Abstract—The development of an Insulator Pollution Severity Application Map (IPSAM) for South Africa is being investigated. This paper discusses the results that were obtained from Directional Dust Deposit Gauges (DDG’s) and Equivalent Salt Deposit Density gauges (ESDD’s) across South Africa. An investigation into the effect of distance-from-seacoast on pollution severity levels is discussed. Correlations between DDG and ESDD and between DDG and corrosion test results are also included.

Keywords—Distance-from-sea, pollution classification, insulator pollution, corrosion.

I. INTRODUCTION

Power lines pass through the following major pollution environments: marine, industrial, desert, and agricultural. These pollution deposits accumulate on insulator surfaces and form a conductive electrolyte when the insulator surface is wetted by rain or fog. This allows the flow and increase of leakage currents over the insulator surface, which in turn results in the decrease of the electrical withstand of the insulator and finally leads to a flashover.

Although the ultimate aim of this project is to produce a map for South Africa, the present study includes data from the Western Cape and South Cape, which are used as the basis to develop a methodology to compile a map.

Pollution measurements are taken at various intersections along a 400 kV power line up to 35 km away from the coast. The aim is to assign pollution severity classification levels along the line. Pollution measurements from other pollution monitoring stations along the coast, up to 35 km’s away, are utilized in conjunction with the results from the 400 kV test site to investigate the effect of distance-from-sea on pollution severity levels.

II. POLLUTION MEASUREMENTS

Various methods of obtaining a measure of insulator pollution severity are investigated. Two direct methods of pollution measurements were utilised: directional dust deposit gauges (DDG) and equivalent salt deposit density (ESDD). Metal corrosion depends on the presence of moisture and ionic salts, the same factors causing insulator pollution flashover. It was therefore decided also to install standard corrosion measurement probes at each measurement point.

Direct insulator pollution measurements

These methods collect the pollution material directly and the collected samples are evaluated monthly intervals.

DDG (Directional dust deposit gauges)

The DDG consists of four vertical collection tubes with slots milled in the sides to collect air-borne pollutants. The four slots face the four cardinal points of the compass: North, East, South, and West as shown in figure 1.

The DDG pollution index is defined as the mean value of the conductivities of all four directional gauges, expressed in \( \mu \text{S/cm} \) and arithmetically normalised to a 30-day month. The equations to calculate normalised conductivity and average (mean) conductivity is given below:

\[
\sigma_N = \frac{C (V/500) (30/N)}{4}
\]

where \( \sigma_N \) = normalised conductivity (\( \mu \text{S/cm} \))

\( C \) = volume conductivity (\( \mu \text{S/cm} \))

\( V \) = volume of distilled water (ml)

\( N \) = amount of days since previous removal of the containers

\[
\text{Average } \sigma = \frac{\sigma_N + \sigma_S + \sigma_E + \sigma_W}{4}
\]

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ESDD (Equivalent salt deposit density)
A unit string, consisting of seven glass disks is used for the ESDD measurements, as shown in figure 2. These discs are not energised and collect air-borne pollutants under the influence of the environmental conditions, the shape and material of the insulator. The discs are removed and the pollution on the surface is washed, using demineralised water, as indicated in figure 2.

The ESDD pollution index is obtained from the measurements of the volume conductivity, temperature, and volume of the wash water. The conductivity probe measures the volume conductivity, $\sigma$, at temperature $t$. The volume conductivity is related to 20 °C using equation 3:

$$\sigma_{20} = \sigma_0 [1 - 0.02277(t - 20) e^{-0.01956(t-20)}]$$  (3)

Where $\sigma_0$ is the measured volume conductivity ($\mu$S/cm), $t$ is the solution temperature (°C) and $\sigma_{20}$ is the volume conductivity corrected to 20 °C.

The salinity, $S_a$ (kg/m³), of the suspension at 20°C is obtained with equation 4 and the equivalent salt deposit density (ESDD) in mg/cm² is then determined with equation 5:

$$S_a = (5.7 * \sigma_{20})^{1.03}$$  (4)

$$ESDD = S_a V / A$$  (5)

Where $V$ is the volume of distilled water (cm³) used and $A$ is the area of the washed insulator (cm²).

Table 1 is a summary of the DDG and ESDD pollution indices as given in [8].

Corrosion measurements
Two methods of corrosion testing were incorporated in the study, CLIMAT and metal coupons.

CLIMAT
For the CLIMAT test; preparation, testing and analysis were done as prescribed by ASTM G116 and ISO 9226 [9], [12]. In principle, this test method is a galvanic corrosion (or dissimilar metal) effect. The CLIMAT Classify Industrial and Marine ATMosphere (CLIMAT) test is also referred to as the wire-on-bolt test.

The ISO equation for the corrosion rate, $r_{corr}$ in micrometers per year (µm/a) is given as [12]:

$$r_{corr} = \frac{\Delta m}{A \cdot D \cdot t}$$  (16)

where $\Delta m$ = is the mass loss (mg), $A$ = is the surface area (m²), $t$ = is the exposure time in years, $D$ = is the density (g/cm³).

where $d_{Fe} = 7.86$ (g/cm³), $d_{Zn} = 7.14$ (g/cm³), $d_{Cu} = 8.96$ (g/cm³), $d_{Al} = 2.70$ (g/cm³).

Metal coupons
The metal coupon test was based on the principles of the ASTM G50 [10] and ISO 9226 [12] standards.

The corrosion rate, $r_{corr}$, in micrometers per year (µm/a) is given as [12]:

$$r_{corr} = \frac{\Delta m}{A \cdot D \cdot t}$$  (16)

where $\Delta m$ = is the mass loss (mg), $A$ = is the surface area (m²), $t$ = is the exposure time in years, $D$ = is the density (g/cm³).

From the table, it is clear that the results of the CLIMAT test are lower than those of the metal coupon test. This may be due to the fact that the CLIMAT test is a more severe test, as it exposes the metal to a more corrosive environment. The metal coupon test, on the other hand, is a more gentle test, as it exposes the metal to a less corrosive environment. This is reflected in the lower corrosion rates obtained for the metal coupon test.

Figure 1: Directional dust deposit gauges
Figure 2: ESDD unit string
Figure 3: CLIMAT and Metal coupons
Figure 3 is a photograph of an actual completed metal coupon assembly installed at a test site 15 km from the coast while Table 2 provides the corrosion indices and classification for the metal coupon test [13].

<table>
<thead>
<tr>
<th>Severity Class</th>
<th>DDG</th>
<th>ESDD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>monthly average</td>
<td>monthly maximum</td>
</tr>
<tr>
<td>Light</td>
<td>0 to 75</td>
<td>0 to 175</td>
</tr>
<tr>
<td>Medium</td>
<td>76 to 200</td>
<td>176 to 500</td>
</tr>
<tr>
<td>Heavy</td>
<td>201 to 350</td>
<td>501 to 850</td>
</tr>
<tr>
<td>Very Heavy</td>
<td>&gt; 350</td>
<td>&gt; 850</td>
</tr>
</tbody>
</table>

Table 2: Corrosion indices

<table>
<thead>
<tr>
<th>Corrosivity (category)</th>
<th>Mild steel (µm/a)</th>
<th>Zinc (µm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low (C1)</td>
<td>≤ 1.3</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>Low (C2)</td>
<td>1.4 to 25</td>
<td>0.2 to 0.7</td>
</tr>
<tr>
<td>Medium (C3)</td>
<td>25 to 50</td>
<td>0.8 to 2.1</td>
</tr>
<tr>
<td>High (C4)</td>
<td>51 to 80</td>
<td>2.2 to 4.2</td>
</tr>
<tr>
<td>Very High (C5)</td>
<td>81 to 200</td>
<td>4.2 to 8.4</td>
</tr>
</tbody>
</table>

III. LOCATION OF MONITORING STATIONS

Figure 4 is a topographical map showing the location of monitoring stations within South Africa; the areas are the Cape Peninsula, West coast and South Cape.

Figure 5 is a topographical map of the monitoring area from the Koeberg Nuclear Power station to Muldersvlei substation, spanning a distance of 30 km from the coast. This site was set up to investigate the effect of aerosol migration from the coast and the impact on DDG and corrosion levels along the Koeberg-Muldersvlei 400kV line. Directional dust deposit gauges and corrosion specimens were installed at the KIPTS (Koeberg Insulator Pollution Test Station) monitoring station, and at every 1 km interval for up to 10 km’s, at 15 km, 20 km and 30 km from the coast. The position of each monitoring station was determined using GPS (global positioning system) mapping technology.

In the analysis of the distance-to-coast effect, the results from the Koeberg-Muldersvlei line (figure 5) were combined with data from other pollution monitoring stations in the West and South Cape (figure 4).

IV. RESULTS AND DISCUSSION

The DDG pollution measurement results from all the monitoring stations up to 35 km’s from the seacoast, including data from the Koeberg-Muldersvlei 400 kV test area, are shown in figure 6 and 7 for average and maximum values respectively. Figure 10 and figure 11 show corrosion rates against the distance-from-coast along the Koeberg-Muldersvlei 400 kV line for CLIMAT (wire-on-bolt) and metal coupon corrosion rates respectively.

Figure 8 (average values) and 9 (maximum values) are plots of the ESDD results.
Figure 6: DDG measurement results (average values)

Figure 7: DDG measurement results (maximum values)

Figure 8: ESDD results (average values)

Figure 9: ESDD results (maximum values)

Figure 10: CLIMAT corrosion testing results

Figure 11: Mild steel corrosion rates

Figure 12: Correlation between ESDD and DDG measurement results (average values)

Figure 13: Correlation between ESDD and DDG measurement results (maximum values)
King et al. reported salt deposition close to the coast (within 10⁴ m) is highly influenced by salt production at surf beaches and by local terrain, whilst salt at 10³ m to 10⁶ m inland is more influenced by transport of the finer aerosol produced by ocean white caps [3].

Comparing pollution levels (figures 6 to 9) close to the coast for up to 1 km, it is clear that the order of magnitude is twice (or even 3 times) that of pollution levels further inland, which agrees with findings from various distance-from-seacoast corrosion studies [3-7].

<table>
<thead>
<tr>
<th>Description</th>
<th>R²</th>
<th>Standard error</th>
<th>Slope, b</th>
<th>P -value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDG vs ESDD</td>
<td>avg</td>
<td>0.617322</td>
<td>0.0147</td>
<td>0.0001099</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>-0.608362</td>
<td>0.08419</td>
<td>0.000118</td>
</tr>
<tr>
<td>DDG vs mild Fe</td>
<td>avg</td>
<td>0.7558815</td>
<td>7.07787</td>
<td>0.060688</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.748623</td>
<td>7.182327</td>
<td>0.01489</td>
</tr>
<tr>
<td>DDG vs CLIMAT</td>
<td>avg</td>
<td>-0.111266</td>
<td>1.9617</td>
<td>0.013788</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>-0.132</td>
<td>1.979958</td>
<td>0.006093</td>
</tr>
<tr>
<td>Mild Fe vs CLIMAT (Al-Fe)</td>
<td></td>
<td>-0.446458</td>
<td>6.0517</td>
<td>2.8534</td>
</tr>
<tr>
<td>CLIMAT vs CLIMAT (Al-Fe vs Al-Cu)</td>
<td></td>
<td>0.589449</td>
<td>3.150925</td>
<td>1.518899</td>
</tr>
</tbody>
</table>

**Impact distance**

The pollutants at KIPTS were found to be predominantly sodium chloride (NaCl) [2], with the sea as the source of the salt-laden aerosol and affecting areas further inland.

Table 3 is a summary of the impact distance for each pollution level based on the distance-from-seacoast analysis. It should be noted that pollution levels could penetrate further than indicated; however, the distances are reflective of the actual measurement results.
Corrosion rates are also significantly increased at RH levels above 75%, which also explains why the distance-from-seacoast pollution profiles are similar for the insulator and corrosion pollution measurement results (see figures 6 to 11).

### Table 3: Impact distance-from-seacoast

<table>
<thead>
<tr>
<th>Description</th>
<th>Maximum distance of impact (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Heavy</td>
</tr>
<tr>
<td>DDG</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>Avg</td>
</tr>
<tr>
<td>ESDD</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>avg</td>
</tr>
<tr>
<td>Mild steel</td>
<td>avg</td>
</tr>
</tbody>
</table>

### Correlations

Figures 12 to 17 are plots from regression studies for various monitoring parameters with the regression for all forced through the origin. Table 4 is a summary of results from regression analyses. A hypothesis test (t-test) was carried out to determine the usefulness of the relationship. A P value greater than 0.01 (P>0.01) indicate that there is no useful linear relationship between the modeled parameters.

To the author’s knowledge no other study have been carried out comparing direct insulator pollution measurement results with corrosion testing results.

It should be noted that the data point appearing as an outlier is not an outlier in the sense of the word. It is ascribed to the location of monitoring stations leaving a gap in the data points between the coastal station (KIPTS) at 40 m from the shore and the next station located 800 m away, producing results in the order of 2 to 3 times in magnitude at KIPTS compared to the next station 800 m away. It would be a good practice to have more monitoring stations over the first few hundred meters from the coast in order to capture data points that are more spread out over the range of the measurement values since the decay is more dominant in this region (see figures 6 to 11) and it becomes more linear after about 800 m from the coast.

### Climatic conditions

Relative humidity (RH) is an indication of the moisture level in the atmosphere. When the RH percentage is high (>75%) there is a good chance that the insulator surface could be wetted, which could dissolve into a conductive electrolytic layer, which further result in increased leakage currents [2].

Vosloo conducted a study at the KIPTS (Koeberg Insulator Pollution Test Station) monitoring site and found that there is a 50% probability that RH will be higher than 94% in winter and 85% in summer. The probability that the RH levels will exceed 75% is approximately 88% in winter and 78% in summer.

Corrosion rates are also significantly increased at RH levels above 75%, which also explains why the distance-from-seacoast pollution profiles are similar for the insulator and corrosion pollution measurement results (see figures 6 to 11).

### V. CONCLUSION

The results from the distance-from-coast study show an exceptional pollution severity over the first 500 to 800 meters from the coast; thereafter a rapid decay is noticeable moving further inland. The DDG and ESDD pollution results are very similar in profile compared to that of the corrosion tests (CLIMAT and metal coupons). The first few hundred meters are exceptional and a rapid decay is noted after about 1 km (10^3 m) from the coast.

A very strong relationship exists between DDG pollution levels, distance from the coast and mild steel corrosivity with an R value of 0.75, while a moderate linear relationship between DDG and ESDD pollution values with an R^2 value of 0.62 have been produced.

Corrosivity and insulator pollution levels at the coast (KIPTS) are 23 times those at sites 800 m from the coast, reflecting the exceptional pollution concentration over the first few hundred meters (up to 10 m) from the seacoast, which is mainly attributed to the high NaCl concentration levels and high relative humidity in the region closer to the coast.

It can be concluded that a corrosion map can be used to predict insulator pollution severity levels in the case where direct insulator pollution measurements are not available.

### ACKNOWLEDGMENT

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### REFERENCES


