# **Atmospheric Corrosion in the Tropics:**

# The Costa Rican Central Valley Case

### J. Rodriguez-Yáñez<sup>1\*</sup>, R. Brenes-Brenes<sup>2</sup>, R. Jiménez-Salas<sup>2</sup>, M. Abdalah-Hernandez<sup>3</sup> and J. Sanabria-Chinchilla<sup>4</sup>

 <sup>1</sup>Laboratory of Urban Ecology, Distance State University, P.O. Box 474-2050, San José, Costa Rica. ORCID. https://orcid.org/0000-0001-5539-3153
 <sup>2</sup>Corrosion research center, Technological Institute of Costa Rica, P.O. Box 10032-1000, Cartago, Costa Rica. ORCID
 <sup>3</sup>National Co-laboratory of Advanced Computing- National Center of High Technology, Pavas, San José, Costa Rica. ORCID
 <sup>4</sup>Center of Electrochemistry and Organic Chemistry, University of Costa Rica, P.O. Box 11501-2060, San José, Costa Rica, ORCID
 \*Corresponding author: jrodriguezy@uned.ac.cr
 Received 09/09/2021; accepted 20/11/2021

https://doi.org/10.4152/pea.2022400602

#### Abstract

The Western Central Valley (WCV) of Costa Rica is an area of interest, due to its high concentration of population and economic activity, presenting itself as a tropical monsoontype atmospheric basin (AB), with well-defined climatic seasons (dry and rainy). The present study proposes the assessment of low carbon steel (CS) atmospheric corrosion, based on ISO 9223 (2012) and associated standards. A general analysis of the atmospheric basin effect was initially performed on these data, followed by the basic modeling of air pollutants and meteorological parameters. The WCV is an area of low contamination, which corresponds to a C2 or C3 category, according to ISO 9223. It mainly shows significant climatic seasons (dry and rainy) effects on the initial corrosion rates, but obtaining similar annual corrosion results for them. The ISO 9223 annual atmospheric corrosion model overestimated the actual obtained corrosion values, whereas linear or logarithmic models gave better results, especially when time and/or time of wetness (TOW) were considered as variables.

Keywords: low CS, mathematical modeling, monsoonal climate, air pollutants, rain, TOW, ISO 9223, ISO 9225.

#### Introduction

The basic metals production is a minor economic activity in Costa Rica. The majority of these materials are obtained by importation. Therefore, it can be set as convenient for the country to know the corrosion mechanisms of basic metallic materials, in order to consider their effects on its economy. Corrosion losses are estimated to be about 3% of the country's gross domestic product (GDP). Much of this impact can be avoided with appropriate protective measures. The main losses

in a tropical country are due to the atmospheric corrosion of structural materials, such as low CS or galvanized steel [1, 2].

Costa Rica main urban areas are located away from the coast line, inside the geographic region known as WCV. WCV concentrates most of the country population (50%) and economic activities (60%). Hence, this sector is of great interest for the assessment of the basic metals deterioration [3-5].

WCV is considered an AB, surrounded by the volcanic mountain range to the north, and the foothills of the Talamanca mountain range to the south and the east. It has an average altitude of 1000 m above the sea level (m.a.s.l.), with elevations exceeding the 2500 m. The climate is monsoonal, with an average annual rainfall of 2300 mm/m<sup>-2</sup>, mainly between the months of May and November (rainy season). The temperature (T) ranges from 20 to 25 °C, while the relative humidity (RH) varies from 70 to 90%, depending on the altitude and the time of the year. Winds have a main direction associated with the Alisios or Trade winds, in the NE towards the SW direction, according to the orography and seasonality [6-8].

In Costa Rica, atmospheric corrosion studies are generally associated to externally funded or company projects with specific purposes, both in terms of the selected location and the used materials. Some of them present only general information about WCV, for low steel alloys and galvanized Fe, without considering the climatic variability in that area [9, 10].

Atmospheric corrosion in WCV was proposed as a mild rural or light urban type of corrosion, with low levels of contamination, and mainly dependent on the meteorological parameters, especially RH, or its equivalent in terms of corrosion, and TOW. This is related to the C2 or C3 corrosion levels, as stated by ISO 9223 [9-13]. None of the studies mentioned any difference in the seasonality effect on corrosion. Meanwhile, Garita et al. (2014) performed a basic corrosion modeling estimate with atmospheric parameters, for WCV [14].

In this work, low CS corrosion was studied to evaluate if there was a seasonal effect, after the metal short exposure in WCV, and to examine different mathematical models for corrosion data estimation.

## Methodology

The studied area is shown in Fig. 1. The study was conducted with low CS.

Low CS composition before analysis is detailed in Table 1, and compared with that stated by the American Society for Testing and Materials (ASTM) for A36 CS, which is commonly used as a standard [15-17].

CS composition was evaluated by optical emission spectrometry (OES), using a Leco model GDS500A spectrometer.

The low CS samples were cut into 100 mm x 50 mm x 1.5 mm coupons. They were initially cleaned with soap and water, to remove grease and dirt. Then, they were polished with wet sandpaper of increasing grades, up to 600 grit. Later, the specimens were cleaned in an ultrasonic bath, and rinsed with distilled water and acetone, before being dried in air. All the coupons were weighed and prepared for the exposure test [17-19].



Figure 1. Location map of WCV in Costa Rica.

**Table 1.** Low CS composition and comparison with that stated by ASTM for A36 CS.

Material	Fe%	С%	Mn%	Si%	S%	P%	Cu%
Exposed CS	99.5	0.055	0.266	0.031	0.007	0.011	0.006
ASTM - A36 CS	>99	Max. 0.25	-	Max. 0.4	Max. 0.05	Max. 0.04	Min. 0.2

Corrosion monitoring stations were built based on ASTM G50-20 and G92-20 standards [17, 20]. Their installation sites are shown in Table 2. These stations were located across WCV, in the main direction of the wind flow, from NE towards SW (see Fig. 1).

Table 2. Corrosion monitoring station installation sites.								
Site	North latitude	West longitude	Altitude (m.a.s.l.)					
CIGEFI*	09° 56' 11"	84° 02' 43"	1210					
San Luis	10° 00' 54"	84° 01' 36"	1341					
Santa Ana	09° 52' 54"	84° 11' 14"	1772					

\* Centro de Investigaciones Geofísicas (Research Center in Geophysics, University of Costa Rica).

For the corrosive atmospheric classification proposed by ISO 9223, climate parameters were evaluated based on meteorological data provided by the National Meteorological Institute (IMN) and the Costa Rican Institute of Electricity (ICE), at stations near the sampling sites. The considered parameters were T, RH, rainfall (R) and wind (W). TOW was estimated according to ISO 9223, by counting the number of hours when RH was greater than or equal to 80%, and T was higher than 0 °C [13]. Atmospheric pollutants were evaluated following ISO 9225 (2012), using humidity candles for chlorides (Cl), and passive monitoring, such as Passam AG (2012), for sulfur dioxide (SO<sub>2</sub>), ozone (O<sub>3</sub>) and nitrogen oxides (NOx) [21, 22].

Public volcanological data, on the dispersion of contaminants emitted by nearby volcanoes (Irazú, Turrialba, in the SE, and Poás, in the North of WCV), provided by the Volcanological and Seismological Observatory of Costa Rica (OVSICORI)

and the Environmental Observatory of the National University, with the support of IMN and the Laboratory of Chemistry of the Atmosphere (LAQAT), were also analyzed. The influence of tropical storms was also considered [23].

CS samples corrosion assessment was performed through the weight loss (WL) gravimetric technique, by chemical pickling, according to ASTM G1 (2003), using the 3.35 method [18].

Two series of samples were exposed to the corrosion process in the rainy (from September 2018 to September 2019) and dry seasons (from March 2019 to April 2020), respectively.

The 2, 6 and 12-month-old samples were additionally analyzed by Scanning Electronic Microscopy (SEM) and X-ray Diffraction (XRD). The SEM microscope was a Carl Zeiss Sigma 300 model, and the diffractometer was a Bruker XDS D8 Focus model.

#### **Corrosion models**

The annual values gravimetrically obtained were compared with those established by the model given in ISO 9223 [13] for low CS, according to the climatic and pollution parameters for each site, as per the formula:

$$Vcorr = 1.77 P_{d}^{0.52} exp (0.020 RH + f_{St}) + 0.102 S_{d}^{0.62} exp (0.033 RH + 0.040 T)$$
(1)  
$$f_{St} = 0.150 \times (T - 10), \quad if T \le 10$$
  
$$f_{St} = -0.054 \times (T - 10), \quad if T > 10$$
  
$$N = 128 R^{2} = 0.85$$

where  $V_{corr} = corrosion$  rate in the first year ( $\mu m y^{-1}$ ),  $f_{st} = factor$  for steel (due to the change of T effect on atmospheric corrosion from a critical temperature near to10 °C), T = annual average temperature (°C), RH = annual average relative humidity, %P<sub>d</sub> = annual average SO<sub>2</sub> deposition (mg/m<sup>-2/</sup>d<sup>-1</sup>) and S<sub>d</sub> = annual average Cl<sup>-</sup> deposition (mg/m<sup>-2/</sup>d<sup>-1</sup>).

Some authors [14, 24-26] proposed a corrosion model based on time, where the most simplified equation corresponds to:

$$Log Corr = A + n Log t$$
 (2)

where Corr = corrosion accumulated in time ( $\mu m$ ), t = accumulated time (in years) and n = slope, which is inversely associated with the protection level of the oxide surface. The A constant is equivalent to Log (Corr), where Corr is the corrosion in the first year.

Other applicable models are lineal, logarithmic or bi-logarithmic [26-30] equations, which are stated as:

$$Corr = a + b Cl + c SO_2 + d TOW + e R$$
(3a)

$$Corr = a + b \ Log \ Cl + c \ Log \ SO_2 + d \ Log \ TOW + e \ Log \ R$$
(3b)

$$\log Corr = a + n \log t + b Cl + c SO_2 + d TOW + e R$$
(4)

where TOW = accumulated time of wetness (in h),  $SO_2$  = accumulated  $SO_2$  deposition (mg/m<sup>-2</sup>), Cl = accumulated Cl<sup>-</sup> deposition (mg/m<sup>-2</sup>) and R = accumulated rain (mg/m<sup>-2</sup>). These equations were contrasted in different seasons, for each site, and by group.

### **Modeling control parameters**

Three possible relationships between the experimental and modeling results were considered as control parameters: Pearson's correlation coefficient ( $PR^2$ ), which should be greater than 0.7, to be taken as acceptable; the residual sum of squares (RSS), a performance evaluator, which is expected to be minimum; and the Fisher's index (F) that should be higher than 100 [31-33].

Prior to the iterative modeling process, Principal Component Analysis (PCA) and basic statistic tests (U Mann Whitney, Kruskal Wallis and Pearson's correlations factors) were initially carried out to determine the main factors [31, 32]. Based on this, the models of the equations 3 and 4 were developed, considering that they must had more data than variables to be modeled.

Model fitting and parameter determination were performed in Python programming language, using the Pandas software library, for data management, and the stat models package, for parameters estimation and control parameters calculation.

#### **Results and discussion**

#### Corrosion and associated parameters

Corrosion assessment, at the sampling sites, and the meteorological and contamination data are shown in Tables 3 and 4, for rainy and dry seasons, respectively. All parameters are expressed in a cumulative form.

Sites	Time	Corr	R	Cl	SO <sub>2</sub>	TOW
	(days)	(µm)	(mm/m <sup>-2</sup> )	$(mg/m^{-2})$	$(mg/m^{-2})$	(h)
CIGEFI	30	3.6	305.4	109.3	199.1	540
CIGEFI	60	6.5	384.2	299.7	519.9	1054
CIGEFI	123	8.5	404.0	534.4	1659.3	1738
CIGEFI	179	11.6	404.0	819.6	2208.1	2272
CIGEFI	273	15.3	1077.2	1354.5	3157.2	3544
CIGEFI	368	16.7	1640.6	1408.7	3678.9	4992
San Luis	30	2.1	241.8	20.7	448.1	645
San Luis	60	5.0	294.4	26.8	667.8	1284
San Luis	123	7.7	354.3	174.8	2160.6	2489
San Luis	179	10.6	381.5	249.7	2637.8	3297
San Luis	273	14.0	717.8	658.5	3772.6	5147
San Luis	364	17.5	1113.3	1311.7	4906.5	7117
Santa Ana	32	2.1	496.8	50.8	205.9	685
Santa Ana	62	8.4	573.0	56.3	456.3	1270
Santa Ana	125	10.2	591.6	499.0	1632.4	2058
Santa Ana	184	14.2	613.2	926.5	2404.6	2683
Santa Ana	275	14.7	1728.1	1314.5	3279.6	4168
Santa Ana	369	17.3	2205.4	1458.3	916.5	5855

Table 3. Corrosion data and accumulated parameters for the first series (rainy season).

Sites	Time	Corr	R	Cl	SO <sub>2</sub>	TOW
	(days)	(µm)	(mm/m <sup>-2</sup> )	(mg/m <sup>-2</sup> )	(mg/m <sup>-2</sup> )	(h)
CIGEFI	35	3.7	17.8	358.4	441.0	319
CIGEFI	64	6.1	244.8	418.5	853.1	769
CIGEFI	126	9.1	816.0	541.6	1081.7	1754
CIGEFI	189	12.2	1236.6	589.1	1470.8	2720
CIGEFI	274	14.1	1803.2	825.3	2748.3	4079
CIGEFI	399	17.9	1883.6	1083.7	3765.1	5328
San Luis	35	2.2	47.5	230.5	582.7	552
San Luis	64	4.4	190.5	344.9	1039.8	1145
San Luis	126	9.5	492.8	809.3	1480.7	2488
San Luis	185	118	7287	1062.0.	2268.7	3747
San Luis	274	15.1	1261.4	1611.9	3463.3	5686
San Luis	399	16.5	1402.1	1835.2	4630.0	8164
Santa Ana	32	2.8	226.5	363.5	299.6	338
Santa Ana	61	4.2	622.2	413.7	639.0	870
Santa Ana	123	8.4	1203.7	466.4	968.5	2034
Santa Ana	185	11.4	1592.2	563.0	1511.9	3172
Santa Ana	271	158	24020	867.6	2839.9	4830
Santa Ana	396	20.4	2505.9	1239.6	4413.7	6414

Table 4. Corrosion data and accumulated parameters for the second series (dry season).

**Note**: The final time for the second series is longer than a year, because, on March 2020, the COVID19 pandemics caused mobilization restrictions in Costa Rica.

Table 5 shows the annual mean values of Cl, SO<sub>2</sub>, RH and T, while Table 6 presents the average W, NOx, and O<sub>3</sub> data for the studied sites.

1 401									
<b>G</b> *4		Cl		SO <sub>2</sub>	R	Н	Т	,	
Site		$(mg/m^{-2}/c)$	lay <sup>-1</sup> )	(mg/m <sup>-2/</sup> day <sup>-1</sup> )	(%	6)	(°C	C)	
	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	
CIGEFI	3.8	2.7	10.0	9.4	80.2	76.5	20.4	20.5	
San Luis	3.6	4.6	13.5	11.6	87.5	90.1	17.8	18.2	
Santa Ana	3.9	3.1	10.6	11.2	84.4	83.9	17.6	17.6	

Table 5. Annual mean values of Cl, SO<sub>2</sub>, RH and T, for each season.

Table 6. Average annual W, NOx and O<sub>3</sub> values at each site.

Sita	Wind	Wind speed (m/s <sup>-1</sup> )		<b>O</b> 3		NOx		
Site	direction			(µg/n	n <sup>-3</sup> )	(µg/m <sup>-3</sup> )		
		Rainy	Dry	Rainy	Dry	Rainy	Dry	
CIGEFI	NE	2.0	2.0	28.4	30.9	13.5	16.0	
San Luis	ENE	3.0	3.0	27.2	30.8	7.1	7.7	
Santa Ana	N (*)	3.0	3.1	33.2	41.7	4.6	5.8	

Note: (\*) The station has an orographic effect that causes the wind to move in a preferential N direction, instead of the usual NE route associated with the Alisios winds.

The average annual values for Cl and  $SO_2$  are low. These were defined, by ISO 9223, as S1 and P0, respectively. In a similar manner, the  $O_3$  and NOx values were found to be in the low contamination level, as stated by ISO 9223. All pollutant parameters measured for WCV indicate a rural or light urban atmosphere [13].

The analysis of the accumulated  $SO_2$  levels, as a function of time, shows a steady increase in them. The small differences between stations are associated to the volcanic activities wind dispersion effects. Regardless of that, the Cl levels are very dependent on the site and season of the year, and influenced by the seasonal wind speed.

The principal wind direction is the expected, and mostly affected by the strength of the Alisios wind (from the NE) in each season, and by orographic effects that produce a small increase in  $O_3$  in the Santa Ana site [34].

The mean RH value is relatively high, and usually above 80%, while T is above 17 °C, being both relatively independent of the seasons. The accumulated R decreases from NE to SW, in WCV, almost equally in both seasons, with lower values than the historical mean in the San Luis and CIGEFI sites [6, 8].

The annual TOW values are mainly in the range of  $\Box 5$ , with more than 5000 h, a considerably high figure [13, 35]. The Corr values measured in both campaigns (started in the rainy or dry seasons) correspond to the C2 category in ISO 9223 [13], in the range from 15 to 18 µm per year. This result is consistent with the concept of rural or light urban atmosphere and high TOW values [9, 14, 36, 37].

### Volcanic activity and tropical storms

The volcanic activity during the studied period was low, mainly originated in the Turrialba volcano, as a result of eruptive emissions between September and December 2018, and in April 2019. The general SW wind direction (Alisios winds) transports most of the Turrialba emissions far from WCV, located to the NW. Part of these emissions were directed to WCV, in November and December, due to prevalent winds, but did not have a significant influence on the overall values. There were also slight emissions from the Poás volcano, between November and December 2018, but the main direction was towards other areas located in the WCV west side [23].

No tropical storms have affected WCV during the course of this work [38, 39].



**Figure 2.** V<sub>corr</sub> values in both seasons (rainy: circles with full line; and dry: triangles with dashed line), in the stations of: a) Santa Ana, b) CIGEFI and c) San Luis, respectively.

#### **Relationship between seasons**

In all sites, accumulated Corr general trend was found to be logarithmic, while  $V_{corr}$  had an exponential decay, which can be seen in Fig. 2, for all sites. Corr was dependent on the site characteristics, but not on the onset season, while  $V_{corr}$  was affected by the onset season in the first months of corrosion.

The relation of Corr with each season is relatively linear, according to the equation which states that Corr (dry) = a Corr (rainy) + b, where the slope is near to 1 (see Table 7).

**Table 7.** Linear fit for the correlation between Corr dry vs. Corr rainy.

Sites	a	b	R <sup>2</sup>
Santa Ana	1.0162	0.0124	0.9751
CIGEFI	0.9833	0.5789	0.9633
San Luis	1.1374	-2.1735	0.8470

 $V_{corr}$  values do not present peaks in the first months, for the Santa Ana site, while, on the other sites, this situation is observed, especially in the rainy season. The initial  $V_{corr}$  values in the rainy season increase when the wind is moving from SW to NE, in WCV (see Fig. 2). CIGEFI and San Luis sites are clearly affected by R and RE effects, possibly because the decrease in the intensity of the Alisios winds brings moisture from the Pacific coast that concentrates in the WCV center and north side, due to the higher altitude of the volcanic mountain range [6-8].

### SEM and DRX

The basic oxide composition is associated to goethite (G) and lepidocrocite (L), in proportions of 35 and 65%, respectively, for the one-year analysis. The values at 2 and 6 months show a similar composition and proportion, with a little trend towards a decrease in L values and an increase in G values, with time. This process is related to the oxide surface stabilization.



Figure 3. SEM image of the typical oxide structure in the CS sample from Santa Ana site.

#### Data models

The values obtained for the different models, considering the climatic season and sampling sites, are presented below.

#### ISO model (equation 1) and measured values

The equation 1 values from ISO 9223 always present higher results than the measured values obtained for WCV (Table 8). This is consistent with the tropical conditions and low contamination levels in WCV. In this situation, the equation is not so representative, because it is mostly originated from subtropical data that reflect different climacteric conditions [9, 14, 28, 36, 37, 40, 41].

Table 8. Annual  $V_{corr}$  values ( $\mu$ m/y<sup>-1</sup>) from ISO 9223 (eq. 1), and those measured in each site.

A (m.a.s.l.)	Site	<u>ISO 9223</u>		Measured values	
		Rainy	Dry	Rainy	Dry
1210	CIGEFI	24.1	20.3	16.7	17.9
1341	San Luis	34.1	35.3	17.5	16.5
1717	Santa Ana	29.5	28.7	17.3	20.4

Note: actual dry season values were calculated for the sampling time.

#### Corr vs. time model (equation 2)

Table 9 shows the correlations associated with equation 2, for the stations, in the different seasons, where Log (Corr) is the experimental value related to A, obtained at each site.

Table 9. Parameters of equation 2, in the rainy and dry seasons.

	Rainyseason				Dry season				
<u>Sites</u> CIGEFI	<u>A</u> 1.2656	<u>n</u> 0.8183	$\frac{\underline{PR}^2}{0.9824}$	<u>Log Corr</u> 1.2194	<u>A</u> 1.2444	<u>n</u> 0.6364	$\frac{\underline{PR}^2}{0.9920}$	<u>Log Corr</u> 1.2137	
San Luis	1.2427	0.6093	0.9850	1.2445	1.2759	0.8517	0.9595	1.1799	
Santa Ana	1.3173	0.7764	0.8392	1.2323	1.2923	0.8138	0.9968	1.2740	
General	1.2753	0.7346	0.8998		1.2711	0.7683	0.9590		

The sites show correlations with PR<sup>2</sup> values generally higher than 0.9, regardless of the season. Parameter A has, in general, a good correspondence with Log (Corr) of real values in one year, and it is similar in all equations.

The n constant has values in the range from 0.60 to 0.85, with an average of 0.73 to 0.76, for the general equations. These values imply corrosion moderate or partial attenuation by the oxides surface formation, which tends to stabilize  $V_{corr}$  over time, in areas such as WCV [14, 26].

While the general equations by season are similar, they provide a general way for estimating low CS corrosion over time, for WCV. In these equations, the correlation in the dry season is more stable in the early stages, and less dependent on the conditions of each site, thus presenting a better PR<sup>2</sup>. The global equation based in equation 2, for WCV, is:

$$Log Corr = 1.2729 + 0.7505 Log t PR^{2} = 0.9277$$
 (5)

Equation 2 usually provides a good fit for low CS in less contaminated media, over short to medium time periods (1 to 5 years) [9, 14, 24-30, 42-46].

#### Lineal and logarithmic models (equations 3 and 4)

Pearson's correlation coefficients for each parameter, in relation to corrosion, were calculated (p > 0.01). The values, for all parameters, have a good correlation (more than 0.7). SO<sub>2</sub> and TOW have the best correlations, followed by Cl and R (see Table 10).

	Corr	R	Cl	TOW	SO <sub>2</sub>
	(µm)	$(mm/m^{-2})$	$(mg/m^{-2})$	(h)	$(mg/m^{-2})$
Corr	1	0.788	0.827	0.949	0.903
Rain		1	0.671	0.765	0.771
Cl			1	0.853	0.842
TOW				1	0.952
$SO_2$					1

 Table 10. Pearson's correlation coefficient between variables.

Comparisons between seasons (U Mann Witney, p > 0.05) and sites (Kruskal Wallis, p > 0.05) show no significant differences.

Since there are no significant seasonal differences, the modeling was globally considered by site, and in WCV, with different numbers of variables. As stated in the methodology, the control parameters to evaluate the quality of models were PR<sup>2</sup>, RSS and F.

The best results for equation 3, in its lineal and logarithmic forms, were:

$$Corr = 2.708 + 2.828 E-3 SO_2 + 1.283 E-3 Cl - 4.603 E-4 TOW + 2.663 E-3 R$$

$$PR^2 = 0.9213 RSS = 77.68 F = 90.77$$
(6)

and

$$Corr = -30.63 + 1.496 \text{ Log } SO_2 + 0.911 \text{ Log } Cl + 2.432 \text{ Log } TOW + 0.919 \text{ Log } R$$
(7)  

$$PR^2 = 0.9193 \qquad RSS = 79.65 \qquad F = 88.33$$

There was no substantial improvement when using the linear form. Similar equations were obtained for tropical environments, by other authors [10, 14, 26-30, 36, 37, 40, 41, 43-46].

The most basic equations with one parameter are the ones that include TOW, expressed as a logarithmic regression. TOW is usually the most important parameter to control the corrosion processes in tropical environments, especially far from the coast, and with low levels of pollutants [9, 11, 14, 26, 35-37, 41-46].

Corr = 
$$12.793*Log TOW - 32.20$$
 (8)  
PR<sup>2</sup>= 0.881 RSS= 117.99 F= 250.5

Table 11 presents equation 4 coefficients for the best correlations with a different number of global variables, in the whole WCV.

Equation 4 is an extension of equation 2. The high correlation of corrosion with time limits the improvement obtained with the addition of new variables. This is seen in a somewhat higher  $PR^2$  value, with respect to equation 5, even when there is a decrease in the number of variables (Table 11) [14, 43].

The most influential variable on corrosion, in equation 4, over time, is  $SO_2$ . Even so, equation 4 does not improve corrosion estimation, being more complex than equations 2 and 3.

						0	1		
# variables		Log t	Cl	SO <sub>2</sub>	TOW	R	PR <sup>2</sup>	RSS	F
	a	n	b	c	d	e			
5	1.5435	1.0130	6.99E-06	-6.89E-05	3.28E-06	-3.17E-05	0.9427	1.71E-01	98.80
4	1.5421	1.0119	-6.48E-05	8.00E-06	ND	-2.99E-05	0.9427	1.71E-01	127.54
3	1.5442	1.0136	ND	-6.31E-05	ND	-2.93E-05	0.9427	1.71E-01	175.40
2	1.4926	0.9650	ND	-6.13E-05	ND	ND	0.9408	1.76E-01	262.19

Table 11. Best correlation obtained for WCV, in general, for equation 4.

Early mathematical models of atmospheric corrosion were based on equations 2 and 3. These were used both cumulatively, and for sites comparison on annual corrosion [9, 11, 14, 24-29, 46-49]. From these models, the main parameters to be considered for atmospheric corrosion, according to the environment, were established. For the case of rural or light urban atmospheres, the environmental factors were more important than the pollutants, obtaining better relationships with time and TOW. Subsequent studies in rural tropical bionetworks showed the strong influence of environmental factors, with higher corrosion rates than those of other subtropical-ecosystems under the same ecological conditions [9, 10, 14, 24, 36, 37, 40, 43, 45, 46, 48, 50-56].

For WCV, equation 2 is presented as a model with a very good correlation between Corr and time, according to equation 5, while equation 3 generates a complex model of which simplification in rural tropical environments tends to be a function of t, RH and/or TOW [14, 28, 36, 37, 43, 45, 50-54]. This agrees, in this case, with the result proposed for WCV, in equation 8.

Equation 4 arises within the process of improving corrosion modeling, by proposing a combination between equations 2 and 3. This equation improves the results, when the contamination effect is more important than time dependence. For WCV, there was no substantial improvement in the corrosion evaluation, and the dependence was associated with time and SO<sub>2</sub> [14, 26-30, 33, 50, 55, 56].

In a similar way, equation 1, stated in ISO 9223, arises from worldwide corrosion evaluations. In this one, there are few tropical data within rural environments, so, it usually gives overestimated values, as in the WCV case [14, 27, 28, 41, 46, 48, 52, 55, 56].

Tropical corrosion assessments in rural environments do not show significant differences in relation to seasonality. However, they do show initial corrosion rates dependent on the onset corrosion time, and in relation to TOW levels [37, 50, 51]. This is consistent with the results obtained for WCV.

### Conclusions

The final low CS Corr values, after one year of exposure, did not show significant differences with the starting climatic season, or with the monitoring site at WCV. On the other hand, the initial corrosion values, during the first six months, were dependent on the site climatic conditions.  $V_{corr}$  values were higher when atmospheric corrosion started during the rainy season and the sites had less rainfall, although there were high TOW values. Because of the above, the modeling was reduced to a single environment independent of the climatic season. While low pollution decreases the influence of these parameters on complex models, making simplified models using time or TOW produces adequate and less complex results. The ISO 9223 equation estimation for annual corrosion is very high, possibly because it is based on measurements in nontropical environments.

## Acknowledgements

Special thanks to the National Meteorological Institute and the Costa Rican Electricity Institute, for providing the WCV meteorological data. The actual corrosion data were obtained from the measurement of the sites located at the facilities of the National Power and Light Company and the Ministry of Security. This study was funded by the National Council of University Presidents (CONARE) of Costa Rica, as part of a collaborative project among the State Distance University (UNED-VINVES-6-1050), the University of Costa Rica (UCR-VI-805-B8-650), the National High Technology Center (CeNAT-VI-269-2017), the National University (UNA- SIA: 0600-17) and the Costa Rica Institute of Technology (ITCR-VIE 1490-021).

Rodríguez-Yáñez acknowledges the support of the Innovation and Human Capital for Competitiveness Program (PINN) of the Ministry of Science, Technology and Telecommunications (MICITT) of Costa Rica.

## Authors' contributions

J. Rodriguez-Yáñez: conceived and designed the analysis; collected the data; inserted the data or analysis tools; performed the analysis; wrote the paper. R. Brenes: conceived and designed the analysis; collected the data; inserted the data or analysis tools; reviewed the paper. R. Jiménez-Salas: conceived and designed the analysis; collected the data; inserted the data data or analysis tools; performed the analysis; wrote the paper: M. Abdalah Hernandez: inserted data or analysis tools; performed the analysis; wrote the paper; made language revision. J. Sanabria-Chinchilla: conceived and designed the analysis; collected the data; performed the analysis; reviewed the paper.

## References

- 1. Apuy E. Caracterización de la Industria Metal Mecánica en Costa Rica. PROCOMER Report number: 2. 2016. http://servicios.procomer.go.cr/aplicacion/civ/documentos/Caracterizacion% 20d e%20la%20industria%20metalmecanica%20costarricense.pdf
- 2. NACE International Impact. International measures of prevention, application and economic of corrosion technology study. Houston, TX, USA: NACE International, 2016. http://impact.nace.org/executive-summary.aspx

- 3. PRUGAM. Planificación Regional Urbana del Gran Área Metropolitana, San José, Costa Rica, Ministerio de Vivienda y Asentamientos Humanos, 2009. Ministerio de Vivienda y Asentamientos Humanos. http://www.mivah.go.cr/PRUGAM.shtml
- 4. INEC. Anuario Estadístico 2010. San José, Costa Rica: Instituto Nacional de Estadística y Censos, Ministerio de Hacienda, 2011. https://www.inec.cr/sites/default/files/documentos/anuario\_estadistico/publicaciones/ reanuarioestad2010-02.pdf
- 5. Estado de la Nación. Vigésimo Informe del Estado de la Nación. Estado de la Nación, 2014. http://www.estadonacion.or.cr/20/#inicio2
- Solano J, Villalobos R. Regiones y Subregiones Climáticas de Costa Rica. San José, Costa Rica: Instituto Meteorológico Nacional, 2000. https://www.imn.ac.cr/documents/10179/20909/Regionalizaci%C3%B3n+cli m%C3%A1tica+de+Costa+Rica#:~:text=Esta%20misma%20disposici%C3 %B3n%20monta%C3%B1osa%2C%20junto,cual%20pertenece%20la%20R egi%C3%B3n%20Valle
- Muñoz AC, Fernández W, Gutiérrez JA, et al. Variación estacional del viento en Costa Rica y su relación con los regímenes de lluvia. Tópicos meteorológicos y oceanográficos. 2002;9(1):1-13.
- Instituto Meteorológico Nacional de Costa Rica. Segunda Comunicación sobre Clima, variabilidad y cambio climático en Costa Rica. San José, Costa Rica: MINAET, IMN, PNUD, CRRH. 2008. http://users.clas.ufl.edu/prwaylen/geo3280articles/el\_clima\_variabilidad\_y\_c am bio climatico en cr version final.pdf
- Morcillo M, Chico B, de la Fuente D, et al. Looking Back on Contributions in the Field of Atmospheric Corrosion Offered by the MICAT Ibero-American Testing Network. (Hindawi Publishing Corporation, Ed.). Int J Corros. 2012;824365:1-24. DOI: https://doi.org/10.1155/2012/824365
- Robles J. Evaluación de la Corrosión Atmosférica en Tres Zonas Geográficas de Costa Rica por Medio de Técnicas Electroquímicas y Gravimétricas. Heredia, Costa Rica: Tesis de Grado para Licenciatura en Química Industrial, Universidad Nacional, 2013.
- 11. Morcillo M, Almeida E, Rosales B, et al. Corrosión y Protección de Metales en las Atmósferas de Iberoamérica, Parte I: Mapas Iberoamericanos de Corrosión Atmosférica (MICAT). Madrid, España: Programa CYTED, 1998.
- International Organization of Standardization. ISO 9223:1992. Corrosion of Metals and Alloys - Corrosivity of Atmospheres - Classification. Geneva, Switzerland.
- International Organization of Standardization. ISO 9223:2012. Corrosion of Metals and Alloys - Corrosivity of Atmospheres - Classification. Geneva, Switzerland.
- Garita L, Rodríguez-Yáñez J, Robles J. Modelado de la Velocidad de Corrosión de Acero de baja aleación en Costa Rica. Revista Ingeniería. 2014;(24)2:79-90. DOI: https://doi.org/10.15517/ring.v24i2.14624.
- 15. Davies J. Metals Handbook, Ohio, USA: ASM International, 1998.

- American Society for Testing and Materials. ASTM A36/A36M-19. Standard Specification for Carbon Structural Steel. West Conshohocken, PA, USA: ASTM International; 2019. DOI: https://doi.org/10.1520/A0036\_A0036M-19
- American Society for Testing and Materials. ASTM G50-20. Standard Practice for Conducting Atmospheric Corrosion Tests on Metals. West Conshohocken, PA: ASTM International; 2020. DOI: https://doi.org/10.1520/G0050-20
- American Society for Testing and Materials. ASTM G1-03 e1. Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. West Conshohocken, PA, USA: ASTM International; 2017. DOI: https://doi.org/10.1520/G0001-03R17E01
- 19. American Society for Testing and Materials. ASTM G33-99. Standard Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens. West Conshohocken, PA, USA: ASTM International; 2020. DOI: https://doi.org/10.1520/G0033-99R20
- 20. American Society for Testing and Materials. ASTM G92-20. Standard Practice for Characterization of Atmospheric Test Sites. West Conshohocken, PA, USA: ASTM International; 2020. DOI: https://doi.org/10.1520/G0092-20
- International Organization of Standardization. ISO 9225.6. Corrosion of Metals and Alloys – Corrosivity of Atmospheres – Measurement of pollution. Geneva, Switzerland: ISO; 2012.
- 22. Passive sampler. Passam AG. 2016. Productos. http://www.passam.ch/products
- 23. OVSICORI. (2019). OVSICORI UNA. Estado de los volcanes. 2020. http://www.ovsicori.una.ac.cr/index.php/extension/estado-de-los-volcanes
- Feliu S, Morcillo M, Feliu S Jr. The prediction of atmospheric corrosion from meteorological and pollution parameters. I. Annual corrosion. Corros Sci. 1993;(34):403-4014. DOI: https://doi.org/10.1016/0010-938X(93)90112-T
- 25. González PM, Mos DM, Santana FJ, et al. Modeling of the Atmospheric Corrosion of Copper in the Province of Las Palmas. Studies Using Classic and Electrochemical Techniques. Port Electrochim Acta. 2008;(26):125-145. DOI: https://doi.org/10.4152/pea.200801125
- Morcillo M. Fundamental and research frontier of atmospheric corrosion. Madrid, Spain. Materials. 2017. DOI: https://doi.org/10.3390/books978-3-03842-642-4
- 27. Mikhailov A, Tidblad J, Kucera V. The Classification System of ISO 9223 Standard and the Dose–Response Functions Assessing the Corrosivity of Outdoor Atmospheres. Prot Met. 2004;(40):541-550. DOI: https://doi.org/10.1023/B:PROM.0000049517.14101.68
- 28. Ríos-Rojas JF, Aperador-Rodríguez D, Hernández-García EA, et al. Annual atmospheric corrosion rate and dose-response function for carbon steel in Bogotá. Atmósfera. 2017;(30):53-61. DOI: https://doi.org/10.20937/atm.2017.30.01.05
- 29. Roberge PR, Klassen RD, Haberecht PW. Atmospheric corrosivity modeling. A review. Mater Des. 2002;(23):321-330. DOI: https://doi.org/10.1016/S02613069(01)00051-6
- 30. Santana J, Santana F, González J. The effect of environmental and meteorological variables on atmospheric corrosion of carbon steel, copper, zinc and aluminium in a limited geographic zone with different types of environment. Corros Sci. 2003;45(4):799-815. DOI: https://doi.org/10.1016/S0010-938X(02)00081-1

- 31. Wilks D. Statistical Methods in the Atmospheric Sciences. United States: Academic Press, 2011.
- 32. Miller M. Estadística y Quimiometría para química analítica. Madrid: Pearson, 2002.
- Díaz V, Martínez-Luaces V, Guineo-Cobs G. Corrosión atmosférica: validación de modelos empleando técnicas estadísticas. Rev Metal. 2003;39(4):243-251. DOI: https://doi.org/10.3989/revmetalm.2003.v39.i4.335
- Neurohr E, Monge-Nagera J, González M. Air pollution in tropical city. The relationship between wind direction and lichen bio indicators in San José, Costa Rica. Int J Trop Biol. 2011;(59):899-905. DOI: https://doi.org/10.15517/rbt.v0i0.3148
- Rodríguez-Yáñez J, Garita AL, Saborío LE. Mapas estimativos de la corrosión atmosférica de acero de baja aleación en Costa Rica. UNED Res J. 2015;7(2):181-191. ISSN: 1659-4266. https://revistas.uned.ac.cr/index.php/cuadernos/article/download/1144/1097
- Restrepo A, Botero C, Correa E. Corrosión del acero al carbono, acero galvanizado y aluminio en diferentes atmósferas colombianas. Sci Techn. 2007;(36):7-12. DOI: https://doi.org/10.22517/23447214.4857
- Corvo F, Pérez T, Martín Y, et al. Time of wetness in tropical climate: Considerations on the estimation of TOW according to ISO 9223 standard. Corros Sci. 2008;(50):206-219. DOI: https://doi.org/10.1016/j.corsci.2007.06.012
- 38. Instituto Meteorológico Nacional de Costa Rica, Boletines meteorológicos. https://www.imn.ac.cr/en/boletin-meteorologico
- 39. National Oceanographic and Atmospheric Administration, National Hurricane Center and Central Pacific Hurricane Center. https://www.nhc.noaa.gov/data/tcr/index.php?season=2019&basin=atl
- Vera R, Troconi de Rincón O, Bagnara M, et al. Tropical/non-tropical marine environments impact on the behaviour of carbon steel and galvanised steel. Mater Corros. 2017;(69):614-625. DOI: https://doi.org/10.1002/maco.201709873
- 41. Rodríguez-Yáñez J, Rivera-Fernández E, Alvarado-González D, et al. Prediction of atmospheric corrosion from meteorological parameters: case of the atmospheric basin of the Costa Rican Wester Central Valley. Atmósfera. 2021. ISSN 2395-8812. https://www.revistascca.unam.mx/atm/index.php/atm/article/view/52966
- 42. International Organization of Standardization. ISO 9224:2012. Corrosivity of Atmospheres Guiding values for the corrosivity categories. Geneva, Switzerland: ISO; 2012
- Rodriguez-Yáñez J. Niveles iniciales de corrosión atmosférica antes de la puesta en marcha de la Planta Geotérmica de las Pailas, Guanacaste, Costa Rica. UNED Res J. 2015;7(2):201207. ISSN 1659-4266. https://www.scielo.sa.cr/pdf/cinn/v7n2/1659-4266-cinn-7-0200201.pdf
- 44. González-Sánchez JA. Environmental Degradation of Infrastructure and Cultural Heritage in Coastal Tropical Climate. Kerala, India. Transworld Research Network. 2009; chapter 1 and 2.
- 45. Veleva L, Maldonado L. Classification of atmospheric corrosivity in humid tropical climates. Br Corros J. 1998;33(1):53-58. DOI: https://doi.org/10.1179/bcj.1998.33.1.53
- 46. Mariaca L, Genescá J, Uruchurtu J, et al. Corrosividad Atmosférica. (MICAT-México). México. Plaza y Valdés Editores, 1997.

- 47. Benarie M. A general corrosion function in terms of Atmospheric pollutant concentrations and Rain Ph. Atmos Environ. 1986;20(10):1947-1958. DOI: https://doi.org/10.1016/0004-6981(86)90336-7
- 48. Mariaca L, Menchaca C, Sarmiento E, et al. Atmospheric corrosion dose/response functions from statistical data analysis for different sites of Mexico. Innov Corros Mat Sci. 2014;4:11-20. DOI: https://doi.org/10.2174/2352094904666140609221321
- 49. Morcillo M, de la Fuente D, Díaz I, et al. Atmospheric corrosion of mild steel. Rev Metal. 2011;47(5):426-444. DOI: https://doi.org/10.3989/revmetalm.1125
- 50. Corvo F, Pérez T, Martin Y, et al. Electroanalytical Chemistry: New Research, Chapter 2, Corrosion research frontiers. Atmospheric corrosion in tropical climate. On the concept of time of wetness and its interaction with contaminants deposition. Editor: Smithe G. M., Nova Science Publishers, Inc., 2008. ISBN: 978-1-60456-347-4.
- 51. Do TB, Strekalov PV, Nguyen VK. Effects of Seasonal Conditions and the Slope of a Specimen on the Atmospheric Corrosion of Steel in the Tropics of Vietnam. Prot Met Phys Chem. 2003;39(3):278-287. DOI: https://doi.org/10.1023/a:1023927506575
- 52. Mikhailov AA, Strekalov PV, Panchenko YM. Atmospheric Corrosion in Tropical and Subtropical Climate Zones: 3. Modeling Corrosion and Dose– Response Function for Structural Metals. Prot Met. 2007;43(7):619-627. DOI: https://doi.org/10.1134/S0033173207070028
- 53. Castaño JG, Botero CA, Restrepo AH, et al. Atmospheric corrosion of carbon steel in Colombia. Corros Sci. 2010;(52):216-223. DOI: https://doi.org/10.1016/j.corsci.2009.09.006
- 54. Karpov VA, Lapiga AG, Kalinina EV, et al. Modeling of Atmospheric Corrosion in the Tropical Climate of Vietnam. Prot. Met Phys Chem. 2017;53(7):1205-1213. DOI: https://doi.org/10.1134/S2070205117070085
- 55. De la Fuente D, Díaz I, et al. Annual atmospheric corrosion of carbon steel worldwide. An integration of ISO CORRAG, ICP/UNECE and MICAT Databases. Materials. 2017;10(6):601. DOI: https://doi.org/10.3390/ma10060601
- 56. Yikun Cai, Yu Zhao, Xiaobing Ma, et al. Application of hierarchical linear modelling to corrosion prediction in different atmospheric environments. Corros Eng Sci Technol. 2019;54(3):266-275. DOI: https://doi.org/10.1080/1478422X.2019.1578067