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# Atmospheric Corrosion Survey of New Zealand - Six Year Exposure Results

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# Atmospheric corrosion survey of New Zealand — six year exposure results

Chris Kane[1], BSc(Hons)

*Coupons of mild steel, galvanised steel and aluminium have been exposed to the New Zealand atmosphere at 98 sites for six years. The corrosion rate for each coupon has been determined by weight loss measurements, and compared with earlier results obtained from the same sites after one and two years' exposure. It is concluded that the results after six years strongly support those obtained in the earlier experiments, and also support general atmospheric corrosion rate theory. Data analysis has shown that despite significant climatic irregularities during the study, variation in the results has been minimal, giving a good indication of the robustness of the experimental methodology.*

***Keywords:*** *aluminium — atmosphere — corrosion — galvanised steel — New Zealand — steel*

## 1. Introduction

In the early 1980s, BRANZ (Building Research Association of New Zealand) began investigating the corrosivity of the New Zealand atmosphere. These investigations were small in scale, and restricted to one particular area of the country at a time, measuring either corrosivity directly, or measuring corrosion-related parameters[1,2,3]. A map of suggested zones of corrosion hazard for the country had been produced in 1982, based on sodium distribution in grass[4]. However, concern still existed that the coastal areas on the map (representing the majority of urban New Zealand) had not been properly surveyed and defined.

Work commenced in 1987 on a country-wide corrosion survey, using steel, galvanised steel and aluminium exposure coupons to directly measure atmospheric corrosivity at 168 sites spread across New Zealand. Coupons were retrieved in 1988 (one year exposure)[5] and 1989 (two years)[6], and stripped of corrosion products then weighed to determine the corrosion loss. This paper presents the data obtained after six years' exposure, and compares that with earlier results.

## 2. Experimental

The experimental method has been explained previously[5], but in brief is as follows. Mild steel, galvanised steel and aluminium panels were exposed on racks facing approximately north at 45° to vertical, about 1.8 m from the ground. The original 168 sites were spread through most of the inhabited areas of New Zealand, with no racks on the East Cape, in Kahurangi and Abel Tasman National Parks, or in Fiordland. As these areas are only sparsely habitated, the consequent lack of data was not considered important.

Rack minders were originally asked to return panels after one, two, five and ten year exposure periods. After four and a half years exposure, the original time periods were reviewed, and it was decided to retrieve the third set of coupons after six and not five years' exposure, in an attempt to better define the shape of the steel weight loss *vs* time curve. After the first year, panels were returned from 168 sites; after two years from 156 sites; and now, after six years, from 98 sites. This represents a loss of 42 percent of the original rack sites, the attrition being due primarily to Meteorological Service restructuring, and also to the passing of time which has seen some rack minders move on without explaining the purpose of the rack to the new owners.

The returned coupons were stripped of corrosion products according to ASTM G1-90[7], and weighed to determine the amount of metal lost. The corrosion rate was then calculated in $g.m^{-2}.y^{-1}$ for both sides of the coupon, including edges for the steel and aluminium coupons. No allowance was made for the metal held in the plastic channels, or the small blobs of neutral cure sealant holding the panels in the racks. Ten unexposed "blank" panels of each metal were run through the cleaning process to determine whether blank corrections would need to be made to the final corrosion rates. None were needed. The nominal date for return of the panels was June 19th 1993. Most of the retrieved panels were received shortly after this, but three sets arrived some months late. The corrosion rate calculations for these coupons have been adjusted accordingly, and they have been incorporated into the main body of data. Although simply reducing the derived rate by ratio to a six-year exposure period will result in the calculated rate not being representative of the true rate at six years, the difference is minimal and is in any case obscured by the experimental error.

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| | Mild Steel | Galvanised Steel | Aluminium |
|---|---|---|---|
| Judgeford | 52.9, 55.6, 62.7, 74.1 | 2.4, 2.8, 4.4, 2.6 | 0.3, 0.2, 0.2, 0.2 |
| Castlepoint | — | 10.8, 9.0 | — |
| Taradale | 22.3, 22.3 | — | — |
| Owairaka | 70.9, 78.3 | — | — |

*TABLE 1: Corrosion rates ($g.m^{-2}.yr^{-1}$) at sites returning duplicate panels after six years' exposure*

# 3. Results

***Aluminium results.*** All of the measured aluminium corrosion rates were extremely low, below 1 $g.m^{-2}.yr^{-1}$. Because of the very low rates, it was not possible to say with any certainty that any correlations existed between the environment and the observed corrosion rate of aluminium. As in previous reports, the only conclusion which can be drawn is that the rates are very low on a macro-exposure scale, and that microclimatic effects are undoubtedly more important. Also, more importantly, it must be stated that the experimental methodology used in obtaining these results does not give any indication of the degree of pitting corrosion of the aluminium coupons, and as this is the usual mode of failure of aluminium in atmospheric exposure, the rate figures should be interpreted with caution.

Attempts were made to rate the aluminium pitting using ASTM G 46-76 when the one-year exposure coupons were returned. However, the inconsistency of ratings between operators, and sheer number of inspections required prevented this. Subsequently, only weight loss measurements were taken for all aluminium coupons. The weight-loss derived rates are presented for completeness, but no further attempts will be made to interpret these in the present paper.

The tabulated corrosion rates after six years are shown in Appendix 1, along with the one and two-year data for comparison. Table 1 gives a comparison between results from duplicate coupons from the same site, to indicate the inherent variance in the measurements. The within-site standard error for steel is 4.73 $g.m^{-2}.yr^{-1}$; for galvanised steel is 0.46 $g.m^{-2}.yr^{-1}$; and for aluminium 0.025 $g.m^{-2}.yr^{-1}$. These errors are slightly lower than those obtained for the one- and two-year data, which could be expected from the greater length of time each coupon has spent in an identical environment to others from the same site. Figures 1 to 4 give the comparisons between the one-, two- and six-year data on a linear plot, as in a previous report. Note that in these figures two of the data points from the Rotorua geothermal region have not been included, as they are an order of magnitude larger than the rest of the results and, when included, distort the graphs of results too much to be useful.

Spearman rank correlations were also run on the data, comparing results from year to year and between metals. The Spearman Correlation Coefficient is a measure of the agreement of rank position between ranked lists, and varies from 1 to -1. A coefficient of 1 means the rankings are precisely in agreement, whilst when one ranking is exactly the reverse of the other the rank correlation coefficient will be -1. No correlation at all gives a coefficient of zero[8]. For the purposes of the present work, high correlation coefficients mean that there has been minimal variation in the relative corrosivities of the environments between each site. If there was a gross uniform change in corrosivity across the entire country, the correlation coefficient would not change, but the measured corrosion rates would, by comparison to previous years. The results of these correlations are shown in Appendix 2.

When the panels were inspected prior to stripping, the general appearance was of uniform general corrosion across the surface of the steel and galvanised samples, and of widespread small-scale pitting on the aluminium samples. A few steel coupons had corroded to the extent that rust deposits had to be carefully removed with a hammer and cold chisel prior to stripping. The steel coupon from Ngapuna in Rotorua was severely perforated, and the galvanised ones from the same site had totally corroded away. One set of samples were returned, but could not be used because they had been maintenance painted in year 4, along with the rest of the climate station.

# 4. Discussion

## 4.1 Six-year data absolute values

The absolute corrosion rate values for steel ranged from 6 $g.m^{-2}.yr^{-1}$ at an alpine hut buried in snow for half of the year to 1351 $g.m^{-2}.yr^{-1}$ at a sewage treatment plant in a heavily geothermally-influenced area. For galvanised steel, the range was from less than 1 $g.m^{-2}.yr^{-1}$ in inland South Island areas to 18.2 $g.m^{-2}.yr^{-1}$ on a wind-swept coast near an aluminium smelter. It should be noted that with the exception of the coupons which had corroded totally away in Rotorua, none of the galvanised coupons had corroded to the extent that red rust was beginning to appear. Hence, it is reasonable to preclude effects from the intermetallic alloy layer on the corrsion rate, and treat the panels as being made of zinc, rather than zinc coated.

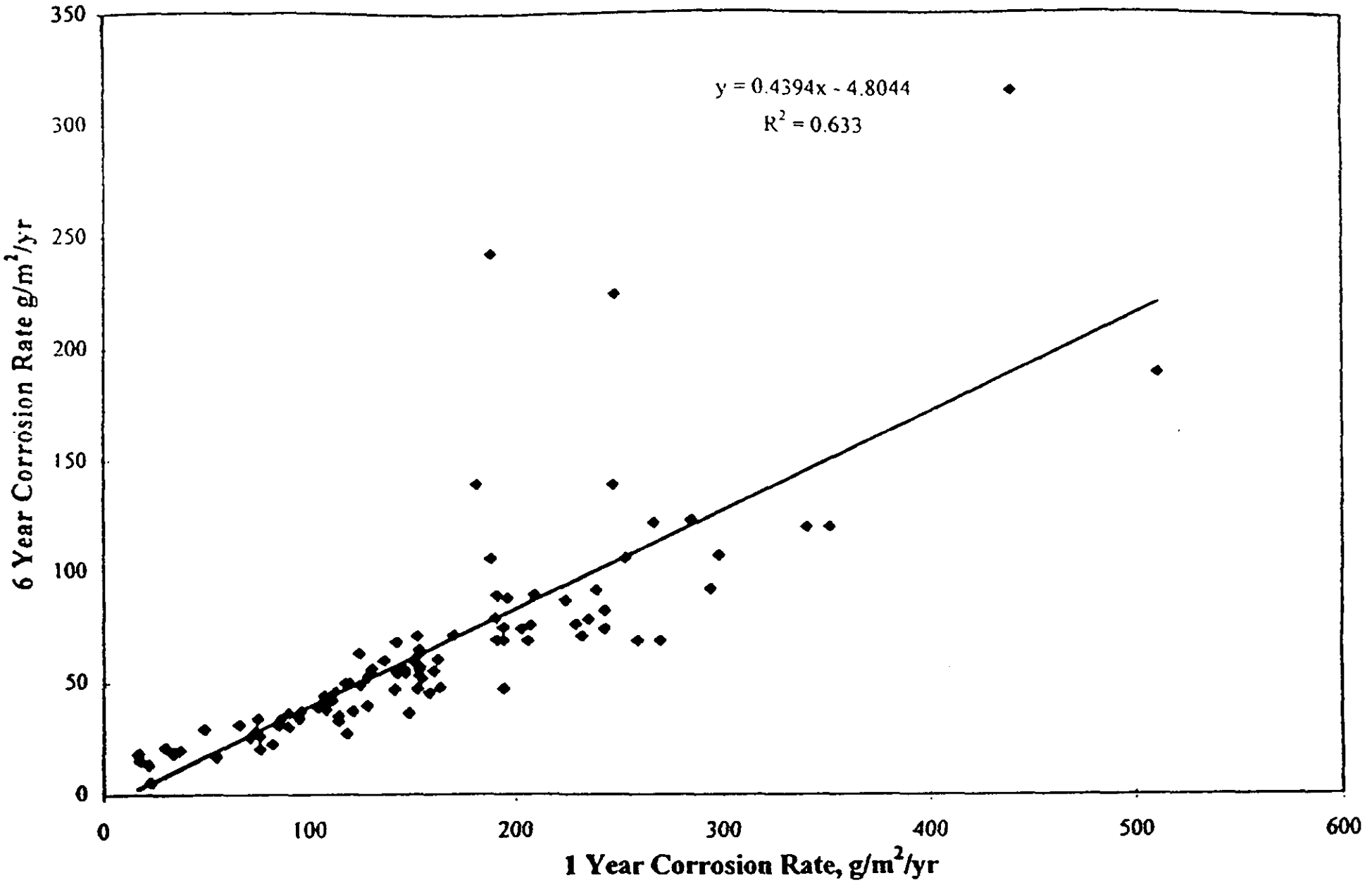


*FIGURE 1: 1 year vs 6 year corrosion rates for mild steel*

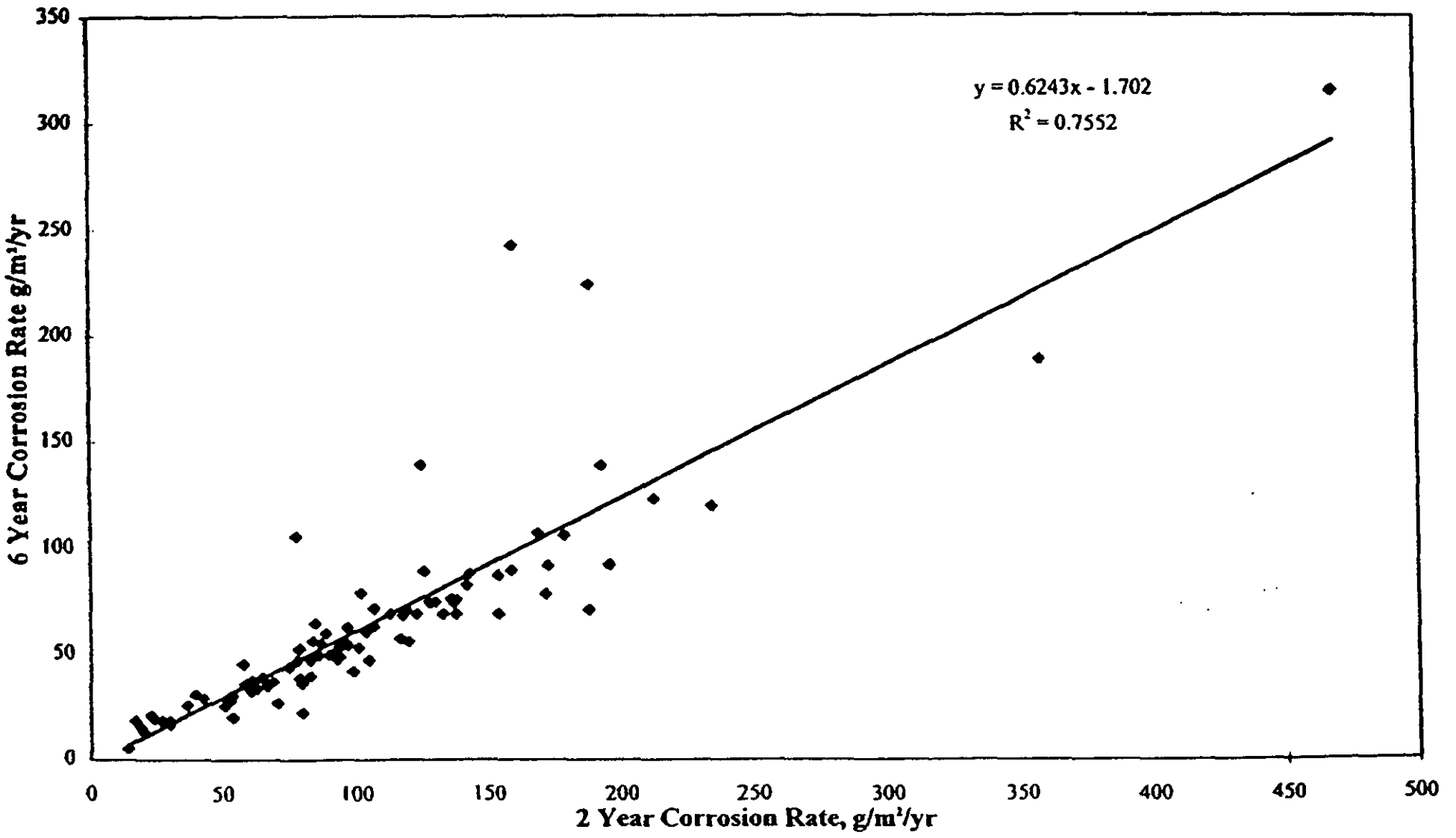


*FIGURE 2: 2 year vs 6 year corrosion rates for mild steel*

The zinc results from Waipukurau and Taradale present the most anomalous observation of the experiment; the corrosion rates are so low that after six years' exposure, less metal had been removed than after two years' exposure at the same site. No explanation can be given for this, and it may be due to a labelling error prior to the exposure of the coupons, since no mistakes could be found in the retrieval and stripping process. Note that at several sites there was more than one rack, or more than one set of coupons

returned; where this has occurred, the average value is presented in Appendix 1.

## 4.2 Comparison with previous results

The linear plots and correlation coefficients given in Figures 1-4 show similar trends for steel and zinc, namely that the six-year exposure results are more closely correlated to the second year results than the first.

A summary produced by the National Institute of Water and Atmospheric Research (NIWA)[9] of the southern oscillation index for the last 15 years shows a significant El Niño in 1987, the year the present study commenced, and also in 1991-94, with a slight La Niña in 1989. These climatic events are manifested in irregular regional weather variations, such as the extremely low rainfall in the north and east of the North Island in 1994. The El Niño in 1987 is probably the reason that the six-year data correlate better to the two-year data (Figures 1-4) than the one-year data; detailed climate data will be sought to confirm this when the final set of coupons are retrieved. The degree of agreement between the three exposure period results indicates that despite climatic fluctuations during the experiment, the general distribution of the primary corrosion inducing parameter has not changed.

Zinc corrosion rates (stationary rates) are believed to be reasonably linear with time where there are no significant climatic variations[10]. This is due to the nature of the atmospheric corrosion mechanism, the reaction interface being the atmospheric surface of the corrosion products (and not at the corrosion product/metal interface, as is the case with steel). If this were the case in the present study, the slope of the correlation line-of-best-fit for Figures 3 and 4 would approach unity. However, the observed slopes are .56 and .80 for one and two versus six years' exposure respectively, suggesting that the actual zinc corrosion rates have dropped over the six-year period. As noted by Duncan and Cordner[6], experience shows that theory is not always reflected in practice[11]; it has been reported[12] that zinc is more sensitive to the initial exposure environment than steel, with elevated initial corrosion rates remaining high for extended periods of time. It is also mentioned, however, that there is significant variation in this observation from site to site and it is not reported for how long the effect will ultimately be significant. It is surmised that atmospheric conditions (such as high onshore winds, high humidity, high rainfall) at the time of exposure of many of the zinc specimens may have caused initially high zinc corrosion rates, which, with climatic variation and the passing of time, have dropped to more closely resemble their "stationary" rates.

The rank correlations run across all sites (Appendix 2), all produce correlation coefficients above 0.7, which indicates that a general correlation exists between the relative corrosivities measured from year to year, and between the different metals for the same year. In all cases, the p-level is zero, indicating that the results are certainly not chance occurrences, and the Student's *t* test results are above the 99 percent confidence level. Thus the correlations are measuring real relationships, and when comparing like metals from year to year are extremely good, indicating that in general, across the country, there have not been any major localised changes in corrosivity for the six-year period. The steel results show a slightly better correlation than the zinc results, which may be due to the difference in corrosion mechanisms between steel and zinc, and the greater sensitivity of zinc specimens to initial exposure conditions, as mentioned above. The good correlations between steel and zinc over time are very encouraging, indicating that a real effect has been measured, and that it is very probably the same effect for both metals. This effect is that of wind-borne chloride from the sea, substantiated by the higher corrosion rates found in coastal areas. Despite this, it must still be noted that using the results for one metal to predict the rate of attack on a different metal in the same environment can be unreliable. The results derived, and their relative consistency from year to year, give reassurance that the experimental methodology used is a robust one, which appears to be relatively free from operator error.

The coupon return from the Rotorua area was too small to determine whether any changes had occurred in the distribution of zones of extreme corrosivity around the area. However, government initiatives to curtail the use of private bores, and thus "repressurize" the thermal outputs could well have altered the pattern of corrosivity throughout the city and environs. A detailed study of this area, such as has been carried out in Melbourne, Australia[13], is warranted, as much to gain a scientific understanding of the nature of the geothermal attack and its relationships to seasonal variation and local weather patterns as to prevent monetary loss through corrosion.

A trial was run on the massed data, removing the two grossly geothermally affected sites from the equation, to determine whether they were affecting the rankings, which had been considered as a factor before the statistical analysis was done. With the two sites removed, there was a slight decrease in the correlation coefficient for both

*El Niño Effect.* When the air pressure is abnormally high in the Indonesian region, it is correspondingly low in the South Pacific and vice versa. This phenomenon is called the "southern oscillation". When southern oscillation episodes occur the usual weather patterns in the South Pacific, including New Zealand, are significantly altered. A southern oscillation index has been constructed using air pressure data from Tahiti and Darwin (Australia). Usually there is a lag of some months between a major excursion of the oscillation, either positive (La Niña) and negative (El Niño), and the development of a characteristic weather pattern. In general, very negative values of the oscillation index (El Niño's) are associated with an increase in frequency of southerly winds over New Zealand in winter, south westerlies in autumn and spring, and westerlies in summer.

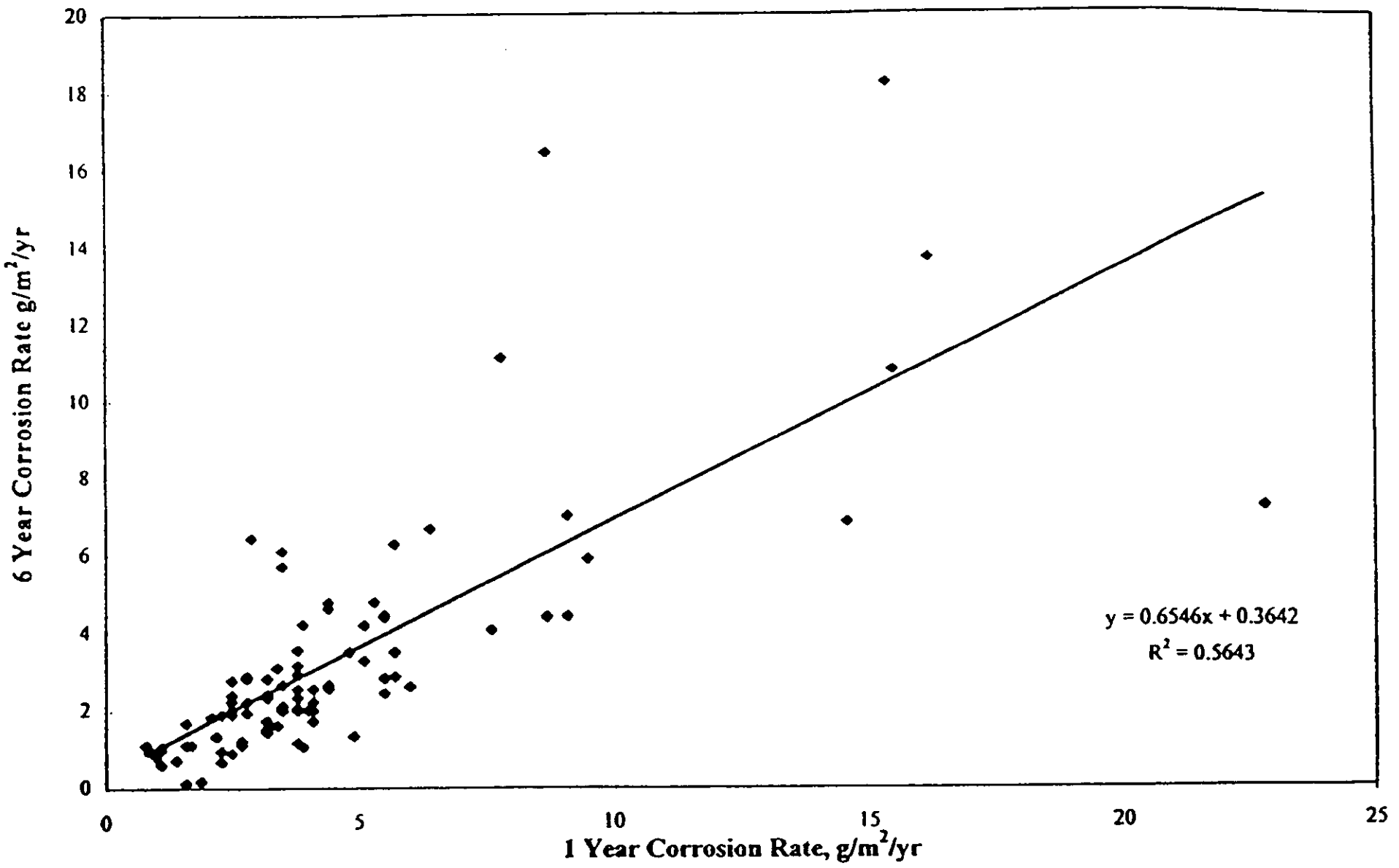


*FIGURE 3: 1-year vs 6-year corrosion rates galvanised steel*

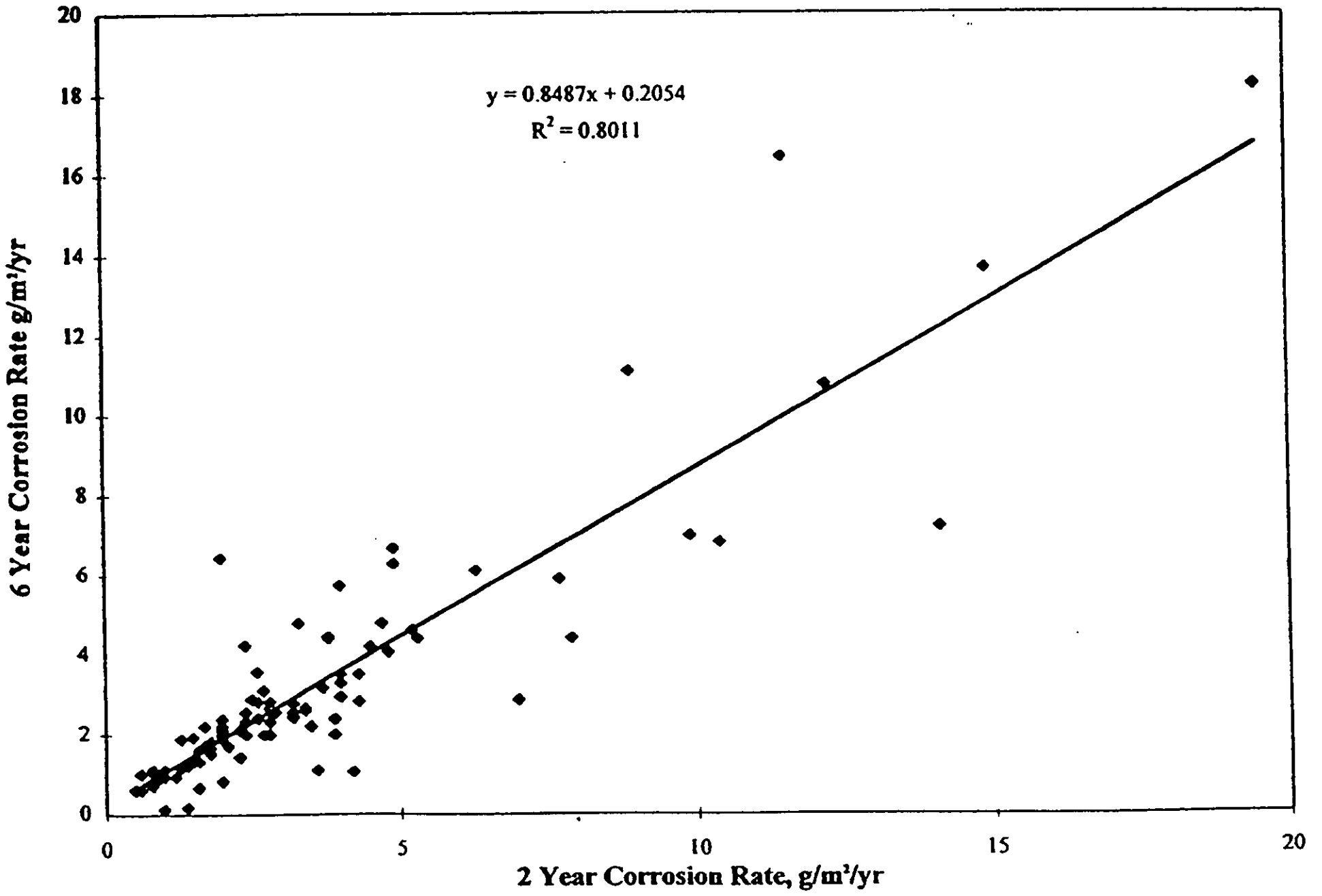


*FIGURE 4: 2-year vs 6-year corrosion rates for galvanised steel*

steel and zinc, but as it was of the order of -0.002 it was discounted as an important effect.

The original salt distribution map published by Duncan and Whitney, which formed the basis of MP2312:1987, "Commentary on AS 2312: 1984 Guide to the protection of iron and steel against exterior atmospheric corrosion"[14], has been generally validated by the three sets of exposure results. A map drawn from the data obtained in this work has been included in Appendix 3. This map depicts mild steel corrosion

rates after the first year of exposure, and is drawn from corrosion rate data, meterological data, and topography, to correspond with the corrosivity zones established in AS/NZS 2312-1994[15]. The corrosivity zone descriptors are given on the map. For quick comparisons, the corrosion rates in mild areas are less than 80 $g.m^{-2}.yr^{-1}$. For Moderate areas, corrosion rates are between 80 $g.m^{-2}.yr^{-1}$ and 200 $g.m^{-2}.yr^{-1}$. For Marine areas, between 200 $g.m^{-2}.yr^{-1}$ and 400 $g.m^{-2}.yr^{-1}$, and in Severe Marine areas, above 400 $g.m^{-2}.yr^{-1}$. Although there are slight variations in the contours, and naturally in the descriptors, the two maps are quite similar, and certainly prove that sea-salt is the main corrosion inducing agent present in New Zealand. Note that there is an implicit Marine zone around the entire coast; its absence on the east coast of the South Island is due to the small extent of the zone inland. Similarly, there is a Severe Marine zone on much of the west coast of the North Island, but again this could not be well enough defined to justify inclusion on the map.

The large body of results produced will be useful in determining the limitations of the atmospheric corrosion rate prediction algorithms given in ISO 9223 (1992)[16]. Inspection of meterological and corrosion rate data, and enquiries of others working in the field (King, G.A., *pers comm.*) have indicated that the Time-of-Wetness definition used by the ISO may not be sufficiently accurate as a base for corrosion rate predictions. Future work will focus on defining where the discrepancy lies. In the interim, however, it may be unwise to base durability prediction work for New Zealand on the ISO 9223 algorithms.

# 5. Conclusions

The results after six years strongly support the results obtained after one and two years. The linear correlations support the general relationship between the site corrosivities over time, despite the expected slight variations due to changing weather patterns.

The expected fall-off in steel corrosion rates has been observed, but cannot yet be investigated in a quantitative manner as at least one further data point is required for a reliable polynomial fit. This will be attempted when the fourth and final set of coupons is retrieved. The expected linearity of zinc corrosion rates over time has not been observed, there being instead a general decrease. The aluminium corrosion rates are again so low as to be useless for comparative purposes.

# 6. Acknowledgements

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# Appendix 1: Corrosion Rates after 1, 2 and 6 Years Exposure

| Location | 1 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 2 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 6 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fe | Al | Galv | Fe | Al | Galv | Fe | Al | Galv |
| **AUCKLAND** | | | | | | | | | |
| AUCKLAND AIR C74082 | 298 | 0.3 | 13 | 169 | 0.8 | 6.3 | 106.9 | 0.43 | 6.11 |
| ALBERT PARK A64871 | 152 | 0.3 | 3.8 | 120 | 0.6 | 6.7 | | | |
| OWAIRAKA A64971 | 152 | 0.6 | 4.1 | 119 | 0.5 | 3.2 | 74.6 | 0.16 | 2.56 |
| AUCKLAND CITY A64878 | 259 | 1 | 7.6 | 154 | 0.8 | 4.8 | 68.8 | 0.16 | 4.06 |
| PENROSE | 229 | 0 | 6 | 136 | 0.4 | 3.4 | 76.2 | 0.37 | 2.61 |
| PARNELL | 165 | -0.3 | 2.5 | 108 | 0.6 | 2.6 | 68.3 | | |
| HARBOUR BRIDGE | 390 | 2.2 | 19 | 349 | 2.6 | 16 | | | |
| ARDMORE C74091 | 209 | 0.3 | 3.5 | 159 | 0.6 | 2.3 | 89.4 | 0.26 | 2.11 |
| WHENUAPAI A64761 | 248 | 0.3 | 5.7 | 189 | 0.9 | 4.3 | 223.8 | 0.32 | 3.5 |
| TAKAPUNA | 142 | 0.3 | 3.2 | 118 | 0.5 | 2.6 | 68 | 0.21 | 2.83 |
| ELLERSLIE | 190 | 0 | 3.2 | 102 | 0.4 | 2.3 | 78.8 | 0.32 | 1.44 |
| **BAY OF PLENTY** | | | | | | | | | |
| WHANGAPOUA FOREST | 158 | 0 | 5.7 | 126 | 0.4 | 4.3 | | | |
| TAIRUA FOREST B75182 | 170 | 0.6 | 3.5 | 107 | 0.5 | 3.4 | 71.4 | 0.16 | 2.67 |
| KATIKATI B75592 | 146 | 0.3 | 3.8 | 97 | 0.7 | | 54 | 0.32 | 2.06 |
| WAIHI B75381 | 163 | 0 | 4.4 | 93 | 0.7 | 2.8 | 47.6 | 0.21 | 2.67 |
| KAINGAROA B86451 | 109 | 0.3 | 2.5 | 76 | 0.3 | 2.4 | | | 2 |
| WHAKATANE AIR B76994 | 196 | 0.3 | 5.1 | 143 | 0.6 | 4.5 | 87.8 | 0.26 | 4.19 |
| OHAAKI PS | 109 | 0.3 | 3.5 | 73 | 0.6 | 0.6 | | | |
| ROTOEHU FOREST | 155 | 0.3 | 3.2 | 98 | 0.8 | 4 | | | |
| OHAAKI IPD | 391 | 0 | 12.4 | 188 | 0.1 | 10.1 | | | |
| TAURANGA AIR B76621 | 195 | 0.3 | 4.4 | 163 | 0.8 | 7.4 | | | |
| KAWERAU B86071 | 294 | 0.6 | 9.5 | 196 | 0.8 | 7.7 | 92.1 | 0.32 | 5.89 |
| MURUPARA | 96 | 0.3 | 1.8 | 75 | 0.6 | 1.5 | | | |
| EDGECUMBE B76835 | 146 | -0.6 | 2.2 | | | | | | |
| TE PUKE B76835 | 154 | 0 | 2.8 | 93 | 0.5 | 2.8 | 51.9 | 0.16 | 2.83 |
| **CANTERBURY** | | | | | | | | | |
| HIGHBANK PS H31572 | 76 | 0.4 | 2.5 | 54 | 0.4 | 0.9 | 20.1 | 0.16 | 0.89 |
| ASHBURTON H31971 | 138 | 0 | 2.1 | 132 | 0.5 | 1.9 | | | |
| CRAIGIEBURN FOREST H31172 | 25 | 0.4 | 2.5 | 9 | 0.3 | 0.9 | | | |
| ARTHURS PASS H21951 | 49 | 0.4 | 3.9 | 43 | 0.5 | 4.2 | 29.1 | 0.26 | 6.6 |
| BROMLEY H32573 | 207 | -0.4 | 3.5 | 125 | 0.6 | 2.9 | | | |
| HANMER SPRINGS G22581 | 37 | 0 | 0.8 | 24 | 0.2 | 1 | 19.6 | 0.11 | 1.11 |
| CULVERDEN H22783 | 76 | 0 | 2.3 | 37 | 0.4 | 1.6 | 25.9 | 0.05 | 0.67 |
| CHEVIOT H23822 | 108 | 0 | 3.8 | 61 | 0.2 | 1.3 | 37.6 | 0.16 | 1.17 |
| KAIKOURA G23471 | 223 | 0.8 | 4.2 | 149 | 0.8 | 3.7 | | | |
| EYREWELL FOREST H32424 | 74 | 0.4 | 1.6 | 53 | 0.3 | 1 | 28 | 0.05 | 1.11 |
| LINCOLN H32641 | 175 | 0 | 2.4 | 112 | 0.5 | 1.3 | | | |
| CHRISTCHURCH CITY H32561 | 152 | 0 | 2 | 83 | 0.5 | | 47.1 | 0.11 | 1.28 |
| **HAWKE'S BAY** | | | | | | | | | |
| MOHAKA FOREST D97004 | 114 | 0 | 2.5 | 61 | 0.4 | 2 | 32.5 | 0.05 | 1.89 |
| NAPIER D96481 | 153 | 0.6 | 3.2 | 117 | 0.6 | 3.9 | 57.1 | 0.26 | 2.39 |
| ESKDALE D96272 | 86 | 0.3 | 2.5 | | | | 33.3 | 0.05 | 1.5 |
| HAVELOCK NTH D96689 | 101 | 0.3 | 5.4 | 65 | 0.7 | 4 | | | |
| WAIPUKURAU DO6051 | 119 | 0 | 1.9 | 86 | 0.4 | 1.4 | 44.2 | 0.05 | 0.18 |
| TARADALE | 82 | 0 | 1.6 | 80 | 0.6 | 1 | 22.3 | 0.1 | 0.13 |
| FRASERTOWN D97042 | 153 | 0 | 3.2 | 85 | 0.4 | 2.6 | 64.6 | 0.11 | 2.42 |
| ONEPOTO D87811 | 90 | 0.6 | 2.8 | 59 | 0.4 | 1.5 | 36 | 0.21 | 1.94 |
| GISBORNE AIR D87692 | 194 | -0.3 | 2.8 | 133 | 0.4 | 2.5 | 68.8 | 0.26 | 2.89 |
| MANUTUKE D87683 | 141 | 0 | 2.2 | 78 | 0.3 | 1.5 | 46.8 | 0.11 | 1.33 |
| WHARERATA D87881 | 175 | 0.3 | 3.2 | 81 | | 1.5 | | | |

| Location | 1 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 2 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 6 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fe | Al | Galv | Fe | Al | Galv | Fe | Al | Galv |
| **MARLBOROUGH** | | | | | | | | | |
| TAPAWERA G12382 | 97 | 0.4 | 2.6 | 98 | 0.3 | 1.8 | | | |
| RAI VALLEY G13251 | 105 | 0 | 3 | 63 | 0.6 | 2 | | | |
| ST ARNAUD F12752 | 34 | 0.4 | 4.9 | 27 | 0.5 | 1.6 | 18.7 | 0.05 | 1.33 |
| L GRASSMERE G14711 | 270 | 0.8 | 8.7 | 138 | 1.1 | 11.5 | 68.8 | 0.63 | 16.44 |
| RIWAKA G12191 | 95 | 0 | 2.3 | 62 | 0.4 | 1.3 | 33.7 | 0.16 | 1.89 |
| BRANCOTT VALLEY G13584 | 58 | 0 | 2.3 | 36 | 0.6 | 1.3 | | | |
| APPLEBY G13211 | 104 | 0 | 3.4 | 65 | 0.5 | 1.8 | | | |
| NELSON AIR G13222 | 162 | 0 | 3.4 | 104 | 0.4 | 2.7 | 60.3 | 0.26 | 3.11 |
| **NORTHLAND** | | | | | | | | | |
| WHANGAREI AIR A54733 | 234 | 0 | 5.1 | | 6.2 | | | | |
| MARSDEN PS A54842 | 285 | 0.3 | 16.2 | 213 | 0.7 | 14.9 | 122.8 | 0.43 | 13.69 |
| KERIKERI AIR A53293 | 203 | 0.6 | 4.8 | 128 | 0.3 | 4 | 74.1 | 0.16 | 3.5 |
| WARKWORTH A64463 | 191 | 0.3 | 5.7 | 126 | 0.2 | 7 | 88.9 | 0.32 | 2.87 |
| WAIPOUA FOREST A53651 | 158 | 0 | 4.1 | | 0.4 | 2.8 | 45.2 | 0.11 | 2 |
| KAITAIA OBS A53125 | 188 | 0.3 | 5.1 | 160 | 0.4 | 4 | 242.1 | 0.16 | 3.28 |
| WAIOTEMARAMA A53541 | 179 | -0.3 | 4.4 | 128 | 0.4 | 2.9 | | | |
| HD MURAWAI | 440 | 1 | 22.8 | 469 | 0.7 | 14.1 | 314.8 | 0.32 | 7.22 |
| LEIGH OXYPLAST | 304 | 1.4 | 9.2 | 228 | 1.4 | 9 | | | |
| WOODHILL FOR A64741 7YR | | | | | | | | | |
| WOODHILL FOREST A64741 | 191 | 0.3 | 3.5 | 113 | 0.6 | 3.9 | 68.8 | 0.26 | 2 |
| DARGAVILLE A53982 | 212 | 0 | 3.6 | | | | | | |
| **ROTORUA** | | | | | | | | | |
| KOUTU | 117 | 0 | 4.4 | 90 | 0.6 | 2.9 | 44.2 | 0 | 2.56 |
| NGAPUNA | 2293 | 0.3 | 71.6 | 5349 | 0.7 | 76.4 | 1351.3 | 0.37 | |
| SPRINGFIELD | 218 | 0 | 6.7 | 134 | 0.6 | 6.8 | | | |
| OHINEMUTU | 222 | -0.3 | 5.4 | 158 | 0.6 | 4.6 | | | |
| L.ROTOATAMAHEKE | 4800 | | 141.6 | 4182 | | | | | |
| ROTORUA AIR B86131 | 207 | 0.3 | 5.7 | 138 | 0.7 | 4.9 | 75.7 | 0.32 | 6.28 |
| TIKITERE B86034 | 243 | -0.3 | 9.5 | | | | | | |
| WAIOTAPU B86341 | 111 | 0.3 | 3.2 | 99 | 0.6 | 2.8 | 41.8 | 0.21 | 2.33 |
| **SOUTHLAND** | | | | | | | | | |
| RANFURLY I50113 | 34 | 0 | 0.7 | 26 | 0.4 | 0.6 | | | |
| ALEXANDRA I59234 | 34 | 0 | 1 | 30 | 0.4 | 2 | 18.3 | 0.11 | 0.83 |
| PALMERSTON I50921 | 90 | 0.3 | 1.7 | 53 | 0.5 | 0.8 | 29.9 | 0.05 | 1.11 |
| DUNEDIN AIR I50921 | 127 | -0.3 | 1.7 | 94 | 0.5 | 1.1 | | | |
| MUSSELBURGH I50951 | 243 | 0.3 | 6.4 | 142 | 0.8 | 4.9 | 82.3 | 0.26 | 6.67 |
| FINEGAND I69273 | 145 | 0.3 | 2.3 | 114 | 0.4 | 3.3 | | | |
| WINTON I68133 | 148 | 0 | 2.7 | 80 | 0.4 | 1.4 | 36 | 0.16 | 1.22 |
| TAIAROA I50771 | 239 | 0.3 | 4.4 | 173 | 0.7 | 3.3 | 91.5 | 0.37 | 4.78 |
| TIWAI I68533 | 341 | 1 | 15.4 | 235 | 0.8 | 19.5 | 119.6 | 0.63 | 18.22 |
| GORE I68192 | 121 | 0 | 2.3 | 69 | 0.5 | 1.2 | 36.9 | 0.16 | 0.94 |
| INVERCARGILL AIR I68433 | 253 | 0.3 | 4 | 135 | 0.5 | 3.2 | | | |
| TAPANUI I59921 | 73 | -0.3 | 1.7 | | | | | | |
| GERALDINE H41127 | 75 | 0 | 1.1 | 63 | 0.4 | 0.8 | 33.6 | 0.11 | 1.06 |
| FAIRLIE H40193 | 53 | 0.3 | 1.8 | 24 | 0.4 | 0.6 | | | |
| L TEKAPO H40041 | 18 | 0.3 | 1.1 | 19 | 0.4 | 0.5 | 15.1 | 0.11 | 0.61 |
| THE HERMITAGE H30711 | 30 | 0 | 3.9 | 23 | 1.1 | 2.4 | 21 | 0.11 | 4.22 |
| KELMAN HUT | 23 | -0.6 | 2.7 | 14 | 0.5 | 3.6 | 5.9 | 0.05 | 1.1 |
| KUROW I40742 | 55 | 0 | 1.1 | 30 | 0.4 | 0.6 | 16.7 | 0.11 | 1 |
| OMARAMA I49591 | 17 | 0 | 1.4 | 17 | 0.5 | 0.8 | 18.4 | 0.16 | 0.72 |
| TIMARU AIR H41323 | 144 | -0.4 | 1.8 | 71 | 0.6 | 1.4 | | | |
| TWIZEL H40212 | 22 | 0.3 | 1.1 | 20 | 0.5 | 0.6 | 13.5 | 0.16 | 0.61 |
| WAIMATE H41701 | 74 | 0.7 | 1.8 | 43 | | 1.4 | | | |

| Location | 1 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 2 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 6 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fe | Al | Galv | Fe | Al | Galv | Fe | Al | Galv |
| **TARANAKI** | | | | | | | | | |
| PATEA E94743 | 218 | 1 | 14.6 | 140 | 1 | 10.1 | | | |
| WANGANUI AIR E95903 | 352 | 1.1 | 33.6 | | | | 119.6 | 0.69 | 13 |
| KAPUNI E94413 | 230 | 0.6 | 4.8 | 147 | 0.5 | 2.8 | | | |
| STRATFORD E94333 | 188 | 0.3 | 3.8 | 78 | 0.4 | 3.7 | 105.4 | 0.21 | 3.17 |
| NEW PLYMOUTH AIR C94011 | 247 | 0.6 | 7.8 | 193 | 1.1 | 8.9 | 138.6 | 0.74 | 11.11 |
| AHU AHU E95614 | 112 | 0 | 2.1 | 58 | 0.5 | 1.8 | 45.5 | 0.21 | 1.83 |
| PALMERSTON NTH AIR E05361 | 168 | 0.6 | 3.6 | 110 | 0.5 | 2.5 | | | |
| WAITARERE E05521 | 224 | 0.6 | 5.5 | 154 | 0.9 | 3.8 | 86.8 | 0.26 | 4.44 |
| OHAKUNE E95445 | 85 | 0 | 3.4 | 54 | 0.4 | 1.6 | 30.6 | 0.05 | 1.61 |
| WAIOURU E95465 | 155 | 0 | 2.7 | 106 | 0.3 | 2.2 | | | |
| TAIHAPE E95683 | 71 | 0 | 0.9 | 51 | 0.4 | 1 | 25.4 | 0.05 | 0.94 |
| PARAPARAUMU AIR E04991 | 240 | 0.6 | 9.1 | 139 | 0.6 | 6.7 | | | |
| LEVIN E05622 | 194 | 0.6 | 4 | 105 | 0.4 | 2.7 | 47.1 | 0.11 | 2 |
| KAIRANGA E05343 | 203 | 0.6 | 2.7 | 117 | 0.6 | 3.2 | | | |
| FLOCKHOUSE | 208 | 0.3 | 5.5 | 123 | 0.5 | 5.6 | | | |
| **TAUPO** | | | | | | | | | |
| WAIRERE DAM C85502 | 163 | 0.3 | 2.2 | 94 | 0.6 | 2 | | | |
| MOHAKATINO C84761 | 267 | 0.3 | 14.6 | 191 | 0.9 | 10.4 | 121.7 | 0.32 | 6.83 |
| WAIKERIA C85132 | 128 | 0.3 | 3.8 | 83 | 0.6 | 2.4 | 39.6 | 0.16 | 2.33 |
| TE KUITI C85314 | 124 | 0.3 | 3.8 | 107 | 0.6 | 2.4 | 63 | 0.26 | 2.56 |
| PUREORA FOREST C85551 | 107 | 0.6 | 3.2 | 75 | 0.6 | | 43.9 | 0.05 | 2.33 |
| CHATEAU C95152 | 96 | 0 | 3.5 | 62 | 0.4 | 4 | 37 | 0.11 | 5.72 |
| ARAPUNI DAM P C85061 | 104 | 0.3 | 2.9 | 72 | 0.3 | 1.8 | | | |
| ARAPUNI DAM P C85061 | | | | 77 | 0.5 | 1.7 | | | |
| KINLEITH B85285 | 308 | 1.3 | 5.4 | 167 | 0.9 | 3.3 | | | |
| ATIAMURI B86403 | 74 | 0.3 | 2.9 | 47 | 0.6 | 1.8 | | | |
| TAUMARUNUI C95821 | 105 | -0.3 | 2.9 | 77 | 0.5 | 2.4 | | | |
| WAIRAKEI PS B86611 | 155 | 0 | 4.8 | 105 | 0.5 | 4.2 | | | |
| TURANGI C95085 | 107 | 0.3 | 2.5 | 65 | 0.3 | 2 | 39.1 | 0.21 | 2.39 |
| TAUPO AIR B86702 | 104 | 0 | 4.1 | 79 | 0.5 | 2.1 | 38.6 | 0.11 | 1.72 |
| WAIMIHIA FOREST B86821 | 91 | 0 | 3.2 | 64 | 0.5 | 2.4 | | | |
| TAUPO B86602 | 120 | 0.6 | 2.9 | 72 | 0.4 | 2.4 | | | |
| **WAIKATO** | | | | | | | | | |
| NZS SM P | 155 | 0.8 | 3.3 | | | | | | |
| PUKEKOHE C74282 | 192 | | 4.1 | 130 | 0.5 | 2.4 | | | |
| HAMILTON AIR C75832 | 142 | 0.6 | 3.5 | 95 | 0.7 | 2 | 54 | 0.32 | 2.11 |
| MAIORO FOREST C74371 | 181 | 0 | 3.8 | 125 | 0.5 | 2.6 | 138.6 | 0.11 | 3.56 |
| TE KAUWHATA C75412 | 217 | 0.6 | 5.7 | 138 | 0.6 | 4.3 | | | |
| RUAKURA C75731 | 130 | 0.6 | 1.6 | 84 | 0.3 | 1.8 | 56.1 | 0.05 | 1.67 |
| CAMBRIDGE C75953 | 131 | 0.3 | 2.5 | 96 | 0.2 | 2.8 | | | |
| NZS MILL P | | | | 108 | 0.7 | 2.3 | | | |
| NZS MILL P | | | | 110 | 0.8 | 2.4 | | | |
| NZS SM P | | | | | | | | | |
| PAEROA B75361 | 160 | 0.3 | 3.2 | 96 | 0.6 | 1.7 | 55 | 0.26 | 1.73 |
| THAMES B75152 | 136 | 0 | 3.1 | | | | 59.8 | 0.16 | 2.31 |
| TE AROHA B75571 | 115 | 0.3 | 2.9 | 71 | 0.7 | 2.3 | | | |
| MARAMARUA FOREST C75321 | 150 | -0.3 | 2.5 | 89 | 0.5 | 3.2 | 59.8 | | 2.78 |
| HUNUA C75003 | 180 | 0 | 4.1 | 104 | 0.3 | 2.9 | | | |
| **WAIRARAPA** | | | | | | | | | |
| TAUHERENIKAU D15134 | 124 | -0.3 | 2.9 | 94 | 0.5 | 2 | 48.7 | 0.26 | 6.44 |
| CASTLEPOINT D06921 | 232 | 0.3 | 15.5 | 188 | 1.1 | 12.2 | 70.9 | 0.48 | 9.89 |
| DANNEVIRKE D06212 | 114 | -0.3 | 3.2 | 67 | 0.6 | 1.8 | 34.9 | 0.16 | 1.53 |
| MT BRUCE D05765 | 128 | 0 | 3.5 | 88 | 0.5 | 3.2 | | | |
| WAITAPU P D05964 | 142 | 0 | 3.5 | 79 | 0.6 | 2.8 | | | |

| Location | 1 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 2 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | | 6 Yr Corrosion Rate ($g.m^{-2}.y^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fe | Al | Galv | Fe | Al | Galv | Fe | Al | Galv |
| **WELLINGTON** | | | | | | | | | |
| JUDGEFORD | 153 | 0 | 5.5 | 101 | 0.5 | 3.2 | 61.3 | 0.2 | 3.06 |
| KELBURN E14272 | 128 | 0 | 2.5 | 79 | 0.6 | 2 | 52.4 | 0.26 | 2.22 |
| KAITOKE E15011 | 146 | 0.3 | 3.8 | 96 | 0.4 | 4 | 55.6 | 0.05 | 2.94 |
| WALLACEVILLE E15102 | 145 | 0.3 | 4.1 | 87 | 0.5 | 3.5 | 55 | 0.16 | 2.22 |
| WAINUIOMATA E14296 | 165 | -0.3 | 4.1 | 97 | 0.5 | 3.6 | | | |
| AVALON E14195 | 164 | 0.3 | 5.1 | 90 | 0.3 | 4.2 | | | |
| GRACEFIELD | 167 | 0.6 | 7 | 102 | 0.5 | 6.2 | | | |
| SOMES ISLAND | 243 | 0.6 | 4.4 | 137 | 1 | 5.2 | 74.1 | 0.26 | 4.61 |
| WELLINGTON AIR E14387 | 268 | 2.6 | 18.3 | 180 | 2.7 | 18.1 | | | |
| THORNDON | 173 | 0.9 | 13 | 96 | 1.1 | 6.5 | | | |
| THORNDON (SHELTERED) | 194 | 0.4 | 12.2 | 130 | 1 | 6.2 | 78.8 | 0.65 | |
| **WEST COAST** | | | | | | | | | |
| OTIRA F21851 | 102 | 0 | 6.4 | 63 | 0.5 | 6.2 | | | |
| FRANZ JOSEPH F30313 | 118 | 0 | 9.1 | 71 | 0.3 | 7.9 | 27 | 0.16 | 4.4 |
| HOKITIKA AIR F20893 | 235 | -0.8 | 8.7 | 172 | 0.2 | 5.3 | 78.3 | 0.16 | 4.39 |
| CHRISTCHURCH AIR H32451 | 206 | 0.4 | 2.8 | 123 | 0.5 | 1.7 | 68.7 | 0.21 | 2.22 |
| SPRINGS JUNCTION F22311 | 66 | 0 | 3.8 | 40 | 0.6 | 2 | 30.9 | 0.11 | 2 |
| WESTPORT AIR F11752 | 375 | 0 | 7.2 | 235 | 0.6 | 6.7 | | | |
| REEFTON F21182 | 253 | 0 | 5.3 | 179 | 0.9 | 4.7 | 105.8 | 0.43 | 4.78 |
| GREYMOUTH F21422 | 511 | 0.8 | 9.1 | 358 | 0.8 | 9.9 | 188.4 | 0.48 | 7 |
| HARIHARI F30153 | 150 | -0.4 | 4 | | | | | | |

# Appendix 2: Spearman Rank Correlations

| Sample Area | Correlation | Sites Compared | Spearman R | t(N-2) | p-level |
|---|---|---|---|---|---|
| **All Sites** | Fe1 v Fe2 | 157 | 0.94 | 33.55 | 0.000 |
| | Fe1 v Fe6 | 100 | 0.89 | 19.31 | 0.000 |
| | Fe2 v Fe6 | 96 | 0.92 | 23.51 | 0.000 |
| | Zn1 v Zn2 | 154 | 0.88 | 23.17 | 0.000 |
| | Zn1 v Zn6 | 98 | 0.84 | 15.03 | 0.000 |
| | Zn2 v Zn6 | 93 | 0.89 | 18.86 | 0.000 |
| | Fe1 v Zn1 | 168 | 0.70 | 12.94 | 0.000 |
| | Fe2 v Zn2 | 157 | 0.74 | 13.76 | 0.000 |
| | Fe6 v Zn6 | 98 | 0.76 | 11.51 | 0.000 |

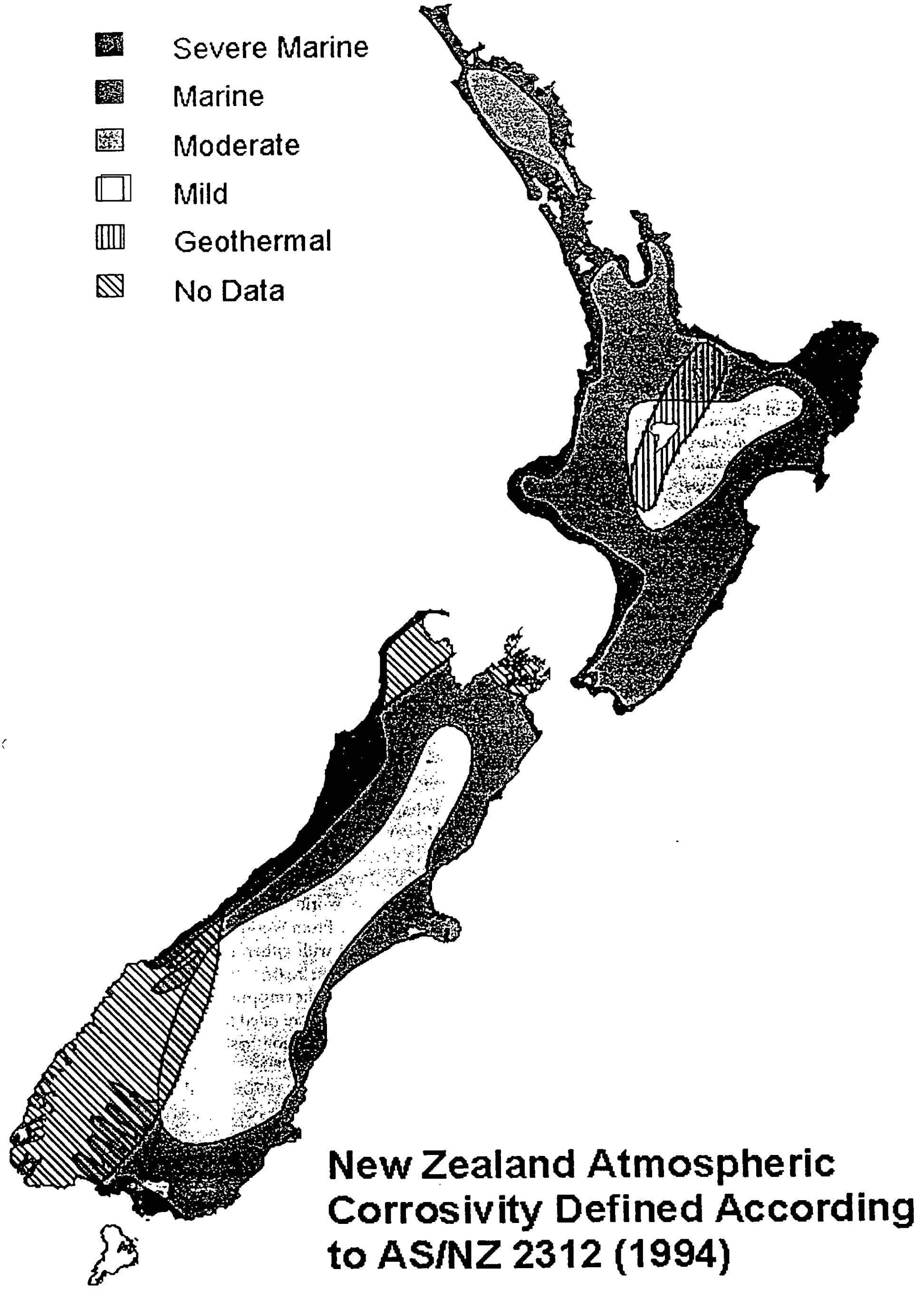
Key: Fe1 = Steel corrosion rates after one year's exposure

Fe2 = Steel corrosion rates after two year's exposure

Zn1 = Galvanised steel (hence zinc) corrosion rates after one year's exposure

Etc.

Appendix 3: Corrosivity map of New Zealand for mild steel, defined according to AS/NZS 2312:1994.



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