https://doi.org/10.32854/agrop.vi.1595

Evaluation of the functionality of a constructed wetland system under semidesert and saline conditions

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ABSTRACT

Objective: Evaluate the functionality of a constructed wetland used to treat the wastewater from a school by recording water inflow and outflow, in addition to the local conditions that affect its operation and compliance with environmental regulations.

Design/methodology/approach: Verification of the installation specifications; programmed measurements of the inflow-outflow water balance and ambient temperature; and analysis of the salinity effect and wetland performance.

Results: The high evapotranspiration at the site contributed to the decrease in the resident volume of water within the wetland, causing water stress to the vegetation, not complying with the regulation about the reduction/elimination of water pollutants.

Study limitations/implications: The high daytime temperature significantly decreased the daily inflow volume of wastewater, even after adding the precipitation water, which affects the biological activity of the vegetation; therefore, the study was performed on half of the wetland surface. Thus, the wetland was unable to reduce the pollutants to safe levels.

Findings/conclusions: The amount of recovered treated water is minimal. The inflow is five times lower than the designed flow of the construction. The weekly log was appropriate to observe fluctuations in the water balance and its effect on the vegetation within the wetland.

Keywords: rural constructions, biological processes, water balance, wastewater treatment, climatic conditions.

Agroproductividad: *Vol. 13, Núm. 11, noviembre. 2020. pp: 115-121.*

Recibido: *enero, 2020.* **Aceptado:** *octubre, 2020.*

INTRODUCTION

The Universidad Autónoma de San Luis Potosí (UASLP), the most prestigious university in San Luis Potosí (SLP), Mexico, is working on a comprehensive project to implement appropriate technologies for the treatment of the wastewater generated in its different campuses. In 2015, an artificial wetland was designed and constructed in the Altiplano Oeste Campus in Salinas, SLP, Mexico. This facility had to comply with the maximum permissible limits of contaminants in treated water for its safe discharge into water bodies (Marín-Muñiz, 2017; NOM-001-SEMARNAT-1996, 2003).

Furthermore, the constructed wetland (CW) had to withstand variations in temperature and biological reactions, which should consider a water flow similar to that produced in a piston, hence the importance of considering climate and water balance.

However, the original design did not consider the climatic conditions at the site. Therefore, it has not been possible to evaluate its performance. Hence, it is convenient to evaluate the facilities and wetland under high-stress situations. It is also impossible to define the reaction of the water balance, salinity, and biochemical effects. The following priorities have been established to comply with the NOM-001-SEMARNAT-1996: 1. Evaluation of the sizing of the CW; 2. Water balance; 3. Salinity; and 4. Wetland performance.

The current hydraulic and biological design of the CW in the Altiplano Salinas Campus of the UASLP is located at 22° 37′ 39″ N and 101° 42′ 52″ W and represents a suitable facility to study its performance, without interference from the available underground water, with an appropriate pretreatment of the sewage influent. The current facility includes a preliminary treatment (P: separation of coarse solids), a sand trap (D), two parallel cells (A and B) that consist of horizontal subsurface flow wetlands (HSF), and a collection pond (E) (Figure 1). The inflow from cells A and B discharges in pond E.

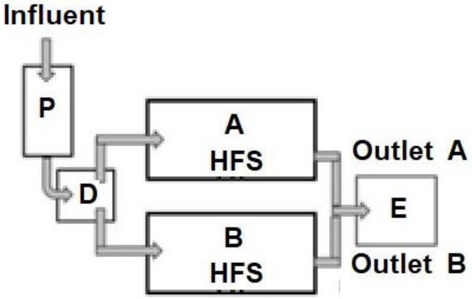

Figure 1. Schematic diagram of the flow of wastewater in the treatment system. Preliminary treatment (P: separation of coarse solids and D: sand trap); horizontal subsurface flow wetland (HSF), and collection pond (E).

The treatment capacity considers flow rate of 14 m3 d^{-1}; a biochemical oxygen demand (BOD) of 290 mg L^{-1}; total suspended solids (TSS) of 226 mg L^{-1}, total nitrogen (TN) of 35 mg L^{-1}, total phosphorus (TP) of 12 mg L^{-1}, and 8E07 MPN (Most probable number of microorganisms in the sample)/100 mL of fecal coliforms (FC). Table 1 documents the technological characteristics of the constructed wetland, and Figure 2 shows an overview of this wetland in 2017.

Table 1. Characteristics of the horizontal subsurface flow wetland.

Parameter	Wetland	Each cell
Area (m^2)	378	189
Length (m)	21	21
Width (m)	-	9
Water depth (h, m)	0.6	0.6
Factor of safety (Fs, m)	0.4	0.4
Wetland total depth (m)	1	1
Ks hydraulic constant (m^3 m^{-2} day^{-1})	5,000	
Effective size of granular medium D10 (mm)	8-16	
Porosity (%)	35	
Wetland slope (%)	1.0	
Vegetation considerations		
Parameter	Cell A	Cell B
Species	*Phragmites australis*	*Typha latifolia*
Planting density (n m^{-2})	3	3

MATERIALS AND METHODS

This study was carried out in the Altiplano Oeste Campus of the UASLP in Salinas de Hidalgo. At the beginning of the study, there was no effluent in both cells, and *T. latifolia* showed little development since its planting. Therefore, we decided to close the inflow entrance of cell B, restricting the evaluation of the wetland efficiency to cell A.

Biological and hydraulic sizing: The current sewage-generating population consists of 364 people. The University Campus consumes 25 L per person per shift, of which 75% are wastewater. Therefore, the generation of wastewater is 18.75 L per person per day, with a mean

Figure 2. View of the wastewater treatment plant. Vegetation within cell A (left) and complete view of the area (right).

flow of 6.825 $m^3\ d^{-1}$. Resulting in a flow of 14 $m^3\ d^{-1}$ for the construction of the CW, and the biological sizing consists of applying the equation of Kadlec (1996) (Table 2) and rigorously ensuring the maximum limits of the Official Mexican Standard (NOM-001-SEMARNAT-1996).

Once the area is defined, we proceed with the hydraulic sizing to determine the length and width of the wetland applying Darcy's Law and from there the cross-sectional area is obtained:

$$A_s = \frac{Q}{K_s \times s} \tag{1}$$

Where: A_s = cross section of the wetland with the flow direction, m^2, Q = mean flow rate, $m^3\ d^{-1}$, K_s = hydraulic constant of the medium in a cross-section unit with the flow direction, 5000 $m^3\ m^{-2}\ d^{-1}$ (Table 2), s = hydraulic gradient, 0.01 $m\ m^{-1}$ (Table 1). Width and length are determined with the following equations:

$$w = \frac{A_s}{h} \tag{2}$$

$$L = \frac{s}{w} \tag{3}$$

Where: w = width, m; L = length, m; h = depth, m (0.6 m of Table 2); S = surface area, m^2.

Contaminant removal efficiency of the constructed wetland for sewage treatment

During March-June 2018, the flow rate and *in situ* physical parameters were measured every week; the chemical parameters were measured monthly. The inflow (influent) and outflow (effluent) rates of cell A were determined by a volumetric method. The ambient and wastewater temperatures, the pH, and electrical conductivity were determined every hour by triplicate in the influent and effluent. For the determination of the chemical parameters in the laboratory, we collected influent and effluent composed samples to measure BOD, QOD, TSS, PO_4, NO_2, NO_3, anions, cations, and four simple samples for total and fecal coliforms. The water analysis was performed following the NMX-AA 028-SCFI-2001 for BOD. The water balance components of the CW are shown in Figure 3.

It is important to mention that the infiltration was not measured, so the result of equation (4) is not completely correct, although it can be used with certain restrictions. The following equation expresses the global water dynamics within the wetland(Kadlec, 2009).

$$\frac{dV}{dt} = Q_a - Q_e + Q_c - Q_b - Q_i + Q_{dh} + (P \times A) - (ER \times A) \tag{4}$$

Table 2. Considerations for calculating the required area for the removal of contaminants.

Equation	Parameter	Q (m^3d^{-1})	K_A($m^3\ d^{-1}$)	C_0 (mg L^{-1})	Q_1 (mg L^{-1})	C*(mg L^{-1})
$S = \frac{Q}{K_A} \times \ln\left(\frac{C_0 - C*}{C_1 - C*}\right)$	BOD	6.825	0.43	800	30	18.87
	TSS		8.22	226	40	22.04
	TP		0.033	15	5	0.02
	FC		0.26	5E+14 MPN/100 mL	1000 MPN/100 mL	10.00

S, superficial area; Q, mean flow; C0, initial concentration of the contaminant; C1, final concentration of the contaminant (NOM-001-SEMARNAT-1996); KA = first-order kinetic constant; C*, concentration at the bottom; BOD, biochemical oxygen demand; TSS, total suspended solids; TP, total phosphorus; FC, fecal coliforms.

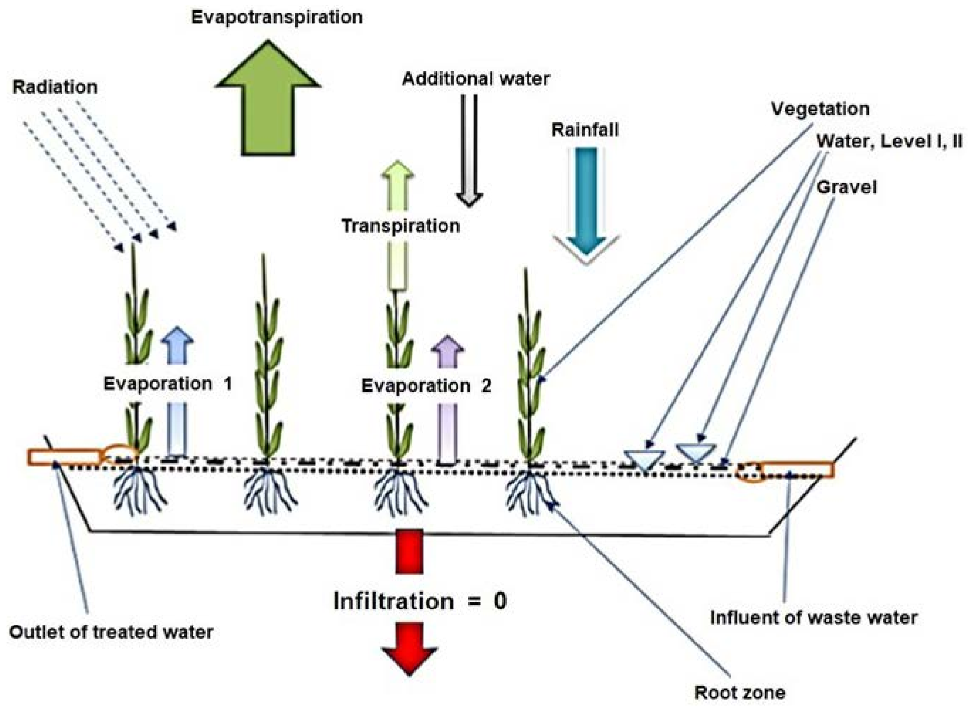

Figure 3. Water balance components and constructed wetland (CW) model.

Where: *A* = wetland surface area, m^2; *ER* = evapotranspiration rate, m day^{-1}; *P* = precipitation rate, m day^{-1}; Q_a = inflow, m^3 day^{-1}; Q_e = outflow, m^3 day^{-1}; Q_c = runoff capture rate, m^3 day^{-1}; Q_b = loss rate due to the strip between the outer edge and the gutter, m^3 day^{-1}; Q_i = infiltration, m^3 day^{-1} = 0 (there is no interaction with groundwater); Q_{dh} = thaw rate, m^3 day^{-1}; *dt* = time, *d*; *V* = volume of water stored in the wetland, m^3.

In the evaluated wetland, the evapotranspiration rate was higher than the precipitation rate. In this case, the important factors are: 1. The dual coefficient (FAO, 2016) of plant growth (plants, based on their age, depend of different evapotranspiration values) with the values of 1.20 ($K_{c\ med}$) from March to June and 0.70 from June to July, 2. The irrigation lamina per day, determined by the influent and possible precipitation at the wetland site.

RESULTS AND DISCUSSION

Evaluation of biological sizing

The biological sizing of the wetland is shown in Table 3 for removing contaminants; biochemical oxygen demand, total suspended solids, total phosphorus, total nitrogen, and fecal coliforms. To comply with the NOM-001-SEMARNAT-1996 a surface area of 296.63 m^2 is required to remove the contaminants, considering an average flow rate of 6.8 m^3 day^{-1}.

The area that ensures the removal of fecal coliforms (707.4 m^2) also guarantees the removal of other contaminants. This area is larger than that used for the design, even though the system was built for a total population of 750 people with a flow rate of 14 m3 day^{-1}. The sizing of the wetland differed from the real size of the constructed wetland. This difference is related to the variation of the hydraulic sizing up to a 4:1 ratio. This variation does not affect the functioning of the wetland.

Temperature, pH, and conductivity

During the sampling period, the average pH values of the influent and effluent in cell A were 7.8 and 5.0, respectively. The mean daily temperature was 22.2 ± 4.2 °C. The average temperature of the influent water was 21.1 ± 2.6 °C, and 4.2 ± 5.9 °C in the effluent. The average electrical conductivity for the influent was 5.5 mS cm^{-1}, and 11.35 mS cm^{-1} for the effluent. The electrical conductivity was higher in the effluent due to the salt accumulation resulting from its concentration-evapotranspiration.

Contaminants removal

Table 4 shows the average values of the removal percentage and the standard deviations of BOD, COD, PT, TSS, and FC for the entire system during the sampling stages.

The concentration of influent contaminants (except FC and TC) was significantly higher than the typically

Table 3. Area required for the removal of each contaminant.

Parameter	Area (m^2)		
	Design	Evaluated	Real
BOD	90.67	67.5	378
SST	4.14	2.02	
TN	171.95	---	
TP	372.4	227.5	
FC	608.45	707.4	

Table 4. Average concentrations of BOD, COD, TP, TSS, and FC during March-May. Standard deviation in parenthesis.

Parameter (mg L^{-1})	Influent	Effluent	Removal %
BOD	658.4 (85.9)	117.7 (48.2)	82.2
COD	1549.5 (116.8)	493.9 (372.4)	68.8
TSS	202 (139.1)	60.7 (35.2)	62.3
TP	13.3 (1.3)	0.65 (0.4)	95.2
TC, (MPN 100 mL^{-1})	8.80E+12 (9.78E+12)	9.86E+08 (1.22E+09)	98.8
FC, (MPN 100 mL^{-1})	8.40E+08 (5.35E+08)	1.61E+08 (2.00E+08)	80.8

reported composition, which results in an evident reduction of TP (95.2%). However, although the removal percentages are above 60% for BOD, COD, and TSS, the final concentration exceeds the limits in Mexico. These results only correspond to cell A.

Biochemical oxygen demand (BOD) removal

The removal percentage of BOD during the sampling period was 82.2% due to its different treatment units and operation conditions (TRH, plants used, etc.). The average value of inflow BOD (658.4 mg L^{-1}) was significantly higher than the system design value (290 mg L^{-1}).

Water balance evaluation

The elements of equation (4) and the measurement values were fundamental to evaluate water balance. Table 5 summarizes the measured and calculated values of water balance in the constructed wetland.

The reserve volume refers to the water that enters the cell and does not come out as a liquid, which increases the water level in the cell (+ indicates an increase in level; − decrease in level). In the effluent, this value reduces the amount of water in the influent; thus, it is not included in the water balance calculation of the cell. Due to the porosity volume (35%), 1 mm of precipitation represents an increase in the water level 3 mm. Therefore, the height of the liquid in the cell is only 600 mm (total reserve), which means that an evapotranspiration of 200 mm results in the total restriction of plant development.

Figures 4 and 5 show the great variation in the distribution of the influent and effluent values, respectively, during successive periods of academic activities.

Figures 6 and 7 clearly show the importance of climate impact on water balance evaluation. Figure 7 represents

Table 5. Sampling schedule to calculate the water balance (mm m^{-2}).

Date	Inflow volume			Outflow volume			Reserve volume
	Q_a	PP	total	ERc	Q_e	Total	
March 12 -18	6.50	0.047	6.54	4.80	0	4.8	1.74
March 19 -25	5.67	0.000	5.67	4.68	0	4.7	0.99
March 26 - April 1	0.00	0.431	0.43	6.53	0	6.5	−6.10
April 3-8	0.00	0.000	0.00	9.78	0	9.8	−9.78
April 9-15	6.17	0.000	6.17	8.74	5.88	14.6	−8.45
April 16-22	7.48	0.000	7.48	6.69	5.08	11.8	−4.30
April 23-29	8.43	0.669	9.10	6.82	5.59	12.4	−3.31
April 30 - May 6	11.10	6.522	17.62	5.90	0.66	6.6	11.07
May 7-13	8.76	0.384	9.14	5.52	5.08	10.6	−1.46
May 14-20	13.79	0.384	14.17	5.90	0.9	6.8	7.37
May 21-27	14.27	0.000	14.27	7.81	4.53	12.3	1.93
May 28 - June 3	2.04	0.384	2.42	8.24	0	8.2	−5.82
June 4-10	1.81	0.000	1.81	7.36	0	7.4	−5.55
June 11-17	1.91	4.358	6.26	4.01	0	4.0	2.25
June 18-24	1.64	17.322	18.97	4.29	0	4.3	14.67
June 25 - July 1	1.82	2.442	4.26	3.33	0	3.3	0.93
July 2-8	1.60	0.297	1.90	3.76	0	3.8	−1.86
July 9-15	1.53	0.397	1.93	3.24	0	3.2	−1.31

the average precipitation from 2000 to 2018 in each of the months of those years. Thus, the average accumulated precipitation of those months during those years is 350.8 mm per year.

The blue-colored lines of Figures 6 and 7 indicate the period in which this study took place and qualitatively explain the behavior of the constructed wetland. The average climate conditions from 2006 to 2018, being adverse, are the main cause for which a balance was not achieved between the evapotranspiration, representing the output, and precipitation values, as an additional contribution added to the entry of sewage.

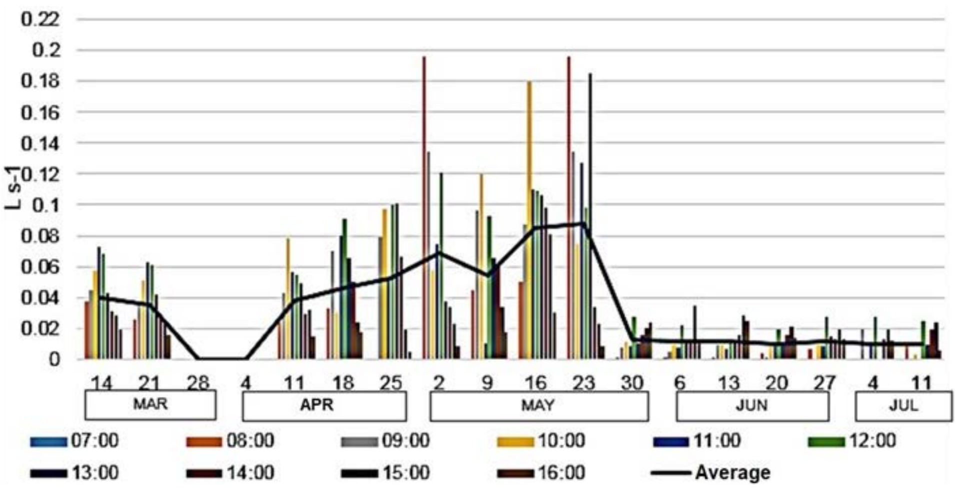

Figure 4. Inflow rate (L s^{-1}) of the HSCW-Salinas during the academic activities on campus.

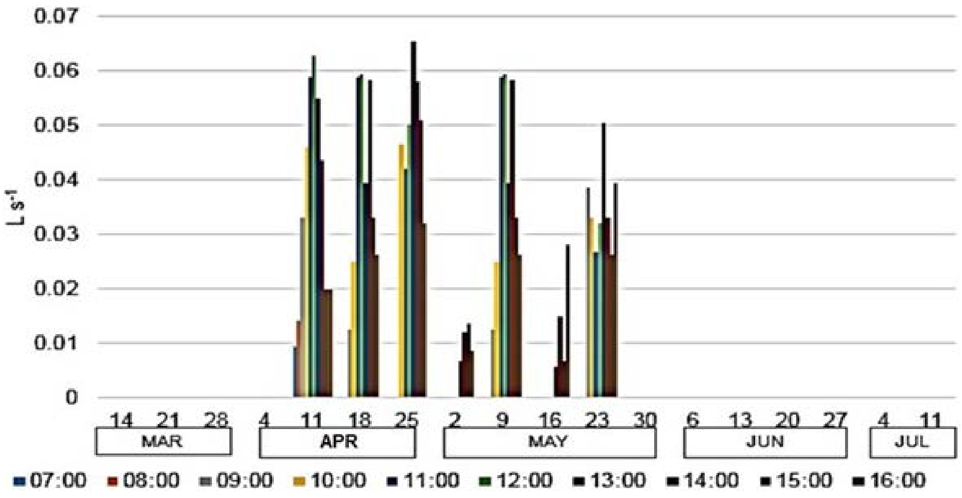

Figure 5. Outflow rate (L s^{-1}) of the HSCW-Salinas during the academic activities on campus.

CONCLUSIONS

The extreme climatic conditions and high to low temperature fluctuations had an adverse effect on the amount of water recuperated from sewage treatment. Additionally, the inflow rate was overestimated. The study demonstrated that the inflow rate was five times lower than the flow rate considered for the wetland design and that, due to the effects associated with climate change, the expected temporary precipitations were not enough to increase the wetland reserve. Evapotranspiration was the main factor responsible for reducing the water reserve in a shorter time, which induces hydric stress in the cell plants. The weekly sampling and data analysis of the water balance allowed us to observe specific changes in the four components of water balance, particularly the change in the water reserve.

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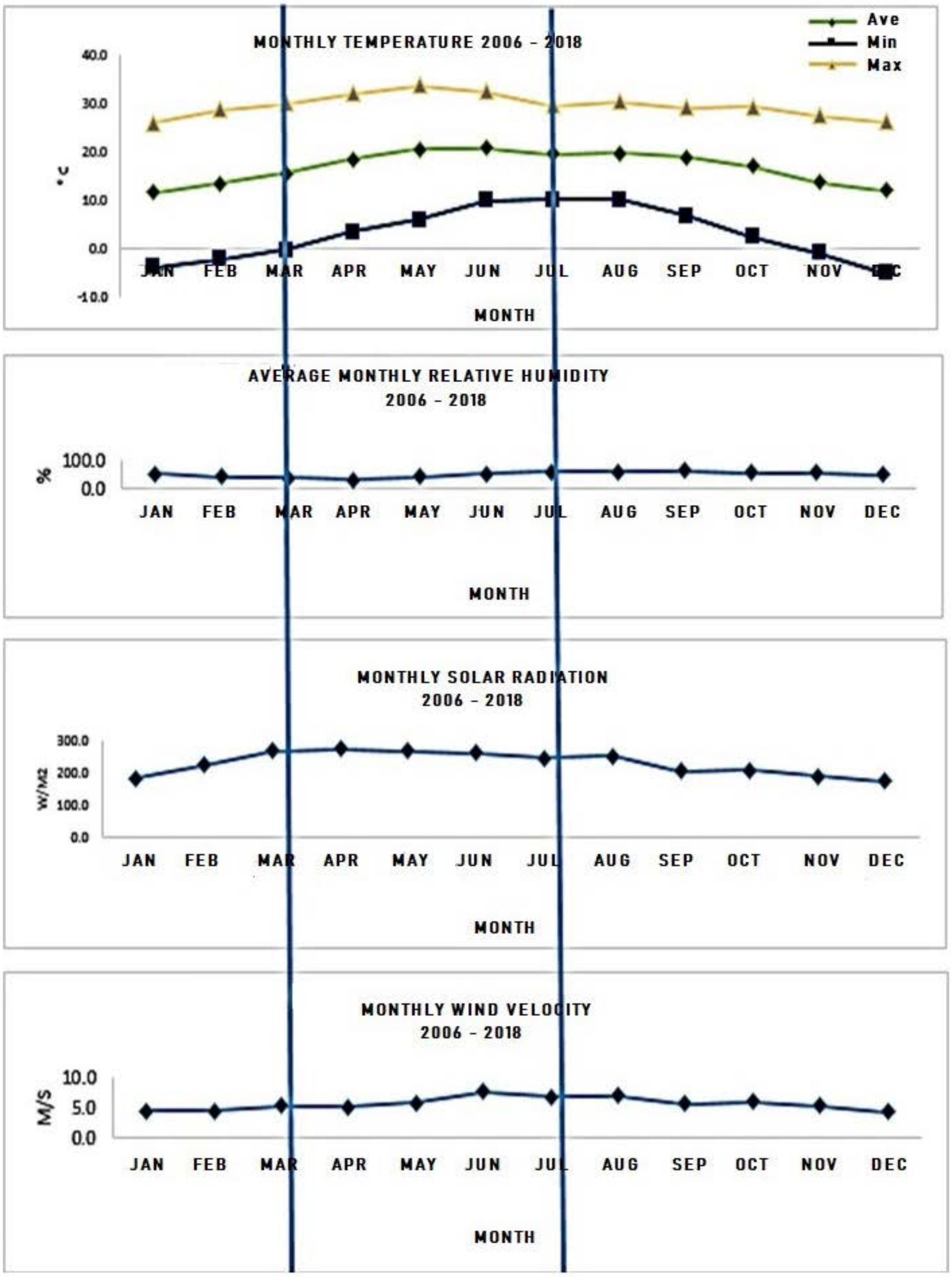

Figure 6. Monthly average climatic values of the study site in Salinas, San Luis Potosí, Mexico.

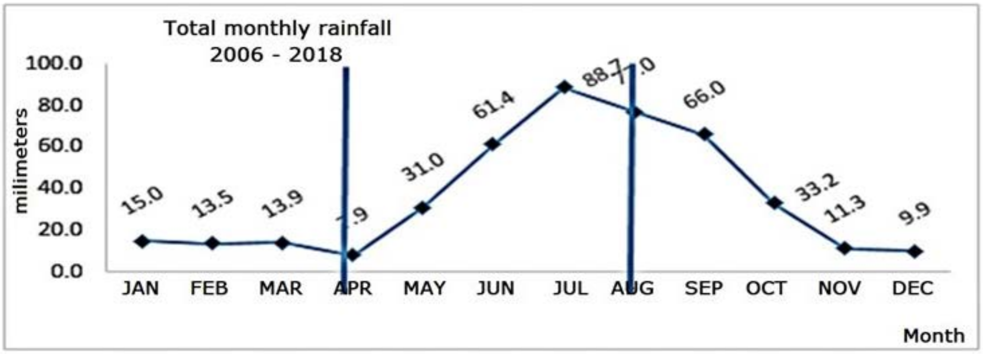

Figure 7. Monthly total precipitation of the study site in Salinas, San Luis Potosí, Mexico.