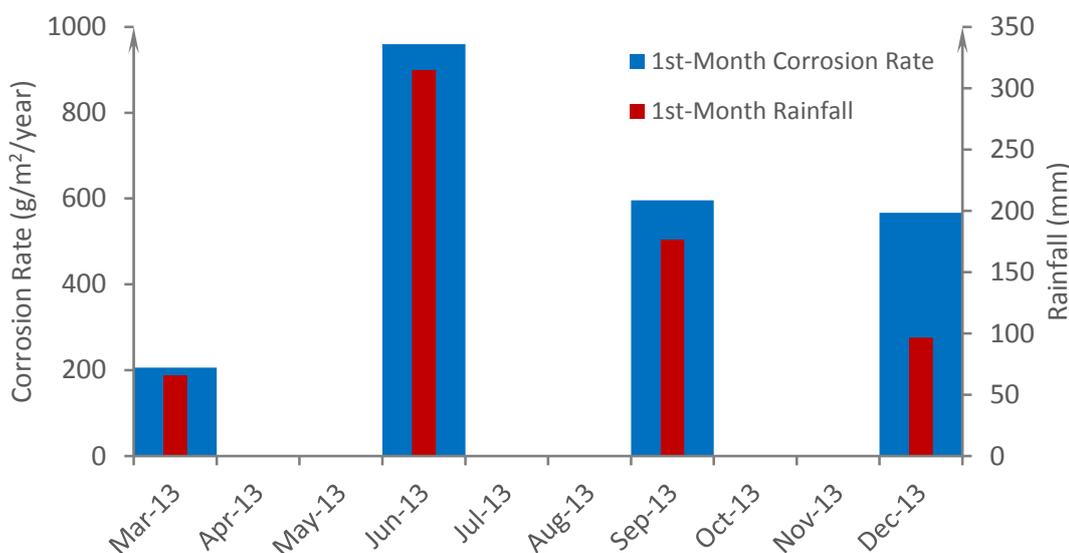


Figure 14. Correlation between first-month corrosion rate of mild steel and first-month rainfall

The quantities of rainfall during the first-month exposures were calculated and are presented in Figure 14, together with the first-month mild steel corrosion rates. It can be seen that the change in the first-month corrosion rate correlates very well with the change in the first-month rainfall. It is believed that rain promotes the initial corrosion through some mechanisms. As mentioned before, the atmosphere of the Judgeford exposure site is relatively benign due to the limited influence of marine produced salts or industrial emissions. Therefore, moisture would be the main contributor to corrosion. Persistent or heavy rain could lead to the prolonged presence of water on the metal surfaces. It could also maintain high humidity in the surrounding environment, thereby prolonging the

corrosion processes. Other studies also indicated that monthly corrosion rates of aluminium, zinc, and mild steel were related to rainfall [Vashi and Kadiya 2009].

Just after the installation of samples on 19 June 2013, the exposure site was hit by a storm, with heavy rain and strong wind for two days. Corrosion products were formed quickly with obvious marks and signs on the steel surfaces, implying mechanical impacts of rainwater driven by strong winds. Under this rough weather condition, more sea salt particles could be produced and carried for longer distances. This would increase the corrosivity of rainwater to a larger area. These might explain the extremely high first-month corrosion rate obtained with the samples installed at this point.

The mass losses after one year of exposure were similar for all mild steel samples. It is interesting to note that the total amounts of rainfall during the exposure periods of Mar 2013 – Mar 2014, Jun 2013 – Jun 2014, Sept 2013 – Sept 2014, and Dec 2013 – Dec 2014 were also similar. They were calculated as 1321, 1213, 1038, and 1057 mm, respectively. This implies that at this site, the initial corrosion process could be greatly influenced by environmental conditions, and are, thus, highly variable. As the corrosion product layer grows thicker, the changes in the initial stage tend to have less and less effect on the long-term corrosion behaviour [Odnevall Wallinder and Leygraf 2001]. A near-stable state governed mainly by the long-term atmospheric conditions will gradually be approached. However, it is noted that the tests commencing in winter and summer produced the highest and lowest corrosion rates after one year, respectively. This difference is around 27%.

5.2 Time Dependence of Atmospheric Corrosion Rate

Based on results derived from extensive field tests in a variety of environments, the long-term atmospheric corrosion kinetics of steel can be described by the following empirical equation [Hou and Liang 1999; Landolfo et al 2010; Ma et al 2010; de la Fuente et al 2011; Morcillo et al 2011]:

$$D = A \times t^n$$

where

D : metal thickness loss,

t : exposure time,

A : a constant that can be a measure of the corrosivity of a specific environment, and

n : a constant that can be an indication of the protective capability of the growing corrosion product layer.

An analysis of mild steel atmospheric corrosion rate data collected from six-year exposures [Kane 1996] has shown that the above equation is applicable for most New Zealand environments. Figure 15 shows the log-log fitting for data collected from several typical environments, e.g. rural (Judgeford), urban (Auckland city), marine (Greymouth), and industrial (Tiwai Point).

However, some studies showed that transitions may occur in the long-term corrosion kinetics for some metals exposed to some environments. This would lead to variations in A and n with time. Therefore, a single equation could not fit data properly [Ma et al 2010; Melchers 2010 & 2015].

As mentioned in Section 4.1, mild steel samples exposed from June 2013 were retrieved after 1, 3, 6, 9, and 12 months to measure progressive atmospheric corrosion rates. Figure 16 is a log-log plot of the corrosion rate against exposure time. This curve was fitted linearly with $R^2 = 0.9966$.

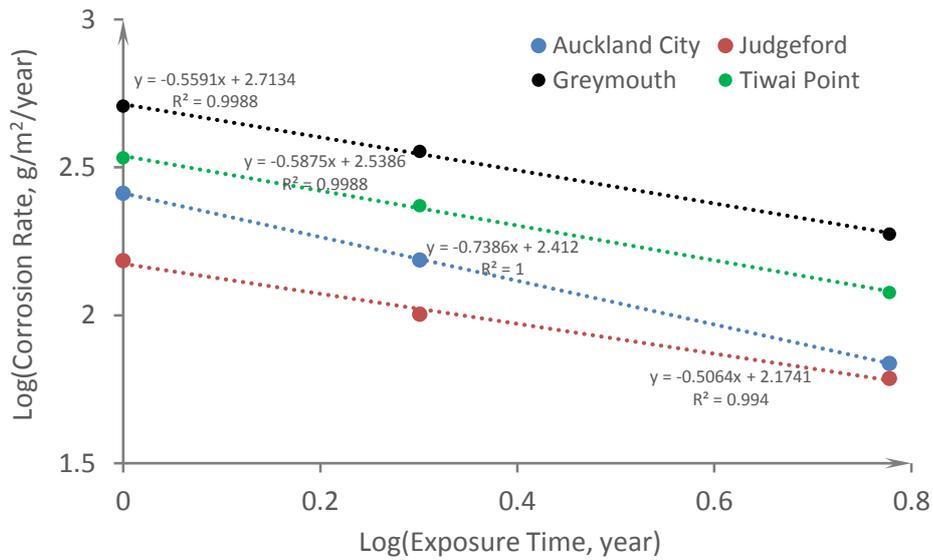


Figure 15. Logarithmic plot of corrosion rate vs. exposure time for mild steel exposed at different sites in New Zealand

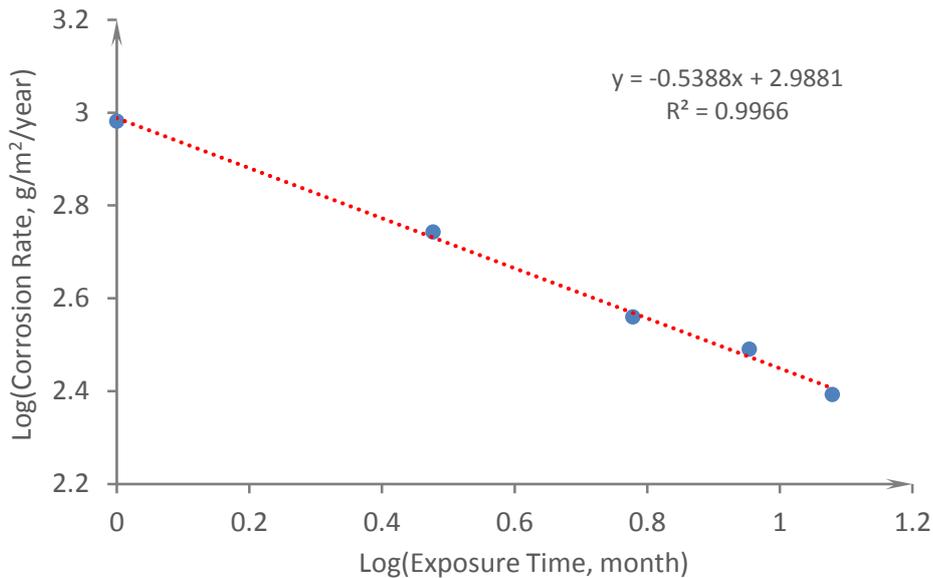


Figure 16. Logarithmic plot of mild steel corrosion rate vs. exposure time

Therefore, the short-term mild steel corrosion rate could be calculated using the following equation with exposure period at this site:

$$CR = 973 \times t^{-0.5388}$$

where

CR: corrosion rate, g/m²/year

973: constant, the first-month corrosion rate, g/m²/year

t: exposure time, month

This result implies that the bi-logarithmic fitting equation for long-term exposure might also be applicable to short-term exposure. If this is true, relatively short atmospheric monitoring might still be able to generate results that will be reliable for atmospheric

corrosivity category classification. However, its validity needs further verification in more typical New Zealand environments.

Figure 17 shows the results collected by BRANZ with samples influenced, more or less, by industrial emission in Christchurch. Data for most sites could be linearly fitted into log-log scales with R^2 very close to 1. However, this might not be the case with data from some sites (e.g. sites 4 and 5, curves in the light green area). In these cases, a multi-phase log-log fit might be more suitable. More data points would be helpful to verify this.

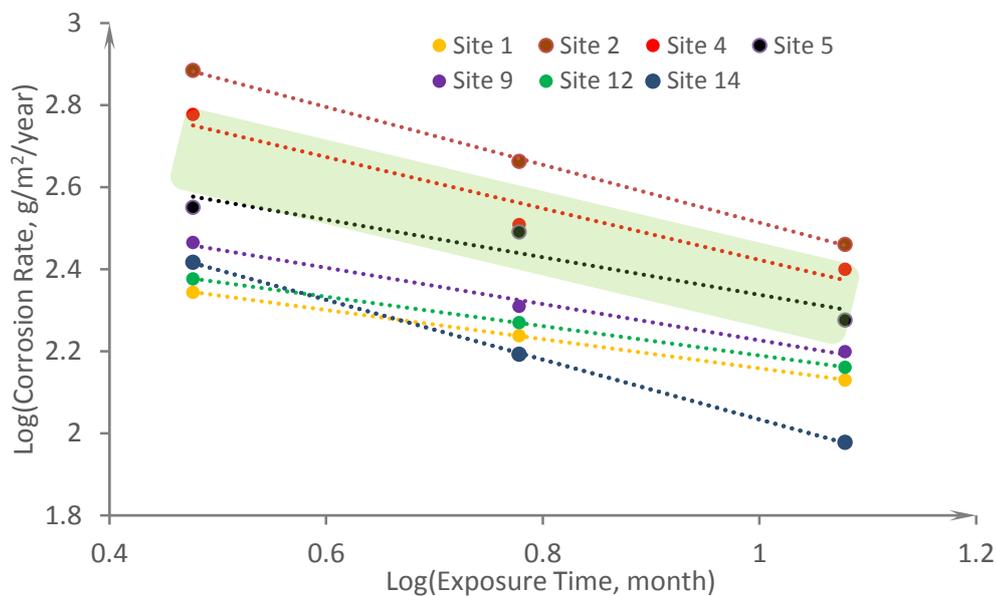


Figure 17. Logarithmic plot of corrosion rate vs. exposure time for mild steel exposed at different sites in a small region with industrial emissions

Corrosion products formed on mild steel after short exposures would more likely to respond to environmental variations quickly. This is probably because microstructure and/or phase composition of the thin, growing corrosion product layer(s) have not reached the stable state. Any significant changes in climatic factor and/or atmospheric pollution could affect corrosion processes. This would lead to variations in its protective capability, and thus transitions in kinetics.

5.3 Summary

This research showed that the first-month atmospheric corrosion rates of mild steel samples exposed in different seasons could be quite different. However, after one year of exposure, their corrosion rates were similar. Corrosion products formed on mild steel in initial stage are generally thin and have large amounts of chemical and structural defects. Their growth could be affected by large variations in environmental condition. For example, a large quantity of liquid water and/or moisture, sourced from rainfall, could accelerate corrosion by inward transportation through cracks and/or pores and/or by partially removing loose corrosion products. However, these corrosion product layer(s) would gradually approach to a relatively stable state. Under certain conditions, the growth kinetics within this transient process could be described by the bi-logarithmic law equation commonly used for long-term atmospheric corrosion kinetics. Please note that these were observed with mild steel samples exposed at Judgeford where the atmospheric environment is relatively clean and benign. Further studies are necessary for a better understanding of influences of commencing conditions on short- and long-term atmospheric corrosion processes and rates of metals exposed to different environments.

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