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**Cover**: Lake Patzcuaro. Endemic fish exist in the country's various bodies of water. Their care, maintenance and production— for consumption or sale at different scales— has varied, and in many cases has produced parasitic symptomatology. Lake Patzcuaro is no exception. Studies about this issue are crucial because of the importance to human health and the fish species themselves. See article: Helminthological Characterization of Cyprinid *Algansea lacustriss* in Three Different Areas of Lake Patzcuaro, Michoacan, Mexico, (pp. 75-87), by María Verónica Gabriel-Luciano and Jaime Uribe-Cortez.

**Photo**: Roberto Menéndez.

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# Solar Brackish Water Treatment for Irrigation Using Low-Pressure Nanofiltration

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## Abstract

Flores-Prieto, J. J., Ramírez-Luna, J. J., Calderón-Mólgora, C. G., Delgado-Quezada, E., & Morales-García, A. J. (November-December, 2015). Solar Brackish Water Treatment for Irrigation Using Low-Pressure Nanofiltration. *Water Technology and Sciences* (in Spanish), *6*(6), 5-17.

This work relates a solution for brackish water treatment by low pressure NF using photovoltaic energy oriented to offer space to agricultural activities in remote areas. The study area was the sub basin Aj of the Pánuco River basin, in the RH26 hydrological region of the Chihuahua desert, which was considerate representative of endorheic basins around sampling zone. The raw water had high content of sulfate (1863 mg/l), which mainly demerits its quality. The total dissolved solids (TDS) were 2 195 mg/l. A photovoltaic low pressure nanofiltration treatment was proposed to primarily remove sulfates (divalent oin). The treatment was studied using synthetic and raw water, determining the removal efficiency of TDS and sulfates, the specific energy, the daily production and the viability of its field operation. In the results, the removal efficiency of TDS, the specific energy and the productivity were significantly associated with irradiation, and then linear correlations were obtained for each case. Sulfates and TDS were removed 98.21 and 75.15%, respectively, at equal or higher level of irradiation of 750 W/m$^2$ and specific energy of 1.94 kWh/m$^3$. Under field conditions, the permeate productivity was 3.2 m$^3$/day, at average insolation of 6.3 peak-sun-hours/day, above PV modules. The continuous operation of the desalination system by users during four months, without specialized assistance, showed feasibility of the proposed solution.

**Keywords**: Nanofiltration photovoltaic, solar desalination nanofiltration low pressure, solar irrigation.

## Resumen

*Flores-Prieto, J. J., Ramírez-Luna, J. J., Calderón-Mólgora, C. G., Delgado-Quezada, E., & Morales-García, A. J. (noviembre-diciembre, 2015). Tratamiento de agua salobre mediante nanofiltración solar a baja presión para irrigación.* Tecnología y Ciencias del Agua, *6*(6), 5-17.

*En este trabajo se presenta una solución para tratar agua salobre mediante nanofiltración fotovoltaica a baja presión (NF-FV-BP), orientada a la habilitación de tierras improductivas en términos agrícolas. La zona de estudio fue la región hidrológica RH26 del desierto de Chihuahua (subcuenca Aj Río Verde), la cual se consideró representativa de cuencas con sedimento salino debido a drenaje ineficiente. El agua subterránea disponible presentó un alto contenido de sulfatos (1 863 mg/l) y 2 195 mg/l de sólidos disueltos totales (SDT), lo que compromete su viabilidad para riego. El tratamiento de NF-FV-BP se propuso por ser apto para la remoción de iones divalentes como los sulfatos, para así disminuir la concentración de SDT. El tratamiento se realizó utilizando tanto agua sintética como la disponible en la región de estudio, determinando la eficiencia de remoción de SDT y de sulfatos, energía específica, producción diaria y viabilidad de su operación en campo. En los resultados se observó que la eficiencia de remoción de SDT, energía específica y productividad se relacionan con la irradiación, y se obtuvo una correlación lineal para cada caso. Los sulfatos y los SDT se redujeron en un 98.21 y 75.15%, respectivamente, a una irradiación igual o superior a 750 W/m$^2$, con una energía específica de 1.94 kWh/m$^3$. En campo, la productividad de permeado resultó de 3.2 m$^3$/día, a insolación promedio de 6.3 hora pico/día en el plano de los módulos fotovoltaicos. La operación continua del prototipo durante cuatro meses por parte de usuarios mostró viabilidad de la solución propuesta.*

***Palabras clave***: *nanofiltración fotovoltaica, desalinización solar, nanofiltración a baja presión, irrigación solar.*

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## Introduction

In Latin America, and particularly in Mexico, there are large areas of salinized land where vegetation is scarce or non-existent. Fifteen percent of potential productive land in Mexico has an excess of salts (Oosterbaan, 1995; Pulido-Madrigal, 1996). The salinization of land largely corresponds to locations in basins with insufficient drainage, where runoff from rainfall leaves sediments deposits containing salts and only the water evaporates during the dry season. Thus, when the land is not adequately level and agrochemicals are not appropriately used the salinity of the water in the subsoil intensifies with every cycle. The combination of soil having inefficient drainage and a high incidence of solar irradiance makes these types of locations barren, where marginalized human settlements are common. The purpose of this work is to treat brackish water in order to increase the capacity of isolated/marginalized communities to grow crops and the amount of cultivatable land in these areas, as well as to broaden the studies about arid regions that have been performed in other countries, as reported by Yu, Liu, Wang and Liu (2011).

Inverse osmosis (IO) has primarily been used to desalinize brackish water since this technology is associated with lower energy costs and a relatively large daily productivity, as reported by Ludwig (2010), Mac- Harg (2011), Isaka (2012), and Dévora-Isiordia, González-Enríquez and Ruiz-Cruz (2013), among others. The use of nanofiltration (NF) with inverse osmosis makes it possible to eliminate particles foreign to water, to a certain extent, given that the size of the particles that permeate is larger than the size of the particles treated by IO alone. Some authors consider nanofiltration to fall within the IO spectrum (<0.01 nm), and it has been used to eliminate particles with diameters over 2 nm since it is a less expensive process in terms of energy and the equipment required (Leo, Yahya, Kamal, Ahmad, & Mohammad, 2013; Pontié, Dach, Leparc, Hafsi, & Lhassani, 2008). Since NF operates with lower hydraulic pressures it can use less robust equipment than IO. And in some cases NF is used with IO as a pretreatment to better control membrane fouling.

Many studies have observed that NF is becoming an alternative or part of the solution for the desalinization of brackish water for human consumption, particularly when divalent ions need to be removed (Ghermandi & Messalem, 2009); that is, for cases involving the quality of water for human consumption in which monovalents ions are not a problem. NF operates with a lower osmotic pressure than IO, by retaining larger ions, and therefore the pressures needed to remove salts from water are lower with NF than with IO. As a result, less robust equipment and less powerful pumps are needed, for which photovoltaic solar energy has been widely applicable. Several works have reported on the use of NF systems operating with relatively low optimal pressures, in which robustness is lower and therefore operating and investment costs are obviously reduced, as reported by Koyuncu, Yazgan, Topacik and Sarikaya (2001), Schäfer, Broeckmann and Richards (2005), Richards and Schäfer (2003), and Hrayshat (2008). Nevertheless, as has already been mentioned, the use of NF for brackish water has been applied particularly to obtain water when human consumption is a priority, as reported by Werner and Schäfer (2007). In addition, it is useful to perform studies to optimize treatments to remove specific substances that degrade the quality of water in isolated/marginalized irrigated farming regions.

Several different investigations have observed the feasibility of photovoltaic NF (PV-NF) to treat water for human consumption in isolated locations (Isaka, 2012). In general, specific energy and productivity are reported as constants. Average daily and monthly values are also obtained, as well as those associated with specific seasons (Hrayshat,



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2008). Richards, Richards and Schäfer (2011) reported on a retention study that depends on the available irradiance in the interval 0.2-1.0 kW/m$^2$. It is useful to perform detailed water treatment studies of low-pressure PV-NF for specific agricultural purposes in which the critical substance or substances are removed while reducing the removal of minerals needed for irrigation or fertilization. In some cases, previous studies considered the use of PV-NF for isolated places in order to obtain water for both human consumption and irrigation, as shown by Kaldellis, Meidanis and Zafirakis (2011). Various works involving the treatment of water for irrigation in general have also been published, such as Ontiveros-Capurata, Diakite-Diakite, Álvarez-Sánchez and Coras-Merino (2013), as well as studies about the application of IO to large-scale irrigation using conventional energy, such as Shaffer, Yip, Jack and Elimelech (2012). Studies about treatments to remove sulfates with different technologies are generally based on conventional energy, such as Phuntsho, Shona, Hongb, Leeb and Vigneswarana (2011) and Phuntsho, Hong, Elimelech and Shon (2013). This suggests the usefulness of detailed studies related to PV-NF for treating water for use in irrigation in order to optimize energy consumption, processes and the removal of specific substances.

The present investigation is a study of low-pressure PV-NF to treat brackish water for use in irrigation, in order to restore lands located in basins with inefficient drainage and which are not currently fertile for agricultural purposes. This study begins with the determination of water quality in a region that is representative of basins with inefficient drainage. Then, a low-pressure PV-NF design is proposed that is simple in terms of configuration, operations and maintenance. Its feasibility is determined according to its efficiency for removing sulfates ($SO_4^{-2}$) and total dissolved solids (TDS) with different irradiances. Specific energy and productivity are evaluated according to the irradiances, and the operability of the system by the potential producers/users of the technology is determined.

## Materials and Methods

### *Sampling*

Two synthetic water samples were treated, which were prepared with well water with low TDS contents (c.e. 250 μS/cm). NaCl, $Na_2SO_4$ and $CaSO_4$ were added to concentrations of 1 107 and 1 843 mg/l for the first lot and second lot, respectively. Water samples from the study area were also treated.

#### *Location of the Study Area*

The study area was located in the Chihuahua Desert, Mexico. The samples were taken from Hydrological Region RH26 in the Aj Rio Verde sub-basin of the Panuco River Basin, municipality of Rio Verde, San Luis Potosi (21°59´ 16.98´´ N, 99° 48´ 34.84´´ W; elevation 1 065 m). Figure 1 shows the orographic location of the sampling area. As can be seen, it is nestled in the plains of a closed basin, bordered by the Sierra Madre Oriental, between the Alvarez and Tablon mountains to the west, and the Sierra de Cardenas and Sierra de Ciudad del Maiz to the east. The area is considered representative of basins with inefficient drainage that contain salinized sediments due to being closed and the lack of large rivers, leading to the accumulation of sediments. In terms of topography, the valley of Rio Verde is made up of silts, sands, gravel and clay from the accumulation of sediments (Noyola-Medrano *et al*., 2009). The study area has an average annual irradiance of 6.3 peak-hours /day.

#### *Field Sampling*

The pH and TDS of raw water from the field were determined in triplicate using an Orion

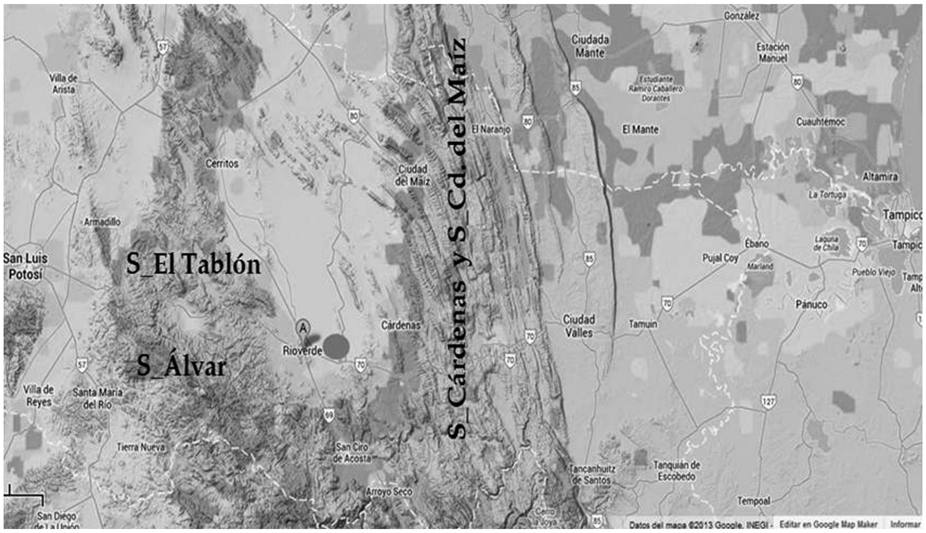


Figure 1. Orographic location of the sampling area.



brand meter, model 420a, with an uncertainty of 0.5%. The pH was 6.95 and the maximum TDS content was 2 195.0 mg/l (EC = 3 430 μS/cm$^2$). Table 1 shows the ion and cation contents, which were determined in the laboratory in accordance with EPA 60-10C (2007), NOM-117 SSA1 (1994) and the procedure described by the Colorimeter Manual (HACH/DR 890, 2013). Sulfate anion contents considerably exceeded values recommended for irrigation or ferti-irrigation. The sodium adsorption ratio (SAR) had a relatively high value of 11.4, indicating very high salinity and high sodium contents, as described by other works, such as Silva *et al*. (2014), among others.

### *Synthetic Water Sample*

In the study, two synthetic water samples were prepared with chlorine-free well water (from a well at the Mexican Institute of Water Technology, IMTA, Spanish acronym) (18° 53´ 03.16´´ N, 99° 09´ 34.37´´ W; elevation 1 363 m). NaCl, $CaSO_4$ and sodium sulfate were added to the samples. The salinity of the samples were within the salinity interval (electrical conductivity (EC)) of the aquifers in the study area (Piña-Soberanis & Calderón-Mólgora, 2008). Sample A had a pH of 7.86, TDS was 1 107 mg/l (EC = 2 080 μS/cm), sulfates were 520 mg/l (divalent ions) and chlorides were 288 mg/l (monovalents ions). Sample B had a pH of 8.54, TDS was 1 843 mg/l (EC = 3 690 μS/cm), sulfates were 740 mg/l and chloride was 626 mg/l. Samples A and B were characterized in the same way as the samples taken from the field.

### *Method*

The method to treat the water and evaluate the feasibility of the technology began by determining the raw water quality in terms of TDS/EC (indicator of salinity), pH and SAR (indicator of risk of salinity), as well as anion and cation contents. These parameters were used to identify the critical components in the samples, which made it possible to select the strategy to use for its treatment. The proposed treatment system was evaluated under laboratory conditions using synthetic samples and

Table 1. Chemical properties of the field sample. The tolerance is presented according to CAPMA-UE (2012).

| | Elements | Contents | Tolerance | Units |
|---|---|---|---|---|
| Cations | Na | 207.53 | < 180 | mg/l |
| | Mg | 105.24 | < 58 | mg/l |
| | Ca | 546.78 | - | mg/l |
| | K | 39.81 | < 54 | mg/l |
| Anions | $Cl^-$ | 87.8 | 150-355 | mg/l |
| | $SO_4^{-2}$ | 1 863 | < 371 | mg/l |
| | Ca $CO_3$ | 162 | - | mg/l |
| | N-$NO_3$ | 1.15 | <32.3 | mg/l |
| SAR | -- | 11.4 | < 10 | -- |

its functionality in the field was then tested. The desalinator was evaluated by determining: a) the removal efficiency for sulfates and TDS/EC; b) specific energy; c) productivity and d) users' ability to operate the system in the field (operability of the system).

### *Water Quality and Treatment*

The quality of water for irrigation was identified according to its salinity, which was based on TDS and the risk of salinity as indicated by the sodium adsorption ratio (SAR). The SAR was evaluated based on the contents of sodium, calcium and magnesium cations using equation (1), as reported by Richards (1982) and Silva *et al*. (2014) :

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad (1)$$

The cation and anion levels in the sample taken from the field showed that the $SO_4^{-2}$ contents (1 863 mg/l) considerably exceeded (502%) reference values established by the CNA (2009) and NOM-001- ECOL-1996 for crop irrigation. Given that sulfates, divalent ions, are greatly responsible for adding salinity to water, and the rest of the components deviated very little from the reference values, NF treatment was selected since it is typically used to remove divalent ions and enables operating the system with relatively low pressure, which also reduces the robustness needed of the solar pumping system.

### *Desalinizing Performance*

The experiments were carried out in open air both in the laboratory and the field. The $SO_4^{-2}$ removal efficiency was determined with an insolation of 750 to 1 000 W/m$^2$ under clear and cloudy sky conditions. The contents in the samples were compared before and after treatment. TDS removal efficiency, specific energy and productivity were determined according to different levels of incident irradiance on the plane of the photovoltaic (PV) modules, from the amount needed for the system to function up to 1 000 W/m$^2$ on average, with intervals of 100 W/m$^2$ on average. To this end, the different variables were recorded and series of 8 to 12 experimental data were averaged for each irradiance. Next, each group of data were analyzed according to the amount of irradiance.

The specific energy (SE) for each irradiance, *G*, on the plane of the photovoltaic modules (PVM) was determined by the relationship between the electric power supplied to the pumping system (closed circuit) and the flow of the permeate, or productivity, based on equation (2):

$$SE(G) = \frac{f_{p\,(G)}}{P_{PVp(G)}} \quad (2)$$

where $f_p(G)$ is the average mass flow of the permeate in one hour, for an insolation, and the average electric power supplied to the pumping system during the same hour, $P_{PVp}(G)$. The power is obtained by multiplying the voltage ($V_{PV}$) by the amperage ($I_{PV}$) supplied to the hydraulic pump.

The functioning of the system was verified by installing and operating it in the field, while evaluating TDS removal efficiency, hourly productivity and operability. The latter was determined by the number of technical consultations by qualified personnel to reset the system, in relation to the operating time in the field (in the agricultural unit).

## *Solar Desalinator*

After determining the critical substances in the raw water and the viability of the low-pressure PV-NF, the system was designed to treat brackish water with high sulfate contents ($SO_4^{-2}$), while reducing NF membrane fouling with a high reject-permeate relationship. The design of the system considered low operating pressures, no electric storage and direct coupling of a photovoltaic solar plant with a hydraulic pump. This design was considered in order to lower the robustness needed of the system, thereby increasing the viability of farmers operating it in the field.

Figure 2 shows a diagram of the configuration and Figure 3 a photograph of the system. The desalinator is composed of a microfiltration system, nanofiltration system (NF) and a photovoltaic pumping system. The NF system has a permeate capacity of 0.2 l/s (12 l/min), with 60 l/min of brackish feed water, a 1:5 permeate:feed ratio and four polyamide membranes (ESNA1-LF-4040) arranged in parallel, with a total equivalent area of 30.6 m$^2$. The photovoltaic pumping system contains a photovoltaic plant with a nominal system power of 1.92 kW, with 8 polycrystal-

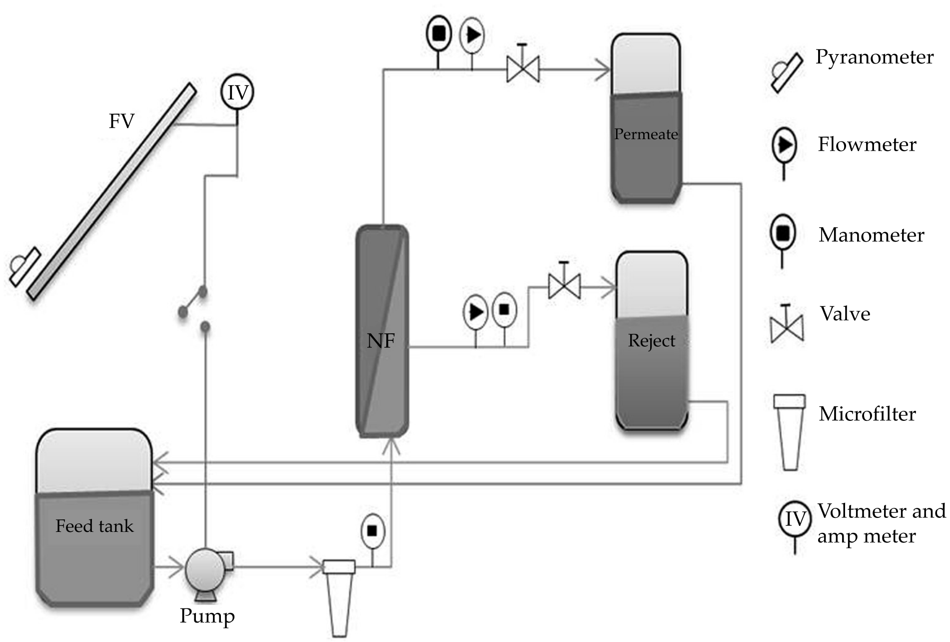


Figure 2. Diagram of the experiment.



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Figure 3. Experimental laboratory equipment.

line silicium modules and a nominal power of 240 W each, which supplies a submerged centrifugal pump (SQF-10 model SQFlex16). According to the manufacturer, the pump's operating range is 30 to 300 VDC. It becomes optimal above 100 VDC and as it approaches 300 VDC. The photovoltaic pumping system can feed water with up to 1.42 kW. The photovoltaic plant and the pump are directly coupled and are controlled only with a start-stop switch and the power that the solar plant supplies to the hydraulic pump. In the coupling of the photovoltaic plant and the pump, the output voltage to the modules was optimized by connecting them in a chain series with a maximum voltage output of 240 VDC.

In terms of the hydraulics, three storage tanks were used in the laboratory to obtain a continuous recycling of the supply, reject and permeate of 0.6 and 1.1 $m^3$. Meanwhile, in the field, the permeate was deposited in a 500 $m^3$ storage tank for later use in irrigating crops. The feed water tank (also 500 $m^3$) was fed with raw water pumped from the well to minimize variations in the total dissolved contents.

### *Instrumentation*

Irradiation was determined with a First Class Eppley pyranometer, on the plane of the photovoltaic module (PVM) with an uncertainty of ±1.0%. The volumetric flow was determined in duplicate using volumetry with an uncertainty of 0.1 l/min and a flow meter with a resolution of 0.25 l/min. The voltage and amperages were measured with 4.5-digit multimeters. Temperature was measured with a Type K Thermocouple, with an uncertainty of ± 0.5°C, and the hydraulic pressure was measured with manometers with a resolution of 0.015 bar.

## Results and Discussion

The laboratory tests were performed from September 26 to October 11, 2013 in Jiutepec, Morelos, Mexico, and the field tests were conducted from October 19, 2013 to February 15, 2014 in the municipality of Río Verde, San Luis Potosi, Mexico.

### *Laboratory Tests*

During the experimental laboratory campaign, the radiative solar power on the plane of the PVM ranged from 60 to 1 040 W/m$^2$. This was primarily due to natural variations in solar radiation and the presence of clouds.

### *Water Quality*

With an irradiation between 750 and 1 000 W/m$^2$, between the high and low salinity limits (2 080 to 3 690 µS/cm), the evaluation determined an average decrease in TDS of 75.15% with a variation of 0.4%, an average decrease in $SO_4^{-2}$ of 98.21% with a variation of 0.7% and an average reduction in $Cl^-$ of 55.16% with a variation of 8.9% (Table 2). In the interval used by the study, the TDS and sulfate removal percentages had virtually no dependence on the initial contents of the raw water. The removal percentages obtained for polyvalence molecules were consistent with reports by Izadpanah and Javidnia (2012).

Figure 4 shows the behavior of TDS removal and the pump supply pressure for sample A, where both can be seen to increase with the rise in irradiation. The TDS removal efficiency varied from 65.2 a 75.6%, within the range of the natural variation of irradiation on the plane of the PVM (60 to 1 050 W/m$^2$). The hydraulic pressure ranged from 0.12 a 0.49 bar. The range of the operating pressure contributed to the viability of the PV-NV being operated by farmers in isolated areas, since the system can use a common hydraulic pump without special pressure requirements.

### *Energy Performance*

The laboratory tests showed that the treatment system began operations with a supply of 124 W to the hydraulic pump, irradiation of 60 W/m$^2$, production of 0.15 m$^3$/ and a SE of 1.30 kWh/m$^3$. In the 60 to 750 W/m$^2$ interval, the increases in $f_p$ and SE were practically linear to the irradiation, as seen in Figure 5. An 80% variation in the permeate and a 34% variation in the SE can be observed. At irradiations of 750 W/m$^2$ or higher, the system shows an increase in $f_p$ of no more

Table 2. Water quality (salinity) with laboratory tests.

| | Units | Supply | Rejection | Permeate | Efficiency (%) |
|---|---|---|---|---|---|
| **Sample A: Low salinity limit** | | | | | |
| pH | --- | 7.86 | 7.91 | 7.49 | --- |
| EC | µS/cm | 2 080 | 5 890 | 531 | 74.47 |
| TDS | mg/l | 1 107 | 3 007 | 282 | 74.56 |
| $SO_4^{-2}$ | mg/l | 520 | 1 900 | 13 | 97.50 |
| $Cl^-$ | mg/l | 288 | 800 | 115 | 60.07 |
| **Sample B: high salinity limit** | | | | | |
| pH | ---- | 8.54 | 8.48 | 8.74 | ---- |
| EC | µS/cm | 3 690 | 4 140 | 892 | 75.83 |
| TDS | mg/l | 1 843 | 2 090 | 446 | 75.80 |
| $SO_4^{-2}$ | mg/l | 740 | 880 | 8 | 98.92 |
| Cl- | mg/l | 626 | 698 | 312 | 50.16 |



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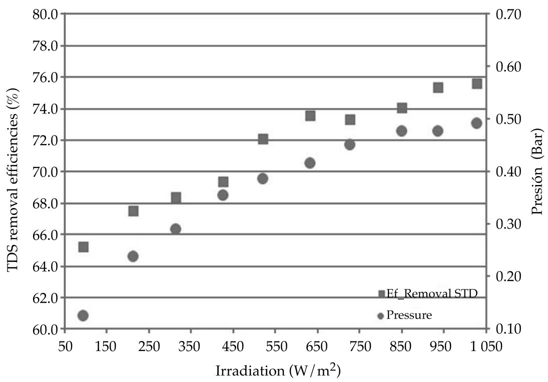


Figure 4. Desalinization efficiency (TDS) and supply pressure to the pump vs. irradiance for Sample A.

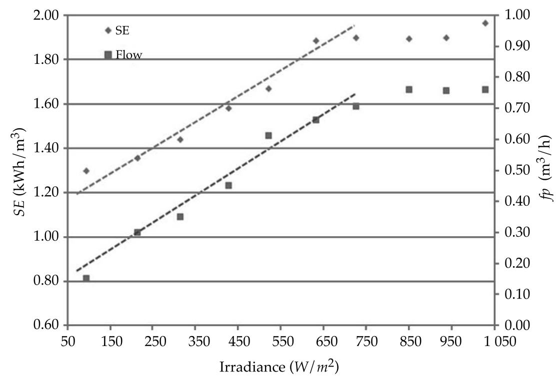


Figure 5. Specific energy and permeate *vs*. irradiance.

than 0.76 $m^3/h$ and 1.94 ± 0.04 $kWh/m^3$ in SE. The maximum productivity values, or flow of the permeate and the SE, were obtained with the maximum power of the hydraulic pump (1.42 kW), since above this amount the pump's control system drains the energy supplied by the PVM to a resistance circuit and is not quantified. This protects overloading the hydraulic pump.

The linear correlations of SE and $f_p$ with the irradiation on the plane of the PVM are shown in equations (4) and (5), respectively, which present a standard estimation error of 0.25 $kW/m^3$ and 0.20 $m^3/h$, with a reliability $R^2$ of 0.9694 and 0.9797.

$$SE = 1 \times 10^{-3} G + 1.1511 \quad kW/m^3 \quad 60 \leq G(\theta) \leq 750$$
$$SE = 1.94 \quad kW/m^3 \quad G(\theta) \geq 750 \quad (3)$$

$$f_p = 9 \times 10^{-4} G + 0.085 \quad m^3/h \quad 100 \leq G(\theta) \leq 750$$
$$f_p = 0.76 \quad m^3/h \quad G(\theta) \geq 750 \quad (4)$$

### *Field Operations*

The system was installed in the field and began operating on October 19, 2013. It was still operating adequately by February 15, 2014. The field operations tests recorded an insolation of 750 $W/m^2$ or higher on the plane of the PVM. Table 3 shows the results from the quality of the permeate water with the field tests. The SE evaluated in the field were consistent with those obtained in the laboratory, with a difference of only 8.2%, which can be attributed to the difference in the fall in pressure in the hydraulic installation.

At irradiations equal to or over 750 $W/m^2$ and with the hydraulic pump operating at maximum power (1.42 kW), sulfates decreased 97.8% (from 1 863 to 40.99 mg/l) and the average TDS removal efficiency was 76.7% (from 2 195 to 510.1 mg/l). This was consistent with the report by Izadpanah and Javidnia (2012). Therefore, the hydraulic operating pressure used was 0.49 bar to supply the permeate at a rate of 0.6 to 0.66 $m^3/h$, with a SE of 2.1 $kWh/m^3$. With this performance, the daily productivity was 3.2 $m^3$/day with an average insolation of 6.3 kWh/day in the study area, with which up to 15 tons of tomato could be grown at a conservative rate of 35 $kg/m^3$ over a cycle of 137 days using hydroponic greenhouse technology, as reported by Flores, Ojeda-Bustamante, López, Rojano and Salazar (2007).

Only one technical consultation was needed during the field test. This was due to the fouling of the filter in the pre-filter

Table 3. Water quality with field tests.

| | Units | Supply | Permeate | Efficiency (%) |
|---|---|---|---|---|
| $SO_4^{-2}$ | mg/l | 1 863 | 40.99 | 97.8 |
| TDS | mg/l | 2 195 | 510.1 | 76.76 |
| SAR | --- | 11.5 | 16.4 | --- |
| Na | mg/l | 207.53 | 45.27 | 78.19 |
| Ca | mg/l | 546.78 | 12.7 | 97.68 |
| Mg | mg/l | 105.24 | 3.1 | 97.05 |

system from the considerable growth of algae in the supply tank. Therefore, the pump was relocated to the brackish feed water container. Since the system stopped due to unforeseen conditions caused by the design of the installation, the system is considered to have operated without requiring specialized technical assistance during the test period (October-February).

As seen in Table 3, in terms of the risk of salinity according to the SAR, the NF eliminated a larger amount of Ca and Mg ions given its greater affinity with sulfates, and less Na ions were eliminated because of its affinity with chlorides. For this reason the SAR increased from 11.5 to 16.5, but with smaller Na concentrations, which led to a possible re-mineralization of only Ca and Mg, preventing damage from salinity. Re-mineralization should be done based on the requirements of each crop and soil type. It can be performed by mixing the permeate with raw water or substances that add Ca and/or Mg, such as calcium hydroxide ($Ca(OH)_2$), and/or fertilizers containing Mg in the proportions required.

Based on the above— considering the quality of the permeate, energy costs and the productivity and operability of the system— this evaluation found that low-pressure PV-NF can be used to treat water with high sulfate concentrations for use in irrigation, and can be applied in isolated/marginalized regions where it is more greatly needed. This can be done with the help of irrigation technology such as plastic mulch and shade cloth, or in greenhouses with hydroponic conditions to optimize the use of water for crops.

## Conclusions

This work presented an alternative method using low-pressure PV-NF to treat brackish water containing high concentrations of sulfate for use in crop irrigation, in order to restore lands located in basins with inefficient drainage and which are not currently fertile for growing crops.

At the high and low salinity limits (2 080 to 3 690 μS/cm) with an irradiation of 750 to 1 000 W/m$^2$, an average decrease of 75.15% in TDS was observed and 98.21% in $SO_4^{-2}$, with minimal variations. The monovalent $Cl^-$ anions decreased 55.16% with a variation of 8.9%. The natural variation in insolation, 60 to 1 040 W/m$^2$, caused changes in TDS removal up to 11.5%.

The flow of the permeate and the SE presented maximum values of .76 m$^3$/h and 1.94 ± 0.04 kWh/m$^3$, respectively, for irradiations of 750 W/m$^2$ or higher. For lower values the decrease was linearly proportionate to irradiation. The SE varied 32% and the permeate flow varied 80% in the irradiation interval of 60 to 750 W/m$^2$. The operating pressure ranged from 0.12 to 0.49 bar along with the irradiation, with a profile that can be considered to be linear in the interval, where the PVS is not able to supply the nominal pumping power. The SE stabilizes at 1.94 kWh/m$^3$ once reaching the nominal power or higher. The system can function even with relatively low pressures and specialized technology for the hydraulic pump is not strictly required, making it possible to use a common, centrifugal pump operated with PV solar energy.

The low-pressure NF-PV desalinization system is an option for increasing the agricultural productivity of lands with saline water tables, as is common in basins with inefficient drainage. This was determined by observing that the hydraulic pressure required (0.12 to 0.49 bar) can be supplied by a conventional centrifuge pump and the users were able to operate the system during 4 months without specialized technical assistance.

The desalinator resulted in an average of 3.2 $m^3$/day, with 6.4 solar peak-hours in the study area, which enables growing up to 15 tons of tomato in the study area at a rate of 35 kg/$m^3$ over a 137 day cycle with hydroponic greenhouse technology, as reported by Flores *et al*. (2007). By determining SE, permeate flow and TDS removal efficiency based on irradiance values, it was possible to dimension the system with a higher degree of certainty.

Future studies about this topic should be aimed at optimizing the system's energy based on the available solar irradiance and the capacities of the components of the photovoltaic pumping system, optimizing the coupling of the photovoltaic module with the hydraulic pump according to the maximum power limit. In addition, it should be noted that the rejection water was considerably polluted and therefore future investigations should consider its treatment.

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# Efficiency of Three Hybrid Wetland Systems for Carbamazepine Removal

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## Abstract

Tejeda, A., López, Z., Rojas, D., Reyna, M. Z., Barrera, A., & Zurita, F. (November-December, 2015). Efficiency of Three Hybrid Wetland Systems for Carbamazepine Removal. *Water Technology and Sciences* (in Spanish), *6*(6), 19-31.

In general, it has been found that constructed wetlands are effective in different levels for pharmaceutical removal; however, there are cases with very low removal efficiencies such as that of carbamazepine. The aim of this study was to evaluate the mass removal efficiencies of the drug in three hybrid constructed wetland systems with two-stage treatments, including horizontal subsurface flow wetlands (HSSF), vertical subsurface flow wetlands (VSSF) and stabilization ponds (SP). The three different configurations were: HSSF-SP, HSSF-VSSF and VSSF-HSSF, which were identified as SI, SII and SIII respectively. In addition, measurements of DO, $E_h$, pH, EC, ET and temperature were taken in situ in order to know the system conditions. The results revealed significant differences ($p < 0.05$) among the three hybrid system for mass removal efficiencies, with an average of 60 ± 4.45% for SI, 55 ± 4.45% for SII and 36 ± 4.45% for SIII. The systems I and II, were statistically similar and also, both were different to SIII. In general, the higher efficiencies were obtained in systems with DO low concentrations, $E_h$ negative values and pH conditions near to 8, which mainly occur in horizontal sub-surface flow constructed wetlands. In contrast, aerobic conditions demonstrated less efficiency. These results confirm the ability of constructed wetlands to remove carbamazepine and show that it is possible to increase its mass removal efficiency by combining different types of wetlands.

**Keywords**: Horizontal sub-surface flow constructed wetland, vertical sub-surface flow constructed wetland, carbamazepine, hybrid systems, operating conditions.

## Resumen

*Tejeda, A., López, Z., Rojas, D., Reyna, M. Z., Barrera, A., & Zurita, F. (noviembre-diciembre, 2015). Eficiencia de tres sistemas de humedales híbridos para la remoción de carbamazepina.* Tecnología y Ciencias del Agua*, 6(6), 19-31.*

*En general, se ha encontrado que los humedales construidos son efectivos en diferentes grados para la remoción de fármacos; sin embargo, existen casos como el de la carbamazepina (CBZ), cuyas eficiencias de remoción reportadas han sido muy bajas. El objetivo de este estudio fue evaluar las eficiencias de remoción másica de dicho fármaco en tres sistemas de humedales híbridos con dos etapas de tratamiento, incluyendo humedales subsuperficiales de flujo horizontal (HSSFH), humedales subsuperficiales de flujo vertical (HSSFV) y lagunas de estabilización (LE). Las tres diferentes configuraciones fueron HSSFH-LE, HSSFH-HSSFV y HSSFV-HSSFH, denominados como SI, SII y SIII, respectivamente. Además, se realizaron mediciones in situ de OD, $E_h$, pH, CE, ET y temperatura, con el propósito de conocer en qué condiciones operaban dichos sistemas. Los resultados revelaron diferencias significativas ($p < 0.05$) en la eficiencias de remoción de los sistemas híbridos, con un promedio de 60 ± 4.45% para SI, 55 ± 4.45% para S II y 36 ± 4.45% para SIII, siendo SI y SII estadísticamente iguales y ambos diferentes a SIII. En general, las mayores eficiencias se presentaron en los sistemas con concentraciones bajas OD, valores negativos de $E_h$ y condiciones de pH cercanas a ocho, que se tienen principalmente en los humedales subsuperficiales de flujo horizontal. En contraste, condiciones aerobias de operación demostraron ser menos eficientes. Dichos resultados corroboran la capacidad de los humedales construidos para remover carbamazepina y demuestran que es posible incrementar su remoción mediante la combinación adecuada de diferentes tipos de humedales.*

***Palabras clave**: humedales subsuperficiales de flujo horizontal, humedales subsuperficiales de flujo vertical, carbamazepina, humedales híbridos, condiciones de operación.*

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## Introduction

The indiscriminate use of pharmaceutical products and unrestricted discharges of wastewater into aquatic environments have led to these substances being found in surface water, groundwater and water for human consumption (Jones, Lester, & Voulvoulis, 2005). Because of its recalcitrant nature, its presence has been reported in a wide range of concentrations in conventional treatment plant effluents (Herberer, 2002). Given the large diversity of pharmaceutical compounds found, it is impossible to entirely and precisely know their eco-toxicological effects on human health. Nevertheless, different studies with animals have shown that some may be carcinogenic and teratogenic, or may alter the endocrine system (Rosal *et al*., 2010).

Constructed wetlands have been studied over the past decade as a new method to treat water polluted by drugs (Ávila, Pedescoll, Matamoros, Bayona, & García, 2010). Pollutants are removed through complex physiochemical and microbiological interactions that occur when wastewater is slowly passed through a substrate bed (sand, gravel, clay) containing the roots and rhizomes of emergent vegetation in the horizontal sub-surface flow of the wetlands. They can also be removed by quickly running wastewater with pulses through the vertical flow of sub-surface wetlands. Some of the mechanisms involved in removing pharmaceutical components are plant uptake, microbial biodegradation, adsorption in the bed and volatilization (Kadlec & Knight, 1996; Matamoros, Caselles-Osorio, García, & Bayona, 2008). Thus, the three components of constructed wetlands (emergent vegetation, filtration medium and microorganisms) participate as determinants. Direct uptake, accumulation and translocation of pharmaceutical compounds by plants are important mechanisms (Dordio *et al*., 2011; Zhang, Gersber, Jern-Ng, & Keat-Tan, 2014), as demonstrated by studies with and without plants (Matamoros & Salvadó, 2012). These compounds move towards and within the tissue of plants simply by diffusion, given that the plants do not have specific transporters in their cellular membranes to move them. Adsorption can occur from the direct interaction of a drug with the filtration medium (Li, Zhu, Jern-Ng, & Keat-Tan, 2014), or through hydrophobic interactions of aromatic and aliphatic groups of organic compounds with the lipophilic cellular membrane of microorganisms adhered to the filtration medium (Matamoros, García, & Bayona, 2005). The degradation of pharmaceutical compounds primarily depends on the chemical structure of the particular compound. Recalcitrants can biodegrade through co-metabolism reactions (Carballa, Omil, Alder, & Lema, 2006; Carballa, Omil, Ternes, & Lema, 2007). In addition, degradation in constructed wetlands is affected by the filtration medium, vegetation, dissolved oxygen, redox potential, temperature, pH, availability of nutrients and presence of toxic substances (Li *et al*., 2014). Several investigations have shown that treatment systems operated with anoxic conditions contribute to the removal and/or degradation of recalcitrant pharmaceutical compounds, such as carbamazepine and diclofenac (Xue *et al*., 2010). It has been suggested that the reductive agents stored in anaerobic microorganisms may be indispensable by reducing the electron deficiency that could produce molecules such as carbamazepine (Knackmuss, 1996).

The efficiency in removing pharmaceutical compounds is higher with constructed wetlands than with conventional treatment plants (Zhang *et al*., 2011). Nevertheless, average removals of only 20 to 50% have been obtained with horizontal sub-surface flow (HSSFW) and vertical flow (VSSFW) wetlands, especially in the case of carbamazepine which is considered to be one of the most persistent drugs (Matamoros, Arias, Brix, & Bayona, 2007; Park *et al*., 2009; Hijosa- Valsero *et al*., 2010; Zhang *et al.*, 2011; Zhang *et al.*, 2012). Few studies have evaluated hybrid wetland systems designed to remove this compound. Therefore, the objective of the present work was to evaluate and compare the mass removal of carbamazepine using three different configurations of hybrid wetland systems.

## Methodology

### *Description of the Experimental Unit*

This study was performed at the pilot plant of the University Center of Cienega, University of Guadalajara, in Ocotlan, Jalisco, Mexico, at 1 530 m above sea level and a latitude of 20° 21′ 00′′. This zone has a humid sub-tropical climate with an average annual temperature of 21°C, with dry and temperate winters and hot and humid summers (Zurita *et al.*, 2012). The study was conducted for 7 months, from June to December 2013. It consisted of three hybrid wetland systems, each one in duplicate (Figure 1) and all protected from rain and direct solar radiation. In the first system (SI), an HSSFW was used as the first treatment stage and stabilization lagoons (SL) as the secondary treatment. The second system (SII) used HSSFW as a first stage and VSSFW as a second stage, and the third system (SIII) consisted of VSSFW as the first stage and HSSFW as the second stage. The cells used in the wetlands were manufactured from fiberglass with lengths, widths and depths of 1.2 x 0.4 x 0.5 m, 0.48 x 0.48 x 1.2 m, and 0.7 x 0.7 x 0.7 m for the HSSFW, VSSFW and SL, respectively.

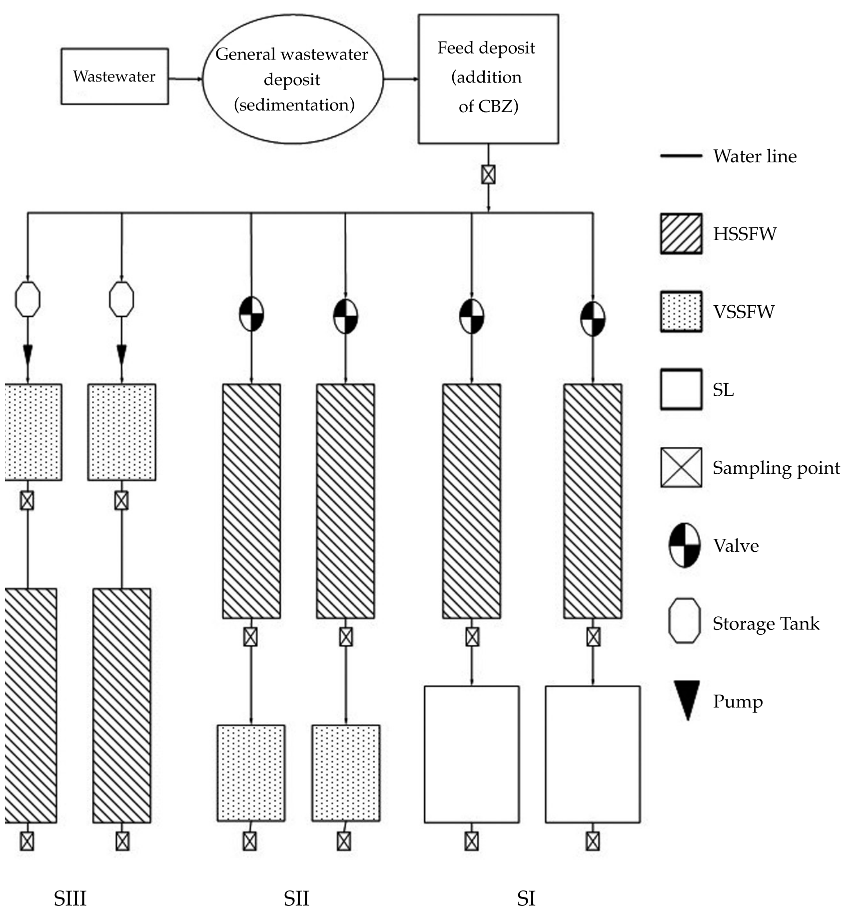


Figure 1. Layout of the hybrid wetlands studied. SI = HSSFW-SL; SII = HSSFW-VSSFW; SIII = VSSFW-HSSFW.

The HSSFW were planted with a polyculture of three macrophyte species, randomly distributing three individuals from each species on the surface of each wetland. The species used were *Zantedeschia aethiopica*, *Iris sibirica* and *Thypha latifolia*. A polyculture was used to promote the development of the largest variety of microorganisms (Karathanasis, Potter, & Coyne, 2003; Vacca, Wand, Nikolausz, Kuschk, & Kästner, 2005; Zurita, De Anda, & Belmont, 2009) to aid in the biodegradation of carbamazepine. Meanwhile, in the VSSFW, only one plant species, *Strelitzia reginae,* was used as an emergent vegetation. Both types of wetlands used ground tezontle as a substrate, with a $d_{10}$ of 0.645, $d_{60}$ of 2.3 mm and a uniformity coefficient of 3.6. Tezontle is a low-cost volcanic rock which is abundant in Mexico (Ponce *et al*., 2013). The wastewater used as the influent for the systems was produced at the university center. Carbamazepine (Sigma-Aldrich, 98% purity) was added after settling to obtain a concentration of 25 µg/l. The SI and SII HSSFW were continuously fed at a flow rate of 23 ml/min and the VSSFW (SIII) was fed intermittently with 2.8 l every two hours using an automated control device.

En los HSSFH se plantó un policultivo de tres especies de macrófitas; tres individuos de cada especie distribuidas de modo aleatorio en el área superficial de cada humedal. Las especies utilizadas fueron la *Zantedeschia aethiopica*, *Iris sibirica* y *Thypha latifolia*. El uso del policultivo fue con el objetivo de promover el desarrollo de una mayor variedad de microorganismos (Karathanasis, Potter, & Coyne, 2003; Vacca, Wand, Nikolausz, Kuschk, & Kästner, 2005; Zurita, De Anda, & Belmont, 2009) que coadyuvaran en la biodegradación de la carbamazepina. A diferencia de los HSSFH, en los HSSFV sólo se utilizó una especie de planta como vegetación emergente y fue la *Strelitzia reginae*. En ambos tipos de humedales, el sustrato utilizado fue tezontle molido con $d_{10}$ de 0.645 mm y $d_{60}$ de 2.3 mm, así como un coeficiente de uniformidad de 3.6. El tezontle es una roca volcánica de bajo costo, abundante en México (Ponce *et al*., 2013). Las aguas residuales con las que se trabajó como influente de los sistemas fue una porción de las aguas residuales generadas en el centro universitario, a las que una vez sedimentadas se les adicionó carbamazepina (98% de pureza de la marca Sigma-Aldrich), para tener una concentración de 25 µg/l. Los HSSFH en los SI y SII se alimentaron en forma continua con un caudal de 23 ml/min, mientras que los HSSFV se alimentaron en forma intermitente, descargando 2.8 l cada dos horas, mediante un dispositivo de control automático.

### *Monitoring Water Quality Parameters*

#### *Quantification of Carbamazepine*

The quantification of the carbamazepine started three months after beginning to feed the wastewater into the wetland systems. This provided a stabilization period during which the emergent plants adapted to the systems and their internal physiochemical and microbiological processes were presumably established. Samples were taken weekly at the inlet and outlet of each treatment stage (Figure 1), for a total of 13 samples. In triplicate, 100 ml of each sample was filtered through a paper filter (Whatman # 41) to eliminate suspended solids and then submitted to three consecutive extractions with 100 ml of methylene chloride (1:1). The organic phase was concentrated until dry with a rotary evaporator (IKA HB 10) at 40°C and gas nitrogen. The extracts were then resuspended in 1 ml of methanol. Each resuspension was filtered using a PTFE filter with a pore diameter of 0.20 µm. The recuperation percentage was 96.5 ± 1.5%.

Lastly, the carbamazepine was quantified in a reverse-phase HPLC using Waters equipment composed of a binary pump (Waters 1525) and a UV-Vis detector with a diode arrangement (Waters 2998). The techniques described by Đorđević, Kilibarda and Stojanović (2009), and Dordio, Carvalho,



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*Water*

Teixeira, Dias and Pinto (2010) were adapted for analytical purposes. A 75 mm-long Waters column (Symetry $C_{18}$) was used, with a 4.6 mm internal diameter and a 3.5 μm particle size. The mobile phase consisted of a mixture of acetonitrile, water and orthophosphoric acid (55:45:0,1). The flow was 1 ml/min and carbamazepine was detected at 285 nm, in a retention time between 3.37 and 3.41 min. Each sample was injected in duplicate with a volume of 20 μl in a loop of 100 μl. For each series of samples in triplicate, calibration curves were obtained with standards prepared using Sigma-Aldrich brand carbamazepine at 98%. The fit of the curve was verified based on the coefficient of determination ($r^2$), which was over 0.999. The detection and quantification limit was 0.47 ± 0.00 μg/l.

*Measurement of Control Parameters*

In addition, measurements were performed *in situ* of dissolved oxygen, oxidation reduction potential, temperature, pH, electrical conductivity and outlet flows in each of the systems, in order to identify the operating conditions of the systems. A portable HACH meter (HQ40d series) with IntelliCAL digital probes was used for the first three parameters. Electrical conductivity and pH were measured with portable HI 981410 and HI 981408, respectively (Hanna brand). The mea-

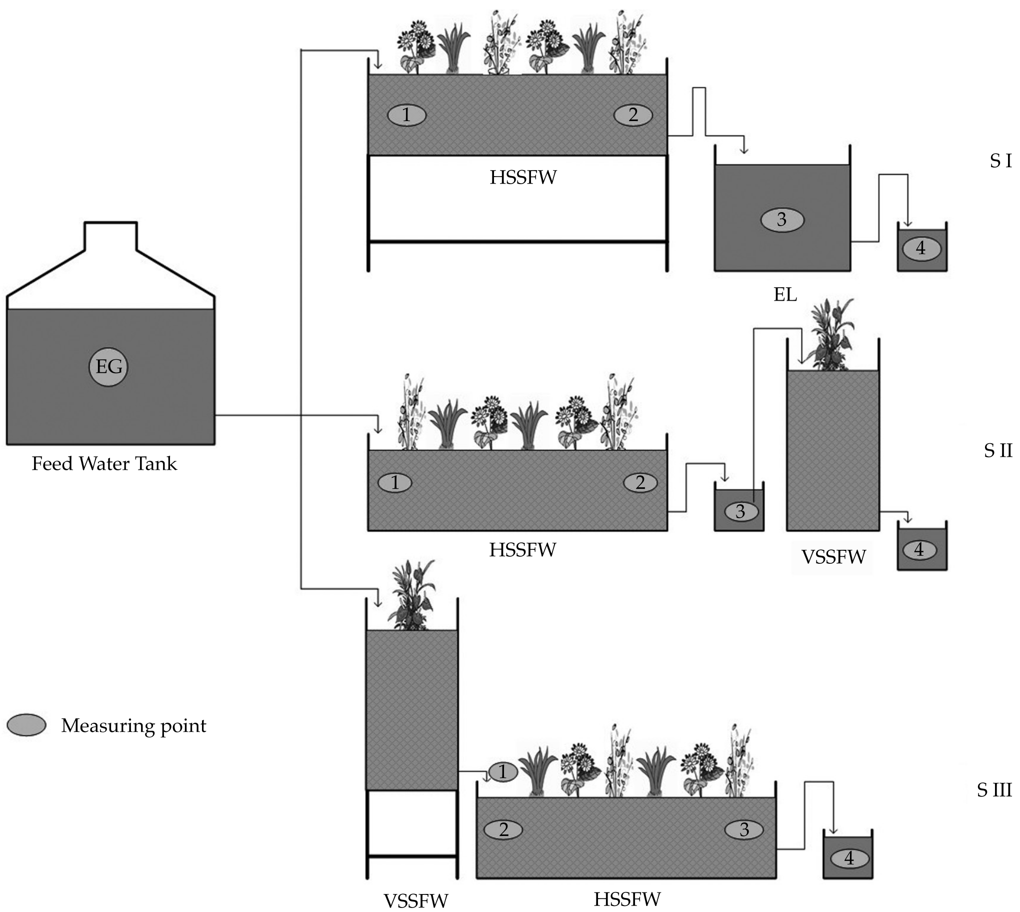


Figure 2. Location of the points for measuring control parameters during the monitoring period.



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surements were taken at four different points, inside and outside the treatment systems (Figure 2). Perforated tubes were installed inside the HSSSFW at the beginning and end of the wetland to install the measuring devices.

In the case of the SL, these measurements were performed inside the lagoons and at the treatment outlet. For the VSSFW, the measurements were taken before treatment and at the treatment outlet. The measurements were taken weekly at the same time as the sampling to quantify carbamazepine over the course of the monitoring period. Lastly, the outlet flows from each one of the stages of the different systems and the effluent volume at the end of each treatment train were measured daily to identify the evapotranspiration rate in each system.

## Calculation of Mass Removal Efficiencies for Carbamazepine

The mass removal efficiency is the most reliable method for evaluating the efficiency of constructed wetlands since it takes into account not only concentrations at the inlet and outlet but also water losses and gains (Hijosa-Valsero *et al*., 2010). Therefore, the removal results are closer to reality than taking into account only reductions in the concentration of the pollutant (Kadlec & Wallace, 2009). The calculation of the mass removal efficiency (MRE) is expressed as follows:

$$MRE(\%) = \frac{M_r}{M_i} \times 100 = \frac{C_i Q_i - C_e Q_e}{C_i Q_i} \times 100 \qquad (1)$$

Where $M_r$ (mg/d) is the mass of the pollutant removed from the wetland; $M_i$ (mg/d) is the mass of the pollutant that enters the wetland; $C_i$ (mg/l) is the concentration of the pollutant in the influent; $Q_i$ (l/l) is the influent flow rate; $C_e$(mg/l) is the concentration of the pollutant in the effluent and $Q_e$ (l/d) is the effluent flow.

### *Statistical Analysis*

To evaluate and compare the mass removal efficiencies for the pollutant over time, a randomized complete block (RCV) design was used with three treatments, one replication and a block factor, with a significance level of $p = 0.05$. The constructed wetland systems (HSSFW-SL (SI), HSSFW- VSSFW (SII) and VSSFW-HSSFW (SIII)) represent the three different treatments. The block factor was the sampling date and the response variable was the mass removal of carbamazepine. The ANOVA was calculated with *Statgraphics Centurion XV.II*.

## Results and Discussion

### *Behavior of Dissolved Oxygen (DO)*

The DO concentration in the constructed wetland systems is most important since it is required by the aerobic mechanisms that remove pollutants and therefore determines the type of microbial metabolism that is prevalent in the system (Kadlec & Wallace, 2009). The behavior of the DO in the three systems evaluated was as expected, based on reports in the literature (Figure 3a). System I had the lowest DO concentrations throughout the treatment train. The low concentration in a HSSFW system is due to the saturated water matrix which prevents the diffusion of oxygen from the surface (Vymazal & Kröpfelová, 2008). As a result, anoxic conditions are prevalent in the wetland (Saeed & Sun, 2012). Meanwhile, a low DO concentration in the stabilization lagoon can be explained by the low production of algae due to indirect exposure to sunlight (Kadlec & Wallace, 2009). This leads to less photosynthetic activity and, thus, a low production of oxygen in the lagoon.

With regard to System II, the behavior in the HSSFW used as the first treatment stage was very similar to that of System I.



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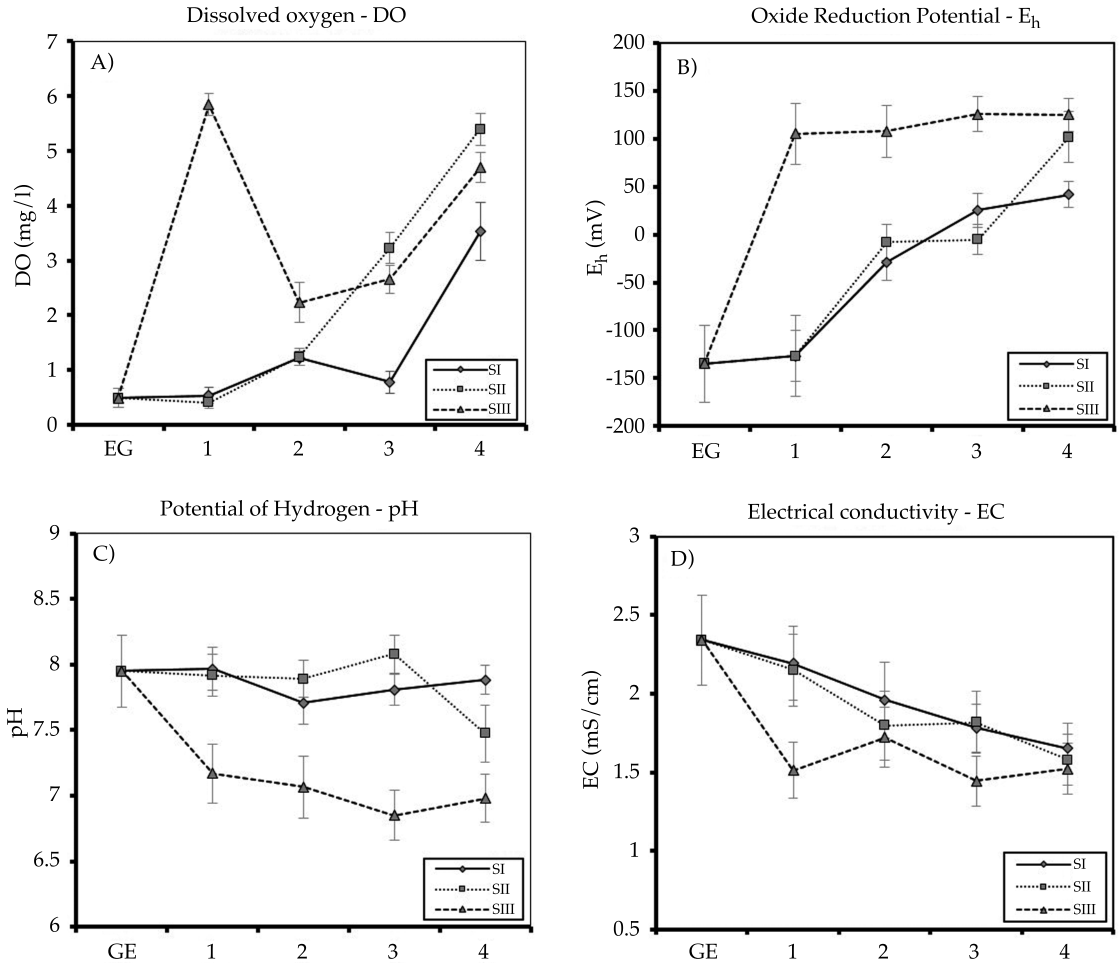


Figure 3. Averages of the control parameters at each measuring point and confidence interval (95%): a) dissolved oxygen, b) oxidation reduction potential, c) potential of hydrogen, d) electrical conductivity. GE, general entrance. 1, 2, 3 and 4 are measuring points at the different parts of each system, as shown in Figure 2.

Meanwhile, the results from the second stage (VSSFW) showed an increase in DO resulting from the intermittent feed used in this type of wetland. The intermittent feed in the upper portion of the VSSFW drags oxygen from the surface to the interior of the matrix (Kadlec & Wallace, 2009), resulting in an effluent with a high concentration of DO (Matamoros *et al.*, 2007). An increased DO concentration was also observed in the VSSFW used in the first stage of system III. In this case, the direct discharge of effluent having a high DO concentration affected the operating conditions of the HSSFW used in the second stage of the system. Although the observed decrease in DO concentrations was characteristic of this type of wetland, it remained above the 2 mg/l amount which is indicative of aerobic operations, and differs with the similarities in Systems I and II.

### Behavior of $E_h$ Oxidation Reduction Potential

$E_h$ is a quantitative measurement of the tendency of a system to oxidize or reduce pollutants and, similar to DO, is indicative of the biological processes that can occur in the system (Patrick, Mikkelsen, & Wells, 1985; Gambrell, Khalid, & Patrick, 1987; Kadlec & Wallace, 2009). The results from this measurement were consistent with those of DO.

Negative $E_h$ values were obtained in the first stage of System I, with a slightly higher value at the outlet than the inlet (corresponding to an increase in DO concentration from 0.76 to 1.42 mg/l). These negative values denote reduction conditions while the increase in $E_h$ and DO can be explained by two main factors —a decrease in BOD as the wastewater passes through the system (Kadlec & Wallace, 2009) and a constant supply of oxygen to the matrix provided by the macrophytes (Barko, Gunnison, & Carpenter, 1991; Sorrell & Boon, 1992; Brix, 1997), which creates slightly higher oxidation conditions in the outlet area of the HSSFW. The SL presented an increase at the outlet of the first stage, which was likely due to the atmospheric oxygenation of the effluent when discharged by gravity into the SL (Figure 3b). Nevertheless the change in DO concentration was less notable. With respect to System II, the behavior of the first stage (HSSFW) was similar to that of the first stage of SI, while the second stage presented a higher $E_h$ at the outlet, along with a notable increase in DO concentration (Figure 3a). This was a result of the oxygenation of the wastewater as it passed through the VSSFW. System III presented higher oxidation conditions throughout the treatment process, with values of around 100 mV. This behavior also continued in the second stage of the HSSFW system, confirmed by DO concentrations over 2 mg/l, as discussed in the section "Behavior of Dissolved Oxygen – DO."

### *Behavior of Potential of Hydrogen – pH*

The pH plays a very important role in removing pollutants from constructed wetlands since it directly affects the sorption capacity of the substrate (Li *et al*., 2014) and microbial processes (Meng, Pei, Hu, Shao, & Li, 2014). The behavior of System I was very stable throughout the treatment train, with pH values of around 8 (Figure 3c). This behavior can be explained by the buffer capacity of subsurface systems and by the little variability in pH in the lagoons due to the low production of algae mentioned (Kadlec & Wallace, 2009). The same stability was also present in the first stage of System II, with values very similar in the inlet and outlet zones. Nevertheless, a decrease in the pH was registered at the outlet of the system's second treatment stage (VSSFW). This behavior can be explained by nitrification in vertical wetlands, which generates H+ ions (Vimazal & Kröpfelova, 2008). The values obtained were very close to neutral and consistent with those reported in the literature (United Kingdom Constructed Wetland Association (CWA Database, 2006).

The behavior of System III was very different than that of SI and SII. In the first two systems, the pH remained around 8 throughout nearly the entire treatment train, while in System III the pH values were around 7. The pH decreased notably between the influent and outlet of the first stage (VSSFW) due to nitrification, which is common in this type of wetland. Later in the HSSFW, these values showed little variation as a result of the buffer capacity of the system, as mentioned. Nevertheless, the values at the outlet zone were slightly less than at the inlet (Figure 3c), perhaps due to the possible continuation of the nitrification process in the HSSFW as a result of predominantly aerobic conditions.

### *Behavior of Electrical Conductivity – EC*

EC is the measurement of total ionic salts and is nearly proportional to the total dissolved solids (TDS) in the wetland. Although biological processes can alter this measurement, the factors that most influence these values are physical dilution and evaporation processes (Kadlec & Wallace, 2009). The results from these processes, obtained by this study, showed a decrease in electrical conductivity in the flow at the outlet of the three systems (Figure 3d) in spite of the effects of evapotranspiration, which will be discussed in this section. According to Kiambadde, Kansiime and Dalhammar (2005), a decrease in EC can be explained by ion capture, micro and macro elements in plants and adsorption by their roots. In addition, in this particular study case, the removal of these types of compounds likely increased because of the tezontle which was used as a substrate in the sub-surface of the systems, which has been proven to have a high TDS removal capacity (Zurita *et al*., 2012).

### *Evapotranspiration – ET*

In constructed wetlands, evapotranspiration is a crucial factor which affects the hydrodynamics and functioning of the treatment (Chazarenc, Naylor, Comeau, Merlin, & Brisson, 2010). It affects the reduction of the water volume at the treatment outlet and therefore increases the concentration of pollutants (Borin, Milani, Salvato, & Toscan, 2011). The growth in the plants along with solar radiation, relative humidity, temperature and wind are factors that affect the evapotranspiration rate (Xu, Ma, & Liu, 2011). In tropical climates, high evapotranspiration rates are a very important aspect to be considered because of the negative impact on the concentration of pollutants in effluents from constructed subsurface flow wetlands. Table 1 summarizes the evapotranspiration data corresponding to the three systems (mm/day) for each of the months studied, as well as average monthly water temperatures in the systems.

### *Mass Removal of Carbamazepine (CBZ)*

The analysis of the efficiency of System I for removing CBZ demonstrated a significant increased ($p < 0.05$) between the first and second stages of the system. The average removal increased from 43± 3.8% in the first stage (HSSFW) to 17 ± 3.8% in the second stage. Meanwhile, with respect to System II, the removal efficiently did not increase significantly in the second stage (average efficiencies of 48 ± 3.5% and 7 ± 3.5% in the first and second stages, respectively). System III also did not show a significant increase ($p < 0.05$), with average removal of efficiencies of 34 ± 5.7% in the first stage and 2 ± 5.7% in the second stage. Figure 4 shows the accumulated removal between the two stages for each system and each monitoring date. These results were used to compare the total removal efficiencies obtained with the three systems.

When calculating the ANOVA for the removal totals, Systems I and II were found to be more effective and equal, and significantly different than SIII ($p < 0.05$). The averages were 60 ± 4.45% for SI, 55 ± 4.45% for SII

Table 1. Average monthly evapotranspiration (mm/day) by the treatment system and confidence interval (95%).

| Month | Water temp. ° C | Evapotranspiration | | |
|---|---|---|---|---|
| | | SI | SII | SIII |
| September | 20.5 | 26.68 ± 2.02 | 27.8 ± 3.67 | 22 ± 0.00 |
| October | 18.5 | 23 ± 2.81 | 19.9 ± 3.33 | 22 ± 0.00 |
| November | 16.1 | 24.3 ± 2.33 | 24.46 ± 9.91 | 20.76 ± 1.79 |
| December | 14.3 | 24.7 ± 7.84 | 29.9 ± 8.6 | 20 ± 10.76 |

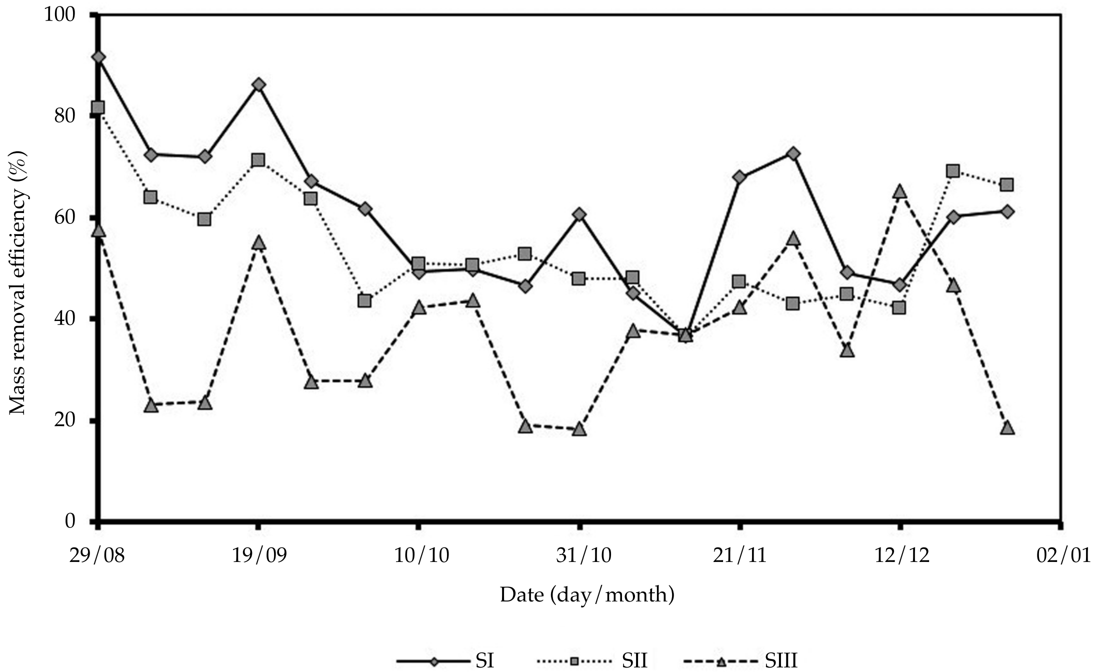


Figure 4. Mass removal of carbamazepine by each system, throughout the monitoring period.



and 36 ± 4.45% for SIII. The slightly better efficiency of System I compared to System II was probably due to the nearly anoxic conditions (DO: 0.53 – 0.78 mg/l, $E_h$: -126.7 – 25.3 mV) that were predominant throughout the system which, unlike aerobic conditions, contribute to the removal of carbamazepine, according to Park *et al*. (2009), and Hai, Li, Price and Nghiem (2011). Meanwhile, a 45% removal efficiency was obtained with the HSSFW used as the first treatment stage. This coincides with results reported by Park *et al*. (2009), who obtained removal percentages between 30 and 47%, which is higher than those reported by Matamoros *et al*. (2008), Hijosa-Valsero *et al*. (2010) and Zhang *et al*. (2011, 2012). This difference is probably due to a greater degree of biodegradation resulting from the polyculture and/or the uptake by the species used. Furthermore, an average mass removal of 34% was obtained with the VSSFW used as a first stage, which is higher than the 26% reported by Matamoros *et al*. (2007).

## Conclusions

The results from the three systems evaluated confirm the ability of constructed wetlands to remove carbamazepine, as reported by various authors, and therefore enable affirming that higher removal efficiencies can be obtained using hybrid wetlands. During the evaluation period, the hybrid system composed of a horizontal sub-surface flow followed by stabilization lagoons most effectively removed carbamazepine. This suggests that anoxic operating conditions as well as pH values around 8 contribute to removing this pharmaceutical. With respect to System III, a modification of the anoxic conditions commonly reported in horizontal sub-surface flow wetlands was observed, caused by the direct discharge of effluent from the prior vertical stage which created aerobic operating conditions in this system, apparently unfavorable to the removal of carbamazepine. This suggests a probable negative correlation between the removal of the pharmaceutical compound and the dissolved oxygen and oxidation reduction potential. Nevertheless, further research is needed to evaluate these operating conditions at different levels in constructed wetlands in order to determine the ideal values for removing this drug.

Thus, this study demonstrated that constructed hybrid wetlands are a good option for removing pharmaceutical compounds from domestic wastewaters, including those that are recalcitrant, such as carbamazepine. Constructed wetlands can potentially be applied in Mexico, particularly because they are low-cost, can be applied as centralized or *in situ* systems, and are easy to operate. To obtain similar efficiencies with full-scale applications, the information generated by the present investigation should be taken into account, including the filtration medium (tezontle with its corresponding granulometry), the macrophyte species (*Z. aehtiopica*, *I.sibirica* y *T. latifolia*) and the design criteria used (retention time, length-width relationship, etc.). The implementation of these systems will improve the treatment of domestic wastewater and better protect aquatic and human ecosystems from the documented adverse effects caused by pharmaceutical compounds.

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# Seasonal Trend of the Rainfall and the Influence of El Niño-Southern Oscillation on the Occurrence of Extreme Rainfalls at the Watershed of Valencia's Lake, Venezuela

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## Abstract

Paredes-Trejo, F., Guevara-Pérez, E., Barbosa-Alves, H., & Uzcátegui-Briceño, C. (November-December, 2015). Seasonal Trend of the Rainfall and the Influence of El Niño-Southern Oscillation on the Occurrence of Extreme Rainfalls at the Watershed of Valencia's Lake, Venezuela. *Water Technology and Sciences* (in Spanish), *6*(6), 33-48.

The Valencia lake basin is the endorheic watershed larger of Venezuela (VLB). VLB is densely populated and industrialized; therefore the extreme climate events can cause severe impacts. In the Venezuelan territory, it is known that ENSO (El Niño-Southern Oscillation) can modulate the rainfalls, however no has been explored in detail as ENSO can affect the rainfalls on VLB. This study analyzes the spatio-temporal trends of the seasonal rainfalls and explores the association between the occurrence of extreme rainfall months and the phases of ENSO (El Niño, La Niña and Neutral) on VLB. Eight stations were selected by the quality control of their registers. We considered two periods for our analysis: 1934-2005 (local scale) and 1966-1992 (regional-local scale). In addition, were identified the months of occurrence of the rainy and dry seasons. The accumulated rainfall by season in each station was calculated and after was explored the occurrence of a long-term trend by Mann-Kendall test. Seasonal precipitation in each station and season was categorized in extreme dry, extreme-no, or extreme wet (ED, EN and EW) using the 10th and 90th percentiles as threshold. The likelihood of occurrence of a month ED, EN or EW at local scale according to season and phase of ENSO was estimated. The association between these categorical variables was analyzed by chi-square test for independence. The results more remarkable were: there is no evidence of a long-term trend at local scale on seasonal precipitation; the Niño/Niña episodes are partially associated with the occurrence of extreme rainfall at seasonal scale; a high-proportion of the extreme rainfall events could have been driven by local factors which were not evaluated here.

**Keywords:** Valencia's Lake, El Niño-Southern Oscillation, climate change, extreme rainfall.

## Resumen

*Paredes-Trejo, F., Guevara-Pérez, E., Barbosa-Alves, H., & Uzcátegui-Briceño, C. (noviembre-diciembre, 2015). Tendencia de la precipitación estacional e influencia de El Niño – Oscilación Austral sobre la ocurrencia de extremos pluviométricos en la cuenca del lago de Valencia-Venezuela.* Tecnología y Ciencias del Agua, *6(6), 33-48.*

*La cuenca del lago de Valencia (CELV) es la cuenca endorreica de mayor tamaño en Venezuela. Por su elevada densidad poblacional e industrial es susceptible a los extremos pluviométricos. Se sabe que el fenómeno ENOA (El Niño-Oscilación Austral) modula las lluvias en el territorio venezolano, pero no se ha explorado su incidencia en detalle en la CELV. En este estudio se analiza la tendencia espacial y temporal de la precipitación estacional y se explora la asociación entre la ocurrencia de meses con extremos pluviométricos y las fases de ENOA (El Niño, La Niña, neutro) en la CELV. Se seleccionaron ocho estaciones climáticas con buena calidad de registros. Los periodos 1934-2005 y 1966-1992 se adoptan para los análisis a escalas local y regional. Se identificaron los meses de la temporada seca y húmeda. En cada estación se calculó la precipitación acumulada estacional y se evaluó su tendencia de largo plazo utilizando la prueba de Mann-Kendall. Se categorizó la precipitación mensual local y estacional en extrema seca (ES), no extrema (NE) y extrema húmeda (EH), usando como umbrales los percentiles 10 y 90. Se analizó la ocurrencia probabilística espacial y simultaneidad de un mes ES, NE y EH, según la temporada y fases de ENOA. La asociación entre ENOA y la precipitación estacional se explora con una prueba Chi-Cuadrado. Se encontró lo siguiente: no existen tendencias locales de largo plazo en la precipitación total estacional; la ocurrencia de extremos pluviométricos estacionales está parcialmente asociada con los eventos El Niño/La Niña; la incidencia de extremos pluviométricos podría estar vinculada con factores climáticos locales.*

***Palabras clave**: El Niño-Oscilación Austral, lago de Valencia, cambio climático, extremos pluviométricos.*

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## Introduction

The Fourth Report by the Intergovernmental Panel on Climate Change indicated that annual precipitation increased considerably between 1900 and 2000 north of South America. The meteorological phenomenon El Niño-Southern Oscillation, or ENSO (ENSO), is one of the components of the global climate system that most influences the variability in precipitation in that region (Arntz & Fahrbach, 1991; Giddings & Soto, 2006). ENSO also has been widely associated with the largest climatic impacts in Central America, Mexico and the Southern Cone (World Bank, United Nations, 2011; European Commission, 2009). Its effect extends to countries located within and on the periphery of the Pacific and Indian basins (Allan, Lindesay, & Parker, 2000), the Tropics, and in certain extratropical regions in North America (Magaña &Ambrizzi, 2005; PNUMA-CEPAL, 2010).

Venezuela is a tropical country located in the far north of South America (~ 1-12º N, 60-74ºW) with precipitation modulated primarily by the activity and location of the Intertropical Convergence Zone (ITCZ). The trade winds from the northeast and southeast converge in the ITCZ, creating a low-pressure subsystem which moves in a southerly direction (Goldbrunner, 1984;Pulwarty, Barry, Hurst, Sellinger, & Mogollon, 1998). The ITCZ is part of the global climate system and therefore quickly responds to variations in tropical atmospheric circulation (Martelo, 2003a). Precipitation is spatially heterogeneous because orographic barriers control surface winds (Insel, Poulsen, & Ehlers, 2010). Meanwhile, several types of temporal variations in the available precipitation series have been identified (Winemiller,1990). On the scale of a decade, for example, Martelo (2003b) noted that average rainfall had a weakly alternating pattern, that is, normal conditions prevailed from 1951-1960, rainy conditions from 1961-1970, dry from 1971-1980, rainy from 1981-1990 and dry for the incomplete decade of 1991-1998.

In Venezuela, seasonal variability in precipitation can be affected by both the cold El Ñiño and La Niña ENSO phases (Pulwarty, Barry, & Riehl, 1992; Cárdenas, García, & Gil, 2002; Paredes, Guevara, Uzcategui, & Garbi, 2008). The ENSO effect in Venezuela is not homogeneous (CNMeH-CONICIT, 1998), and therefore El Niño tends to result in drier than normal summers and a late start to the rainy season in Guayana and the west, while in the central, plains and eastern regions the influence is much less notable, with cases in which El Niño years coincide with an early, normal or late rainy season. In comparison, a neutral ENSO —that is, when the Pacific Ocean's thermal surface conditions are near the historical average— usually corresponds to an early start of the rainy season. It is worth mentioning that in Guayana, La Niña is associated with dry seasons that are rainier than normal and therefore relatively high currents in the Caroni River, while in Los LLanos it is associated with a late start to the rainy season (Rogers, 1998; Martelo, 2003b).

On a large scale, the influence of ENSO on the precipitation regime in Venezuela has been studied in-depth by Caviedes (1998), Cárdenas and De Grazy (2003), the Ministry of the Environment and Renewable Natural Resources (Ministerio del Ambiente y Recursos Naturales Renovables) (2007), and Rollenbeck and Anhuf (2007); nevertheless the main spatial and temporal characteristics of this modulation has been studied with sufficient detail only in some parts of the country (Guevara & Paredes, 2007; Pierre & Tirado, 2007; Pérez, 2012). One of the regions where the influence of ENSO on precipitation is not well known is in the Lake Valencia basin. The dominant topography in this basin increases its vulnerability to "pluviometric extremes," a term which will be used below to refer to an anomalous dry or anomalous rainy episode lasting at least two consecutive months.

Lake Valencia is the largest freshwater endorheic lake in Venezuela ((Díaz, 2006). It is located in a tectonic depression called the Valencia Graben, between the Cordillera de la Costa mountain range to the north and the Interior range to the south (Bradbury *et al*., 1981). It is surrounded by a highly industrialized and densely populated area (Sequera, 1994). In general terms, agricultural activities occupy 34% of the land, urban activities 18% and industrial 3%. The area of the lake is 359 $km^2$ with a volume of 6.30 $km^3$ and a depth of 18 m, supplied by 18 sub-basins (Guevara & Márquez, 2012; Dourojeanni, Jouravlev, & Chávez, 2002). The permanent rivers include Güey, El Limón, Las Delicias, Turmero, Aragua, Cabriales, Los Guayos, Nepe and Guacara, along with Caño Central and the Papelera, Sudantex and Corpoindustria channels (Filippone, 1999). Mean surface runoff towards the lake is 9 $m^3/s$ during the dry season and 19 $m^3/s$ during the rain season (Guevara, Guevara, & García, 2008).

The level of Lake Valencia has continuously increased over the past decade due to diversions from the Pao Cachinche and Pao La Balsa reservoirs (which feed the Centro I Regional System, the main aqueduct in the Valencia-Maracay axis), as well as the diversion of the Cabriales River to the lake in 1979 and the continuous discharge of urban and industrial wastewater. Between 1995 and 2000, the level of the lake's water mirror increased at a mean rate of 0.40 m/year, reaching a relative maximum elevation of 413.36 masl in the year 2012 (Ministerio del Ambiente y Recursos Naturales Renovables, 2007). During the rainy season of 2013, the Lake Valencia Quality and Level Control Commission, a government agency, reported an elevation of 414 masl with several significant effects: partial flooding of some sectors located in the southern portion of the municipality of Girardot, state of Aragua, as well as in Mata Redonda and La Punta; temporary closure of the road to La Culebra Island; and the permanent flooding of the foundations of the Valencia-Guigue road section, among others.

Agricultural activity in the Lake Valencia basin makes it highly vulnerable to long dry episodes, especially in lower areas. For example, prolonged absences of rain affect the agricultural sector of the region, reducing the yields of some non-irrigated crops such as industrial sorghum, garden vegetables, fruits and citrus (Marín, 2002).

Studies reported by the literature characterize the spatial distribution of rainfall in the Lake Valencia Basin (Guevara *et al*., 2008) and some have estimated some of the relevant hydrological parameters (Ascenzi, Mora, & Pino, 2007) using a probabilistic approach to evaluate annual and seasonal precipitation (Paredes *et al*., 2013). Nevertheless, it is not known whether precipitation in the basin has increased or decreased over time, whether the unusually dry or wet seasons are associated with ENSO phases or if the pluviometric extremes tend to be more frequent. Therefore, the purpose of the present investigation is to explore the influence of the meteorological phenomenon ENSO on the pluviometric extremes in the study basin. The present study analyzes a series of monthly rain gauge measurements available from a set of stations located in the basin for the purpose of analyzing: a) the long-term trend in the seasonal accumulated precipitation and b) the connection between the ENSO phases and seasonal pluviometric extremes using a probabilistic approach.

## Methodology

### *Study Area*

The Lake Valencia basin is located in central Venezuela. It covers an area of 2 943 $km^2$ in the states of Carabobo (53.13%) and Aragua (46.87%). It extends from 9º 55′ 4.26′′ to 10º 24′ 41.74′′latitude north and -68º 4′ 21.2′′ to -67º 16′ 30.15′′longitude west, as shown in

Figure 1. Its hypsometric range is from 426 masl (mean level of the lake) to 2 430 masl (Pico Codazzi).

### *Rain Gauge Records*

Monthly rain gauge records were used from the weather stations located in the study area, provided by the National Weather and Hydrology Institute ((http://www.inameh.gob.ve/). The series with a monthly record length (MRL) equal to or greater than 30 years were selected. Based on this criteria, records were chosen from 8 rain gauge stations with 31 ≥ MRL ≥ 59 and which had the following characteristics: discontinuous records, mean record length of 42.50 years and median of 42.50. These periods correspond to a discontinuous time frame ranging from the year 1934 to 2005. From here on this group will be called the sample.

### *Procedural Steps*

1. Evaluation of the quality of the series. The stationarity of the sample was evaluated using the *t* statistic (acceptance criterion $p \leq 0.05$). The variable of analysis was the slope of the line representing the relationship between annual precipitation and time in years. The serial autocorrelation was evaluated using the Durbin-Watson test (Fox, 2008). The non-homogenous years were detected with the Easterling-Peterson test (Buishand, 1982). The 8 series of rain gauge records used passed the above tests and, therefore, were included in the subsequent analysis (Figure 1).
2. Analysis of the annual trends in seasonal rain gauge measurements. First, the beginning and end of the rainy and dry seasons were identified according to the sign of the rain gauge coefficient, on

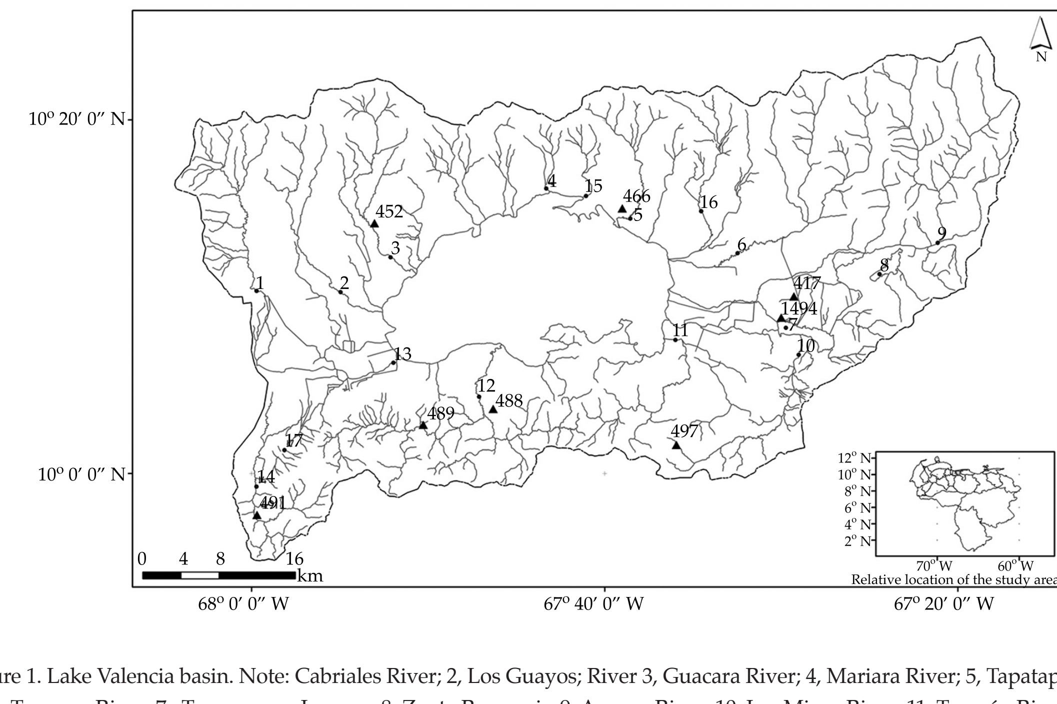


Figure 1. Lake Valencia basin. Note: Cabriales River; 2, Los Guayos; River 3, Guacara River; 4, Mariara River; 5, Tapatapa River; 6, Turmero River; 7, Taguayguay Lagoon; 8, Zuata Reservoir; 9, Aragua River; 10, Las Minas River; 11, Tocorón River; 12, Güigüey River; 13, Caño Central; 14, Las Dos Bocas River; 15, Honda Ravine; 16, Maracay River; 17, Las Delicias Dike. The triangles indicate the locations of the eight rain gauge stations used. The number is station number assigned by the National Meteorology and Hydrology Institute of Venezuela.



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a monthly scale (Carillo, 1999). Accordingly, November-April was considered to be the dry season and May-October the rainy season. In order to avoid overlapping of consecutive years, for 1 year the dry season was identified as January to April. The following were determined for each series and year: seasonal precipitation (SP), variation coefficient of the SP, and amount and year of occurrence of the maximum and minimum seasonal precipitation. Using this approach, the SP represents the annual rainfall accumulated during the season analyzed (dry or rainy). Lastly, the Mann-Kendall test was applied with ranges (Kendall, 1975) to identify statistically significant long-term trends ($p \leq 0.05$) in the SP. The SP variables during the dry and rainy seasons were mapped to identify the occurrence of a spatial pattern.

3. The seasonal analysis of the seasonal anomalies in the pluviometric extremes. The periods in which the series contained years in common was calculated, resulting in 1966 to 1992. In each series, the monthly precipitation (P) was transformed ($P_{ij}$) into monthly anomaly ($a_{ij}$); To this end, the 10th ($P_{10}$) and 90th ($P_{90}$) percentiles were calculated for each month $i$ ($i$ = 1... 12) considering all the years $j$ in the common period ($j$ = 1966… 1992). Each observation was then coded as follows: if $P_{ij} \leq P_{10} \rightarrow a_{ij}$ = -1 (extremely dry month or ED); if $P_{ij} \geq P_{90} \rightarrow a_{ij}$ = +1 (extremely rainy month or ER); if $P_{10} < P_{ij} < P_{90} \rightarrow a_{ij}$ = 0 (not an extreme month (NE)). Seasonal trends in extreme months (ED, ER) were evaluated by applying the Mann-Kendall test to the resulting vector to separately analyze the number of ED and ER months in the years available in the series. The seasonal trends (slopes) were mapped to identify any presence of a spatial pattern.
4. Probabilistic relationships between seasonal rain gauge levels at each station and the ENSO phases. The monthly probability of the occurrence of a ED, ER or NE month was calculated for each station, season and ENSO phase. The prevalent ENSO phase during a month was determined according to the ENSO categorization from the U.S. National Weather Service of the National Oceanic and Atmospheric Administration (NOAA) (www.cpc.ncep.noaa.gov). Since the seasonal precipitation at each station and the ENSO phases are analyzed as factors, a two-way contingency table was constructed, to which the chi-square test was applied to evaluate the association between both categorical variables, with a confidence level of 95% (Greenwood & Nikulin, 1996). To indirectly estimate the average spatial coverage of the ED, ER and NE months in each season from 1966 to 1992, the average percentage of stations that contained one of these months was calculated per year and season. This result was grouped according to the observed ENSO phase to evaluate the association among these variables.

### *Computing Tools Used for the Analysis*

Anclim software was used to evaluate the quality of the series (Štěpánek, 2008). The conversion of the monthly rain gauge series to anomalies and the probabilistic and statistical analyses were conducted in *R* v. 3.2.1. The mapping was generated with *SAGA-GIS 2.1.4*™.

## Results

### *Trends in Seasonal Rain Gauge Measurements during the Uncommon Period, 1934-2005*

The rain gauge series analyzed have different beginning and end dates in the 1945 to 2005 time frame. The separate analysis of all the records in each series of data resulted in the following determinations: mean regional precipitation during the dry season (January – April) of 86.75 mm (Table 1); local minimum and maximum occurring in Maracay (50.17 mm) and Las Dos Bocas (141.75 mm), respectively; and a regional average variation coefficient of 76.14%, with a range from 62.22% in Las Dos Bocas to 86.95% in Maracay. In addition, during the rainy season (May-October), the regional average precipitation was 873.12 mm, with a local minimum and maximum in Las Cenizas (715.67 mm) and Las Dos Bocas (1234.87 mm), respectively (Figure 1); the regional average variation coefficient was 20.13%. The precipitation trends during the rainy and dry seasons (expressed as mm/year) were not statistically significant, for all the stations ($p \leq 0.05$).

### *Seasonal Trends in Pluviometric Extreme Anomalies During the Common Period, 1966-1992*

Table 2 shows the annual trend in the occurrence of extreme months during the dry and rainy seasons for the period 1966-1992. In general, during the dry season (January – April) the largest trend in the group of extremely dry (ED) months occurred in Las Cenizas (0.046 ED events/year). In the group of extremely rainy (ER) months, the largest trends observed were in Santa Cruz (-0.020 ER events/year) and Guacara (-0.020 ER events/year). In terms of the dry season, the ED group averaged 0.026 ED events/ year and the ER group averaged -0.009 ER events/year. Between May and October (rainy season), the largest trend in the ER group was recorded at Colonia El Trompillo (-0.032 ED events/year) and the largest in the ED group was at Guacara (-0.038 ER events/year). Overall, the ED group had an average of -0.003 ED events/year and the ER group -0.006 ER events/year. None of these trends were statistically significant ($p \leq 0.05$).

### *Spatial and Temporal Characteristics of the Seasonal Pluviometric Extremes according to the Prevalent ENSO Phase, 1966 to 1992*

Table 3 shows the probability of an ED, ER or NE month during the dry and rainy seasons (May-October) for each station in the Lake Valencia basin for the period 1966-1992. As an example, when El Niño was present during the dry season (January – April), station 417 recorded a probability of occurrence of an ED, NE and ER month of 31, 56 and 13%, respectively. With La Niña, these probabilities were 13, 71 and 17%, respectively. Meanwhile, for the neutral ENSO phase, values of 28, 63 and 9% were obtained, respectively. The association between ENSO and the rain gauge levels (ED, NE and ER) during the dry season were statistically significant only for

Table 1. Seasonal rain gauge measurements. Uncommon period from 1934 - 2005.

| Station number | Location | Period (years) | Dry season ($P$(mm)/CV(%)) | Rainy season ($P$(mm)/CV(%)) |
|---|---|---|---|---|
| 417 | Santa Cruz | 1966-1999 | 70.36/72.95 | 840.09/19.81 |
| 452 | Guacara | 1949-1993 | 70.66/78.30 | 782.18/19.51 |
| 466 | Maracay | 1934-1992 | 50.17/86.95 | 774.42/22.12 |
| 488 | Colonia El Trompillo | 1960-2005 | 79.52/86.09 | 858.49/24.42 |
| 489 | Agua Blanca | 1934-2005 | 119.69/73.74 | 1 014.78/22.52 |
| 491 | Las Dos Bocas | 1949-2005 | 141.75/62.22 | 1 231.88/13.38 |
| 497 | Las Cenizas | 1960-2003 | 91.19/73.59 | 715.67/22.71 |
| 1494 | Embalse Taiguaiguay | 1951-1999 | 70.63/75.31 | 766.60/16.58 |



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Table 2. Annual Trend in the Occurrence of Extreme Months during the Dry and Rainy Seasons. Common period 1966-1992.

| Station number | Location | Dry season (ED/ER events/year) | Rainy season (ED/ER events/year) |
|---|---|---|---|
| 417 | Santa Cruz | 0.0031/-0.0195 | 0.0024/-0.0122 |
| 452 | Guacara | 0.0250/-0.0195 | -0.0171/0.0379 |
| 466 | Maracay | 0.0269/-0.0006 | -0.0073/0.0214 |
| 488 | Colonia El Trompillo | 0.0140/-0.0183 | -0.0324/0.0024 |
| 489 | Agua Blanca | 0.0379/0.0018 | 0.0098/0.0244 |
| 491 | Las Dos Bocas | -0.0037/0.0122 | 0.0116/-0.0018 |
| 497 | Las Cenizas | 0.0458/-0.0073 | 0.0037/-0.0092 |
| 1494 | Embalse Taiguaiguay | 0.0317/-0.0183 | 0.0031/-0.0183 |

**Note**: ED is extremely dry month, ER is extremely rainy month.

stations 489 and 491 ($p \leq 0.05$), both located in the middle-upper portion of the basin and on the southern side of the lake (Figure 2). During the rainy season (May-October), the chi-square test for independence suggests an association between ENSO activity and seasonal precipitation only at station 1494 (Table 4).

Table 3 shows the quantitative association between the ENSO phases (neutral, El Niño, La Niña) and the dominant rain gauge sign (ED, ER or NE) for each station and season using the probabilistic approach, but does not provide information about the spatial area of these events on the station scale. Figure 3 compensates for this limitation by showing the average regional percentage of stations in which an ED, ER or NE month was observed during the dry (January-April) and rainy (May-October) seasons for the period 1966 to 1992, along with the ENSO phase (neutral, El Niño, La Niña) recorded during each season.

A high average percent in the ED, ER or NE level indicates that this sign was predominant in the group of stations. For example, Figure 3 shows that during the rainy season of 1973 (panel b), roughly 70% of the stations had an ED month along with La Niña (generalized dry condition) while during the dry season of 1981 (panel a) roughly 63% of the stations had an ER month in conjunction with the neutral ENSO condition (generalized rainy condition).

## Discussion

### *Seasonal Trends in Rain Gauge Records for the Period Analyzed*

From the spatial perspective, the rain gauge measurements from the stations tended to decrease as the distance to Lake Valencia increased and the land became flatter (Table 1, Figure 2). The lowest values were observed in the plains located south of Troncal 5 (Los Guayos-Maracay section) and north of the Flor Amarilla-Magdaleno (south side of the lake). The highest occurred in the far southwest (Cerro Las Dos Bocas).

The wind records from the Naguanagua station (10° 14′ 58′′ N and 68° 1′′ 0′′ W) located in a large valley bordered by Filas, La Guacamaya and Orégano (both aligned in the north-south direction) show an interesting characteristic in surface winds. During the dry season, they came from the NW, NNW and WNW (in order of occurrence) with an average speed of 16.2 km/h and decreased during the rainy season to 10 km/h and changed direction to NW, ENE and SW (in order of occurrence). In this regard, it is worth mentioning that the prevailing surface wind

Table 3. Probability of occurrence of an extremely dry month (ED), non-extreme (NE) or extremely rainy (ER) month during the dry and rainy seasons at the stations in the Lake Valencia basin, according to the ENOA observed (neutral, El Niño, La Niña). Common period 1966-1992. The probability of occurrence is expressed as a unit fraction.

| | Dry Season (January-April) | | | Rainy Season (May-October) | | |
|---|---|---|---|---|---|---|
| | Station: 417 | | | Serial: 417 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.28 | 0.63 | 0.09 | 0.11 | 0.77 | 0.11 |
| El Niño | 0.31 | 0.56 | 0.13 | 0.08 | 0.75 | 0.17 |
| La Niña | 0.13 | 0.71 | 0.17 | 0.17 | 0.79 | 0.04 |
| | Station: 452 | | | Station: 452 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.33 | 0.53 | 0.14 | 0.10 | 0.80 | 0.09 |
| El Niño | 0.25 | 0.65 | 0.10 | 0.10 | 0.80 | 0.10 |
| La Niña | 0.42 | 0.54 | 0.04 | 0.14 | 0.69 | 0.17 |
| | Station: 466 | | | Station: 466 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.48 | 0.39 | 0.13 | 0.09 | 0.78 | 0.13 |
| El Niño | 0.35 | 0.55 | 0.10 | 0.23 | 0.70 | 0.07 |
| La Niña | 0.25 | 0.67 | 0.08 | 0.06 | 0.83 | 0.11 |
| | Station: 488 | | | Station: 488 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.20 | 0.67 | 0.13 | 0.13 | 0.78 | 0.09 |
| El Niño | 0.25 | 0.65 | 0.10 | 0.10 | 0.80 | 0.10 |
| La Niña | 0.21 | 0.71 | 0.08 | 0.08 | 0.75 | 0.17 |
| | Station: 489* | | | Station: 489 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.13 | 0.73 | 0.14 | 0.11 | 0.78 | 0.10 |
| El Niño | 0.35 | 0.50 | 0.15 | 0.07 | 0.80 | 0.13 |
| La Niña | 0.13 | 0.88 | 0.00 | 0.14 | 0.75 | 0.11 |
| | Station: 491* | | | Station: 491 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.20 | 0.63 | 0.17 | 0.11 | 0.77 | 0.11 |
| El Niño | 0.05 | 0.95 | 0.00 | 0.10 | 0.77 | 0.13 |
| La Niña | 0.17 | 0.79 | 0.04 | 0.11 | 0.81 | 0.08 |
| | Station: 497 | | | Station: 497 | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.16 | 0.70 | 0.14 | 0.07 | 0.80 | 0.13 |
| El Niño | 0.40 | 0.50 | 0.10 | 0.20 | 0.77 | 0.03 |
| La Niña | 0.25 | 0.71 | 0.04 | 0.14 | 0.72 | 0.14 |
| | Station: 1494 | | | Station: 1494 * | | |
| Condition | ED | NE | ER | ED | NE | ER |
| Neutral | 0.27 | 0.63 | 0.11 | 0.07 | 0.84 | 0.08 |
| El Niño | 0.35 | 0.55 | 0.10 | 0.20 | 0.77 | 0.03 |
| La Niña | 0.25 | 0.63 | 0.13 | 0.14 | 0.61 | 0.25 |

* Note: The occurrence of an extremely dry, non-extreme or extremely rainy month at the station indicates it is dependent on the ENOA conditions, with a confidence level of 95%.

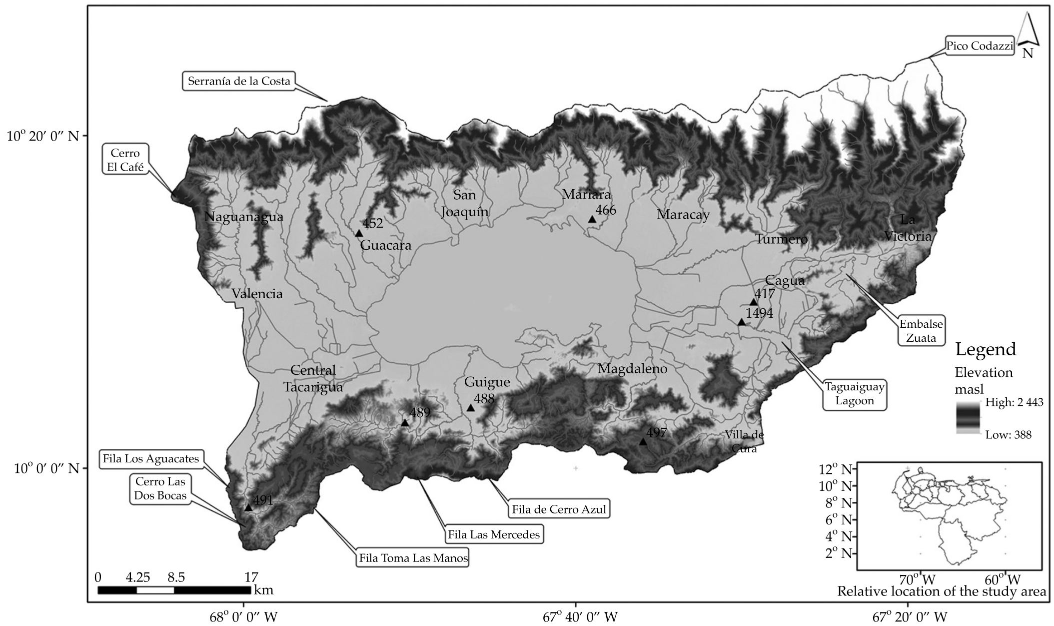


Figure 2. Digital elevation model of the Lake Valencia basin. Note: triangles indicate the location of the eight stations used. The number is the station name assigned by the National Meteorological and Hydrologic Institute.

currents in Venezuela are E, ENE and NE over the course of a year due to the influence of the trade winds on the northern portion of South America (González-Longatt, 2015). Nevertheless, these directions tend to be uncommon in deep inter-mountain valleys because the wind currents are redirected (Golbrunner, 1984; Foghin-Pillin, 2002). The difference in the dominant wind patterns seen at the Naguanagua station during dry and rainy seasons suggests that the orographic barriers direct the air currents to the bottom of the valleys where they interact with local wind circulations (lake breeze systems from the valley-mountain), favoring or inhibiting the formation of rain depending on the direction of the dominant flow and the humidity content. The control by the orography on the distribution of rain in mountain basins has been well documented (Beniston, Diaz, & Bradley, 1997; Guan, Huang-Hsiung, Makhnin, Xied, & Wilsone, 2009; Brito *et al*., 2010).

Inside the Lake Valencia basin, two moisture centers can be seen to remain during the dry and rainy seasons. One was located in the Las Dos Bocas River and the other between Filas, Los Aguacates and Toma Las Manos, a mountainous region located in the southwestern portion of the basin (Figure 2). The second was located northeast of dividing line between the Lake Valencia basin and the Chuao River (called Topo El Guayabo). The first center was previously reported by Paredes *et al*. (2013), who noted the permanent nature of rainfall throughout the year. Both of these centers are located at the bottom of large valleys surrounded by tall mountains and near watersheds or divides. Figure 2 shows the basin with a large network of deep valleys in the north and southern parts of the lake, where the surface wind could be channeled from the lake (local climate sub-system) or neighboring hydrographic basins to higher elevations. In this case, the air currents would

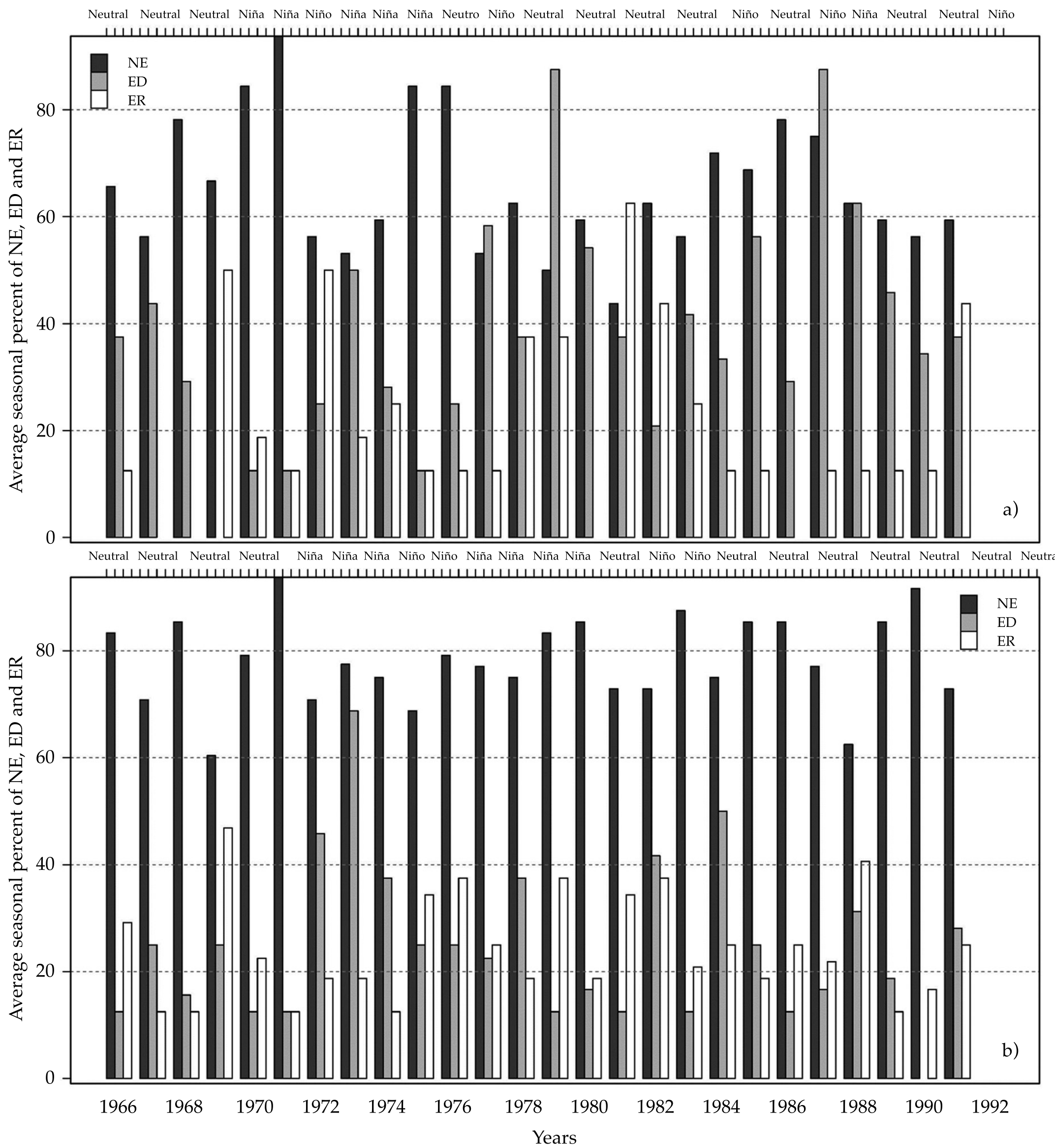


Figure 3. Regional average of occurrence of an extremely dry (ED), non-extreme (NE) and extremely rainy (EH) month during the dry season (panel a) and rainy season (panel b), in the Valencia Lake basin during the period 1966-1992. At the top of each panel the ENOA phase observed is indicated (neutral, El Niño, La Niña). Note: The year 1992 was omitted beacuse of missing data at the stations during the dry and rainy seasons.

rise and progressively cool until reaching the condensation point over the ascending watershed (Barlovento mountainside), favoring the formation of clouds that generate rain. This hypothetical mechanism may explain the high seasonal values and their persistence in Las Dos Bocas and Topo El Guayabo. With this focus, the surface winds that reach Las Dos Bocas likely enter through the Pirital-Boquerón-El Yagual (intra-mountain) corridor.

In the seasonal context, the evidence observed for the periods 1934 to 2005 and 1966 to 1992 does not indicate a sustained decrease or increase in total seasonal pluviometric extremes (Table 2). In general, this suggests that variations in the seasonal rain gauge measurements in the Lake Valencia basin were temporarily stationary during these periods, although it is evident that the spatial distribution of the rainfall is largely controlled by the orography.

Comparing Figure 1 and Tables 1 and 2, a slight increase can be seen in ED months during the dry season in the upper Las Minas basin (tributary of the Taguaguay Lagoon) and a slight decrease in ER months at the headwaters of the Guacara River and in southwest Cagua (plains of the Aragua River). Meanwhile, during the rainy season a slight decrease in ED months is observed in the middle basin of the Guigue River and in ER months at the headwaters of the Guacara River. Most of these locations are located at an intermediate altitude and are relatively near the hydrographic divide. Although these trends were not statistically significant (Table 2), they suggest that the rainfall in the mountainous region was slightly more prone to seasonal variations than at lower elevations. This subtle characteristic suggests that the lake could be the main source of moisture for the formation of rain in the lower part of the basin, particularly during the dry season. It is important to note the trade winds reaching the Lake Valencia basin probably do not contain a large amount of moisture, since they first have to cross coastal mountains (to the north) and inland mountains (to the east), both of which block the advance of trade winds (particularly the coastal mountains) and favor rain falling outside of the basin's watershed (Barlovento-Sotavento effected, described by Pulwarty *et al.*, 1992). Nevertheless, large-scale storm systems can enter the basin, since the altitude of the bottom of the clouds in these systems would be higher than the tallest mountain peaks.

### *Association Between Seasonal Pluviometric Extremes and the ENSO Phases for the Period 1966-1992*

For the period 1966 to 1992, roughly 22% of the months in the dry season (January-April) coincided with La Niña, 19% with El Niño and 60% with the neutral phase. Interestingly, these same percentages were obtained for the rainy season (May-October). Therefore, the incidence of the cold phase of ENSO (La Niña) was dominant during both seasons.

Table 3 shows that during the dry seasons for the period 1966 to 1992, El Niño coincided with an ED, ER and NE month 35, 15 and 50% of the time at station 489, respectively. This suggests that the ED months may be partially due to the warm ENSO phase. Similarly, a statistically significant association was found between ENSO phases and seasonal precipitation at station 491 ($p \leq 0.05$ based on the chi-square test). Nevertheless, in this case the frequency of an ED or ER month was higher during the neutral ENSO phase. In fact, an ED or ER month had a probability of occurrence of only 20 and 17%, respectively, suggesting that, at a local scale, one or several factors not related to ENSO were related to these climate conditions. When analyzing the rainy season (May-October), only the association between ENSO-precipitation at station 1494 was statistically significant (Figure 2). Unlike the previous stations, the response at this station was two-fold, that is, El Niño coincided with 20% of ED months and La Niña with 25% of ER months. In general, these results demonstrate that the occurrence of an ED or ER month at the local scale during the dry and rainy season cannot be attributed only to the ENSO phases but rather to other factors that play a more important role (probably local climate factors).

For the period 1966 to 1992, an ED, ER or NE month during the dry season (January-April) was observed to be common, on average, at 57, 31 and 63% of the stations analyzed



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when an El Niño episode occurred, at 32, 18 and 73% when La Niña occurred, and 39, 34 and 63% when the ENSO was neutral, respectively (Figure 3). These same values for the rainy season (May-October) were: 27, 21 and 78% with El Niño, 33, 26 and 76%, with La Niña and 24, 27 and 79% with a neutral ENSO phase (Figure 3). These percentages demonstrate that during the dry season El Niño events were associated with extensive moderately dry climates in the basin (57% on average), and the spatial extension of ED or ER months during a year corresponding to La Niña was notably smaller than one corresponding El Niño years. During the rainy season, El Niño had just a slightly larger spatial incidence than the neutral phase (27 versus 24%, respectively), while interestingly, La Niña was associated with ED months and this was more extensive than El Niño (ED according to coverage: 27% El Niño; 33% La Niña; and 24% neutral). For the period 1966 to 1992, two dry events occurred during the dry season (January-April) at over 80% of the stations, in 1970 and 1987, which coincided with neutral and El Niño phases, respectively (Figure 3a). When analyzing the rainy season (May-October), the drought of 1973 is notable (Figure 3b), which was associated with ED months at over 60% of the stations and coincided with the neutral ENSO phase.

The comparison of Figure 1 and Table 3 shows a high probability of ED months in the Noguera and Las Minas rivers (tributaries of the Güigüe River and the Taguayguay Lagoon) during the dry seasons and El Niño years. The persistence of these climate conditions over time can cause a decrease in the flow of the Guigue River and in the level of the Taguayguay Lagoon during dry periods, increasing the risk of forest fires due to very dry land. For El Niño years, ED months are more probable during the rainy season in the upper Las Minas River basin and the lower El Limon basin while during La Niña years ER months are slightly more probable only in the Zuata and its surrounding area.

For the period analyzed, the results described demonstrate that the ENSO phenomenon can partially explain the occurrence of ED and ER months at a local scale during the rainy and dry seasons in the Lake Valencia basin. El Niño presents a higher incidence of pluviometric extremes than La Niña and is typically associated with unusually dry conditions with moderate spatial coverage. The moderate to slight connection between the active ENSO phases identified at a local scale suggests that factors not evaluated were determinants of particular pluviometric extreme events (for example, the widespread drought in 1979 during the neutral phase of ENSO).

It is important to note that the association between the ENSO phases and rainfall in Venezuela generally has high spatial and temporal variability (Cárdenas *et al*., 2002). This has been attributed to complex interactions between ENSO and certain large-scale factors in the Atlantic Ocean and the variability in the tropical atmospheric circulation (Martelo, 2003b). In any case, the results are consistent with findings previously reported by Pulwarty *et al*. (1992), Martelo (2003b), and Paredes, Millano and Guevara (2008), among others, who indicate that El Niño years favor the occurrence of ED months and La Niña years favor ER months.

## Conclusions

During the periods 1934 to 2005 and 1966 to 1992, no evidence was found of an increase or decrease in seasonal accumulated rain gauge measurements in the Lake Valencia basin. Although local trends with differing degrees of magnitude were identified, they were not statistically significant.

Over the dry and rainy seasons during El Niño and La Niña years, only some locations showed a slightly higher probability of pluviometric extreme months (ER or ED)



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than neutral years. In general, the droughts coinciding with El Niño tended to be more extensive than the wetter climatic conditions coinciding with La Niña. In any case, a high proportion of persistent droughts or storms in the basin was not associated with active ENSO phases but rather may be associated with unidentified, local climatic factors.

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## Appendices

### *Durbin-Watson Serial Autocorrelation Test*

The application of a simple or multiple regression analysis to one or two groups of variables can detect the occurrence of a serial correlation for a unit shift in the residuals derived from the adjusted model. Given an annual precipitation series at station *k* with length *L* in years, the observations form a vector $a_1 \ldots a_n$, where $i = 1 \ldots L$. If the observations are placed in ascending order then $p\,(x, y) = (1, a_1), (2, a_2) \ldots (L, a_L)$. When applying a linear regression analysis to matrix *p*, an adjusted linear equation is obtained whose residuals form the vector $(e_1, e_2, e_3 \ldots e_L)$. Then, the Durban-Watson (*d*) statistical test is given by:

$$d = \frac{\sum_{t=2}^{t=L}\left(e_t - e_{t-1}\right)^2}{\sum_{t=1}^{t=L} e_t^2} \qquad (1)$$

The statistic *d* is compared to two thresholds, $d_{L,a}$ and $d_{U,a}$, according to Fox (2008). These thresholds depend on the significance level (α) used for the test, *L* and the number of predictors in the regression equation. The decision rules are:

When $d < d_{L,\alpha}$, there is a positive autocorrelation in the error terms.

When $d > d_{U,\alpha}$, there is no positive autocorrelation in the error terms.

When $d_{L,\alpha} < d < d_{U,\alpha}$, the test is not conclusive.

When $(4 - d) < d_{U,\alpha}$ there is a negative autocorrelation in the error terms.

When $(4 - d) > d_{U,\alpha}$, there is not a negative autocorrelation in the error terms.

When $d_{L,\alpha} < (4 - d) < d_{U,\alpha}$, the test is not conclusive.

The detection of a statistically significant serial autocorrelation in the annual precipitation series can be attributed to errors in measuring precipitation.

### *Esterling-Peterson Homogeneity Test*

With this technique, variations can be detected in annual precipitation which are caused by non-climatic factors. Consider an annual precipitation series for station *k* and a record length *L* in years. First, a reference station near the station with an equal length of records (at least 30 years in common) is selected. Then, a difference vector is obtained by subtracting the observations from both stations from year to year, from $t = 1 \ldots L$. This series is then divided into two sub-series, $S_1$ and $S_2$ of length $L_1$ and $L_2$, where $n = 2 \ldots$; therefore, $L_1 = L - n$, $L_2 = L - L_1$, resulting in $S_1 = a_1, a_2 \ldots a_{L-n}$ and $S_2 = a_{L-(n-1)}, a_{L-(n-2)} \ldots a_L$. To identify whether year *n* is not homogeneous, the Student-*t* test for the difference in means is applied to the observations from each sub-series with a confidence level α. If this test is significant, it is concluded that the series is not homogenous for year *n*. A series can have more than one non-homogeneous years that could be caused by a non-climatic factor.

### *Mann-Kendall Test for Trends*

Using this test, a monotonous trend in an annual precipitation series can be detected. Consider the annual precipitation series at a station $k$ with $L$ length of years. Then the observations form a vector $a_1 \dots a_n$, where $i$ = 1... $L$ (note that $L \geq 30$ years). The observations are analyzed in pairs as $p(x, y) = (1, a_1), (2, a_2) \dots (L, a_L)$. First, the Kendall $S$ parameter is calculated.

For $a_2 \rightarrow$ *if* $a1 > a_2$ *score* = +1, if $a_1 < a_2$ *score* = -1, if $a_1 = a_2$ *score* = 0; if $a_3 > a_2$ *score* = +1, if $a_3 < a_2$ *score* = -1, if $a_3 = a_2$ *score* = 0;... if $a_L > a_2$ *score* = +1, if $a_L < a_2$ *score* = -1, if $a_L = a_2$ *score* = 0. This procedure is repeated from $a_3$ to $a_L$. Note that for each constant, $a_j > a_i$ or $a_j < a_i$ whenever $j > i$.

All the scores are then totaled. $P$ represents the total positive scores and $M$ the total negative scores. Once this is performed, then $S = P - M$. The total number of comparisons is given by $L(L-1)/2$. Therefore, the Kendall τ is:

$$\tau = \frac{S}{L(L-1)/2} \tag{2}$$

To estimate the statistical significance of the Kendall τ, consult appendix B in Helsel and Hirsch (1993), using parameters $L$ and $S$ as input variables.

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# Mapeo de la vulnerabilidad del agua subterránea en dos cuencas afectadas por la represa Yacyreta en Paraguay

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## Resumen

Musálem, K., McDonald, M., Jiménez, F., & Laino, R. (noviembre-diciembre, 2015). Mapeo de la vulnerabilidad del agua subterránea en dos cuencas afectadas por la represa Yacyreta en Paraguay. *Tecnología y Ciencias del Agua*, 6(6), 49-62.

Se condujo un mapeo de vulnerabilidad del agua subterránea en dos cuencas hidrográficas de agricultura intensiva y áreas urbanas que drenan al embalse Yacyreta en Paraguay. Se aplicaron y compararon dos métodos de sobreposición ampliamente utilizados (GOD y DRASTIC) para determinar la vulnerabilidad del agua subterránea a la contaminación. También se evaluaron los posibles efectos del cambio climático en los valores de vulnerabilidad utilizando escenarios de cambio climático de terceros autores. Por último, se proyectaron los posibles efectos en la vulnerabilidad derivados de las variaciones en el nivel freático, producto de las operaciones de la represa Yacyreta. La determinación de la vulnerabilidad del agua subterránea utilizando DRASTIC mostró un 56% del área de las cuencas clasificadas como de “media alta” vulnerabilidad (índice DRASTIC 140 – 159) y un 22%, ya sea como “alta”, “muy alta” o “máxima” (índice DRASTIC 160 – > 200). GOD, por otro lado, mostró un 96% del área de las cuencas como de “vulnerabilidad moderada” a la contaminación (valores 0.3-0.5) y un 4% como “alta vulnerabilidad” (valores 0.51-0.6). Las clases de vulnerabilidad se mantuvieron iguales sin importar los escenarios de cambio climático revisados, para un periodo de cien años. Las operaciones de la represa, en específico un escenario de elevación del nivel freático de cinco metros, sugiere un aumento en la vulnerabilidad a la contaminación en las partes bajas de las cuencas. Por último, se compararon los modelos GOD y DRASTIC, y su adaptabilidad a los datos disponibles para la región y la construcción de escenarios.

**Palabras clave**: modelo DRASTIC, modelo GOD, Sistema Acuífero Guaraní, cambio climático.

## Abstract

*Musálem, K., McDonald, M., Jiménez, F., & Laino, R. (November-December, 2015). Groundwater Vulnerability Mapping in Two Watersheds Affected by Yacyreta Dam in Paraguay.* Water Technology and Sciences *(in Spanish), 6(6), 49-62.*

*Groundwater vulnerability mapping was conducted for two intensive agriculture and urban watersheds draining to the Yacyreta Dam in Paraguay. Two widely used overlaying methods (GOD and DRASTIC) were applied and compared to determine groundwater vulnerability to contamination. Possible effects of climate change on vulnerability values were also assessed using climate change scenarios provided by third authors. Finally, the possible effects of water table variations derived from Yacyreta Dam operations was projected on groundwater vulnerability. Determination of groundwater vulnerability using DRASTIC shows a 56% of the area of the watersheds to be classified as “medium high” (DRASTIC index 140 – 159) and a 22% as either “high”, “very high” or “maximum” (DRASTIC index values 160 – > 200). GOD on the other hand showed a 96% of the area of the watersheds with a “moderate vulnerability” to contaminants (values 0.3-0.5) and a 4% of “high vulnerability” (values 0.51 – 0.6). Vulnerability classes remained the same regardless of any climate change scenarios reviewed, for a 100 year span. Operation by the dam, specifically a five meter elevation of the water table scenario, suggests an increase in vulnerability in lower parts of the watersheds. Finally we compare GOD and DRASTIC models and their suitability regarding the available data for the region and scenario building.*

***Keywords:*** *DRASTIC model, GOD model, Guarani Aquifer System, climate change.*

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## Introducción

El agua subterránea constituye la mayor reserva de agua dulce en el mundo, representando más de 97% de toda el agua dulce disponible en la Tierra, con exclusión de los glaciares y capas de hielo. El 3% restante se compone principalmente de las aguas superficiales (lagos, ríos, humedales) y la humedad del suelo (Quevauviller, 2008). A pesar de su relevancia, la contaminación de los sistemas de aguas subterráneas es un problema cada vez más crítico, una vez que un acuífero está contaminado es prácticamente inviable para limpiar y las posibilidades de remediación implica altos costos económicos (Wang, 2006).

El agua subterránea es una fuente oculta que es cuantitativamente mucho más importante que las aguas superficiales, y para el que la prevención de la contaminación y monitoreo de la calidad y la restauración son aún más difíciles que en el caso de las aguas superficiales, sobre todo debido a su inaccesibilidad (Quevauviller, 2008). La prevención de la contaminación es fundamental para una gestión eficaz de las aguas subterráneas (Babiker, Mohamed, Hiyama y Kato, 2005), sobre todo teniendo en cuenta la incertidumbre sobre los futuros escenarios climáticos. Las proyecciones indican que el cambio climático va a variar según la región y localidad, modificando la frecuencia de los fenómenos climáticos extremos, como inundaciones y sequías (Bergkamp, Orlando, y Burton, 2003). El agua subterránea es ampliamente utilizada por los seres humanos como el agua potable, con algunos países que dependen casi por completo de ella, mientras que otros solo en parte, poniendo de relieve la importancia de la calidad de las aguas subterráneas y la conservación de la cantidad como estrategia de adaptación al cambio climático (Quevauviller, 2008).

La vulnerabilidad del agua subterránea en los mapas de contaminación es cada vez más necesaria, ya que, por un lado, el agua subterránea representa la principal fuente de agua potable, y en las demás altas concentraciones de actividades humano/económicas (por ejemplo, industriales, agrícolas y domésticas), representa a las fuentes reales o potenciales de su contaminación (Rahman, 2008). El concepto del mapeo de la vulnerabilidad de las aguas subterráneas es útil para la planificación ambiental y la toma de decisiones, y diferentes métodos han sido desarrollados para la determinación de la contaminación de la vulnerabilidad de los acuíferos a la contaminación (Gogu y Dassargues, 2000). Estos métodos, en su mayoría sobre la base de índices y técnicas de sobreposición, han sido utilizados en distintos contextos geológicos: DRASTIC, SINTACS, AVI y GOD (Expósito, Esteller, Paredes, Rico y Franco, 2010), y también se han empleado en estudios comparativos (Agüero y Pujol, 2002; Gogu y Dassargues, 2000; Lobo-Ferreira y Oliveira, 2004; Napolitano y Fabbri, 1996). La naturaleza del índice es asignar valores a cada característica hidrogeológica, que luego se combinan para calcular un valor global de la vulnerabilidad con el fin de clasificar las regiones en diferentes unidades de contaminación potencial (Kumar, Bansod, Debnath, Thakur, y Ghanshyam, 2015).

Se estima que el 80% de la capa de agua potable en Paraguay en América del Sur se suministra a partir del agua subterránea. Cabral (2005) estima que al menos el 38% de la población del país vive sobre el Sistema Acuífero Guaraní y se suministra por sus aguas y que ciertas condiciones, especialmente la agricultura intensiva y residuos urbanos están o estarán arriesgando la calidad del agua del este sistema, debido especialmente al uso generalizado de tierras para la producción intensiva de soya, así como otros cultivos (por ejemplo, maíz, girasol). Preocupaciones globales sobre la asociación de la producción de soya y otros cultivos como una fuente importante de contaminación del agua subterránea (Clay, 2004) se han tomado como tema de interés para este estudio, específicamente para dos captaciones ubicadas en esta región. Nuestro estudio tuvo como objetivo determinar la vulnerabilidad del agua subterránea actual a la contaminación de los "acuíferos poco profundos" utilizando modelos DRASTIC y GOD para las cuencas de los ríos Mboi Cae y Quiteria y evaluar los posibles efectos del cambio climático en las categorías de la vulnerabilidad, así como de cambios en el nivel freático derivados de las operaciones de la presa Yacyretá. Nuestras dos cuencas de estudio se perciben localmente como una sola unidad socio-hidrológica, compartiendo un comité de una cuenca y los actores comunes implicados en su gestión. Este estudio se centra en el área de las dos cuencas ubicadas dentro de la influencia del Sistema Acuífero Guaraní y la presa de Yacyretá. El mapeo de las aguas subterráneas se llevó a cabo no solo para proporcionar los mapas resultantes al comité de cuenca, sino también como un ejercicio comparativo de la idoneidad de la aplicación de los dos modelos, específicamente la entrada de datos, teniendo en cuenta la información disponible para esta región. Los mapas de vulnerabilidad de aguas subterráneas se presentan aquí como una característica intrínseca del sitio estudiado en la posible amenaza de contaminantes, incluyendo, pero no limitado a, la producción intensiva de soya. (Para obtener una lista de los contaminantes asociados a la agricultura intensiva de soya, véase: Paraíba *et. al*., 2003).

## Materiales y métodos

El Sistema Acuífero Guaraní es uno de los mayores reservorios de agua subterránea del planeta (Oporto y Vassolo, 2003; Fariña *et al*., 2004). Se encuentra en América del Sur entre 12° y 35° de latitud sur y 47° y 65° de longitud oeste. Se estima que el acuífero contiene una reserva de 45 000 kilómetros cúbicos de agua que cubre un área de aproximadamente 1 200 000 kilómetros cuadrados, de los cuales 840 000 kilómetros cuadrados pertenecen a Brasil, 225 500 kilómetros cuadrados a Argentina, 71 700 kilómetros cuadrados a Paraguay y 58 500 kilómetros cuadrados a Uruguay (Cabral, 2005). En Paraguay, el Sistema Acuífero Guaraní se encuentra en el parte oriental del país, formando una franja que se extiende de norte a sur, a lo largo del río Paraná (Fariña *et al*., 2004), parte de la cuenca del río de La Plata.

Dentro del sistema acuífero, se seleccionaron dos cuencas que son de interés local para la Entidad Binacional de Yacyretá y el comité de cuenca hidrográfica local y donde las poblaciones urbanas más grandes del departamento de Itapúa están siendo afectados por el proyecto de la presa Yacyretá en Paraguay, y las actividades agrícolas intensivas representan al menos el 80% del área total de las cuencas. Las cuencas de los ríos Mboi Cae y Quiteria (286 kilómetros cuadrados y 352 kilómetros cuadrados, respectivamente) se encuentran en el Departamento de Itapúa de Paraguay, drenando ambos al río Paraná, que constituye parcialmente la frontera política entre Paraguay y Argentina (Figura 1). Se han utilizado dos modelos para la vulnerabilidad del agua subterránea: DRASTIC, originalmente publicado por Aller, Bennett, Lehr, Petty y Hacket, (1987), y GOD publicado por Foster, Hirata, Gómez, D' elia, y París (2002). Estos modelos se han probando en varios trabajos subsecuentes: en la India (Kumar, Thirumalaivasan, y Radhakrishnan, 2014; Rahman, 2008; Shahid 2000), Paraguay (Laino, Jiménez, Velázquez, Páez y Casanoves, 2006, Larroza, Fariña, Báez y Cabral, 2005), Japón (Babiker *et al*., 2005), El Salvador (Vignola, 2005), Nicaragua (Obando, 2005), México (Ceballos y Ávila, 2004; Expósito *et al*., 2010), Portugal (Lobo-Ferreira y Oliveira, 2004), Estados Unidos (Chowdhury, Iqbal, y Szabo, 2003), Costa Rica (Agüero y Pujol, 2002) e Italia (Napolitano y Fabbri, 1996). Los datos de entrada y las fuentes de los modelos se presentan en la Tabla. 1. Los datos de las condiciones hidrogeológicas se obtuvieron para cada parámetro utilizando diferentes fuentes y métodos y se explica en la Tabla 2.

## Cálculo DRASTIC

El acrónimo DRASTIC corresponde a las iniciales de siete mapas base de la siguiente manera: D: profundidad del agua / R: red de Recarga / A: medios acuíferos: / S: medios de suelo / T: Topografía / I: Impacto de la zona vadosa / C: conductividad hidráulica. Cada uno de los parámetros se mapea y clasifica ya sea en rangos o en tipos de medios importantes que tienen un impacto en el potencial de contaminación. A

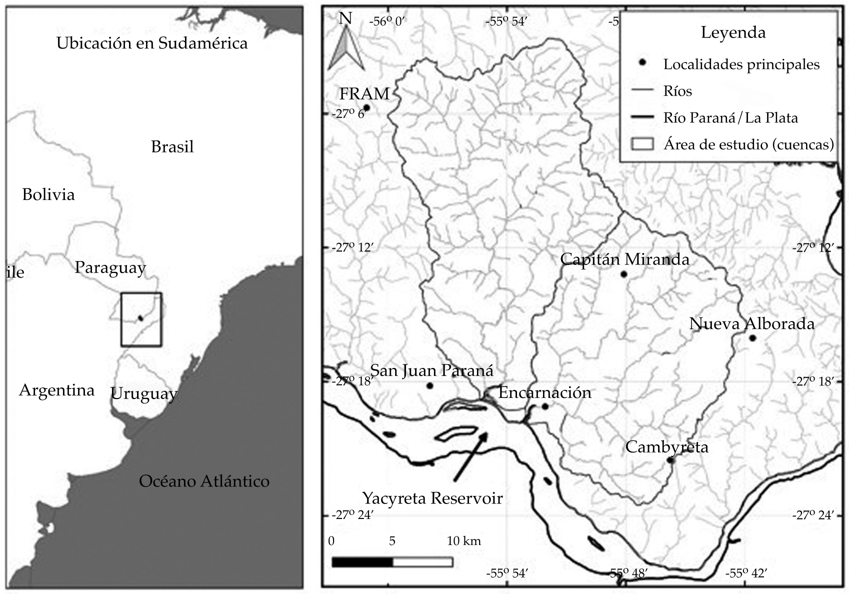


Figura 1. Localización del área de estudio, cuencas Mboi Cae y Quiteria en el departamento de Itapúa, Paraguay. Se muestra parcialmente el embalse binacional de Yacyretá (Argentina y Paraguay). Fuentes: NaturalEarth, Instituto Geográfico Militar del Paraguay y Musalem (2010).



Tabla 1. Resumen de las fuentes de información y los procesos de la tabla seguido para obtener drástica y GOD valoraciones sobre la cuenca de los Mboi Cae y Quiteria ríos en Paraguay.

| Parámetros | Fuente | Resumen del proceso seguido | Unidades |
|---|---|---|---|
| Profundidad de agua | Perfiles de los 41 pozos reportados por SENASA (la agencia de servicios de saneamiento de agua local) que muestran los niveles estáticos y dinámicos del nivel freático dentro de las cuencas | Los niveles estáticos fueron interpolados usando IDW para el área de las cuencas | Profundidad en metros |
| Recarga de red | Mapas de geología (Instituto Geográfico Militar de Paraguay, 1986) y estudios de hidrogeología que estimaron la recarga neta para basaltos y piedra arenisca en el Acuífero Guaraní. Santa Cruz y Silva (2002) en Laino (2005), Kull (2.003), Schmidt (2009) | La recarga neta fue estimada por la geología en función de las precipitaciones. Para las zonas de piedra arenisca, se utilizó directamente un valor estimado de revisión de la literatura | Milímetros por año |
| Medios de acuífero | Mapas de geología (Instituto Geográfico Militar De Paraguay, 1986) | La roca que sirve como acuífero, poros o fracturas relacionada con la vulnerabilidad a la contaminación | Litología |
| Medios de suelos | Mapas de suelos (Instituto Geográfico Militar De Paraguay, 1986). Taxonomía y texturas del suelo local (Consultores Globales, 2008) | Los subgrupos de taxonomía de suelos se vincularon a la textura y tradujeron a las clasificaciones de vulnerabilidad | Textura |
| Topografía | Líneas de contorno de Paraguay (Instituto Geográfico Militar De Paraguay, 1986) | Las isolíneas se procesaron en un modelo de elevación digital. Usando la pendiente GIS se calculó y tradujo a los clasificaciones de vulnerabilidad | Pendiente (%) |

Tabla 1 (continuación). Resumen de las fuentes de información y los procesos de la tabla seguido para obtener drástica y GOD valoraciones sobre la cuenca de los Mboi Cae y Quiteria ríos en Paraguay.

| Parámetros | Fuente | Resumen del proceso seguido | Unidades |
|---|---|---|---|
| Impacto de los medios de la zona Vadosa o estratos de sobreposición | Perfiles de pozos proporcionadas por SENASA + mapas geológicos de Paraguay | Lectura directa de los perfiles de SENASA y la confirmación con mapas geológicos | Litología |
| Conductividad hidráulica | Datos directos de las obras que informaron los valores locales (Godoy, 1991; De Salvo, 1991; en Fariña 2009) | Valores directos reportados de autores traducidos a clasificaciones de vulnerabilidad | Metros/día |
| Confinamiento de aguas subterráneas | Datos reportados por Schmidt (2009) | Características traducidas a clasificaciones de vulnerabilidad (GOD solamente) | Confinamiento |

Tabla 2. Datos utilizados y consideraciones para la aplicación de los modelos GOD y DRASTIC de vulnerabilidad de las aguas subterráneas. Los valores se reclasifican para clases de vulnerabilidad respectivamente, utilizando índices de DRASTIC (Aller *et al*., 1987) y GOD (Foster et al., 1987) para cómputo final. Para más detalles sobre los cálculos de datos ver Musalem (2010).

| Parámetros | Procesamiento de datos : consideraciones y limitaciones | Rangos de datos |
|---|---|---|
| Profundidad hasta el agua | Las profundidades del nivel freático se obtuvieron de los pozos proporcionados por la agencia de saneamiento de agua local. Los datos fueron extrapolados a toda la zona de las cuencas utilizando la ponderación de distancia inversa de ArcGIS. Una imagen matricial con la profundidad hasta el agua de la cuenca se reclasificó en valores de vulnerabilidad de acuerdo a cada autor. Los pozos se distribuyen irregularmente en la cuenca con más datos concentrados en las partes bajas de la misma. Sin embargo, se utilizaron pozos fuera de las cuencas para realizar la interpolación. Los valores se trasladaron directamente a las clasificaciones de DRASTIC y GOD, según los índices de Aller et al. (1987) | La profundidad del agua varió de aguas superficiales (0 m en las fuentes) hasta 75 m |
| Recarga | Se toman en cuenta las consideraciones de Santa Cruz y Silva (2002) en Laino (2005) del programa Piloto Concordia-Salto. Este estudio fue presentado en una investigación realizada por el Proyecto del Sistema Acuífero Guaraní con respecto a la estratigrafía e hidrogeología y estimó una recarga neta de 3% de la precipitación anual en Uruguay. Teniendo en cuenta que el área de estudio tiene un área hidrogeológica similar (formación del Alto Paraná y el Sistema Acuífero Guaraní) el mismo valor de 3% de la precipitación se utilizó para las áreas con geología basáltica dentro de las cuencas. Para zonas con piedra arenisca de la Formación Misiones y de sedimentos, los estudios realizados por el Proyecto Sistema Acuífero Guaraní reportados por Küll (2003) establecieron una recarga de 136 a 150 mm /año y por Schmidt (2009) una recarga neta para la Formación Alto Paraná de 77 mm/año<br>La distribución de las formaciones geológicas, areniscas, basaltos y arenas se obtuvo de los mapas geológicos disponibles en el Instituto Geográfico Militar en Paraguay (1986). La mayor parte de las cuencas se encuentran en áreas de geología basáltica, con depósitos aluviales cerca de la desembocadura de los ríos | La recarga oscila entre 50 a 178 milímetros/año dependiendo de la información geológica y la precipitación anual registrada obtenida a partir de datos del servicio meteorológico nacional paraguayo. La precipitación total varía de 1 878 a 1 988 mm por año para ambas cuencas |
| Medios acuíferos | Información sobre la geología fue tomada de mapas geológicos de Paraguay (1986) y trasladada directamente a una "calificación típica" de acuerdo con la metodología DRASTIC de Aller *et al*., (1987). Medios acuíferos se refiere a la porción de roca consolidada o no consolidada<br>Que sirven como un acuífero | Tres categorías fueron encontradas en las cuencas : (1) camas de arenisca o caliza; (2) de arena y (3) basaltos |

Tabla 2 (continuación). Datos utilizados y consideraciones para la aplicación de los modelos GOD y DRASTIC de vulnerabilidad de las aguas subterráneas. Los valores se reclasifican para clases de vulnerabilidad respectivamente, utilizando índices de DRASTIC (Aller et al., 1987) y GOD (Foster *et al.*, 1987) para cómputo final. Para más detalles sobre los cálculos de datos ver Musalem (2010).

| Parámetros | Procesamiento de datos : consideraciones y limitaciones | Rangos de datos |
|---|---|---|
| Medios de suelo | La distribución de la taxonomía del suelo se obtuvo de mapas digitalizados de suelos de Paraguay (Instituto Geográfico Militar). En segundo lugar, cada subgrupo de suelo se relacionó con su textura según tres estudios diferentes realizados en la zona: Un informe que consta de estudios de suelos en base a la observación de campo, la morfología y el análisis físico y químico de los horizontes del suelo realizado por Global Consultores (2008) en las cuencas de la Entidad Binacional Yacyretá; una investigación de tesis de maestría realizada por Laino (2005) donde se utilizó el modelo DRASTIC; y un estudio geológico inédito en el área realizado por González (2005) (en Laino 2005); también se consultó Taxonomy Keys del Soil Survey Staff de la USDA (2006). La textura de subgrupos se traslado a las calificaciones DRASTIC utilizando Aller *et al.* (1987) | Los suelos que se encuentran en las cuencas fueron Lítico Udorthent (basalto) (más dominante), Rhodic Paleudult y Typic Kandiudox, en los cuales se determinó, con base en la literatura, que tenían áreas de barro y arcilla fina Typic Paleaquult y las áreas Typic Albaquult tenían marga, margas finas y texturas de marga arenosa |
| Topografía | Las isolíneas se disponían a 10 metros de esta área y se transformaban en una (red irregular triangulada) y finalmente en ráster con un tamaño de píxeles cuadrados de 100 m (10 x 10 m). La pendiente se calculó utilizando Arco SIG y se traslado a DRASTIC por la reclasificación del ráster con el índice DRASTIC | La pendiente en porcentaje osciló entre 0%, sobre todo en las partes bajas de las cuenca, y 40% en las zonas superiores |
| Impacto de la zona vadosa o capas de sobreposición | Según Aller *et al.* (1987) de la zona vadosa se define como aquella por encima del nivel freático que es insaturada o saturada discontinuamente. La lectura de 23 perfiles de posos así se utilizó para determinar las características del material por debajo del horizonte típico del suelo y por encima del nivel freático | La geología basáltica fue predominante en las cuencas. También se encontraron otras fracciones más pequeñas de arena y piedras areniscas; sin embargo no se encontraron pozos para estas áreas y se asignaron valores típicos de acuerdo con la geología encontrada |
| Conductividad hidráulica | Fariña (2009) ha reportado que el basalto fracturado tiene una muy alta conductividad hidráulica, que alcanza niveles aún más altos, con base en el trabajo llevado a cabo (Godoy 1991 y De Salvo 1991 en Fariña 2009). La explicación dada para tan alto nivel de conductividad hidráulica es la presencia de fracturas horizontales y verticales y su interconexión en la Formación Geológica del Alto Paraná. Dado que esta era la única información disponible sobre la conductividad hidráulica, un ráster constante fue creado con este valor | 43 m/d basado en Fariña (2009) |
| Confinamiento de aguas subterráneas | Los datos para el confinamiento de las aguas subterráneas se toman directamente de los estudios realizados para el Proyecto Sistema Acuífero Guaraní y reportados por Schmidt (2009). El área de las cuencas hidrográficas es considerado como parte de la "acuífero de basalto" o Formación del Alto Paraná, que es un acuífero no confinado, lo que contrasta con los acuíferos de piedra arenisca (comúnmente llamado guaraní) y acuíferos cuaternarios que se consideran confinados. El Sistema del Acuífero Guaraní se compone de diferentes acuíferos interconectados o interrelacionados entre sí. El acuífero de basalto normalmente recibe la recarga directa de la precipitación, aunque también contribuye a través de goteo al acuífero inferior Guaraní (Formación Misiones) y el acuífero Pérmico (Guaraní -Independencia) (Schmidt, 2009) | Acuífero libre |

Tabla 3. Clasificación del índice DRASTIC de Aller *et al*. (1987) y los valores interpretativos de acuerdo con código nacional de color de los EUA.

| Tasa del índice DRASTIC | Color | R, G, B | Vulnerabilidad potencial |
|---|---|---|---|
| Inferior 79 | Violeta | 238, 130, 238 | Mínimo |
| 80-99 | Índigo | 75, 0, 130 | Muy bajo |
| 100-119 | Azul | 0, 0, 255 | Bajo |
| 120-139 | Verde oscuro | 0, 128, 0 | Medio bajo |
| 140-159 | Verde claro | 0, 255, 0 | Medio alto |
| 160-179 | Amarillo | 255, 255, 0 | Alto |
| 180-199 | Naranja | 255, 127, 0 | Muy alto |
| Mayor a 200 | Rojo | 255, 0, 0 | Máximo |

cada factor o parámetro se le asigna una calificación subjetiva entre 1 y 10. Después se utilizan multiplicadores de peso para cada factor con el fin de equilibrar y mejorar su importancia. La vulnerabilidad final, el índice DRASTIC, se calcula como la suma de sobreposición ponderada de las siete capas, de acuerdo con Aller *et al*. (1987).

Las categorías del índice drástico también fueron tomadas del estudio de caso de Aller *et al*. (1987) para la metodología DRASTIC asignando un esquema de colores conocido como "código de color nacional de EU para rangos del índice DRASTIC " (tabla 3). Utilizamos esta misma categorización para determinar los cambios derivados de los cambios del nivel freático (sección 3.3) y los escenarios de cambio climático (sección 3.4). Se presenta en este trabajo debido a su relevancia como un marco de referencia pocas veces utilizado.

### Cálculo GOD

GOD es el acrónimo de los siguientes parámetros: el confinamiento de las aguas subterráneas (G) en el acuífero en cuestión; superposición de los estratos (O) o zona vadosa en términos de carácter litológico y el grado de consolidación que determinan su capacidad de atenuación de contaminantes (equivalente al impacto de la zona vadosa para DRASTIC); y la profundidad de la capa de las aguas subterráneas (D) o el paro del agua subterráneas en acuíferos confinados (Ver tabla 3 para más detalles sobre cómo se han obtenido los datos y preparado para los modelos). Según la metodología GOD la vulnerabilidad del acuífero resultante del índice de contaminación se considera como el producto de estos tres parámetros, que se traduce en una categorización propuesto por Foster et al. (2002).

### Cambios en la vulnerabilidad de aguas subterráneas por operaciones de presas

Un aumento en el nivel freático debido a las operaciones de la presa Yacyretá ha sido objeto de debate, de cara al aumento final de 5 metros del embalse de Yacyretá a máxima capacidad (años 2008-2009). Información de los estudios hidrogeológicos realizados por Lotti- Associatti (1999) y una revisión realizada por el hidrogeólogo Miguel Auge (n/a), en relación con los posibles efectos de la elevación del nivel freático del acuífero, muestran que aún poco se sabe acerca de cómo las aguas subterráneas se comportará después de que el nivel de agua de la presa de cambios de 78 m a 83 m. Por un lado de las predicciones, Lotti asegura que debido a la hidrogeología de "fuerte basáltica" de la zona, sólo un pequeño "borde marginal" de aproximadamente 12.5 metros se verá afectado y provocará cambios en el nivel freático. Por



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otro lado, Auge se opone a esta predicción al afirmar que no hay suficientes datos hidrogeológicos disponibles en la zona para determinar cómo el cambio en el nivel de agua del embalse afectará a las aguas subterráneas, concluyendo que es necesario un muestreo mayor mediante pozos y el uso de modelos tridimensionales en lugar de modelos bidimensionales utilizados por Lotti. Hasta ahora no se ha encontrado en la literatura estudios complementarios o datos de campo en relación con los cambios en el nivel freático hasta esta publicación.

Un escenario del peor de los casos se utilizó para visualizar y comparar los posibles cambios en la vulnerabilidad de los acuíferos a la contaminación, donde el cambio del nivel freático es equivalente a la elevación del embalse de la presa (5 m). Aunque es poco probable que eso realmente ocurra, teniendo en cuenta la información de Lotti, sirve al propósito de mostrar el evento extremo de afectar el nivel freático (profundidad del parámetro agua en DRASTIC y GOD) en toda la zona de las cuencas.

### *Cambios en la vulnerabilidad del clima Escenarios de cambio*

Utilizamos los escenarios de cambio climático en la precipitación anual media y la temperatura anual media causado por el cambio climático global según tres distintos escenarios de emisiones de gases de efecto invernadero considerados por Limia (2000) y González (2005). Nuestros escenarios de cambio climático consideran cambios de la precipitación anual media (+ 16.2% y -11.5%) en un lapso de 100 años. Estos cambios en la precipitación se utilizaron para cambiar los valores de recarga neta, estimados localmente como 3% de la precipitación de la zona basáltica de las cuencas (Tabla 4).

## Resultados y discusión

El mapeo de la vulnerabilidad como resultado de la aplicación de modelos GOD y DRASTIC se muestra en la figura 2 para condiciones y predicciones de cambio actuales en la vulnerabilidad de las aguas subterráneas provenientes de operaciones de presas. Los resultados del modelo de GOD muestran 96% del área de las cuencas con valores de 0.3 hasta 0.5 (vulnerabilidad moderada a la contaminación) y 4% (valores 0.51 a 0.6) resultó con alta vulnerabilidad. Los valores más altos se encuentran en las zonas bajas de las cuencas, donde la profundidad hasta las aguas subterráneas es mínima y se presentan arenas aluviales. El modelo DRASTIC muestra un 56% del área de las cuencas clasificadas como "medio altas" (índice DRASTIC 140-159) y un porcentaje del 22% como "altas", "muy altas" o "máximas" (valores del índice DRASTIC de 160 > 200).

El escenario del peor de los casos en relación con el aumento del cambio del nivel freático de 5 metros mostró cambios en las categorías de vulnerabilidad en DRASTIC. Mientras los valores "bajos", "medio bajo" bajaron de 21.7 al 9.11% de las cuencas, y los valores medio altos de 56 a 50% del área total de las cuencas, los valores " altos", "muy altos" y "máximo" aumentaron de 22% a 40% de las cuencas.

El cambio de los valores de precipitación, por consiguiente, el cambio de estimaciones netas de recarga, empleando escenarios de cambio climático para un lapso de 100 años, no parecía afectar el resultado final de DRASTIC. A pesar de que los valores cambian en los mapas resultantes, las categorías de vulnerabilidad siguen siendo las mismas. No se analizaron escenarios de cambio climático con el modelo GOD, ya que los valores de recarga no se pueden cambiar directamente en el modelo, sino que en vez de eso se centra en las características geológicas de los estratos de superposición.

## Discusión

Los mapas de resultados de DRASTIC muestran una distribución más heterogénea de las clases de vulnerabilidad en comparación con el modelo GOD. Agüero y Pujol (2002) realizaron observaciones similares mientras analizaron su experiencia en la aplicación de los mismos modelos en el Valle Central de Costa Rica. A



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Tabla 4. Pozos utilizados para la determinación de la "profundidad de agua" (D) a través de la interpolación de nivel estático para determinar la vulnerabilidad del acuífero en las cuencas de Mboi Cae y Quiteria, Itapúa, Paraguay.

| Pozo | Localidad | Profundidad (m) | Fecha (año) | Caudal ($m^3/s$) | Nivel estático (m) |
|---|---|---|---|---|---|
| IT-P0010 | Capitán Miranda | 116 | - | 24.00 | 24.50 |
| IT-P0011 | Capitán Miranda | 115 | - | 12.00 | 0.00 |
| IT-P0012 | Capitán Miranda | 122 | 1996 | 40.00 | 30.60 |
| IT-P0022 | Fram | 62 | 1980 | 30.00 | 0.00 |
| IT-P0031 | Jesus | 139 | 1984 | 5.00 | 65.00 |
| IT-P0034 | Trinidad | 78 | 1986 | 12 | 35.00 |
| IT-P0041 | San Juan del Paraná | 184 | 1992 | 4.60 | 3.70 |
| IT-P0042 | San Juan del Paraná | 100 | 1996 | 35.00 | 3.00 |
| IT-P0047 | B° San Juan | 137 | 1993 | 35.00 | 10.00 |
| IT-P0048 | B° San Juan | 146 | 1995 | 30 | 27.00 |
| IT-P0049 | Cambyreta | 206 | 1993 | 30.00 | 55.00 |
| IT-P0051 | Nueva Esperanza | 228 | 1996 | 20 | 0.00 |
| IT-P0052 | Ita Paso | 282 | 1997 | 10.00 | 19.05 |
| IT-P0055 | Polidedortivo (Diben) | 264 | 1992 | 15.30 | 0.00 |
| IT-P0058 | Potrero Santa María (Villa) | 99 | 1995 | 60.00 | 15.00 |
| IT-P0067 | Campichuelo | 217 | 1997 | 40.00 | 21.10 |
| IT-P0068 | San José Obrero | 80 | 1998 | 20.00 | 10.50 |
| IT-P0078 | Puerto Samuhu | 117 | 1998 | 4.50 | 23.50 |
| IT-P0079 | San Blas Independencia | 170 | 1998 | 25.00 | 23.50 |
| IT-P0084 | San Miguel Kuruzu | 140 | 1997 | 30.00 | 34.50 |
| IT-P0085 | Azotea | 306 | 1998 | 29.00 | 0.00 |
| IT-P0086 | B° Guazu-Arroyo Pora | 158 | 1997 | 40.00 | 7.70 |
| IT-P0088 | Chaipe | 117 | 1997 | 70.00 | 1.00 |
| IT-P0089 | Chaipe | 129 | 1997 | 41.00 | 4.20 |
| IT-P0090 | La Paz | 116 | 1997 | 40.00 | 0.00 |
| IT-P0091 | La Paz | 163 | 1997 | 16.00 | 5.05 |
| IT-P0124 | Santo Domingo | 152 | 2000 | 25.00 | 14.00 |
| IT-P0125 | Pradera Alta | 121 | 2001 | 38.00 | 8.00 |
| IT-P0136 | Copetrol Santa María | 0 | 1996 | | 0.00 |
| IT-P0141 | Paso Guembe | 118 | 2003 | 3 | 75.50 |
| IT-P0198 | Virgen de Itacua | 91 | 2001 | 15.00 | 21.00 |
| IT-P0203 | B° San Juan | 135 | 1996 | 50.00 | 10.40 |
| IT-P0247 | San Antonio Ypecuru | 232 | 2002 | 10.10 | 18.50 |
| IT-P0278 | Ita Paso | 286 | 2001 | 8 | 30.00 |
| IT-P0279 | Ita Paso | 306 | 2002 | 8.00 | 20.00 |
| IT-P0281 | 8 de Diciembre (Ita Paso) | 200 | 2003 | 10.13 | 15.00 |
| IT-P0336 | San Blas Cerro Cora | 103 | 2001 | 20.00 | 29.00 |
| IT-P0362 | Fram | 285 | 2005 | 40.00 | 15.00 |
| IT-P0372 | San Luis del Paraná | 162 | 2004 | 7.97 | 30.00 |
| IT-P0388 | San Nicolás Bº Guarani | 222 | 2003 | 8.44 | 14.85 |
| IT-P0389 | Ytororo | 190 | 2003 | 9.70 | 0.00 |

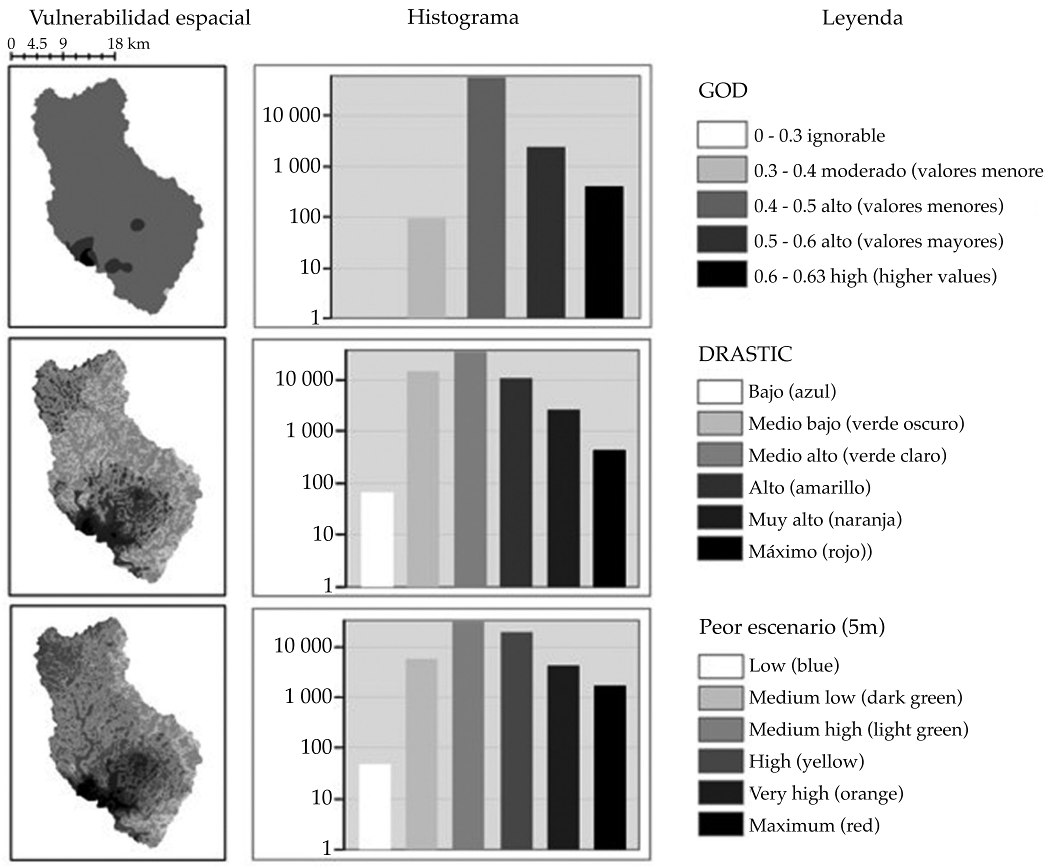


Figura 2. Vulnerabilidad del acuífero a la contaminación de acuerdo con los modelos GOD y DRASTIC y un peor escenario para DRASTIC asumiendo el aumento del nivel freático por operaciones de presa. Cuencas de los ríos Mboi Cae y Quiteria en Paraguay.

pesar de la modelo DRASTIC se está utilizando en todo el mundo para determinar la vulnerabilidad intrínseca de acuíferos, una discusión constante es la relación del índice DRASTIC con la contaminación real que se encuentra en el acuífero. Leona, Ripa, Uricchio, Deak, y Vargay (2009) después de estudiar la evaluación de la vulnerabilidad y el riesgo de la contaminación por nitrógeno agrícola para el acuífero principal de Hungría usando los modelos DRASTIC y GLEAMS concluyen que DRASTIC, como método paramétrico/cualitativo, se comporta mejor en la correspondencia general de las tendencias, lo que significa una correspondencia entre un mayor contenido de nitrato y puntuaciones de DRASTIC superiores. Sin embargo, esto no es necesariamente cierto para todas las áreas donde estos y otros contaminantes han sido vistos; por lo tanto, existe una gran necesidad de entender la aplicación de estos modelos y sus capacidades de predicción y resultados en los artículos que abordan investigación sobre áreas que fueron evaluadas con dichas técnicas, así como cuando estas se aplican en las zonas que ya están contaminadas.

Como una primera aproximación, y sin oponerse a la necesidad de un análisis adecuado adicional de la calidad del agua, proponemos el uso de estos modelos, que también pueden proporcionar ayuda para determinar brechas de conocimiento de características hidrogeológicas de las cuencas. También hay que señalar que la aplicación de estos modelos no busca evaluar las amenazas específicas, lo que requiere estudiar cada amenaza de forma independiente, sino que en vez de eso tiene la intención de determinar la configuración hidrogeológica intrínseca y su vulnerabilidad, lo que podría conducir mejor a la determinación de las áreas que podrían ser dirigidas hacia la conservación o a la consideración de administración especial.

Según Rupert (1999), DRASTIC, a pesar de ser utilizado para desarrollar los mapas de vulnerabilidad de las aguas subterráneas en los Estados Unidos, tiene un éxito variado, ya que por lo general no está calibrado para medir las concentraciones de contaminantes, lo que sugiere mejoras necesarias en mapeo de la vulnerabilidad de las aguas subterráneas de DRASTIC calibrando el esquema de calificación. Sin embargo, DRASTIC todavía puede considerarse un primer enfoque de GVP, especialmente cuando la información es limitada o cuando el concepto de vulnerabilidad no incluye solo una amenaza o riesgo contaminante particular, pero tal como lo describen Lobo-Ferreira y Oliveira (1997) "la vulnerabilidad es lo único que se refiere a las características intrínsecas de los acuíferos, que son relativamente estáticos y más allá del control humano". A pesar de nuestro estudio concuerda con este concepto general, consideramos que las actividades humanas, tales como los efectos de las operaciones de grandes presas que influyen en el nivel freático, podrían afectar la vulnerabilidad a la contaminación.

A nivel local, Laino (2005) encontró valores distintos en la proximidad de la cuenca del río Capiibary. Después de la comparación de clases, 36% mostró una categoría de vulnerabilidad "baja", y 64%, categorías "medio bajo", "alta" "medio-alta". La categorización utilizada por Laino fue diferente a la utilizada en el presente estudio, por lo que la comparación de ambos estudios solo fue posible a este nivel. Esta situación lleva a sugerir una estandarización de los resultados para facilitar la comparación entre los estudios.

Nuestra experiencia en la aplicación de ambos modelos concuerda con las observaciones de Gogu y Dassargues (2000) que consideran el concepto de vulnerabilidad de las aguas subterráneas como una herramienta útil para la planificación ambiental y la toma de decisiones; también encontramos que los modelos sencillos proporcionan resultados similares a los modelos complejos. Para nuestra experiencia, un modelo más simple (tales como GOD) es más probable que cumpla con la entrada de datos disponibles en la actualidad para Paraguay, aunque pierde sutiliza respecto al resultado final. Dado que DRASTIC y GOD son un primer paso para evaluar la vulnerabilidad de las aguas subterráneas y considerando que la revisión de la literatura sugiere volver a confirmar los datos con los contaminantes y riesgos específicos, se sugiere una validación adicional del modelo a nivel local para la investigación futura, incluyendo el análisis de la calidad de las aguas subterráneas y el monitoreo.

## Conclusiones

Se encontró que la vulnerabilidad del acuífero a la contaminación resultó ser intermedia-alta utilizando de manera similar los modelos GOD Y DRASTIC y se obtuvieron resultados más detallados al utilizar DRASTIC que también requiere datos que no estaban disponibles para el área de estudio o en la escala apropiada. Se encontraron valores de mayor vulnerabilidad hacia las partes más bajas de la zona de estudio con ambos modelos mostrando descriptores y valores similares en las respectivas escalas. Una vulnerabilidad "media-alta" demuestra que la preocupación por la contaminación del acuífero en el mediano plazo se debe considerar para instrumentar programas posibles dedicados a la minimización contaminantes en la agricultura; asimismo, dado que las zonas más altas de vulnerabilidad se encuentran en las partes más bajas de las cuencas, donde se asientan zonas urbanas, nuestros resultados sugieren la necesidad de identificar las fuentes de contaminación en las zonas urbanas como posiblemente la mayor amenaza para acuíferos poco profundos. También fue inesperado que los escenarios de



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cambio climático no mostraron cambios en las clases de vulnerabilidad. Esto pone de relieve la importancia de la protección de las aguas subterráneas, el estudio y la conservación como una estrategia de mitigación al cambio climático y justifica la necesidad de comprender mejor las prácticas de gestión y su impacto en las aguas subterráneas.

Proponemos el uso del código de color nacional como marco de referencia para aplicaciones DRASTIC futuras que permitan una comparación simple de resultados. Cabe señalar que la evaluación de la vulnerabilidad implica incertidumbres asociadas con los cálculos y las limitaciones de los datos utilizados (National Research Council, 1993; Kumar *et al*, 2015); por lo tanto, también esta incertidumbre es reconocida para este estudio, y se recomienda más trabajo y más datos para avanzar hacia mejores aproximaciones.

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# Investigación ecohidroclimatológica en el transecto Catacocha-Zamora, Loja y Zamora Chinchipe, Ecuador

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## Resumen

Oñate-Valdivieso, F., & Ponce, V. M. (noviembre-diciembre, 2015). Investigación ecohidroclimatológica en el transecto Catacocha-Zamora, Loja y Zamora Chinchipe, Ecuador. *Tecnología y Ciencias del Agua*, 6(6), 63-73.

Este estudio trata sobre una investigación sobre ecohidroclimatología a lo largo del transecto Catacocha-Zamora en las provincias de Loja y Zamora-Chinchipe, Ecuador. La media de precipitación anual varía entre 400 mm en Catamayo, a lo largo del transecto de estudio, hasta 2 200 mm en Zamora, hasta el límite oriental. Las variaciones altitudinales también son marcadas, entre 1 230 m en Catamayo, 2 930 m en el Cerro del Consuelo y 900 m en Zamora. Se examinan datos ecohidrológicos e hidroclimatológicos para desarrollar las relaciones que apoyen el naciente campo de la ecohidroclimatología. Se prevén aplicaciones en la gestión sostenible de ecosistemas tropicales de montaña.

**Palabras clave**: ecohidrología, hidroclimatología, ecología, bioclimatología, climatología, vegetación tropical, Ecuador.

## Abstract

*Oñate-Valdivieso, F., & Ponce, V. M. (November-December, 2015). Ecohydroclimatological Research Along the Catacocha-Zamora Transect, Loja and Zamora-Chinchipe, Ecuador.* Water Technology and Sciences *(in Spanish), 6(6), 63-73.*

*This study reports on ecohydroclimatological research along the Catacocha-Zamora transect in the provinces of Loja and Zamora-Chinchipe, Ecuador. Mean annual precipitation varies between 400 mm in Catamayo, along the study transect, to 2 200 mm in Zamora, to the eastern limit. Altitudinal variations are also marked, between 1 230 m in Catamayo, to 2 930 m in Cerro del Consuelo, to 900 m in Zamora. Ecohydrological and hydroclimatological data are examined with the aim of developing relations to underpin the nascent field of ecohydroclimatology. Applications are envisioned in the management of tropical montane ecosystems.*

***Keywords**: Ecohydrology, hydroclimatology, ecology, bioclimatology, climatology, tropical vegetation, Ecuador.*

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## Introducción

Ecuador está dotado por la naturaleza de una diversidad ecológica sin igual. Esto se debe a: (1) su ubicación geográfica a lo largo del Ecuador, (2) su posición relativa continental al lado del océano Pacífico, y (3) la presencia de la Cordillera de los Andes, que cruza la mitad del país de norte a sur (figura 1). Esta combinación inusual de latitud casi cero, la proximidad a una fuente de humedad muy grande, y el rango altitudinal amplio son las causas de una diversidad ecológica y biológica sustancial. Por lo tanto, la región constituye un laboratorio de campo verdadero para el estudio de las relaciones tropicales ecológicas, hidrológicas y climatológicas.

Los objetivos generales incluyen la descripción de la singularidad de la región de estudio elegida y sus características climatológicas y geomorfológicas, con el objetivo de establecer las bases adecuadas para el naciente campo de la ecohidroclimatología, interpretado como el enfoque continuo a la ecología, hidrología y climatología.

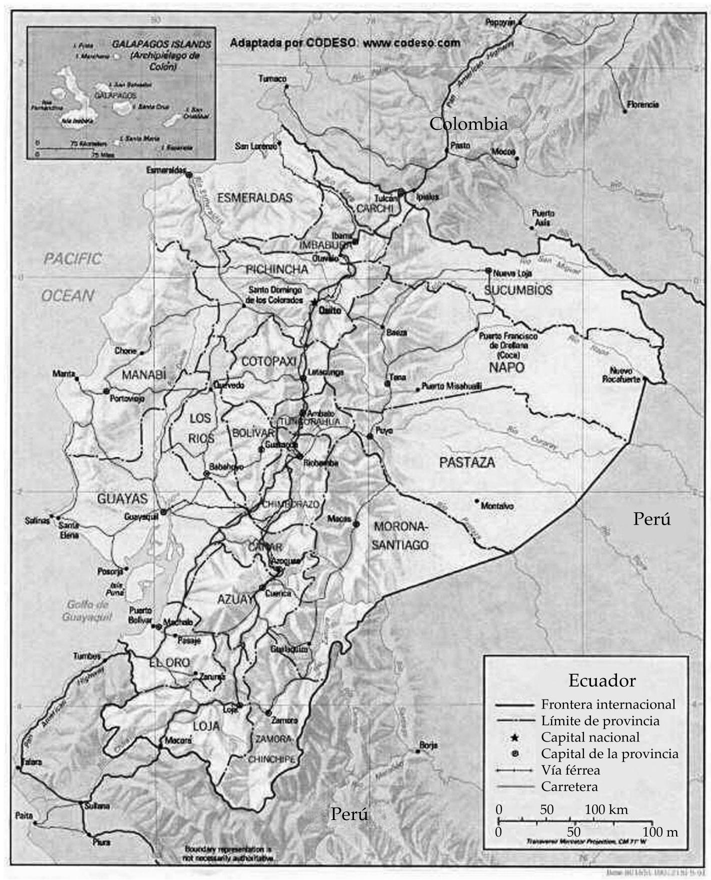


Figura 1. Mapa de Ecuador en el que se muestra que la Cordillera de los Andes pasa por el medio.

Los objetivos específicos incluyen la descripción de la precipitación anual media, la geología y la geomorfología del terreno, la relación de la flora con la distancia a las aguas subterráneas, y los indicadores climáticos adecuados, tales como los diversos índices bioclimáticos.

Este estudio se centra en las provincias del sur de Loja y Zamora-Chinchipe (figura 1). Estas regiones cuentan con gradientes marcados en la precipitación media anual dentro de una distancia relativamente corta. La figura 2 muestra la precipitación anual media en Loja y Zamora-Chinchipe, que varía entre 200 a 400 mm en Loja y de 3200-6400 mm en Zamora-Chinchipe. Por lo tanto, un transecto de longitud relativamente limitada atravesando estas dos provincias es apropiado para el estudio de las relaciones ecohidroclimatológicas.

Este estudio forma parte de un programa de investigación en ecohidroclimatología realizado conjuntamente por la Universidad Estatal de San Diego (San Diego, California, EUA) y la Universidad Técnica Particular de Loja (Loja, Ecuador).

## Configuración geográfica

Las provincias de Loja y Zamora se encuentran en el sur de Ecuador. Wolf (1892) ha descrito la geología, geomorfología, e hidrografía de Ecuador, incluyendo Loja y Zamora. La Cordillera de los Andes atraviesa la región de estudio, desde el nudo de Sabanilla, al sur de Loja, a los páramos de Saraguro, hacia el norte.

Desde el Nudo de Sabanilla, la cordillera de Santa Rosa despega hacia el noroeste y la



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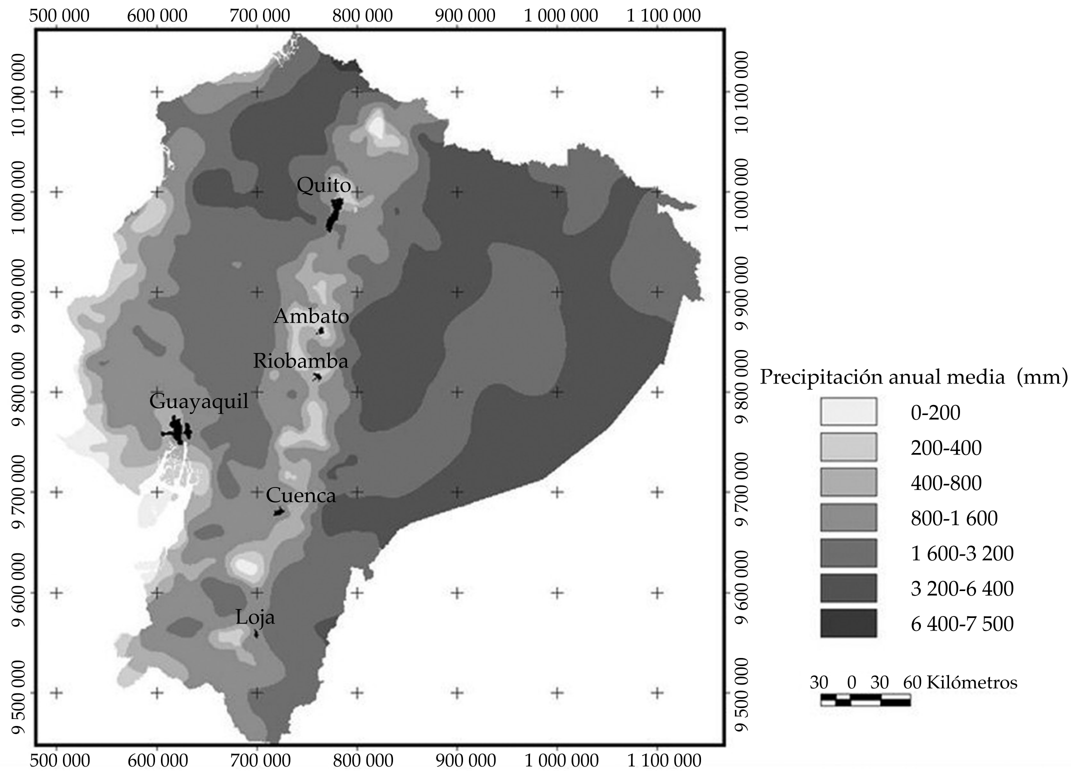


Figura 2. Precipitación media anual en Ecuador.

Cordillera del Cóndor, al sureste. La de Santa Rosa es estrecha, baja y relativamente pequeña. A partir de la Cordillera del Cóndor, varias ramas grandes despegan hacia el noreste.

De 4° 8′ de latitud S, al sur de la ciudad de Loja, la cordillera Occidental corre paralela a la cordillera Oriental en dirección norte general. La cordillera Occidental es estrecha, con ramas cortas en ambos lados, ascendiendo hasta 3000 m en la mayor parte de su longitud. Por el contrario, la cordillera Oriental se eleva hasta 4000 m. Estas dos ramas de los Andes están unidos por dos nudos transversales, el nudo de Cajanuma al sur de Loja, y el nudo Guagra-uma al norte. La región comprendida entre los nudos constituye el valle de Loja.

El valle de Loja, orientado de norte a sur, se divide en dos secciones diferentes. La parte norte es estrecha, parecida a un cañón. La sección sur, propiamente el valle de Loja, es de forma ovalada, con una longitud total que comprende unos 6 km y una anchura máxima de unos 3 kilómetros.

El río Malacatos tiene su cabecera en el nudo de Cajanuma, que fluye hacia el norte para encontrarse con el río Zamora en Loja, donde toma el nombre de este último. Al seguir fluyendo hacia el norte a través del nudo de Guagra-uma, el río Zamora reúne varias afluentes a lo largo de su curso, que con el tiempo se vierten en el río Santiago, en las tierras bajas del este de la provincia de Zamora-Chinchipe.

El valle interandino de Loja es pequeño y bajo, a 2150 m de altitud, con la ciudad de Loja ocupando todo el valle. El punto más bajo en la carretera (paso) desde Loja a través del nudo Cajanuma hacia el sur está en 2525 m de altitud. El punto más bajo en la carretera de Loja a Catamayo a al oeste está a 2786 m. Este paso está al lado de la cima de Villonaco, que se eleva a cerca de 3000 (Wolf, 1892).

## Marco conceptual

Este estudio sienta las bases para describir las características de las comunidades vegetales, utilizando la perspectiva interdisciplinaria de ecohidroclimatológica. Hay varios factores que condicionan el tipo y densidad de comunidades vegetales a través del paisaje. Los más importantes son:

### *Precipitación media anual*

La precipitación media anual determina las provincias de humedad (áridas, semiáridas, subhúmedas o húmedas) (Holdridge, 1947). Las plantas responden rápidamente a la presencia de humedad ambiental, incluida la de que en el aire, la superficie del terreno, la zona vadosa (suelo no saturado), y la subterránea que fluye. La baja humedad relativa en el aire se asocia generalmente con bajos niveles de humedad en la superficie y el suelo del terreno, junto con la presencia de corrientes efímeras y agua subterránea relativamente profunda. Por el contrario, la alta humedad relativa suele asociarse con altos niveles de humedad en la superficie y el suelo del terreno, junto con arroyos perennes y las aguas subterráneas poco profundas. En la práctica, estos elementos del paisaje están todos relacionados, y cuentan con un denominador común: la alta humedad ambiental significa húmedo, mientras que la baja, árido.

### *Terreno Geología y geomorfología*

Junto al tipo de clima, la geología del terreno y la geomorfología son generalmente un buen indicador del tipo de vegetación (Cole, 1960; Ponce y Da Cunha, 1993). Sin perjuicio de otros factores, la geología y la geomorfología del terreno determinan la relación entre las aguas superficiales y las aguas subterráneas. Las plantas pueden transpirar ya sea agua vadosa, aguas subterráneas, o ambas (Ponce, 2006). La pendiente de la tierra y el tipo de roca/suelo determinan la cantidad de flujo superficial, la detención y retención de la superficie, la tasa de infiltración, la profundidad del nivel freático, y la reposición de las aguas subterráneas. En adición, condiciones de drenaje, ya sean exorreicas, endorreicas, o exorreicas-endorreicas mixtas, mediante la interacción con el suelo y la salinidad de las aguas subterráneas, determinan el tipo y densidad de comunidades vegetales que predominan en el paisaje.

### *La proximidad a las aguas subterráneas*

Comunidades vegetales conocidas como freatofitas cubren sus necesidades de agua directamente del agua subterránea subyacente. En esencia, el agua subterránea poco profunda apoya el crecimiento de plantas que habitualmente se alimentan de las aguas subterráneas (Meinzer, 1927). Por lo tanto, la presencia de freatofitas es un buen indicador de las aguas subterráneas poco profundas en la vecindad.

### *Velocidad de drenaje superficial*

Laderas de tierras varían ampliamente, desde mayores que 30% en ciertos paisajes montañosos (Ponce, 2008), a cerca de cero en algunos paisajes deposicionales geológicamente controlados o valles amplios de ríos sometidos a la subsidencia geológica (Ponce, 1995). Las pendientes muy suaves terreno conducen a pantanos y humedales y a sus características estructuras comunitarias vegetativas, incluyendo las dinámicas impuestas por las variaciones estacionales, inundaciones y sequías, y más recientemente, el cambio climático antropogénico.

### *La temperatura media anual*

Las plantas se adaptan naturalmente variaciones de temperatura amplias (desierto) o estrechas (selva tropical). La temperatura media condiciona la capacidad de vida y supervivencia de las diversas comunidades vegetales a través del paisaje, desde árido a húmedo.

## Las variaciones estacionales en la temperatura

Las plantas están adaptadas naturalmente a las variaciones estacionales en la temperatura, que están condicionadas por la latitud, la altitud y la ubicación continental relativa a la fuente de humedad más cercana. Las plantas del desierto se adaptan fácilmente a las amplias variaciones en la temperatura estacional, mientras que las plantas de la selva tropical no.

## Precipitación anual

El transecto elegido para este estudio comprende el tramo entre Catacocha, en la provincia de Loja central, y Zamora, en el oeste de Zamora-Chinchipe (figura 3).

La figura 4 muestra un mapa de precipitación media anual para el transecto de estudio. Se utilizaron datos de diez (10) estaciones climatológicas para desarrollar este mapa. Las estaciones son, de oeste a este: (1) Chaguarpamba, (2) Catacocha, (3) Nambacola, (4) El Cisne, (5) Catamayo, (6) El Tambo, (7) La Argelia (en Loja), (8) Cajanuma, (9) San Francisco y (10) Zamora. Las ubicaciones de las estaciones se muestran en la figura 4.

La media de precipitación anual varía de 400 mm en Catamayo a 2200 mm en San Francisco, que representa a un gradiente de precipitación marcada. La distancia de Catamayo y San Francisco es de 40 km, mientras que la distancia de Catacocha a Zamora corresponde a 80 km. Cabe destacar que la ciudad de Loja, capital de la provincia de Loja, se encuentra a la mitad del subtransecto Catamayo-San Francisco.

La figura 5 muestra una imagen del transecto Catacocha- Zamora, revelando las marcadas diferencias en la vegetación a lo largo del transecto. Albedo, un indicador confiable de la presencia o ausencia de vegetación se estima que varían entre un valor tan alto como 0.30, cerca de Catamayo, hasta uno mínimo de 0.05, cerca de San Francisco (Ponce, Lohani, y Huston, 1997). La figura 6 muestra un perfil longitudinal del transecto Catacocha-Zamora, correspondiente

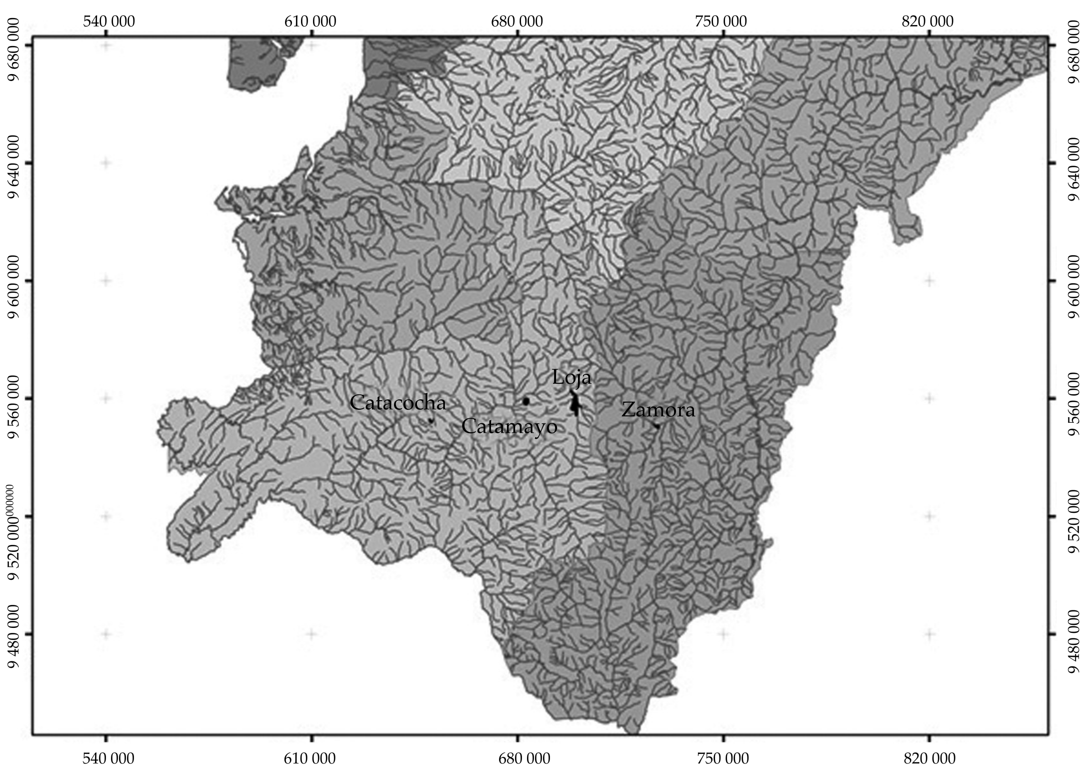


Figura 3. Ubicación general del transecto de estudio en las provincias de Loja y Zamora–Chinchipe.

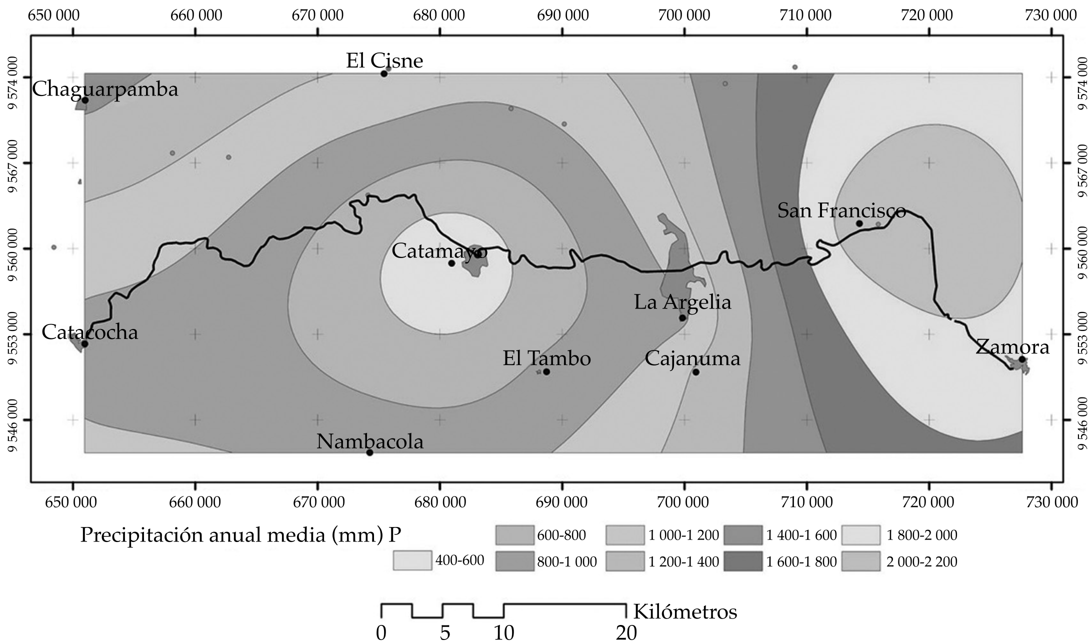


Figura 4. Isoyetas de precipitación anual media para el transecto Catacocha–Zamora.

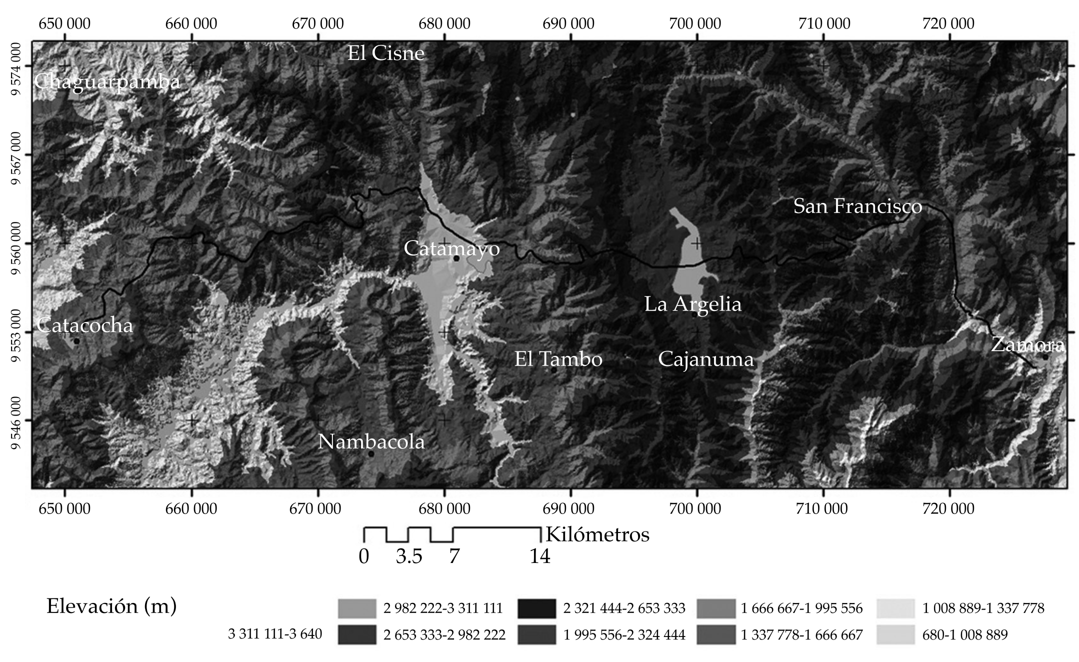


Figura 5. Mapa topográfico del transecto Catacocha–Zamora.

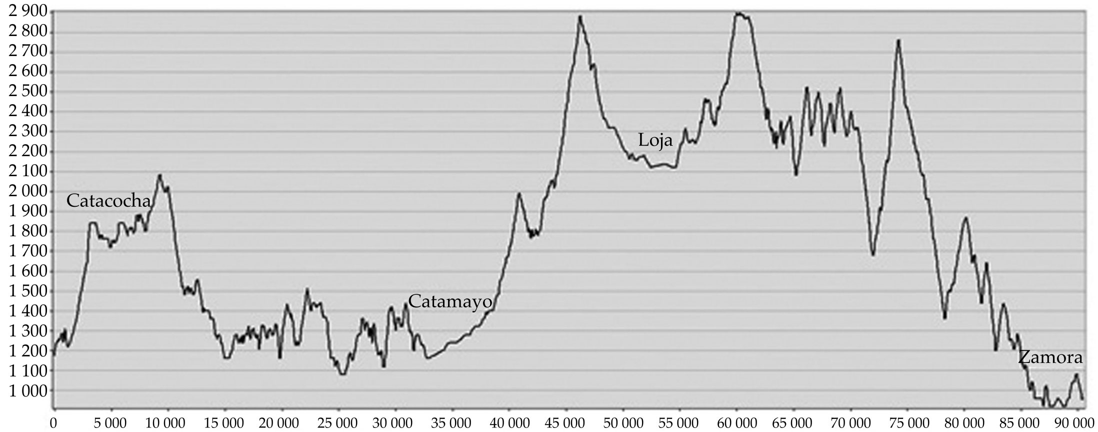


Figura 6. Perfil longitudinal del transecto Catacocha-Zamora.

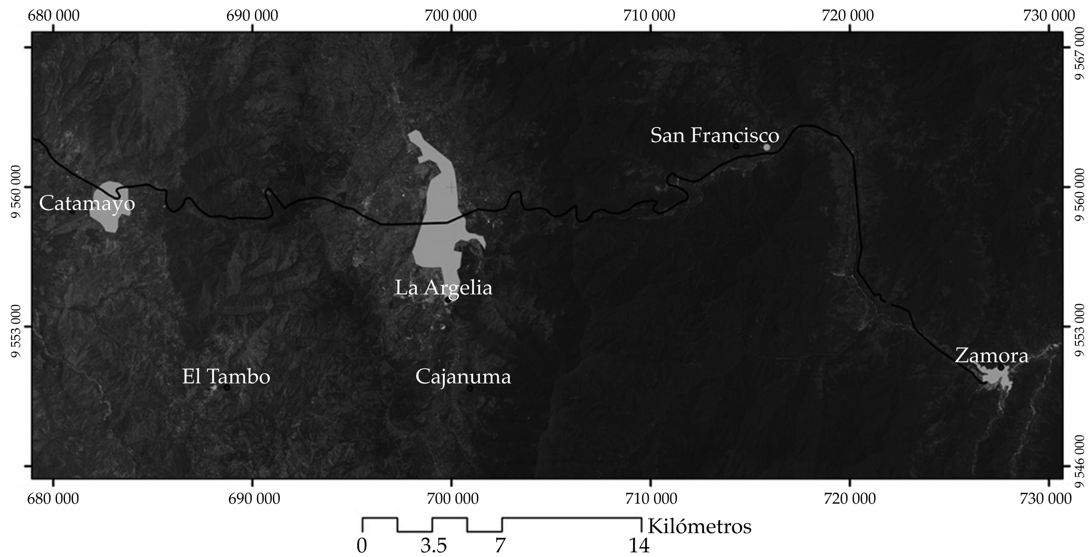


Figura 7. Imagen del transecto Catamayo–Zamora.

a la figura 5. Los valles Catacocha, Catamayo, Loja y Zamora se indican en el perfil.

La figura 7 muestra una imagen del transecto Catamayo- Zamora, a escala algo mayor que la imagen anterior, revelando una vez más las marcadas diferencias en el tipo de vegetación y la densidad a lo largo del transecto. Pulgar, Izco y Jadan (2010) señalaron que la precipitación media anual en un lugar aislado en el Cerro El Consuelo, cerca de San Francisco, se ha medido en 6 259 mm. Además, han documentado el número de meses de lluvia que varía de 1 a 2 para Catamayo (un clima hiperárido) y de 11 a 12 para San Francisco (un clima hiperhúmedo) (Ponce, Pandey y Ercan, 2000). Por lo tanto, el subtransecto Catamayo-San Francisco parece ser óptimo para el estudio de las relaciones ecohidroclimatológicas tropicales.

La figura 7 muestra una imagen centrada en valle de Loja, que muestra las marcadas diferencias en la densidad de la vegetación de las montañas del oeste al este de Loja, a una distancia de menos de 20 km. La precipitación anual media (figura 8) varía de 800-1000 mm al oeste y de 1600 -1800 mm al este.

## Paisajes vegetativos

Las figuras 8 y 9 muestran el contraste entre los paisajes típicos y las comunidades vegetales asociadas en Catamayo y Zamora, respectivamente. La Figura 8 muestra un paisaje montañoso cubierto de arbustos y pastos semiáridos cortos, mientras que la figura 9 muestra un bosque húmedo de una densa montaña tropical, con árboles relativamente altos. La investigación de campo en curso está dirigida a la identificación de la distribución espacial, la densidad, el tamaño y otras características relevantes de las especies y comunidades vegetales a lo largo del transecto de estudio.

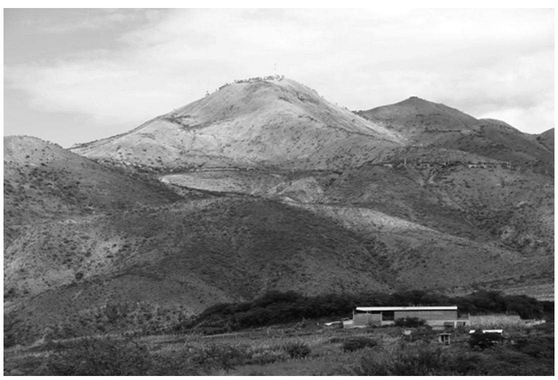

Figura 8. Paisaje montañoso semiárido en las proximidades de Catamayo, provincia de Loja.

Figura 9. Comunidades vegetativas a lo largo de la carretera a Zamora, provincia de Zamora–Chinchipe.

## Índices bioclimatológicos

Se utilizan tres índices para estudiar las relaciones bioclimatológicas (Rivas-Martínez, 2007):

### *Índice de continentalidad*

Este índice es igual a la temperatura promedio del mes más caluroso $T_{caliente}$, menos la temperatura promedio del mes más frío $T_{frío}$.

$$I_c = T_{caliente} - T_{frío} \quad (1)$$

El siguiente procedimiento se utiliza para calcular $T_{caliente}$:

La temperatura máxima diaria, para cada mes y año de registro se identifica, y se calcula la temperatura media máxima mensual.

La media de la temperatura media máxima mensual se calcula para todo el registro.

El mes con mayor media de la temperatura media máxima mensual se selecciona como el mes más caluroso.

Un procedimiento similar se aplica para calcular $T_{frío}$.

El índice de continentalidad varía entre $I_c = 0$ para una influencia oceánica extrema e $I_c = 65$ para una influencia continental extrema.

### *Índice de termicidad*

Este índice es igual a la temperatura anual media $T_{media}$ más la media de las temperaturas mínimas mensuales $T_{mín}$ más la media de las temperaturas máximas mensuales $T_{máx}$. La suma se multiplica por 10.

$$I_t = 10\,(T_{mean} + T_{min} + T_{max}) \qquad (2)$$

La temperatura media anual es la media de las temperaturas promedio mensuales medias (12). La media de las temperaturas mínimas mensuales es la media de la temperaturas mínimas mensuales medias (12). La media de las temperaturas máximas mensuales es la media de las temperaturas máximas mensuales medias (12).

### *Índice de temperatura positivo*

Este índice es igual a la suma de todas las temperaturas mensuales medias positivas (no negativas). La suma se multiplica por 10.

$$T_p = 10\,(\textstyle\sum T_{pos}) \qquad (3)$$

La Tabla 1 muestra la clasificación de los climas como una función del índice de continentalidad. La tabla 2 presenta la clasificación de los climas como una función de los índices de termicidad y temperatura positiva. La Tabla 3 muestra los índices calculados para las siguientes estaciones: (1) Catacocha, (2) Catamayo, (3) La Argelia, y (4) Zamora. La tabla 4 muestra la clasificación climática de las estaciones consideradas en este estudio.

El índice de baja continentalidad de las estaciones a lo largo del transecto estudio justifica su clasificación como hiperoceánica (Tabla 1). Esto se atribuye principalmente a su ubicación geográfica cerca del ecuador, y en segundo lugar a su cercanía al océano Pacífico.

## Resumen

Se reporta la investigación ecohidraclimatológica en marcha a lo largo del transecto Catacocha-Zamora en las provincias de Loja y Zamora-Chinchipe, Ecuador. La precipitación media anual oscila entre 400 mm en Catamayo, a lo largo del transecto de estudio, y 2200 mm en Zamora, hacia el límite oriental. Los datos de la precipitación indican que la precipitación media anual puede llegar a 6259 mm en un punto aislado en el Cerro del Consuelo, en el Parque Nacional Podocarpus, cerca de Loja. Variaciones altitudinales también son muy marcadas, entre 1230 m en Catamayo y 2930 m en el Cerro del Consuelo, a 900 m de Zamora. Los datos ecohidrológicos y ecohidroclimatológicos se examinaron con el objeto de apoyar

Tabla 1. Clasificación de los climas basada en el índice de continentalidad.

| Tipos | Índice de continentalidad $I_c$ |
|---|---|
| Hiperoceánica | 0-11 |
| Oceánica | 11-21 |
| Continental | > 21 |

Tabla 2. Clasificación de los climas basada en termicidad y los índices de temperatura positivos.

| Tipo de clima | Thermicity index $I_t$ | Índice de temperatura positivo $T_p$ |
|---|---|---|
| Infratropical | 710-890 | 2 900-3 700 |
| Termotropical | 490-710 | 2 300-2 900 |
| Mesotropical | 320-490 | 1 700-2 300 |
| Supratropical | 160-320 | 950-1 700 |
| Orotropical | 120-160 | 450-950 |
| Criorotropical | | 225-450 |

Tabla 3. Índices bioclimatológicos para estaciones en la región de estudio.

| Descripción/estación | Catacocha | Catamayo | La Argelia | Zamora |
|---|---|---|---|---|
| Elevación (m) | 1 840 | 1 230 | 2 160 | 970 |
| Latitud (Sur) | 4° 03′ 07″ | 3° 59′ 34″ | 4° 02′ 11″ | 4° 05′ 37″ |
| Longitud (Oeste) | 79° 38′ 29″ | 79° 22′ 15″ | 79° 12′ 04″ | 78° 57′ 00″ |
| Longitud de registro (año) | 17 | 16 | 37 | 28 |
| Periodo de registro | 1965-1981 | 1965-1980 | 1965-2001 | 1965-1992 |
| Mes más caliente | Octubre | Septiembre | Noviembre | Noviembre |
| Temperatura media del mes más caliente (°C) | 18.81 | 24.05 | 16.12 | 22.85 |
| Mes más frío | Marzo | Julio | Julio | Julio |
| Temperatura media del mes más frío (°C) | 17.52 | 23.58 | 14.76 | 20.45 |
| Índice de continentalidad $I_c$ | 1.29 | 0.47 | 1.36 | 2.40 |
| La temperatura media anual $T_{media}$ (°C) | 18.23 | 23.79 | 15.71 | 21.80 |
| La media de las temperaturas mínimas mensuales $T_{mín}$ (°C) | 11.06 | 13.86 | 7.44 | 13.24 |
| La media de las temperaturas máxima mensuales $T_{máx}$ (°C) | 26.06 | 33.33 | 24.68 | 31.85 |
| Índice de termicidad $I_t$ | 553 | 710 | 478 | 669 |
| Índice de temperatura positiva $T_p$ | 2 187 | 2 855 | 1 885 | 2 616 |

Tabla 4. Clasificación de las estaciones con base en índices bioclimatológicos.

| Índice | Catacocha | Catamayo | La Argelia | Zamora |
|---|---|---|---|---|
| Continentalidad | Hiperoceánico | Hiperoceánico | Hiperoceánico | Hiperoceánico |
| Termicidad | Thermotropical | Termotropical | Mesotropical | Termotropical |
| Temperatura positiva | Mesotropical | Termotropical | Mesotropical | Termotropical |

la investigación en el campo emergente de la ecohidroclimatología.

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# Helminthological Characterization of Kind Cyprinid *Algansea lacustris* in Three Different Areas of Lake Pátzcuaro, Michoacán, Mexico

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## Abstract

Gabriel-Luciano, M. V., & Uribe-Cortez, J. (November-December, 2015). Helminthological Characterization of Kind Cyprinid Algansea lacustris in Three Different Areas of Lake Pátzcuaro, Michoacán, Mexico. *Water Technology and Sciences* (in Spanish), *6*(6), 75-87.

In the different waters bodies of the country are endemic fish species. The treatment has given them for the care, maintenance and production, either for consumption or for sale at various scales, has been branded variations in many cases produced parasitic symptoms, the lake of Patzcuaro is no exception. Because of the importance posed to human and fish species own health, this study aimed at determining the helminthfauna in three study areas of Lake Patzcuaro arises. San Andres Tzirondaro, Oponguio and Puácuaro: methodologically, an analysis of parasites in acúmara Algansea lacustris was performed. This method allowed to quantify and identify the various helminths. A total of five species more an ectoparasite, belonging to six groups were recorded: Nematodes (Capillaria patzcuarensis) Flukes (Posthodiplostomum minimum), cestodes (Bothriocephalus acheilognathi) Acantocephalo (Arritmorrynchos brevis), monogenean (Octomacrum mexicanum) and the ectoparasite Arthropod (Lernea cyprinacea). So it is concluded that due to the life cycle, fish parasites contract because of the feces of birds that are formed in the host, in addition, the lack of maintenance of lake areas, among other factors.

**Keywords**: Helminths, lifecycle, Algansea lacustris species, parasites.

## Resumen

*Gabriel-Luciano, M. V., & Uribe-Cortez, J. (noviembre-diciembre, 2015). Caracterización helmintológica del ciprínido Algansea lacustris en tres diferentes áreas del lago de Pátzcuaro, Michoacán, México.* Tecnología y Ciencias del Agua, *6(6), 75-87.*

*En los diferentes cuerpos de agua del país existen especies de peces endémicas. El tratamiento que se les ha brindado para el cuidado, mantenimiento y producción, ya sea para el consumo o venta en diversas escalas ha estado tildado de variaciones que en muchos de los casos ha producido sintomatología parasitaria y el lago de Pátzcuaro no es la excepción. Debido a la importancia que entraña para la salud humana y de las propias especies de peces, este trabajo se plantea el objetivo de determinar la helmintofauna en tres áreas de estudio del lago de Pátzcuaro. Metodológicamente, se realizó un análisis de los parásitos del acúmara Algansea lacustris en San Andrés Tzirondaro, Oponguio y Puácuaro. Este método permitió cuantificar e identificar los helmintos distintos. Se registraron un total de cinco especies, más un ectoparásito, pertenecientes a seis grupos: nematodos (Capillaria patzcuarensis), tremátodos (Posthodiplostomum mínimum), cestodos (Bothriocephalus acheilognathi), acantocephalo (Arritmorrynchos brevis), monógeneo (Octomacrum mexicanum) y el ectoparásito artrópodo (Lernea cyprinacea), por lo que se concluye que debido al ciclo de vida, los peces contraen parásitos por causa de las heces de las aves que se forman en los hospederos, además de la falta de mantenimiento de los espacios lacustres, entre otros factores.*

***Palabras clave**: helmintos, ciclo de vida, especie Algansea lacustris, parásitos.*

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## Introduction

Pedraza (1994) demonstrated that populations of *Algansea lacustriss* are threatened by overfishing, a lack of knowledge about its biological conditions and environmental degradation related to eutrophication, loss of water and a large amount of wasted organic matter. All of this is partly caused by the transport of sediments from the deforestation of forests and by agricultural waste discharges. Such environmental factors considerably affect the health of these fish, threatening their populations. Nevertheless, few investigations have been conducted about the biology, ecology and health of this endemic fish.

Thirteen helminth infections were found in *Algansea lacustris* by Ruiz (1998) and Mendoza- Garfias, García and Pérez-Ponce-de-León (1996), who developed a helminthological registry consisting of 10 species. Meanwhile, Lamothe (1980) described a *platyhelminto* parasite (the monogenea *Octomacrum mexicanum*) and the parasitic patterns contained in this species.

Another study which was equally important, by Marcos-Antonio *et al*. (2009), explains the incidence of helminth infection in *Goodea Atripinnis* fish populations in the same lake, Lake Patzcuaro. This study, as well as Berlanga (1993), mentions that this lake harbors an important ichthyofauna consisting of 12 species, 8 of which are endemic and 4 were introduced. Rosas (1976) reported that *Cyprinidae* is found among the endemic species in this lake, which is better known in the region as "*acumara*" (Patzcuaro chub), the "omnivorous fish."

Studies by Rivera and Orbe (1990) indicate that the species in the lake are important to the local economy, given the amount caught and because market demand is very important to the lakeside residents. They are also a natural resource and source of protein for the Purepechas, who consume it during the period of Lent.

This knowledge is of utmost important to fishermen in the region. It is also important that they learn to identify certain factors that produce helminthiasis in the fish and the possible consequences to humans.

To put the objective of the study in context, it is necessary to know some of the characteristics of the lake and the fish. Therefore, Figure 1 presents the location of Lake Patzcuaro and Table 1, at the end of the document, shows the variety of fish species in the lake, including pike silverside *Algansea Lacustris* and Israel carp, to mention a few.

Figure 1 shows the location of Lake Patzcuaro in the west-central part of Mexico, in Michoacan, at coordinates 19º 30′ 59′′ latitude north and 101º 36′ 35′ longitude west and an elevation of 2 035 meters above sea level. It is 1 096 km in size, of which 90 km corresponds to the shores of the lake (Ceballos, 1994).

*Algansea lacustris* is one of the fish species found in the lake. It has very specific characteristics and is endemic to the lake. It has a thin and long body, a dark dorsal and dark gray ventral, a small mouth, and cycloid and pre-dorsal scales with a row between the beginning of the pelvic fin and the lateral line. A total of 79 to 90% of the scales are cycloid. Figure 2 shows the overall characteristics.

The taxonomy is classified as follows:

Kingdom: *Animalia* (Linnaeus, 1758).
Phylum*:* *Chordata* (Bateson, 1885).
Class: *Osteichthyes* (Huxley, 1880).
Order: *Cypriniformes* (Berg, 1940).
Family*:* *Cyprinidae* (Bonaparte, 1832).
Genus: *Algansea* (Girard, 1856).
Species: *Algansea lacustris* (Steindachner, 1895).

Girard (1856) and Steindachner (1895), cited in Rivera and Orbe (1990), briefly describe the native Patzcuaro chub (*Algansea lacustris*) in Lake Patzcuaro, an organism which has not been widely studied even though it is economically important to the region and there is a high possibility for controlled exploitation.

Table 1. Endemic ichthyofauna and introduced species in Patzcuaro Lake (Berlanga, 1993).

| Species | Common Name | Origin |
|---|---|---|
| **Cyprinidae** | | |
| *Algansea lacustris* | Patzcuaro chub | Endemic |
| *Cyprinus carpio specularis* | Israel carp | Introduced |
| **Goodeidae** | | |
| *Allophoros robustus* | Bulldog Goodeid | Endemic |
| *Goodea artripinnis robustus* | Blackfin Goodea | Endemic |
| *Neophorus diazi* | Choromu | Endemic |
| **Antherinidae** | | |
| *Chirostoma estor* | Pike Silverside | Endemic |
| *Chirostoma grandocule* | Bigeye Silverside | Endemic |
| *Chirostoma attenuatum* | Slender Silverside | Endemic |
| *Chirostoma patzcuaro* | Patzcuaro Silverside | Endemic |
| **Centrarchidae** | | |
| *Micropterus salmoides* | Largemouth Bass | Introduced |
| **Cichlidae** | | |
| *Oreochromis niloticus* | Nile Tilapia | Introduced |
| *Tilapia rendalli* | Redbreast Tilapia | Introduced |

Fuente: elaboración propia a partir de los datos que proporciona Berlanga (1993).

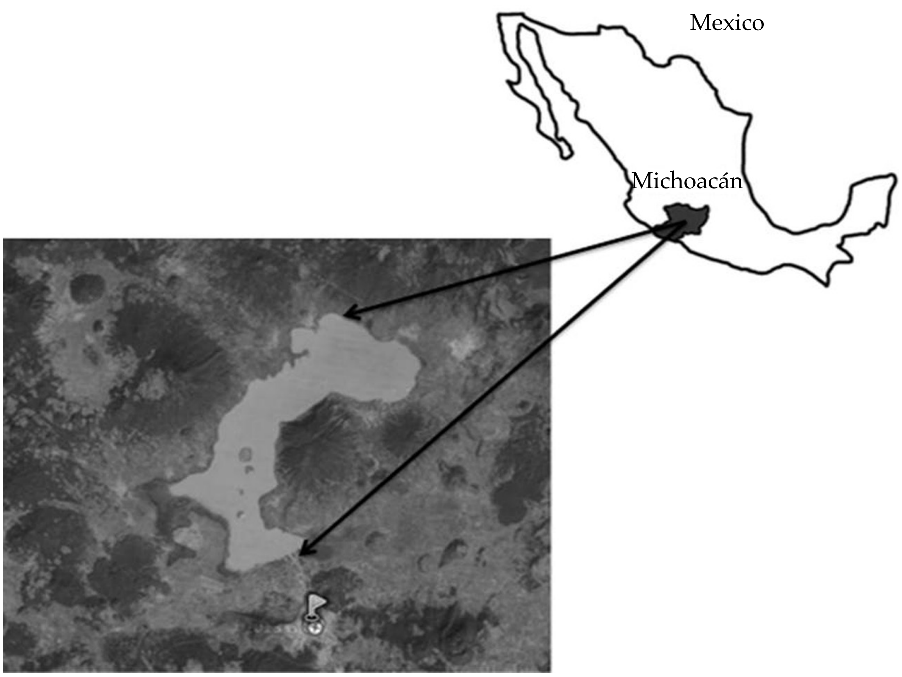


Figure 1. Location of Patzcuaro Lake.

Source: authors based on information from Marcos-Antonio *et al*., 2009.

Figure 2. Adult *Algansea lacustris* fish species.
Source: edited photo

In the work *Ontogenic Phases of Patzcuaro Chub fish (Algansea Lacustris) in the Lake Patzcuaro*, De Buen (1944) mentions that this species, which reproduces from November to April, loses a large amount of fertilized eggs in spawning areas. Some incubation, embryonic and taxonomic data are presented. Samples of *Algansea lacustris* were collected for this work in some of the same areas. A photograph of the areas and the locations on the shore of the lake is presented in Figure 3.

Given the need to contextualize the species, the literature references that best support the development of the helminth fauna and the ichthyology of the lake are noted throughout the text, while the most current reports are those already mentioned, by Ruiz (1998) and Mendoza-Garfias *et al*. (1996). Since the 1990s, the very few investigations about helminth fauna in fish species have required a simple and brief analysis such as the one proposed herein, which identifies the aspects involved in the topic under study, as well as the specialized literature that has been written, and which has been proposed as a basis, a reference, to be consulted currently.

A young Purepecha named Armando, who studies biology at the Michoacan University of San Nicolas de Hidalgo (UMSNH, Spanish acronym), described the need for current research that can provide guides for understanding the importance of aquaculture to human health, in terms of both consumption and commerce. For him, these questions are important (testimony from Armando, resident of Quiroga, interviewed 2010).

Thus, the present study is aimed at characterizing the helminth fauna in *Algansea Lacustris*. The main objective was to characterize the spatial distribution of the parasite hosts and the abundance of helminth in each of the sampling areas, as well as to determine particular measures to prevent disease.

The main hypothesis of this work is that the pollution of the medium inhabited by the *Algansea Lacustris* contributes to this species becoming a host for these parasites. The dependent variable was the medium inhabited by the species since we presumed that it is a factor in the quality of life of the organism as well as its quality for human consumption. The independent variable was the different areas studied, to demonstrate whether the medium in which it lives affects the establishment of helminth and, thus, the existence of helminth fauna.

Lastly, this work provides knowledge about the conditions which favor the adequate reproduction of the species endemic to Lake Patzcuaro, that is, without the presence of large amounts of helminth fauna, to contribute to human health and the survival of aquaculture.

## Methodology

Samples were collected during the Lent season of 2010. As briefly described in the beginning of the document, collections of Patzcuaro chub were taken from the localities of San Andrés Tzirondaro (Area 1), Oponguio (Area 2) and Puácuaro (Area 3). A handmade net was used, with a 2.5-inch mesh opening, which according to Barrera-Bassols (1986) is selective for this type of fish.


Figure 3. Algansea *lacustris sampling* areas.

Source: authors.

Twenty samples from each station were collected, for a total of 60 fish. They were transported in a Koblenz Ultrafreeze™ refrigerator to the Parasitology and Nutrition Laboratory of the UMSNH for analysis.

The following data were recorded for each sample: weight, total length, pattern length and maximum height. Each host was given a general helminthological exam (external and internal). The external exam consisted of inspecting the surface of the body, the base of the fins, the gills, anal opening, mouth and operculum.

The internal exam included extracting the intestines, liver, spleen, brain, eyes and mesentery, which were placed in separate Petri boxes with a 0.6% saline solution. They were examined by tearing them apart with 2 mm bent dissecting needles with a grooved metal handle, of different lengths. Observations were performed with a SZX7 zoom Olympus stereoscopic microscope. Cutting utensils risks dissecting the parasites (Lamothe, 1997).

Dissecting forceps and needles were used to analyze and conserve the adult helminth, which were placed in Petri boxes with saline solution for taxonomic evaluation and determination (Yamaguti, 1961; Olson, Lewis, & Urawa, 1983). They were conserved in 70% ethyl alcohol, in Alcohol Lourdes medium at 96% (not denatured). They were then labeled by date, locality, common name and scientific name of the host, number and group of parasites, and name of the collector. All the helminths found in the fish were counted and fixed for later categorization into the group in which they belonged. Lastly, they were deposited in the Parasitological Collection of the Parasitology Laboratory at the Michoacan University of San Nicolas de Hidalgo.

## Study Analysis

The infection was characterized using four parameters, or ecological equations, as defined by Mendoza-Garfias *et al*. (1996):

Prevalence (prev): percentage of hosts with helminth parasites:

$$\text{Prev} = \frac{\text{Host fish}}{\text{Total fish}} * 100$$

Abundance (Abun): number of individuals of a parasite species found per host.

$$\text{Abun} = \frac{\text{Number of helminths}}{\text{Total fish}} * 100$$

Intensity intervals (II): the highest and lowest number of individuals recorded out of the total parasite hosts for a particular helminth species.

Average intensity (AI): number of individuals of a particular parasite species per infected host.

$$\text{AI} = \frac{\text{Number of helminths}}{\text{Host fish}}$$

## Results

As a result of the parasitological analysis of the *Algansea lacustris* species collected —in three sampling areas (San Andrés Tzirondaro, Oponguio and Puácuaro) with 20 samples from each area, and sizes ranging from 19 to 25 cm— three species were identified in the area of Puacuaro and five in San Andres and Oponguio. These included, among others (one of each); *monogenous* (Carus, 1863); *trematoda* (Rudolphi, 1808); *cestoda* (Carus, 1885); *nematode* (Rudolphi, 1808); *acantocephala* (Kohlreuther, 1771); *arthropod* ectoparasite (Latreille, 1829) (Table 2).

A list is presented below of the taxonomical groups of the parasites mentioned:

*Phylum:* *Platyhelminthe* (Gagenbaur, 1859).
Class: Trematoda (Rudolphi, 1808).
Order: Polyopisthocotylea (Odhner, 1912).
Family: Dicocotylidae (Precios, 1936).
Genus: *Octomacrum* (Mueller, 1934).
Species: *O. mexicanum* (Lamothe, 1982).

*Phylum:* *Platyhelminthes* (Gagenbaur, 1859).
Class: Trematoda (Rudolphi, 1808).
Order: Strigeatoidea (La Rue, 1957).
Family: Diplostomatidae (Poirier, 1888).
Genus: *Posthodiplostomum* (MacCallum, 1921; Dubois, 1936).
Species: *P. minimum* (Hughes, 1927).

*Phylum:* *Platyhelminthes* (Gegenbaur, 1859).
Class: Cestoda (Rudolphi, 1808; Carus, 1885).
Orden: Pseudophyllidae (Carus, 1863).
Familia: Bothriocephalidae (Blanchard, 1849).
Género: *B. othriocephalus* (Rudolphi, 1808).
Especie: *B. acheilognathi* (Yamaguti, 1961).

*Phylum:* *Acanthocephala* (Rudolphi, 1801).
Class: Palaeacanthocephala (Meyer, 1931).
Order: Polymorphida (Meyer, 1931).
Family: Polymorphidae (Meyer, 1931).
Genus: *Arhythmorhynchus* (Luhe, 1911).
Species: *Arhythmorhynchus brevis* (Van Cleave, 1916).

*Phylum:* *Nematoda* (Cobb, 1819).
Class: Adenophorea (Aphasmidia) (Chitwood, 1958).
Order: Trichocephalida (Skrjabin & Schul'ts, 1938).

Family: Capillariidae (Neveu-Lemaire, 1936).
Genus: *Capillaria* (Zeder, 1800).
Species: *C. patzcuarensis* (Osorio, Pérez, & Salgado, 1986).

*Phylum:* *Arthropods* (Latreille, 1829).
Suborder: Crustacea (Brünnich, 1772).
Class: Maxillopoda (Dahl, 1956).
Order: Cyclopoida (Burmeister, 1834).
Family: Lernaeidae (Dana, 1846).



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Table 2. Record of heminths in Algansea lacustris for each sampling area in Patzcuaro Lake.

| Helminth Species | Area 1 (San Andrés T.) | Area 2 (Oponguio) | Area 3 (Puácuaro) |
|---|---|---|---|
| **Monogenous** | | | |
| *Octomacrum mexicanum* | X | X | X |
| **Trematoda** | | | |
| *Posthodiplostomum mínimum* | X | X | X |
| **Cestoda** | | | |
| *Bothriocephalus acheilognathi* | X | X | - |
| **Acantocephala** | | | |
| *Arhythmorhynchus brevis* | X | X | - |
| **Nemátoda** | | | |
| *Capillaria patzcuarensis* | X | X | X |
| **Arthropod** | | | |
| *Lernaea cyprinacea* | X | X | - |

- = absence; X = presence.

Source: authors basin on systematization of the information collected.

Genus: *Lernaea* (Linnaeus, 1758).

Species: *Lernea cyprinacea* (Linnaeus, 1758).

Especie: *Lernea cyprinacea* (Linnaeus, 1758).

Table 2 presents the helminth in the *Algansea lacustris* recorded for each sampling area. The helminths that were found to be very common were were *octomacrum*, *trematode* and *Capillaria patzcuarensis*. Therefore, *Algansea* has a high probability of contracting helminths, and not only this species but the others located there, which are shown in Table 1.

The areas with the largest number of infected fish were Andrés Tzirondaro and Oponguio, with 100%, whereas at the Puacuaro station this study found a prevalence of 60% of helminth fauna in *Algansea lacustris*. In addition, three helminth parasite species from the five helminthological registries were found at the three stations: *Octomacrum mexicanum* (Lamothe, 1980), *Posthodiplostomum minimun (*Hughes, 1927) and *Capillaria patzcuarensis* (Osorio, Pérez, & Salgado, 1986). Meanwhile, *Bothriocephalus acheilognathi* (Yamaguti, 1934), *Arhythmorhynchus brevis* (Van Cleave, 1916) and the ectoparasite *Lernea cyprinacea* (Linnaeus, 1758) were only found in two sampling areas (San Andrés and Oponguio).

Lastly, according to testimony by Alfredo Lopez, the diseases contracted by the fish in the San Andres area were due to the presence of birds that drop feces there. According to Lopez, the birds do this in the mornings and afternoons as they sit in the aquaculture area (interview with Alfredo Lopez, resident of Santa María-Río Verde Hydrographic System Fe de la Laguna, interviewed in 2010).

On the other hand, Margarita Lopez stated that the helminthiasis in the fish was particularly due to the introduction of other fish by producers or farmers who do not understand the endemic conditions of the species. This causes other species to become ill or disappear by being infected by others containing different helminths (interview with Margarita Lopez, resident of Santa Fe de la Laguna, 2010).

Isabel Lopez, a resident of San Andres, indicated that the problem is that producers and the general public do not know how to control the production of the parasites. And therefore no prevention system exists to help to resolve problems as they arise (interview with Isabel Lopez, resident of San Andres Tzirondaro, 2010).

San Andres had the largest abundance of helminths and ectoparasites (84/153), which represents 54.9% of the total parasites isolated. The Patzcuaro chub species found in Puacuaro had a lower abundance (15/153), with 9.8% of helminths, including the ectoparasites (Table 3). Most of the parasites were found in the adult phase and were contracted indirectly, while *Octomacrum mexicanum* was contracted directly.

According to Javier Perez, who is in agreement with Alfredo Lopez, it is logical that a large presence of helminths would be seen in San Andres, especially considering the large number of birds who leave their feces in the area, which touch the lake (interview with Javier Perez, resident of Santa Fe de la Laguna, 2010).

The largest number of helminth infections were found in the intestines, with an abundance of 56/153 (36.6%), followed by the gills, with an abundance of 33/153 (21.5%), the body cavity with 26/153 (16.9%) and lastly, the eyes (1.3%) (Table 3).

Jose Mireles, another resident of San Andres, said that the gills are the organs that are most affected, particularly because this is a vital spot for fish species, practically like the heart, or at least it is the site from which the heart receives its oxygen, its vital inflow (interview with Jose Mireles, resident of San Andres, 2010).

The *Capilaria patzcuarensis* parasite was also found in the intestines of adults, which were inflamed and retain a large amount of water. The presence of *P. mininum* metacercariae was found in the epithelial and muscles of the intestine, which were reddened at the places where they were found.

## Comparison of *Algansea lacustris* infected with helminths in the three areas in Lake Patzcuaro

Table 4 presents the prevalence and abundance of helminths in fish species by sampling area. Most significant is the list of species identified by sampling area, which is presented in Table 2, and the abundance in Table 3. Area 1 presented a greater diversity of helminth species, 5/5 (100%), and an ectoparasites species with a total abundance of 84

Table 3. Abudance of helminths in Algansea lacustris in the three sampling areas in Patzcuaro Lake.

| Helminths | San Andrés T. | Oponguio | Puácuaro | Total | Phase | Life cycle |
|---|---|---|---|---|---|---|
| *Octomacrum mexicanum* | 4 | 3 | 1 | 8 | A | D |
| *Posthodiplostomum mínimum* | 25 | 23 | 2 | 50 | M | I |
| *Bothriocephalus acheilognathi* | 2 | 1 | 0 | 3 | A | I |
| *Arhythmorhynchus brevis* | 1 | 1 | 0 | 2 | Cystacanth larvae | I |
| *Capillaria patzcuarensis* | 42 | 23 | 12 | 77 | A | D/I |
| *Learnea cyprinacea* | 10 | 3 | 0 | 13 | A | I |
| | | | | | | |
| **Total** | **84** | **54** | **15** | **153** | | |

A = adult; M = metacercariae ; D = direct, I = indirect.

Source: authors based on systematization of the information collected for this study.

parasites. Area 2 also had a prevalence of 5/5 (100%), where the abundance of parasites was 54. Area 3 had a 3/5 (60%) prevalence and abundance of only 15 helminths.

Of the total 60 fish collected (20 in each locality) 40 were females and 20 males. Both had the same parasites, which could be found in the hard roes. The males did not present as many as the females, with a weight of 60% in females versus 40% in males. *Botriocephalo acheilognathi* was found in both cases, which had the highest prevalence.

Figure 4 shows the trends in helminths found in the hosts. Area 1 (San Andres) had the highest prevalence rate and thus was the region with the most helminths in the fish hosts, with the greatest diversity of parasites and, therefore, human health is at risk from ingesting *Algansea lacustris* when proper hygiene measures are not used, which basically consists of determining the water quality and caring for the natural resources located there.

Oponguio and Puácuaro were considerably lower than the trend found in San Andres, the area with the largest number of helminths per fish hosts. In numerical terms, both were very similar (exactly 4.0 and 1.0 points), which is interpreted as the presence of a similar number of parasites in the two areas. This provides a reason for other studies to take into account the characteristics related to this difference, and to compare the particularities of the populations and regions where the fish hosts are located in order to understand the local context.

In terms of the prevalence of the helminth species according to their respective ranges of intensity and average intensity, an adjustment can be seen in this datum with the datum for helminths per host species shown in Figure 4, and with Area 1 in Table 4. San Andres had the highest rate, with 30%— higher than in the other two areas— which says a lot about the helminthiasis found in the hosts there. Nevertheless, in terms of the average intensity and the range, the rates are consistently the same as in Oponguio and Puácuaro, indicating a similar number of parasites in the hosts.

To reiterate, the site with the highest prevalence values was Area 1 (San Andres), with 7 (30%) hosts containing parasites and an abundance of 0.7; followed by Area 2 (Oponguio) with a prevalence of 3.33 (15%) and abundance of 0.45; and Area 3 (Puácuaro) with the lowest prevalence, 2.33 (15%), and an abundance of 0.25 (Table 4).

## Discussion

The hypothesis to be tested by this investigation has been accepted, showing that the pollution of the environment inhabited by the *Algansea lacustris* is a factor that affects the parasites that use this species as a host. The presence of birds which generate feces, the little or no care or maintenance of the lacustrine resources and exploitation without consideration of the species are elements that contribute to the presence of helminths in the fish hosts, considerably increasing the prevalence levels.

The helminthological records of a host is very important since their identification contributes to analyzing their biology and thereby understanding the relationship that exists between the parasite and the host (Núñez, 2006).

Lara (2007), in *Extensive and Intensive Cultivation of Pike Silverside in Patzcuaro* shows the problems faced by the systems related to the lake that contains these fish, alluding to a relationship between production systems and helminthological processes which becomes clear during the process, and the consequences to the *Chironomidae estor* species.

In that study, helminthological processes were also present during the production cycles of the fish species, according to their interpretation.

In *Helminth Principles in Fish in Lake Patzcuaro*, Chiman (2008) reports that various areas on the shore have high concentrations of

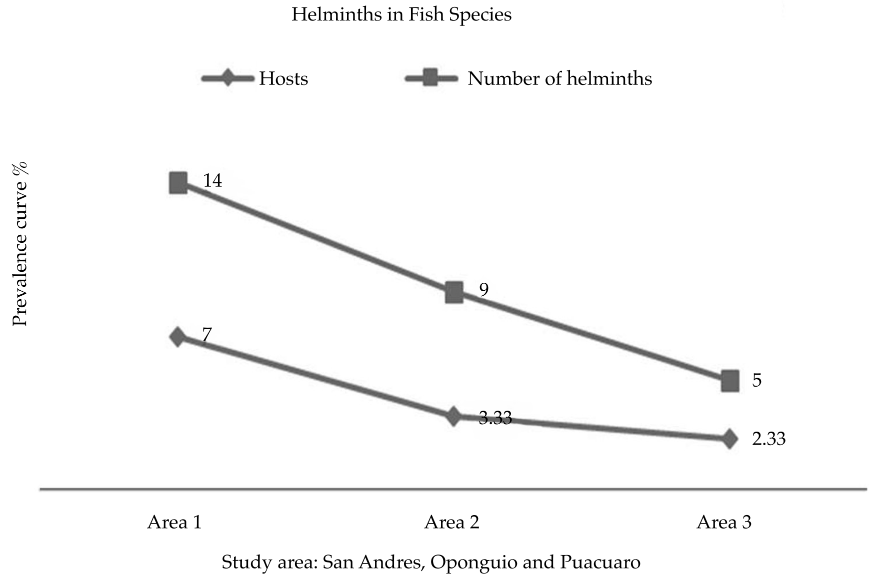


Figure 4. Helminths in fish hosts.

Source: authors with data obtained from the three study areas analyzed.



Table 4. Overall comparison of helminth fauna in *Algansea lacustris* in the three sampling areas.

| *Algansea lacustris* *N* = 20 | Host fish (HF) | Number of Helminth (NH) | Prevalence (%) | Abundance (%) | Intensity ranges (IR) | Average intensity (AI) |
|---|---|---|---|---|---|---|
| Station 1 | | | | | | |
| San Andrés T. | 7 | 14 | 30 | 0.7 | 1-3 | 1.53 |
| Station 2 Oponguio | 3.33 | 9 | 15 | 0.45 | 1-2 | 1.94 |
| Station 3 Puácuaro | 2.33 | 5 | 15 | 0.25 | 1-4 | 1.8 |

Source: authors based on systematization of information collected for this study.

helminth. This coincides with our investigation and subsequent understanding of the existence of a high prevalence of helminths in the San Andres areas, with six different parasites, and therefore is similar to the area of Oponguio.

Miller, Wendell and Minckley (2005), along with Chiman (2008), indicate high helminth indices in nearly all the fish species in Lake Patzcuaro, not only in San Andrés Tzirondaro, Oponguio and Puácuaro, but also in the rest of the localities around the lake. Given these references, the present study was optimistically considered to be a feasible approach to investigating the reality of aquaculture, which is clearly part of the lake's waterfront.

In a study about helminths by Lira (2002), the incidence of parasites in Old World silverside species (Atherinidae) was evaluated. Along with Chiman and Miller, this investigation is a good reference for understanding that the species in the lake are subject to helminthiasis in a manner that is virtually irremediable.

After having referenced this literature, it is important to mention that Area 2 has an actual depth of 7 m. Given that it is so deep, this area should have a lower number of parasites, according to Marcos-Antonio *et al.* (2009) who report lower numbers of helminths at greater depths. Oponguio has various parasites because of the currents in the lake or because of the routes taken by the Patzcuaro chub fish to arrive their spawning sites, where they develop and sexually reproduce.

In addition, piscivorous birds such as anatidae and herons are present, another factor that causes helminthiasis in fish because of the feces that fall in the water and contain infectious forms of *P. minimum*, *A. brevis*, *C. patzcuarensis* and *B.acheilognathi* (Mendoza-Garfias *et al*., 1996; Ruiz, 1998). In addition, the mud found at the bottom of the lake provides a habitat for shrimp, amphipods and copepods which are intermediate hosts for the parasites *B. acheilognathi* and *A. brevis*, which in turn are consumed by the fish (Rosas, 1976).

In Oponguio, five helminth species as well as the ectoparasite were present, but in terms of abundance this area had the highest number of parasites. As in San Andres, the habitat conditions were different. It was shallower (2.92 m), with lentic waters which, combined with the abundance of aquatic weeds provides an ideal habitat for the fish (Marcos-Antonio *et al*., 2009). A variety of aquatic vegetation was also present where many vertebrate and invertebrate organisms find shelter, such as crustaceans and gastropods, which serve as intermediate hosts for helminths, such as *P. minimum*, *A. brevis*, *C. patzcuarensis* and *B. acheilognathi*. In this case, a large variety of birds was also present, which similar to the previous area serve as intermediate hosts.

Puacuaro had three helminth species, and a smaller number of helminths were collected here than in the other areas.

Station 3 had the lowest presence of birds and an intermediate water depth. Unlike the other sampling stations, the aquatic weeds were not proliferate and the parasites were not as diverse or abundant because of the small final and intermediate host populations (Marcos-Antonio *et al*. 2009), another factor related to the prevalence of helminths in hosts.

Of the 10 species described by Mendoza-Garfias *et al*. (1996) and the 13 by Ruiz (1998), the present study recorded and observed six: *Octomacrum mexicanum*, *Posthodiplostomum minimum*, *Bothriocephalus acheilognathi*, *Arhythmorhynchus brevis*, *Capillaria patzcuarensis* and *Learnea cyprinacea.*

A contribution by the present study to investigations of helminths in fish is having returned to the structure of classical and more recent texts to describe the objective of the study presented. The authors cited were able to find a large number and diversity of helminth parasites in the samples used in their studies, which they obtained from local markets in Patzcuaro. Nevertheless, it is worth mentioning that the fish captured for their study were considered to be from altered zones, that is, from areas with a high degree of helminth, which is common in the aquaculture area and in the endemic organisms themselves and, therefore, of course in the analysis.

Another contribution is the dual analysis of helminths-fish hosts conducted at the better maintained stations at the lake. A good deal of complexity was involved in collecting the samples used to find parasites and develop the helminthological analysis.

Two species were notable for their high helminth indices— *C. patzcuarensis* and *P. minimum.* The former is a parasite with an indirect life cycle (Ruiz, 1998). The *A. brevis* and *B. acheilognathi* helminths are involved as intermediate crustacean hosts, while the adult phase develops in *A. brevis*. *B. acheilognathi* was found in fish with incomplete development, in which the *plerocercoid* phase was prevalent without the development of the mature *proglottid C. patzcuarensis*, *O. mexicanum* or the ectoparasite *L. ciprynecea*, observed mostly in the adult stage.

## Conclusions

The helminth species found were *O. mexicanum*, *P. minimum*, *B. acheilognathi*, *A. brevis* and *C. patzcuarensis*, in addition to the ectoparasite *L. ciprynacea* which is also affecting the health of *Algansea lacuastris* fish. The San Andres area had the highest number of helminths (84), followed by Oponguio (54) and Puacuaro (15). In terms of the incidence of the number of parasites, the factor that affected this was the diversity of the organisms that interact, some of which are part of the food chain, especially since these organisms are carriers of helminths in some phase of their life cycle.

Lastly, it is difficult to propose measures to control helminth fauna. This is because the fish as well as the organisms that inhabit those micro-ecosystems contract the parasites mostly from birds, and the majority of the parasites are passed through their feces and reach an intermediate host which is eaten by the fish. In addition, the *A. lacustris* are in their natural habitat.

In terms of human consumption, the fish should be well cleaned and cooked. It is also recommended that they be frozen for three days, during which some of the helminths lose their viability. Nevertheless, no illnesses from the parasites in the fish in Lake Patzcuaro region have been found to have harmed the health of any person.

Technical support recommended to control helminth fauna in the lake area would be provided by groups of professionals who would determine the guidelines to control the production of the parasites. In addition, in terms of controls over the consumption of the fish and for human health, it is necessary to rely on experts in health and biology who are specialized in diagnosing and evaluating the species.

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# Fresh/Brackish Water Interfaces in the Merida-Progreso Region, Yucatan

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## Abstract

Rocha, H., Cardona, A., Graniel, E., Alfaro, C., Castro, J., Rüde, T., Herrera, E., & Heise, L. (November-December, 2015). Fresh/Brackish Water Interfaces in the Merida-Progreso Region, Yucatan. *Water Technology and Sciences* (in Spanish), *6*(6), 89-112.

A coastal karstic aquifer highly exposed to anthropogenic pollution and seawater intrusion is the main water supply source for Merida-Progreso inhabitants (Yucatan, Mexico). In this investigation fresh/brackish water interface changes linked to precipitation events were identified and correlated with the Ghyben-Herzberg principle. Water level elevations and electrical conductivity values were manual and automatic recorded in a 26 wells monitoring network. Results indicate a fast water level increase (hours) to precipitation events, for example a 19 cm water level increase and 570 $\mu$mhos·cm$^{-1}$ decrease measured at the fresh/brackish water interface were recorded in an observation well located west of Merida city less than 24 hours after a 60 mm rainfall. Predictions using the Ghyben-Herzberg principle do not correlate with in-situ measurements. Actual thickness of the freshwater lens change from rainy (33 m) to dry (31.5 m) season below Merida city, minor thickness changes along the year were identified north to Merida city (26 m freshwater lens thickness).

**Keywords**: Groundwater, karst, Freshwater, Brackish water, Ghyben-Herzberg principle, Electrical conductivity, Merida-Progreso, Yucatan.

## Resumen

*Rocha, H., Cardona, A., Graniel, E., Alfaro, C., Castro, J., Rüde, T., Herrera, E., & Heise, L. (noviembre-diciembre, 2015). Interfases de agua dulce y agua salobre en la región Mérida-Progreso, Yucatán.* Tecnología y Ciencias del Agua, *6(6), 89-112.*

*La población en la región Mérida-Progreso, Yucatán, México, depende totalmente del agua subterránea que es obtenida de un acuífero kárstico costero, vulnerable a la contaminación antropogénica y natural por los efectos de la intrusión salina. El objetivo de estudio fue describir, espacial y temporalmente, el comportamiento de las interfases de agua dulce y agua salobre ante eventos de precipitación, y proponer alternativas que ayuden a explicar la respuesta observada y su relación con el principio de Ghyben-Herzberg. Se utilizó una red de 26 pozos de observación para determinar elevaciones del nivel del agua y cambios en la conductividad eléctrica en las interfases mediante mediciones manuales y una red automatizada. Los resultados indican que en general existe una respuesta rápida (del orden de horas) del nivel freático a la precipitación, por ejemplo un incremento de 19 cm en la elevación del nivel del agua al occidente de Mérida y un comportamiento irregular de las elevaciones de las interfases de agua salina (decremento de 570* $\mu$*mhos·cm*$^{-1}$*) y salobre ante eventos de precipitación (60 mm). De acuerdo con los resultados obtenidos, el principio de Ghyben-Herzberg no es aplicable para la determinación de la posición de la interfase de agua salina en la región. Finalmente, se definieron espesores de agua dulce bajo la zona urbana de Mérida para las temporadas de lluvia (33 m) y estiaje (31.5 m), y un espesor promedio de 26 m al norte de Mérida a 15 km de la línea de costa donde no hay una variación entre ambos periodos.*

***Palabras clave****: agua subterránea, karst, agua dulce, agua salobre, principio de Ghyben-Herzberg, conductividad eléctrica, Mérida-Progreso, Yucatán.*

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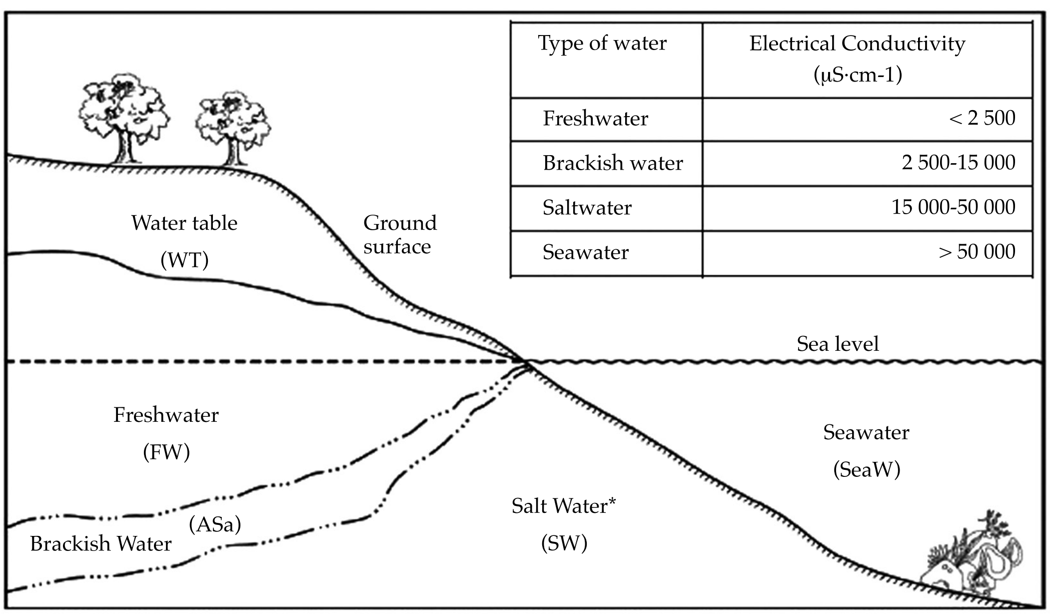
## Introduction

Groundwater has been important to meeting human water demands for a very long time (Custodio & Llamas, 1976). While its intensive use and pollution are common problems, the interaction between freshwater and seawater —called saline intrusion (SI)— creates a unique problem for the sustainability of groundwater. This intrusion involves seawater entering freshwater aquifers, which changes the amount and quality of the groundwater that flows into coastal systems (Barlow & Reichard, 2010). As a consequence, the salinity of coastal aquifers varies over space and time, a condition which merits a special investigation of characteristics related to flow, quality and management (Post & Abarca, 2009). As in many countries, Mexico has long coastlines. The engagement in a variety of economic activities leads to the exploitation of groundwater, creating constant changes in freshwater (FW)–saltwater (SW) ratios (Custodio & Llamas, 1976). The analysis of this ratio (Figure 1) in coastal regions demonstrates an equilibrium state called the brackish water interface (BW). The location and dimensions of the interface are related to the hydrogeological characteristics and density of the SW. It is dynamic and depends on variations in recharge and extraction (Custodio & Llamas, 1976).

A karst medium covers 12% (KWI, 2008) to 25% (Ford & Williams, 2007; LaMoreaux, Powell, & LeGrand, 1997) of the total continental area of the planet, and 25% of the total global population receives some or all of its water from this type of aquifer (Darnault, 2008; Green, Painter, Sun, & Worthington, 2006), including the Yucatan. There is great interest in the karst aquifers located on the coast because their effluents support a large variety of coastal ecosystems (marshes and wetlands, among others) and are also collected to supply water to the population. In these calcacerous mediums, geochemical processes




| Type of water | Electrical Conductivity (μS·cm-1) |
|---|---|
| Freshwater | < 2 500 |
| Brackish water | 2 500-15 000 |
| Saltwater | 15 000-50 000 |
| Seawater | > 50 000 |

* De composición similar al agua de mar, pero que ha interaccionado por largo tiempo con el medio geológico y que subyace al agua salobre.

Figure 1. Overall definition of the types of water in the coastal aquifers applicable to this publication.

develop that can accelerate an increase in secondary permeability through the dissolution of channels. The application of chemical thermodynamic principles has demonstrated that simply mixing two waters in equilibrium or even mixtures oversaturated with calcite can result in a mixture with an undersaturation of that mineral (Hanshaw & Back, 1979). Direct observations corroborate that karstification increases at the brackish water interface. Additionally, in terms of the physio-chemistry of the water/aquifer interaction, ionic exchange (Ca/Na) processes play an important role, as does the dolomitization or increase in the magnesium fraction of limestone. These can also vary over the course of the year due to changes in the composition of freshwater (Fernández, Baquero, Lorca, & Verdejo, 2003).

In Mexico, the greatest problems with SI are found in the states of Baja California and Baja California Sur, while less serious problems have been identified in the Yucutan Peninsula, Veracruz, Sinaloa and Nayarit (Barlow & Reichard, 2010). Reports have been presented of salinization caused by: the diagenetic effects of the interaction with low-salinity groundwater; changes in the flow regime from pumping; percolated effluents produced by agricultural activities in the Valle de Santo Domingo coastal aquifer, Baja California Sur (Cardona, Carrillo-Rivera, Huizar-Álvarez, & Graniel-Castro, 2004); SI problems over 30 km inland in the Costa de Hermosillo aquifer, Sonora (Rangel, Monreal, Morales, & Castillo, 2002); and effects on the quality of water at supply sites for the city of Ensenada due to SI, as a result of the pumping of the Maneadero aquifer, Baja California (Daesslé *et al*., 2005). The location of the SW interface was not identified by any of these investigations. A large portion of the Yucatan Peninsula presents effects from SI due to the high hydraulic conductivities of the Plioceno coastal plains (10-86 000 $m \cdot day^{-1}$ depending on the scale of analysis) (Worthington & Ford, 2009), where the FW water table (WT) elevations are under 2 masl (Bauer-Gottwein *et al*., 2011). The Merida-Progreso area of the state of Yucatan is a very important region with agricultural, industrial and service sectors. In addition to population growth over recent decades, the need to extract more groundwater has increased (Graniel, Morris, & Carrillo-Rivera, 1999; Bauer-Gottwein *et al*., 2011). Some of the problems in the region are: a) lack of sewage systems and, therefore, various ways of disposing of wastewater in the subsoil (Marín, Steinich, Pacheco, & Escolero, 2000); b) very shallow WT; c) soil is practically non-existent; d) karst conditions and e) interaction with SW. This combination of factors has caused the groundwater to be very vulnerable to anthropogenic and natural sources of pollution.

Few efforts have been undertaken in the state of Yucatan to spatially and temporally characterize the thickness of the FW that underlies a more saline water body. Direct measurements (electrical conductivity and temperature) as well as non-invasive geophysical techniques have been used to take *in situ* measurements of the depth of the SW interface in the Yucatan Peninsula in springs, observation wells and wells and caves. Studies have reported variations according to the electrical conductivity (EC) profiles of the SW interface in the Merida-Progresso section (Rodríguez, 2011) and the western coastal region of the state (Palomo, 2012). Isidro (2013) performed a correlation of time-domain geophysical electromagnetic sounding and EC profiles for various sections of the Merida-Progresso region to define the depth of the BW interface. Schmidt (2012) performed a test by pumping groundwater in an experimental well field located at the Engineering School of the Yucatan Autonomous University, demonstrating that the EC changed as a result of an increase in the elevation of the BW interface at different times after the pumping began.

The study of the FW-SW interaction can be divided into two main categories: a) those that consider both fluids to be immiscible (biphasic representation of flow, Dupuit approximation, Ghyben-Herzberg (G-H), representation of the interface using artificial elements) and b) those that recognize their miscibility (flow equation, solute transport equation, character of the solute transport equation, dependency of flow on density) (Jousma, Thorborg, & Verruijt, 1988). The G-H principle suggests that in a homogeneous and isotropic coastal aquifer, the depth of the SW interface and the FW is directly proportional to the water table's elevation above sea level (Ghyben, 1888; Herzberg, 1901; Hubbert, 1940). For a free coastal aquifer, this is expressed as:

$$z = \frac{\rho_w}{\rho_s - \rho_w} h$$

(used with density values measured in the laboratory) (1)

$$z = 40\text{ h (assuming } \rho_w = 1\text{ g} \cdot (\text{cm}^3)^{-1} \text{ and } \rho_s = 1.025\text{ g} \cdot (\text{cm}^3)^{-1}) \quad (2)$$

where $\rho_w$ represents the density of the FW; $\rho_w$ represents the density of SW; *z* the depth of the SW interface below sea level and *h* the hydraulic load of the FW above sea level. One of the limitations of this principle is that it assumes hydrostatic conditions (not flow) and there is no FW-SW mixing zone. While some investigators have used field measurements to confirm the validity of this principle in parts of the Yucutan Peninsula (Perry *et al*., 1989; Gondwe *et al*., 2010; Steinich & Marín, 1996; Marín, Perry, Essaid, & Steinich, 2004), others have found significant variations (Moore, Stoessell, & Easley, 1992; Escolero, Marín, Domínguez-Mariani, & Torres-Onofre, 2007).

Since no systematized records exist of the thickness of the FW lens over space and time, the objective of this study was to define its thickness in the Merida-Progreso region of the Yucatan from the 2012 rainy season through the 2013 dry season (18-month period). This included qualitatively identifying its response to precipitation (P) events and proposing alternatives that help to explain the causes of the phenomena that occur. This investigation is aimed at understanding the spatial and temporal behavior of the FW and BW interfaces in terms of changes in thickness, in addition to verifying whether these are compatible with the G-H principle.

### *Location*

The size of the Merida-Progreso study area is 1 700 km$^2$. It is located in the northwest portion of the state of Yucatan, Mexico, in the area known as the "ring of springs," primarily in the municipalities of Merida and Progreso (Figure 2). The maximum altitude is between 12 and 15 masl in the southern region. According to INEGI (2009a, 2009b), the main climates in the study area are: a) hot sub-humid with summer rainfall, less humidity and semi-dry (very warm and warm) in the southern region (Merida), with an annual mean P of 1 100 mm and mean annual temperature between 24°C and 28°C; and b) dry and semi-dry (very hot and warm) in the north (Progreso and the coastal area), with an annual mean P of 700 mm and an average temperature of 25 °C.

### *Geology*

The geology of the study area is composed of carbonated marine rocks from the Tertiary age as well as Quaternary marine rocks and continental deposits (Butterlin & Bonet, 1963; López, 1973; Brewerton, 1993; Herrera-Rendón, Cardona-Benavides, & Graniel-Castro, 2). The Tertiary is represented by the Carrillo Puerto Formation (Late Oligocene, Miocene- Pliocene). Based on studies of samples of rocks from wells at depths of 55 m (Rivera-Armendáriz, 2014), the study area is composed of: a) restricted platform deposits characterized by wackestone-grainstone pellets and ostracod grainstone, associated with benthic foraminifera, pelecypods and green and blue algae; b) oolitic banks behind reefs made of oolite and oncoids grainstone associated with tubular coral fragments, bryozoa and red algae, benthic foraminifera and iron minerals; c) coral patch reef system composed of red algae framestone and tubular corals, with allelochemicals benthic foraminifera and plankton, pelecypods, brachiopods, red algae, pellets, oolite, dolomite and iron minerals; d) open platform deposits composed of cyanobacteria wackestone, bivalvia, foraminifera (*Nummulites* sp.) and gastropods, bivavia packstone and *Nummulites* sp. grainstone with bryozoa and some iron minerals. The Quaternary in the area next to Puerto Progreso is represented by alternating fossil calcarea (grainstone-packstone), coquina (boundstone), and clay limestone (mudstone-wackestone) all with a white to yellowish tone, and are porous and somewhat cemented due to textural modifications from the FW-SW mixing zones (Herrera-Rendón *et al*., 2014).

### *Hydrogeological Framework*

Since the Yucutan Peninsula is virtually flat and karst, no surface runoff exists. The storage and flow of groundwater occurs regionally in large cavernous systems with turbulent regimes. The preferential flowpaths are variable and present a range of different scales classified as regional fractures (10 -100 km), large dissolution channels (1 – 10 km) and small-scale fractures and dissolution cavities (tens of meters) (Bauer-Gottwein *et al*., 2011). In addition, the distribution of the groundwater is characterized by a FW lens with a thickness between 1 and 30 m, situated over a 2 to 20 m-thick BW zone which overlies the SW. There is a constant interaction with the coastal zone where the saltwater penetrates over 40 km inland (Graniel *et al*., 1999; González-Herrera, Sánchez-y-Pinto, & Gamboa-Vargas, 2002). With respect to pumping, Escolero *et al*. (2002) indicate that approximately 3.8 $m^3 \cdot s^{-1}$ of water is extracted in Merida, and Conagua (2010) reports an extraction in the entire aquifer zone of roughly 1.4% of the annual average precipitation. A free karst aquifer is located in the study area. Based on the information generated by the present study, the depth of the water level was determined to range from 6.50 to 9.50 m in the south and from 2.50 to 4.00 m in the north. The heights of the water table ranged from 0.50 to 2.00 masl in the south in the area of Merida and -0.10 to 1.50 masl in the north, 11 km from the coastline. The groundwater generally flowed from south to north and the average hydraulic gradient was 0.022 $m \cdot km^{-1}$. The hydraulic conductivity values defined and reported for the study area ranged from $9 \times 10^{-4}$ to $1 \times 10^{-2}$ $m \cdot s^{-1}$ in Merida well field I (Andrade-Briceño, 1984), $1.75 \times 10^{-2}$ to $4.37 \times 10^{-2}$ $m \cdot s^{-1}$ in the FIUADY well field (Schmidt, 2012), and $3 \times 10^{-4}$ and $5 \times 10^{-2}$ $m \cdot s^{-1}$ in the coastal zone west of Progreso (Reeve & Perry, 1990).

## Methodology

To carry out the study, the spatial-temporal variations in water levels in the wells were defined and changes in the thickness of FW were identified based on EC profiles. Variations in the EC profiles were determined using an automated network. Lastly, the behavior of P was associated with effects on the water level and the EC, along with the geology of the subsoil. Information was obtained from a network that monitored 26 observations wells (OW) (Figure 2), in which 20 automated meters were installed to record levels (WL) and 19 to measure EC. The locations of the EC meters were based on the depths at the beginning of the BW interface. In order to identify different response types, some were placed in the FW lens, some in the BW and others at the boundary between these two zones. All the meters generated four records per day for the period June 17, 2012 to November 12, 2013, at 00:00, 06:00, 12:00 and 18:00 hours. Four EC



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*Water*

measuring campaigns were performed in all the OW in August and November 2012, and January and March 2013. These profiles were performed slowly (1 m/2 minutes) for each meter in each well water column. For each measurement, the sensor was left in place for two minutes before recording the value in order to stabilize the reading. The batteries of each device were changed before and after each measurement and the EC sensors were calibrated with standard solutions of 1 413 μS·cm$^{-1}$ and 5 000 μS·cm$^{-1}$. Atmospheric pressure (AP) was obtained by installing two automated meters which covered the study region, making it possible to correct the recorded pressures in order to define the variations in the water level in the OW. The daily mean P and temperatures corresponding to the Progreso Observatory, Chicxulub Puerto, Mocochá and Mérida Observatory

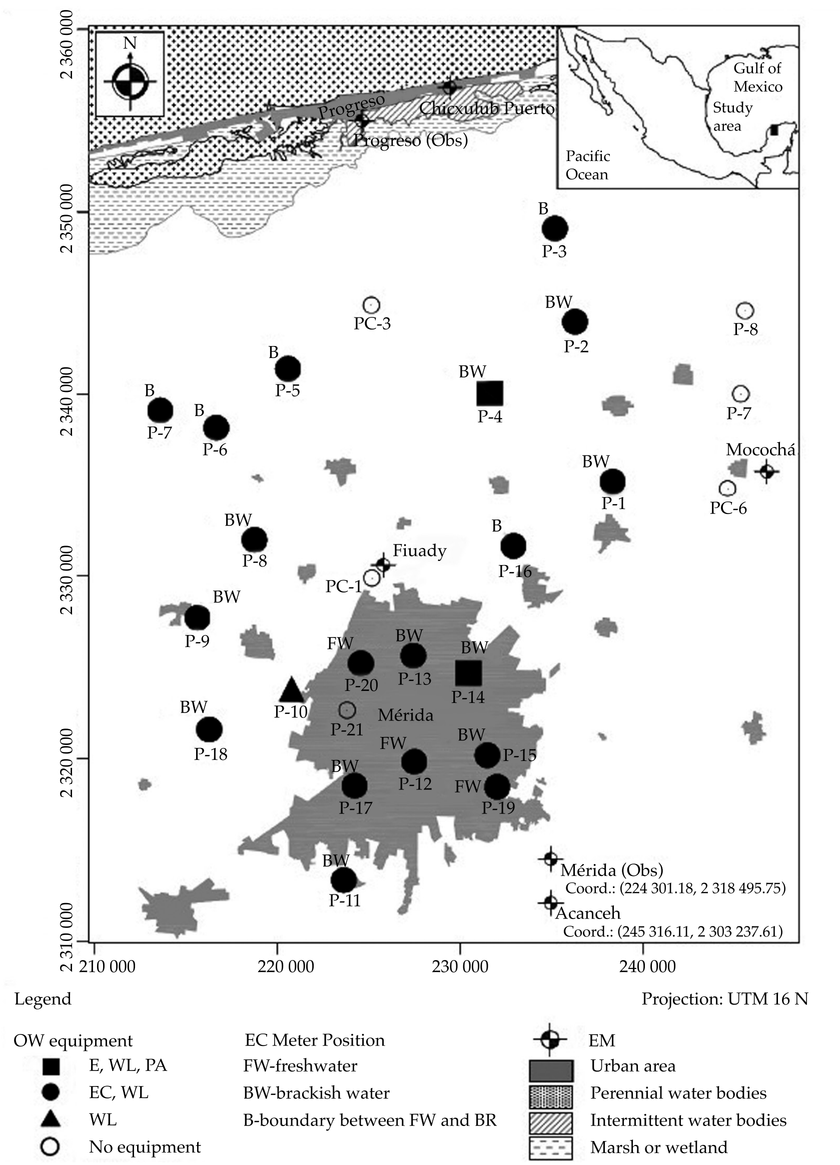


Figure 2. Location of observation wells and weather stations in the study area.

weather stations (WS) were obtained from the National Water Commission (Conagua, Spanish acronym). Information was also obtained from the FIUADY WS. In all cases, the total depths of the OW were between 30 and 60 m, which varied according to the distance from the coast (shallower depths closer to the coast). They had a diameter of 0.25 m with a smooth 6-m strut and a concrete seal to prevent direct seepage from the surface. All the OW were located over 1 km from deep wells which collected over 10 lps of groundwater, and thus, for practical effects, they were considered not to have been affected by extraction. A comparison was made of the elevations of the saltwater interface (ESWI) obtained through direct measurements of EC profiles versus those calculated with the G-H principle using equations (1) and (2). A sampling of groundwater and a laboratory analysis (gravimetric method) were used to obtain water densities by differences of masses, with 50 ml glass pycnometers, and analytical balance at air temperature in the FW, BR and SW interfaces.

## Results and Discussion

*Response of the Water Table Level to Precipitaiton*. Due to the presence of cavities and fractures of various sizes, the water table level in karst aquifers generally responds very quickly to P. This investigation is the first to present this relationship continuously over nearly 18 months. Figure 3 shows the response of the water level to P at P-3 (northern portion of the study region). Given the karst nature of the free aquifer and a water table level of 3.73 m, its response to P is very notable and rapid. The records also show that the increase in the water level at P-3 is not only associated with local rainfall but a notable increase in the level is also observed at the Chicxulub Puerto WS with no direct relationship to any recorded P

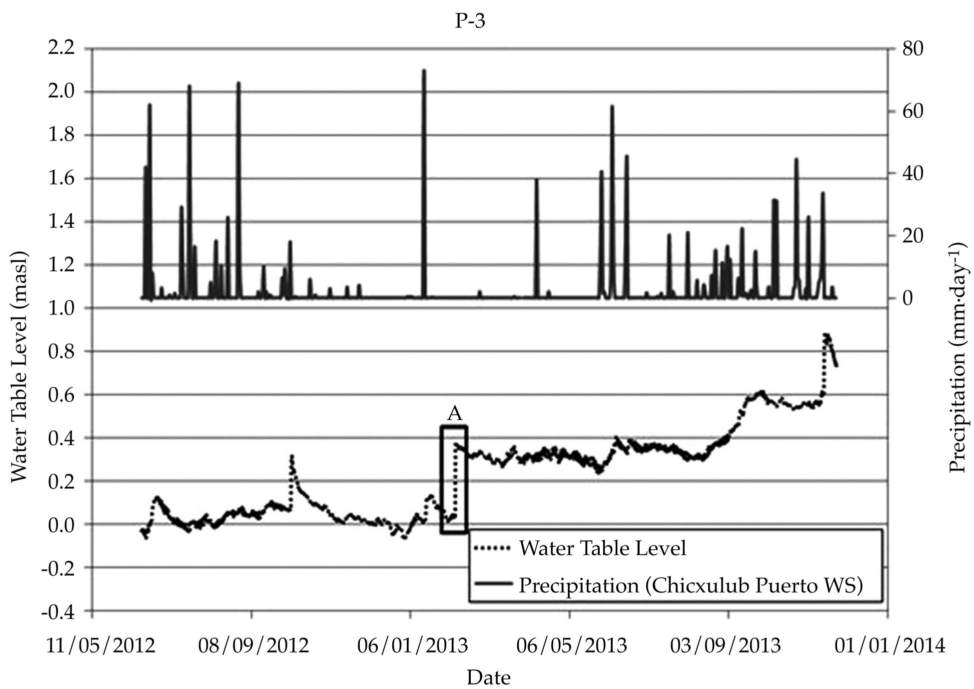


Figure 3. Water table level/precipitation for P-3.

event (box A). This effect occurred in the majority of the OW (information not shown) and is due to the recharge of groundwater in the southern portion of the OW site. Well P-3 is located in the northern region near the natural discharge area of the flow systems, and therefore the recharge in the southern area during the 2012 rainy season (February to September 2013), by flowing toward the coastline, kept the water level between 0.2 and 0.4 masl. The 2013 rainy season later increased the water level to 0.8 masl.

*Relationship with the G-H Principle*. According to the G-H principle, the elevation of the water table from the effect of natural recharge from P should result in a deeper SW interface. An indirect technique was used to identify this effect, which consisted of recording the EC at a point slightly below the FW lens, in the BR zone. Conceptually, the "expected effect" is that the elevation of the water table would move the FW/BR, FW/SW boundaries to a lower depth and therefore EC would decrease. Figure 4 shows the results indicating whether the following were identified based on the G-H principle: a) the expected effect; b) the opposite effect; c) both effects or d) none of the previous effects. The heterogeneity of the karst aquifer was a condition for identifying the four scenarios expected, where the spatial distribution shown in Figure 4 shows a lack of any spatial pattern that would indicate such behaviors.

In Figure 5, corresponding to P-18 located west of the Merida metropolitan area, at a distance of 33.31 km from the coast in the north-south direction, the water table level/EC behaves as expected (box A) according to the G-H principle. Because of a precipitation recorded on October 2, 2012, the water table rose from 0.86 to 1.05 masl and the EC recorded by the automated meter immediately decreased (from 3 620 to 3 050 μmhos·cm$^{-1}$). When the water level slowly began to decrease 0.04 m, the EC quickly increased (3 610 to 4 125 μmhos·cm$^{-1}$), even more than before the precipitation event, and stabilized (at 3 440 μmhos·cm$^{-1}$) when the level reached 0.90 masl. Box B shows an abrupt increase in the water level with no corresponding change in EC. Even with the effect expected by the G-H principle, the rebound effect and stabilization of EC indicates a complex response. The rapid variations (300 to 400 μmhos·cm$^{-1}$) identified over the course of the measuring period, which do not correspond to changes in the well's water level, demonstrate a very dynamic FW/BR mixing zone in terms of the mixing proportions at the bottom of the wells.

Figure 6, corresponding to the EC profile at P-18, shows the position of the automated EC meter in the BR interface zone. The EC profiles during the rainy season (August-November 2012) and dry season (January-March 2013) clearly indicate that the thickness of the freshwater lens remained relatively constant over the course of the year, that is, natural recharge did not notably increase its thickness. For example, on the dates when the EC profiles were measured, the water table was at 0.75 masl on August 9, 2012 and 0.56 masl on March 13, 2013, while in the EC profile, there were no significant changes in the FW thickness in the well water column.

Figure 7 corresponds to P-6 located in the northwest portion of Merida, at 16.77 km from the coast in the north-south direction. The water table/EC relationship behaved opposite to the behavior established by the G-H principle. The water level rose in boxes A, B and C (from 0.37 to 0.63; from 0.23 to 0.78 and from 0.90 to 1.41 masl, respectively) from the effect of natural recharge from P, and EC increased (from 2 395 to 2 560; from 2 415 to 2 490 and from 2 450 to 2 535 μmhos·cm$^{-1}$, respectively). In addition, in D, increases and decreases are seen in the water level in the well with no observed effects on EC. The hydrogeological conditions of the karst medium correspond to a different BR interface in P-6 than in P-18. In P-6, with a thickness of 5 m (elevation between -15 and -20 masl), the EC increased roughly 20 000 μmhos·cm$^{-1}$,



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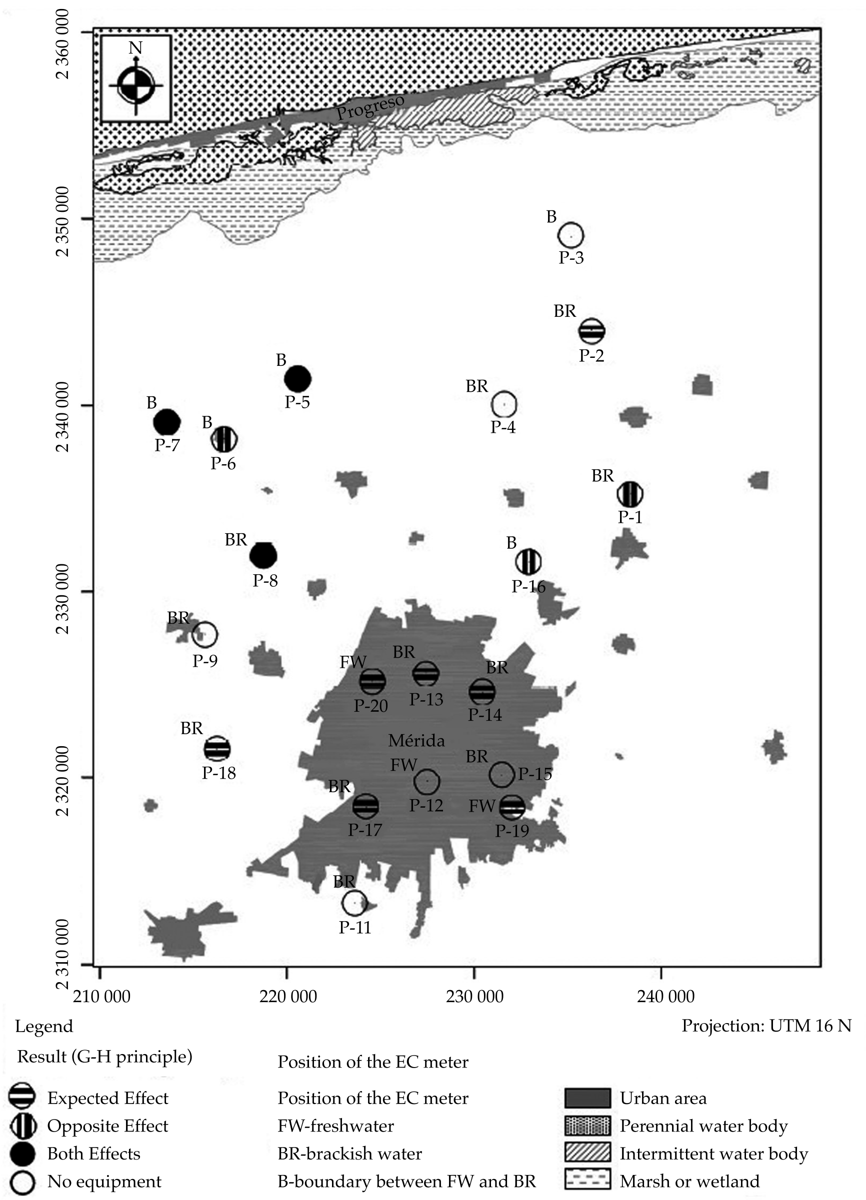


Figure 4. Brackish water infterface/precipitation and relationship with the Ghyben-Herzberg principle.

while it increased roughly 1 500 μmhos·cm$^{-1}$ in P-18, with a thickness of 6 m (elevations between -22 and -28 masl). And the EC values remained within a small range, with the exception of the records corresponding to boxes A, B and C.

Figure 8, corresponding to well P-6, shows the position of the EC meter in the zone defined as the boundary between FW and Br. For the four periods in which EC was characterized, no temporal changes in depth occurred when the first abrupt change in EC began. This indicates that natural recharge did not notably change the thickness of the FW lens. The EC at the BR interface on January 2013 was lower than the other months, while there were no significant changes among the other months.

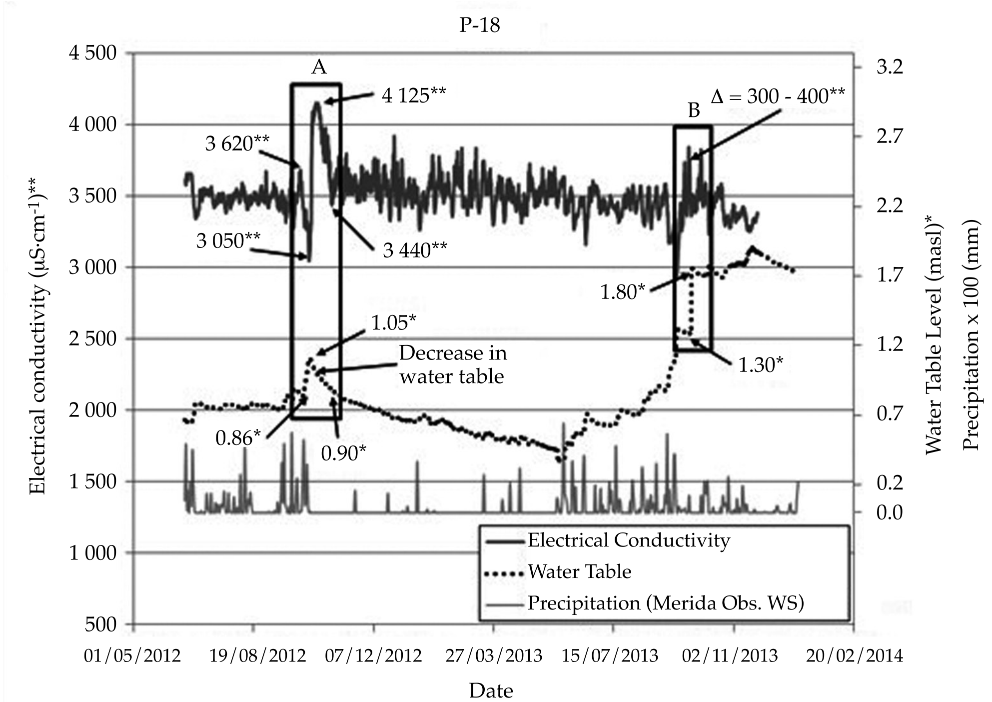


Figure 5. Water Table Level/Electrical Conductivity for P-18.

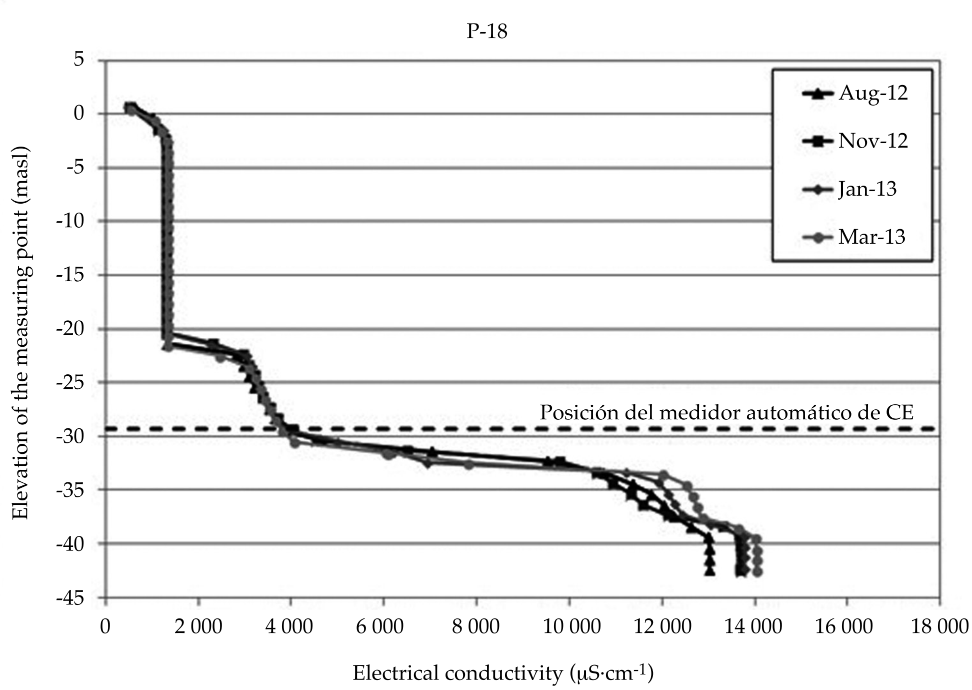


Figure 6. Electrical Conductivity Profile for P-18.

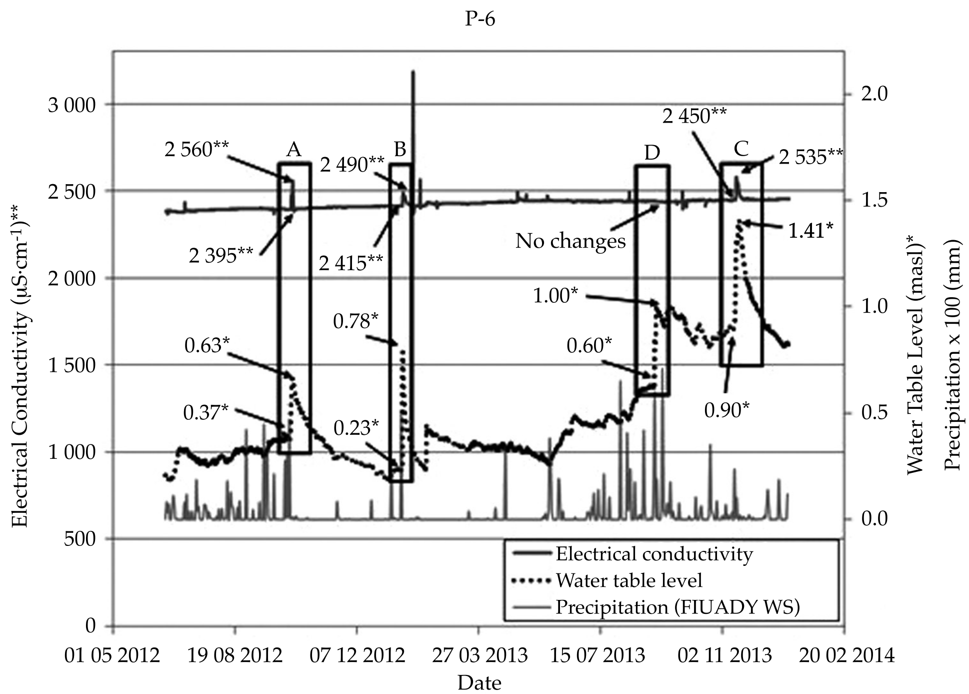


Figure 7. Water table level/electrical conductivity for P-6.

In Figure 9, corresponding to P-5 located northwest of Merida at a distance of 14.36 km from the coast in the north-south direction, two different behaviors are seen in how EC responded to a rise in the water level in the well. For event A, the water level increased (0.16 to 0.60 masl) in response to rainfall on October 6, 2012 and EC decreased (2 880 to 2 845 μmhos·cm$^{-1}$). The water level then began to decrease and the EC increased (2 845 to 2 960 μmhos·cm$^{-1}$), a behavior which is consistent with the G-H principle. For event B, the water level increased (0.62 to 1.20 masl) and EC increased (2 885 to 3 160 μmhos·cm$^{-1}$), then the water level decreased (1.20 to 0.61 masl) and EC decreased (3 160 to 2 870 μmhos·cm$^{-1}$), which is opposite to the behavior predicted by the G-H principle. Figure 20 shows the location of the automated EC meter at the BR interface. During the four periods in which EC was evaluated, no temporal changes in depth were observed prior to the abrupt change in EC, with the exception of the month of August 2013 in which EC was slightly higher than the other three months. This indicates that natural recharge did not notably change the thickness of the FW lens. At the BR interface, an increase in EC was observed in March 2013, under the -20 masl of the other months, which did not present significant differences among them.

Different causes could explain the irregular behavior in the changes in the water level elevations and the EC at the FW/BR interfaces. First, given that the water level in B is greater (0.62 masl) than A (0.16 masl), it is possible that some fractures or cavities, whose hydraulic behavior is fluctuating as a canal under pressure (full tube), may be activated and deactivated as the water level varies. Schmidt (2012) characterized the wells in the experimental FIUADY field using video of the main dissolution channels (over 30 cm) associated with faults and fractures (Figure

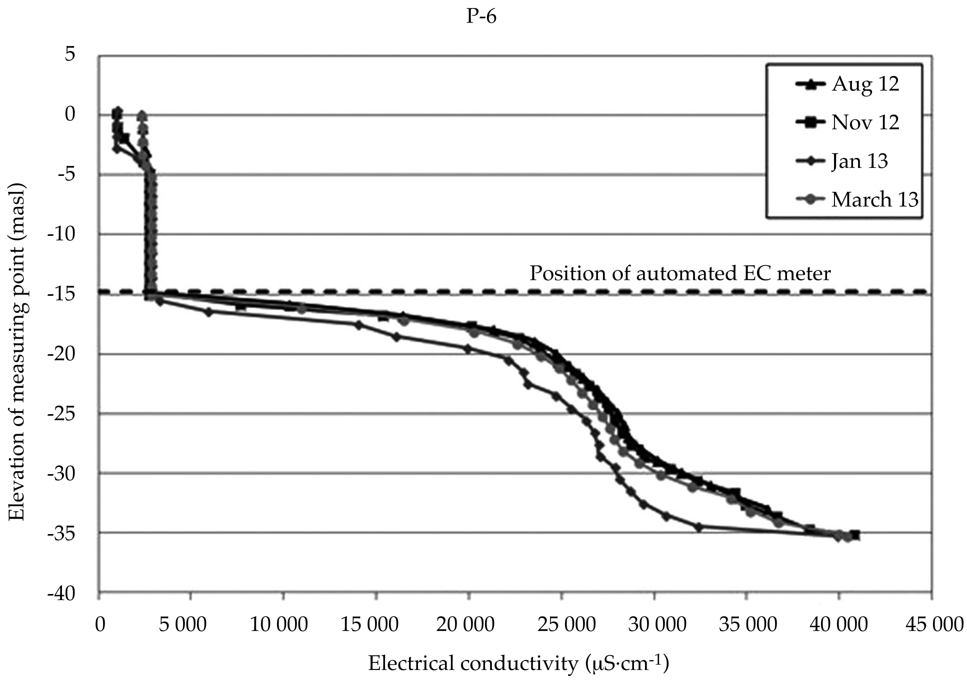


Figure 8. Profile of electrical conductivity for P-6.

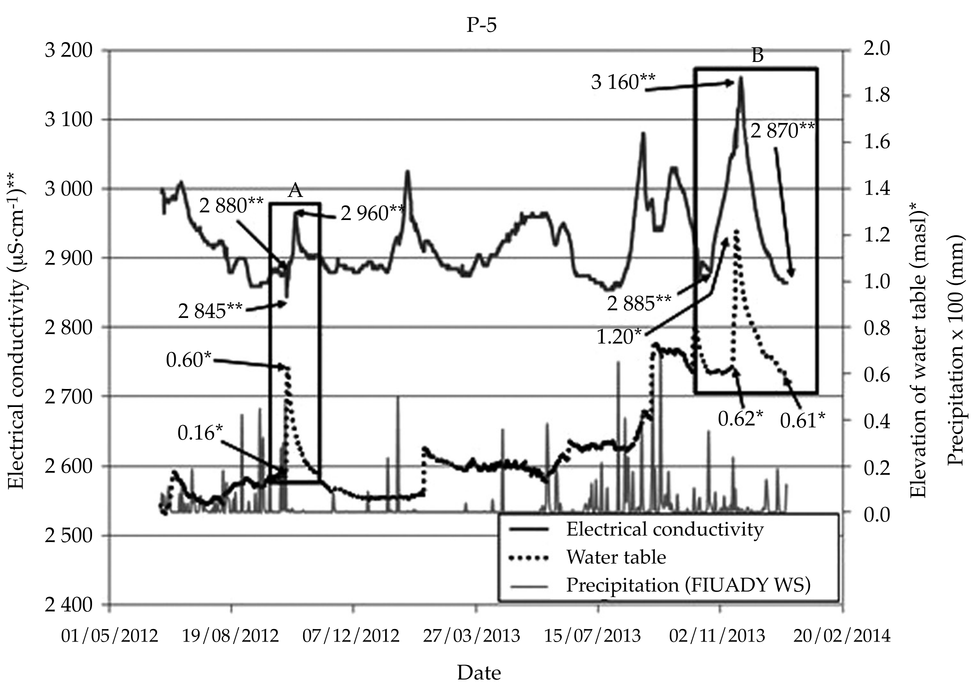


Figure 9. Elevation of water table/electrical conductivity for P-5.

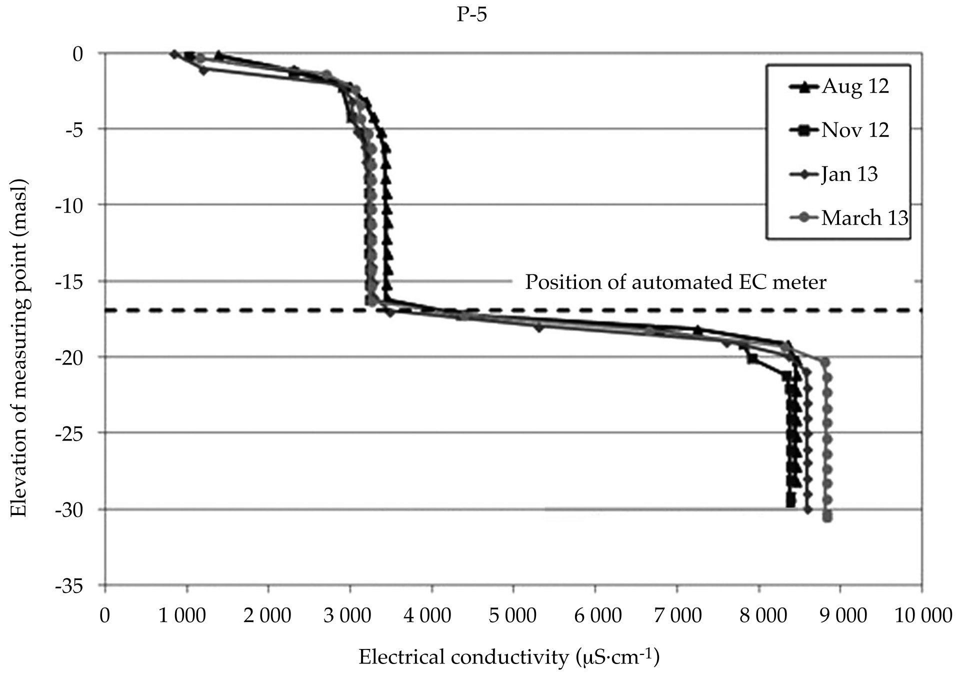


Figure 10. Profile of electrical conductivity for P-5.



11). This provided an idea of the presence of preferential flow routes in the study region. It also strengthens the proposal related to how these channels behave when the water table level changes. This behavior could generate local horizontal and/or vertical flows that affect flow velocities and changes in EC in certain areas as a result of the mixing of different concentrations of salts in the FW and BR. The mixing of FW and BR, both in equilibrium with calcite, generates water undersaturated in this mineral, which produces the dissolving of carbonates. These phenomena may be influenced by variations in salts in the groundwater, which affects the EC and is not necessarily dependent on changes in the water level.

The tide is another factor that may affect the water level and the EC at the FW/BR interface. Heise (2013) reported measurements of the tide's effects on discharge flow and water quality in artesian wells located in the coastal zone between 500 and 1 800 m from the coastline. Beddows, Smart, Whitaker and Smith (2002), and Villasuso *et al*. (2011) reported that the tide can affect groundwater levels at 9 and 13 km inland, respectively. In this investigation, the well nearest to the coastline was located 9.3 km from the shore and therefore the effect of the tide was not considered to have influenced the study area. The elevation of the SW interface (ESWI) was obtained for OW 18, 6 and 5 (Table 1) based on the G-H principle by calculating equation (1) ($ESWI_1$) and (2) ($ESWI_2$), and through direct measurements of the EC profiles ($ESWI_{meas}$). For the EC profiles corresponding to P-18 (Figure 6), it is inferred that the $ESWI_{meas}$ was under -43 masl and the elevation of the BR interface (ESWIa) began at roughly 22 masl (both based on the criterion in Figure 1). When calculating $ESWI_2$, the estimation with the G-H equation did not represent the $ESWI_{meas}$ on any of the dates analyzed, since

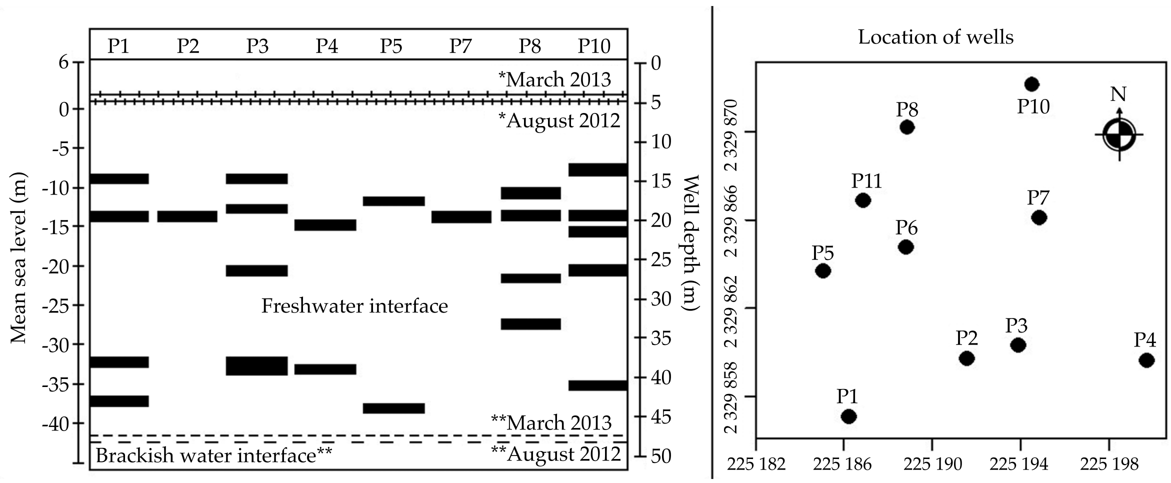


Figure 11. Fractures and cavities in experimental field wells in FIUDAY (adapted from Schmidt, 2012).



none of the calculations were below -31 masl. In addition, the calculation of $ESWI_1$ cannot be compared to the $ESWI_{meas}$ since it was not possible to monitor EC at those depths. For the EC profiles corresponding to P-6 (Figure 8), the $ESWI_{meas}$ was roughly -17.5 masl and the ESWIa began at -16.7 to -18 masl (based on the criterion in Figure 1). When calculating $ESWI_2$ the estimation with the G-H equation did not represent the $ESWI_{meas}$ on any of the dates analyzed (with differences up to roughly 6 m). The estimations with $ESWI_1$ were very close to the $ESWI_{meas}$ (with maximum difference of roughly 1.50 m), except on January 18, 2013, which presumes a depth greater than the actual depth (difference of roughly 10 m). For the EC profiles corresponding to P-5 (Figure 10), it is inferred that the $ESWI_{meas}$ was under -30 masl and ESWIa began at roughly -2 masl (based on the criterion in Figure 1). When calculating $ESWI_2$, the estimation with the G-H equation did not represent the $ESWI_{meas}$ on any of the dates analyzed, since none were below -7.60 masl. The results from $ESWI_1$ indicate that the ESWI was below the -22 masl, and therefore no direct relationship was observed with the measurement on January 17, 2013 and a comparison cannot be made with the $ESWI_{meas}$ since there were no EC measurements with elevations under -30 masl, given that EC could not be measured at those depths.

Based on the calculation of $ESWI_2$ using the G-H principle, it can be said that no similitude was found, as mentioned by prior studies by Moore *et al*. (1992) and Escolero *et al*. (2007). With respect to the estimation of $ESWI_1$, a good similitude was found with $ESWI_{meas}$, while a comparison with P-18 and P-5 observation wells (OW) was not possible.

*Definition of the Thickness of the Freshwater Lens*. According to the records from the OW for the different dates, different types of elevation and time configurations can be developed. This information is useful for generating a spatial representation of the vertical changes in the overall groundwater compositions associated with the rainy (November) and dry (March) seasons, which determine the geometry of the FW in the study area. For example, the spatial distribution of EC at an elevation of -15 masl indicates that the lower values (around 1 000 μmhos·cm$^{-1}$) are located in the E-SE portion of the study area, and gradually increase towards the W-NW (near observation wells P-5, P-6 and P-7) to around

Table 1. Estimation of the elevation of the interface based on the Ghyben-Herzberg principle.

| Well | Date | Elev. of WT (h) (masl) | $ESWI_2$ | FW | | BR/SW | | $ESWI_1$ | $ESWI_{meas}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | = -40h (masl) | EC ($\mu S \cdot cm^{-1}$) | $\rho_w$ ($g \cdot (cm^3)^{-1}$) | CE ($\mu S \cdot cm^{-1}$) | $\rho_s$ ($g \cdot (cm^3)^{-1}$) | $= \frac{\rho_w}{\rho_s - \rho_w} b$ (masl) | (masl) |
| P-18 | 9/Aug/2012 | 0.75 | -30.0 | 1 319 | 0.9961595 | 13 022 | 1.0020110 | -127.68 | < -43.0 |
| | 24/Nov/2012 | 0.77 | -30.8 | 1 319 | 0.9961595 | 13 699 | 1.0023495 | -123.92 | < -43.0 |
| | 21/Jan/2013 | 0.68 | -27.2 | 1 319 | 0.9961595 | 13 783 | 1.0023915 | -108.70 | < -43.0 |
| | 12/Mar/2013 | 0.56 | -22.4 | 1 319 | 0.9961595 | 14 029 | 1.0025145 | -87.78 | < -43.0 |
| P-6 | 7/Aug/2012 | 0.29 | -11.6 | 2 833 | 0.9969165 | 40 800 | 1.0159000 | -15.23 | -16.7 |
| | 22/Nov/2012 | 0.30 | -12.0 | 2 833 | 0.9969165 | 40 800 | 1.0159000 | -15.75 | -16.7 |
| | 18/Jan/2013 | 0.54 | -21.6 | 2 833 | 0.9969165 | 40 800 | 1.0159000 | -28.36 | -18.0 |
| | 15/Mar/2013 | 0.33 | -13.2 | 2 833 | 0.9969165 | 40 800 | 1.0159000 | -17.33 | -16.7 |
| P-5 | 14/Aug/2012 | 0.09 | -3.6 | 3 437 | 0.9972185 | 8 450 | 0.9997250 | -35.81 | < -30.0 |
| | 22/Nov/2012 | 0.11 | -4.4 | 3 242 | 0.9971210 | 8 373 | 0.9996870 | -42.74 | < -30.0 |
| | 17/Jan/2013 | 0.06 | -2.4 | 3 242 | 0.9971210 | 8 592 | 0.9997960 | -22.37 | < -30.0 |
| | 14/Mar/2013 | 0.19 | -7.6 | 3 242 | 0.9971210 | 8 819 | 0.9999100 | -67.93 | < -30.0 |

6 000 $\mu mhos \cdot cm^{-1}$ (Figure 12). A similar spatial EC distribution was identified at an elevation of -25 masl, where lower values of around 1 000 $\mu mhos \cdot cm^{-1}$ in the SE region increased to around 25 000 $\mu mhos \cdot cm^{-1}$ in the NW. The comparison of the configurations developed for the different conditions indicate spatial changes in the overall chemical composition of groundwater at the depths selected, and that the temporal effects of the infiltration of water, which increased the water table level during the rainy season, did not significantly affect the overall chemical composition of the groundwater during the rainy season, as compared to the dry season. According to the geophysical exploration performed by Kind (2014), the increase in EC in the W-NW portion may be associated with dissolution channels that are well-developed in the sediments of the Tertiary formation, creating local networks that facilitate the direct interaction of the FW, BR and SW interfaces. In addition, given that the sulfate concentrations in observation wells P-5, P-6 and P-7 (130 $mg \cdot l^{-1}$ on average; Salazar, 2014) were higher than in P-2, P-3 and P-4 (35 $mg \cdot l^{-1}$ on average) which are located at similar distances from the coast, it can be inferred that the increase in salinity may be associated with the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) present in the Carrillo Puerto Formation.

The effect of the infiltration of water from P and the displacement of the groundwater flow in the karst aquifer is more notable when analyzing the water table level and the spatial configuration of P (Figure 13). The period of rainfall analyzed, in which the mean P was obtained with the arithmetic method based on information from the WS analyzed, began in August 2012 (mean P = 125.9 mm) and in this case ended in mid October 2012. Therefore, the configuration for November 2012 (mean P = 12.7 mm) represents the effect of infiltration at the end of that period and the configurations for January 2013 (mean P = 56.2) and March 2013 (mean = 6.2 mm) represent the beginning and the end of the dry season, respectively (with an increase in the mean P between November 2012 and January 2013 due to isolated rains in January), given that rainfall began again in mid May, 2013, according to the available meteorological records.

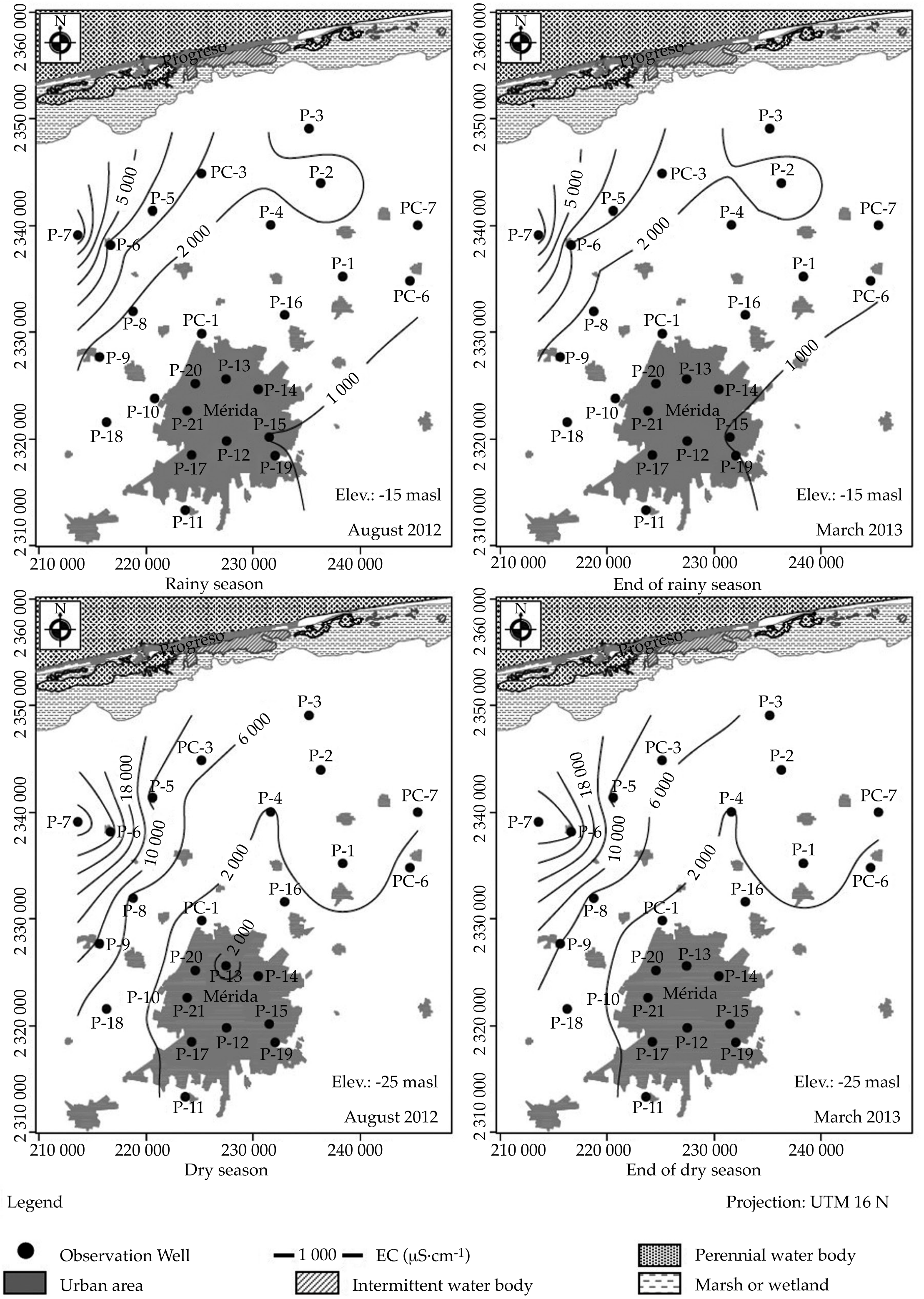


Figure 12. Spatial and temporal configurations of electrical conductivity in freshwater (-15 masl) and brackish water (-25 masl).

Although sporadic precipitations occurred after that period, according to the records they did not significantly affect the water table level. In terms of the overall distribution of groundwater flow, the highest elevations were recorded in the southern portion of the study area, near the Merida metropolitan region. The effects of the infiltration of P as well as planned induced recharge and unplanned recharged associated with urban infrastructure generated a type of dome with maximum elevations of around 1.3-1.0 masl, which was also reported by Graniel *et al*. (1999) and Marín *et al*. (2000). The lowest elevations were recorded in the northern portion of the study area, which is consistent with groundwater flowing towards the coastline. During the rainy season, the elevations were around 0.05-0.0 masl at 6 km south of the coastline. The elevations in the area near the coast were much lower (0.25-0.30 masl) during the dry season than during the rainy season, which reflects the dynamics of the groundwater flow when it runs through the karst medium. When the infiltrated groundwater reached the coastal area the elevations of the water level increased, and also generated an interesting dynamic in the coastal ecosystems, in which the natural discharge of groundwater increased during the dry season. In addition, changes in the patterns of equipotential lines suggest changes in the flow direction of the groundwater. Being a heterogeneous and anisotropic medium, the flow lines were not necessarily perpendicular to the equipotentials. In any case, the configurations presented clearly reflect changes in flow directions over the course of the year, especially during the dry season. The main changes were observed under the Merida metropolitan area, which may be due to continuous extractions and artificial recharge. Changes in the flow direction were observed between Merida and Progreso particularly in March 2013, when the main direction was NW, as opposed to N, NE and NW during previous months. The dynamic of the FW lens was analyzed based on the EC records obtained, which are jointly presented in the plans and indicate that changes in groundwater levels were not proportionally reflected by changes in the thickness of the FW lens. Figure 14 shows the upper limit of the ESWIa (at the first abrupt change in the EC graph). The ESWIa in the north remained between -20 and -10 masl throughout the year. The increase in the water level during the dry season did not deepen the ESWIa. In the south, the ESWIa was between -36 and -30 masl during the dry season. Meanwhile, a notable depression in the ESWIa was observed in the northern portion of Merida, with elevations between -32 and -40 masl; for example, the -16 masl elevation contour line. Figure 15 presents the FW thickness (considering its lower limit at the first abrupt change in the EC graph) for the four months analyzed. In addition, the area where the upper limit of the ESWIa (first abrupt change in the EC graph) had an EC > 2 500 $\mu S \cdot cm^{-1}$ was divided into zones. In the northern portion of the Merida metropolitan area, it was spatially higher in January 2013 than during the other three months analyzed (which may be due to a combination of a decrease in P and the SI). No significant changes were observed in the FW thicknesses, except for March 2013 which was 6 to 8 m lower than the other months in some of the E and SE areas of the study region. This lower FW thickness may be due to a lack of groundwater recharge from precipitation, given the notable decrease in P as of mid October 2012. The average FW thickness was also estimated for a selected area, the Merida metropolitan region, where an increase of 0.5 m was seen between August and November 2012, and 0.7 m between November 2012 and January 2013 (increasing as a result of rainfall in January 2013). In addition, a decrease of 3 m in the mean FW thickness was seen between January and March 2013, which was during the dry season.



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*Water*

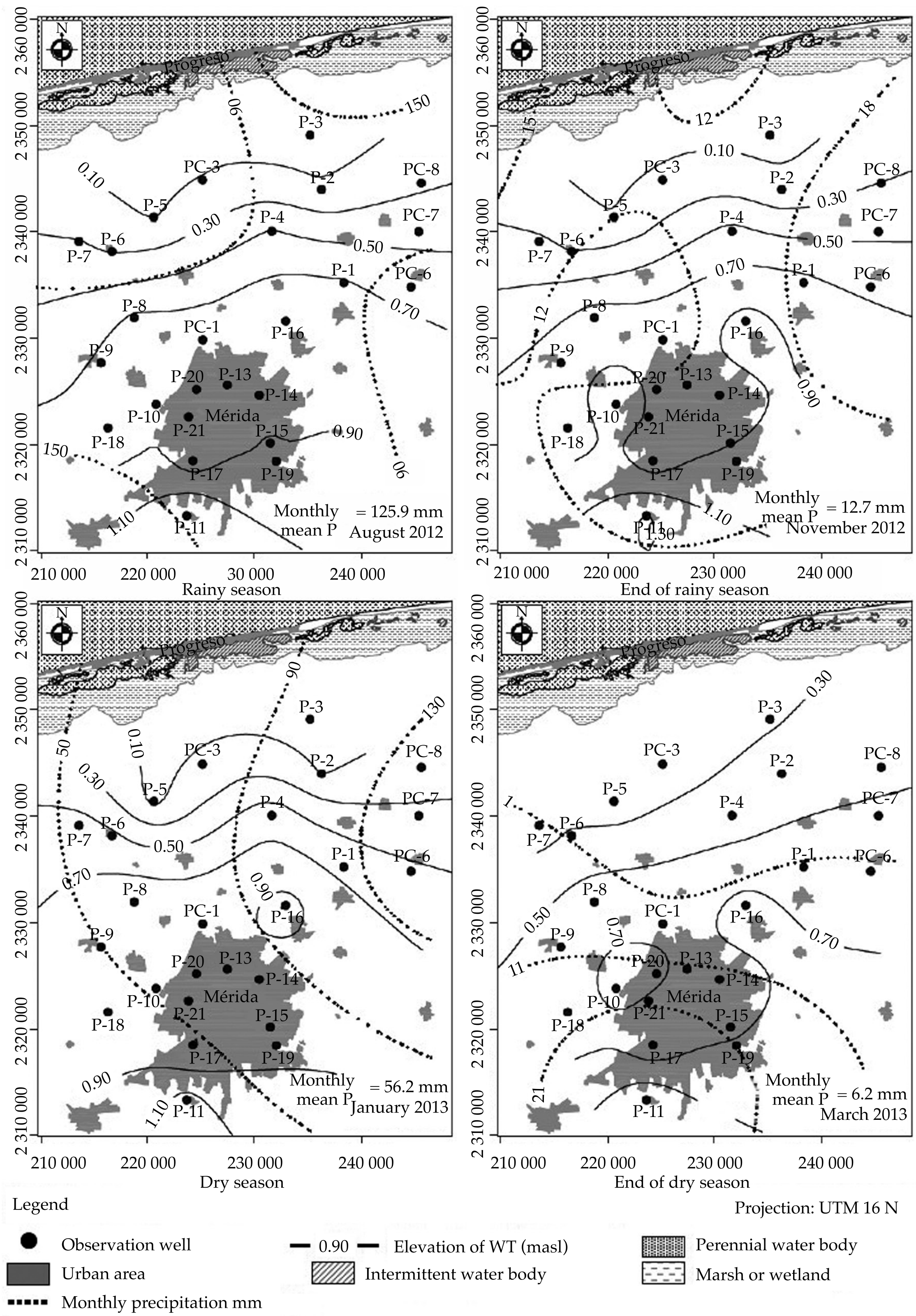


Figure 13. Water table levels.



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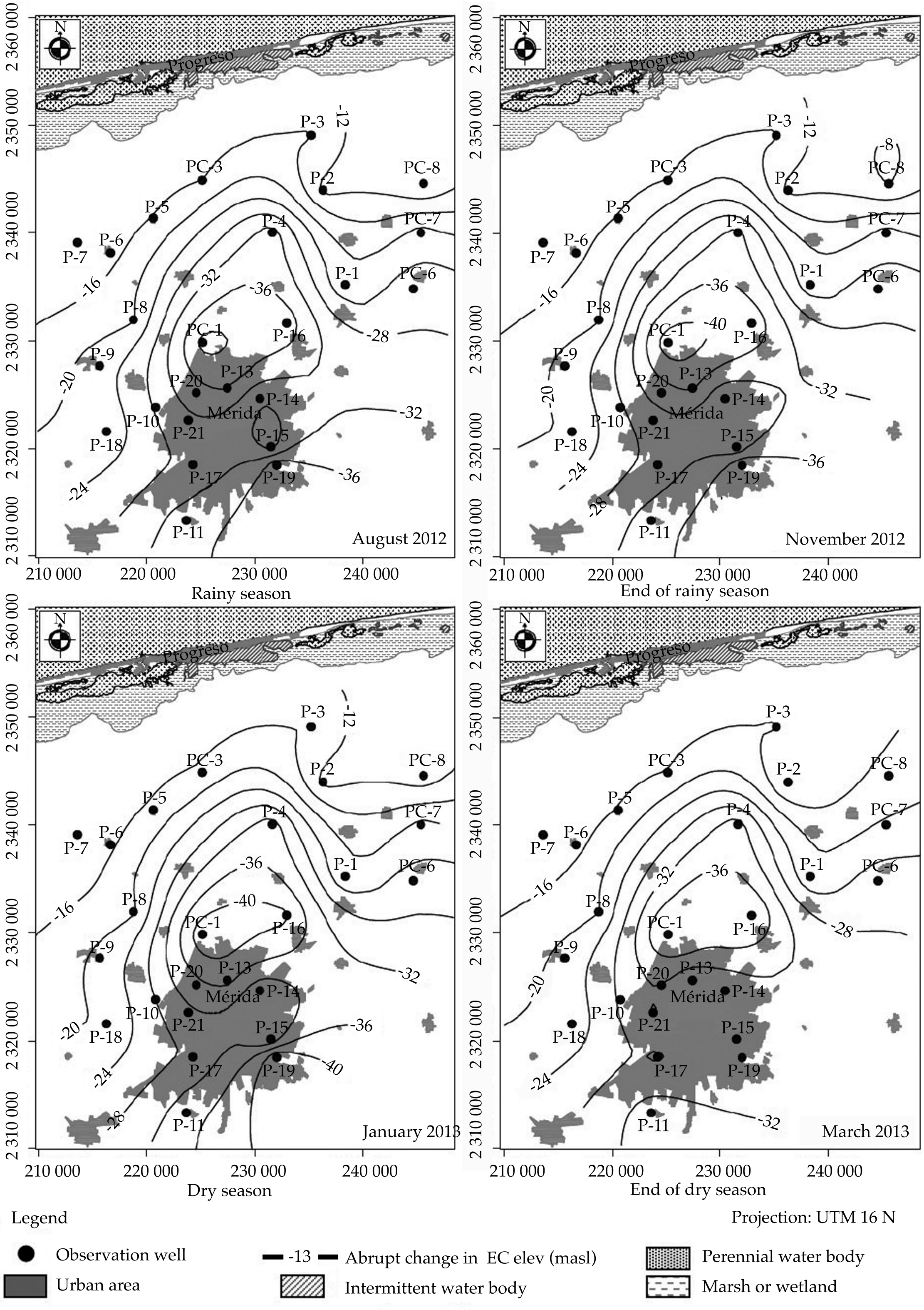


Figure 14. Elevations in the brackish water interace (first abrupt change in the electrical conductivity profile).

## Conclusions

This investigation was the first of its type given the number of observation wells and size of the study area. It enabled defining the FW thickness and ESWIa and their spatial and temporal variations. This is highly important to the sustainable management of groundwater in the region. From a regional perspective, the results from the measurements taken by the automated network which measured water level and EC did not indicate any significant spatial or temporal variations (rainy and dry seasons) in the thickness of the FW interface or in the upper limit of the ESWIa, independently of direct groundwater recharge and the recharge in the southern portion of the study area. This is likely due to karst conditions which have high hydraulic conductivities, as well as the preferential flow paths and low hydraulic gradients. In addition, the salinity under the FW lens varied (8 000 to 40 000 $\mu S \cdot cm^{-1}$). Locally, under the Merida metropolitan area, an average decrease in the FW thickness of 3 m was estimated during the dry season as compared to the rainy season, and the flow direction of groundwater changed primarily under this region, which may be due to continuous natural and artificial extraction and recharge (planned and unplanned). An interesting dynamic was observed in the southern area when infiltrated groundwater reached the coastal area, in which the natural discharge increased and the flow changed direction during the dry season. The response of the water table to P events was immediate and had different effects on the ESWIa, where the rise in the water table level due to a P event could generate an increase or decrease in the ESWIa or have no effect in the different regions of the study area. This indicates a large degree of heterogeneity, characterized by the karst environment of the region. Density values measured with water samples indicated that the G-H principle was not valid for estimating the FW thickness, similar to findings by Moore *et al*. (1992) and Escolero *et al*. (2007) who studied other regions of the Yucutan Peninsula. Lastly, it is recommended that this information be complimented by additional investigations that include more details regarding the structural geology of the region and the monitoring of the FW, BR and SW interfaces (which requires studies of deeper monitoring wells). This would make it possible to evaluate the behavior of the water interfaces in response to precipitation and tides at specific points, and to implement the information for the calibration of a numerical flow and density model which could be used as a tool to determine the optimal amount of groundwater exploitation.

## Acknowledgements

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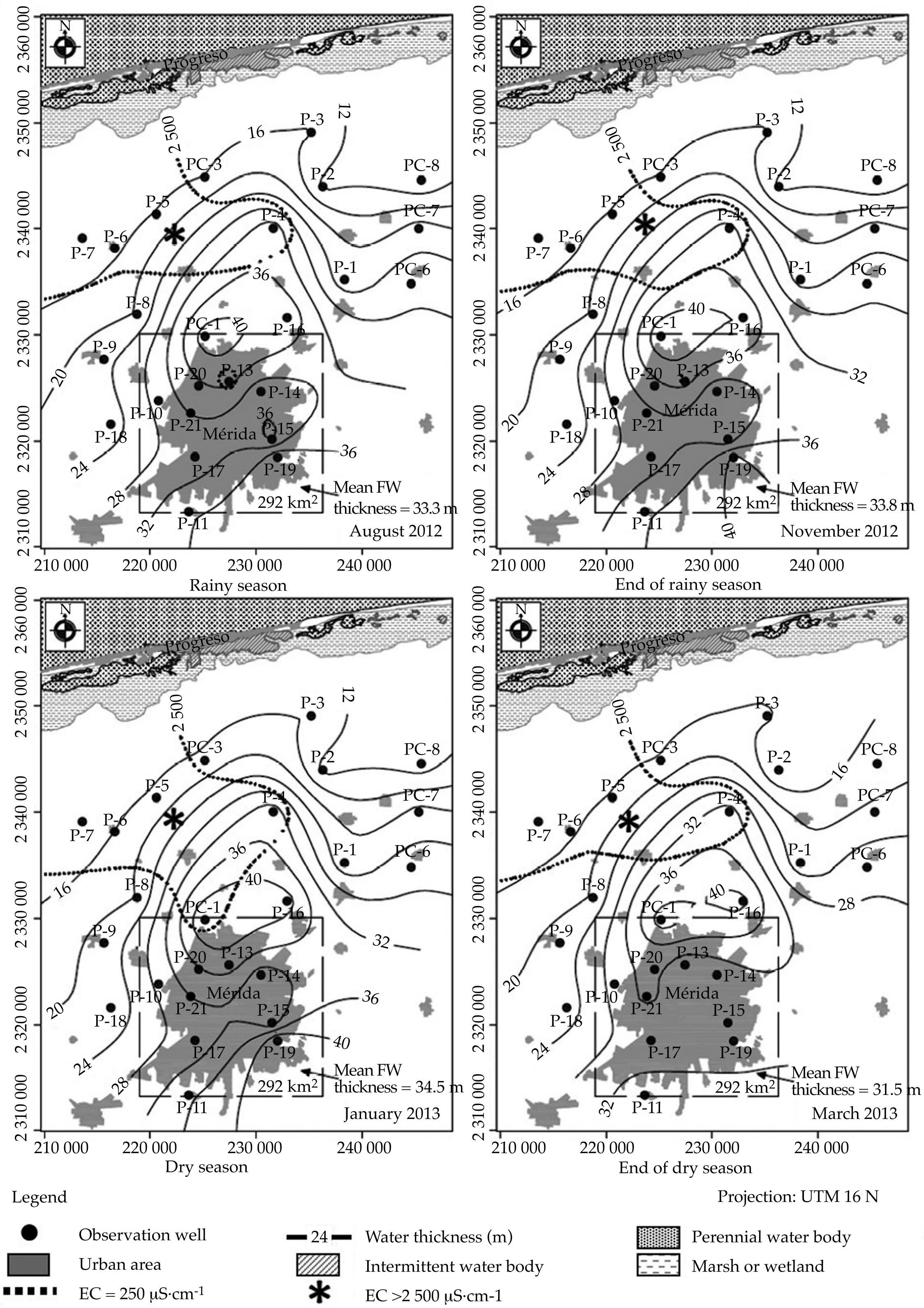


Figure 15. Freshwater thickness based ont he first abrupt change in electrical conductivity.

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# Problemas de drenaje y salinidad en los distritos de riego de México: una panorámica de 1962 a 2013

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## Resumen

Palacios-Vélez, O. L., & Pedraza-Oropeza, F. J. A. (noviembre-diciembre, 2015). Problemas de drenaje y salinidad en los distritos de riego de México: una panorámica de 1962 a 2013. *Tecnología y Ciencias del Agua*, 6(6), 113-123.

Se presenta una breve descripción de las condiciones naturales que han motivado el desarrollo de la irrigación en México y se discuten algunos de los principales problemas que enfrenta la irrigación. Se presenta también un panorama de la modernización de las prácticas de riego, que empezaron en 1962 cuando se crearon las oficinas de riego y drenaje. Estas oficinas tenían como propósito dar un soporte técnico a los trabajos de rehabilitación que se iniciaron en varios distritos de riego. Sus principales funciones estaban relacionadas tanto con el mejoramiento de las técnicas de riego como con el monitoreo de los niveles freáticos y la salinidad del suelo. Se describen las actividades del llamado "Plan de Mejoramiento Parcelario", mejor conocido como Plamepa, que tenía como objetivos el mejoramiento de la eficiencia en el manejo del agua, así como con trabajos requeridos para aumentar el rendimiento de los cultivos. Se comentan los problemas que surgieron para la elaboración de mapas de niveles freáticos y salinidad de suelos. Estos problemas incluyen la definición de un valor umbral de la salinidad del suelo para que pueda considerarse "salino", la definición de la intensidad requerida de muestreo de suelos salinos y los métodos de interpolación con fines de mapeo. Esta información es crucial para la planeación de la recuperación de suelos salinos mediante lavado. Por último se comentan algunas consecuencias de la transferencia de los distritos de riego a las asociaciones de usuarios en lo que concierne a la operación de los distritos de riego, y a los estudios de drenaje y salinidad.

**Palabras clave**: distritos de riego, drenaje de suelos, salinidad de suelos, Plamepa.

## Abstract

*Palacios-Vélez, O. L., & Pedraza-Oropeza, F. J. A. (November-December, 2015). Drainage and Salinity Problems in the Mexican Irrigation Districts: An Overview 1962-2013.* Water Technology and Sciences *(in Spanish), 6(6), 113-123.*

*A brief description of the natural conditions that led to the development of irrigation in Mexico is presented, and some of the main problems that irrigation faces in present day are addressed. An overview of the modernization of the irrigation techniques, which began in 1962, when the first offices of irrigation and drainage engineering were created, is presented. These offices were created to give a technical support to the rehabilitation works that started in several irrigation districts. The main activities carried out by these offices were related to the irrigation improvement, as well as to the monitoring of water table levels and soil salinity. The activities of the so-called "Plan de Mejoramiento Parcelario" (best known as "Plamepa", or Plan for Irrigation Improvement at the farm level), which had to do with the improvement of the overall water management efficiency, as well as with the works needed to increase the main crop yields, are also described. The problems that arise during the elaboration of water table and soil salinity maps are also commented. These problems include the definition of the threshold soil salinity content to consider a soil "saline"; the definition of a proper soil salinity sampling intensity, and the method of spatial interpolation for mapping. This information is crucial when planning the reclamation of saline soils by means of leaching. In the final part the consequences of the irrigation districts transfer from the federal government to the water users, on the irrigation, drainage and salinity studies and practices are commented.*

***Keywords****: Irrigation Districts, Soil Drainage, Soil Salinity, Plamepa.*

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## Introducción

En México, la cantidad media anual de la disponibilidad de agua per cápita es de solo 4 263 $m^3$ (esta y otras estadísticas fueron tomadas de EAM, 2014), diez veces menos que Brasil (42 886 $m^3$) y 10 y 15 veces menos que otros países hermanos, como Perú (66 338 $m^3$), Bolivia (64 215 $m^3$), Chile (54 868 $m^3$) o Colombia (47 365 $m^3$). La disponibilidad de agua por habitante, como sucede a menudo, tiene fuertes variaciones espaciales. Por ejemplo, en los estados del suroeste de México hay más de 20 000 $m^3$ por habitante y año, mientras que en el Valle de México, la región más poblada del país, la disponibilidad anual por persona es de poco más de 140 $m^3$. La figura 1 muestra la distribución de las precipitaciones anuales, lo que da una buena idea de cómo los recursos de agua varían espacialmente (la precipitación media anual para todo el país es de 772 mm).

En la mayor parte del país la temporada de lluvias es de mayo-junio a octubre-noviembre, y como en muchos otros países del mundo, en México la precipitación media mensual varía mucho a lo largo del año, por lo que incluso en algunas zonas húmedas como por ejemplo en el sur y sureste del país, hay períodos en los que es necesario el riego para aumentar el rendimiento de los cultivos.

Esta situación ha hecho necesario el riego desde tiempos prehistóricos para satisfacer las necesidades de los diferentes cultivos. La tabla 1 muestra un resumen de la principal infraestructura hídrica construida en México hasta 2013.

En la actualidad, México cuenta con aproximadamente 6.4 millones de hectáreas bajo riego; de ellos, 3.4 millones se encuentran dentro de 85 distritos de riego, que tienen una superficie media de 41 059 ha; los otros 3 millones de hectáreas se encuentran dispersas en más de 39,000 unidades de riego; es decir, áreas pequeñas promedian solamente 76 ha. Esto hace que sea muy difícil para los organismos gubernamentales darles la atención adecuada. Para completar el cuadro, hay que añadir que de

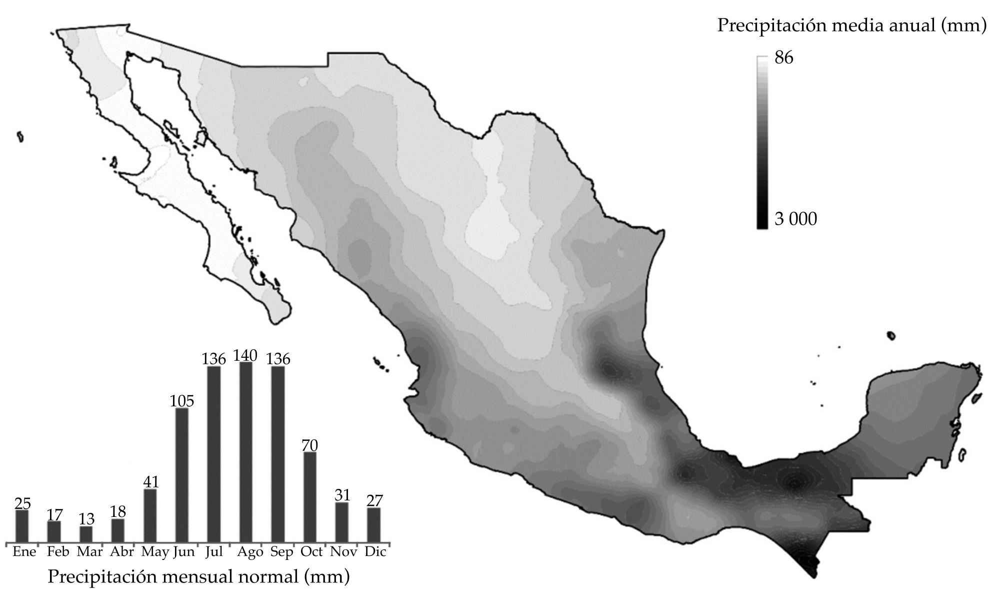


Figura 1. Variación espacial de la precipitación media anual en México.



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Tabla 1. Infraestructura hidráulica principal construido hasta 2013.

| **Infraestructura hidráulica construida hasta 2013<br>5 163 presas y embalses de almacenamiento, con una capacidad total de 150 km³** | |
|---|---|
| **Infraestructura para riego** | **Infraestructura para el suministro de agua en zonas urbanas** |
| 6.4 millones de hectáreas de los cuales:<br>3.4 millones en 85 distritos de riego y área de 3.0 millones situada en más de 39 000 pequeñas unidades de riego | 742 plantas de tratamiento de agua potable |
| 62 $km^3$/año se utilizan para el riego, de los cuales 21 $km^3$/año se bombean de los acuíferos. | 2 287 plantas de tratamiento de aguas residuales municipales y 2 617 plantas de tratamiento de aguas residuales industriales |
| La producción de los principales cultivos, como el grano de maíz, sorgo en grano, trigo y frijol bajo riego es de 2.2 a 3.3 veces el de la agricultura pluvial | 3 000 km de acueductos |

toda el agua utilizada para el riego (62 $km^3$), un tercio (21 $km^3$) proviene de los 653 acuíferos en el que nuestro país se ha subdividido. De ellos, 104 están sobreexplotados y muchos tienen un alto contenido de sales solubles. El riego es esencial para la economía mexicana, ya que la producción de los cultivos de regadío es de 2.2 a 3.3 veces la de la agricultura alimentada por lluvia.

Entre los principales problemas que el riego enfrenta en México en nuestros días, pueden mencionarse:

1) La falta de conciencia sobre el valor real del agua, por parte tanto de los diferentes usuarios del agua y las autoridades, que se manifiesta en el uso ineficiente de este recurso en las zonas agrícolas y las ciudades.
2) La sobreexplotación de corrientes superficiales; no se está respetando el caudal ecológico y muchos pequeños arroyos ya no son permanentes. Por otra parte, la calidad de las corrientes naturales se ha deteriorado como consecuencia del vertido de aguas residuales urbanas en los arroyos sin tratamiento alguno.
3) La sobreexplotación de muchos acuíferos; prohibiciones no son respetadas, y hay muchos pozos clandestinos que toman agua para la agricultura, así como para otros usos.
4) Salinización de los suelos de regadío, lo que reduce la productividad del cultivo, es causada por la elevación de los niveles freáticos y por el uso de agua con alto contenido de sales solubles.

Por otra parte, se espera que estos problemas se vuelvan críticos como consecuencia del cambio climático global. Las predicciones de cambio climático en México han sido pronunciada por dos grupos principales de investigadores; en el Centro de Ciencias de la Atmósfera (CCA) de la Universidad Nacional Autónoma de México (UNAM) (Gay, Conde y Sánchez, 2006; Magaña, 2010) y el Instituto Mexicano de Tecnología del Agua (IMTA) (Martínez-Austria y Patiño-Gómez, 2010). Sus estudios han considerado varios escenarios de emisiones de $CO_2$, como los denominados A1B, A2 y B1 (en el caso de los estudios realizados por el CCA UNAM) y A1B y SRES-A2 (en los estudios de IMTA). Además, se han utilizado varios modelos climáticos globales desarrollados en diferentes países de todo el mundo. Los resultados de estos estudios predicen que a mediados del siglo XXI, podemos esperar:

a) Una reducción de 10 a 30% de la precipitación media anual.
b) $2.3 \pm 1.0$ °C la temperatura del aire más altas.
c) Un incremento de hasta el 10% en la tasa de evapotranspiración potencial.

Esto provocará una reducción de 20 a 40% en agua disponible para el riego, y esto, a su



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vez, hará que el área afectada por la salinidad aumente del presente 10 a 15% a de 20-30% o más del área de regadío del país. Esta tendencia también corresponde aproximadamente con el crecimiento de la zona en la que será necesaria la instalación de sistemas de drenaje de campo.

Este artículo presenta una visión general de las acciones principales que se han tomado en los distritos de riego de México para diagnosticar, supervisar y resolver en parte los problemas de altos niveles freáticos y de salinidad del suelo. Estas acciones se basan en la idea de que la salinidad de los suelos irrigados en regiones áridas y semiáridas tiene dos causas principales: 1) la elevación de las capas freáticas salinas hasta 1,5 m o menos de la superficie; esto a su vez se debe a diversas pérdidas de agua de riego, tanto en el transporte y distribución en canales sin revestimiento y deficiente aplicación del riego en los campos (lo que se llama "salinización secundaria"), y el uso de agua con alto contenido de sales solubles ("salinización primaria", en general, menos frecuente que la secundaria). Una descripción detallada de los complejos procesos que conducen a la acumulación de sales en el suelo superficial no está dentro del alcance de este documento. La premisa de partida, simplificada pero correcta, es que *la mejor manera de prevenir o combatir los problemas de salinidad en el largo plazo es la reducción de las pérdidas de agua, es decir, la mejora de la eficiencia de conducción mediante el forro de los canales (o la instalación de los tubos cuando es económicamente posible), la mejora de eficiencia de riego, y la instalación de tubos de drenaje subterr*áneos en aquellas áreas donde los niveles freáticos *(salinos) están cerca de la superficie y no se puede bajar por otros medios*.

## Un poco de historia de la modernización del riego en México

Se puede decir que la modernización de la irrigación y los estudios de supervisión de los niveles freáticos de riego y la salinidad del suelo comienza formalmente en México en 1962, con la creación de las Oficinas de Ingeniería de Riego y Drenaje (conocido como "IDRYD"). Estas obras se iniciaron por primera vez en los distritos de riego que se estaban rehabilitando en ese momento (Culiacán, Sin., Valle del Fuerte, Sin., Río Mayo, Son., y Río Yaqui, Son.), y más tarde en los principales distritos de riego del país. El propósito de estas oficinas era dar apoyo técnico a estas obras de rehabilitación (SARH, 1976).

Amaya Brondo y Robles-Espinosa (1963) describen en detalle las funciones de estas oficinas en la forma siguiente: "Las funciones de las oficinas de Ingeniería de Riego y Drenaje son conservar el suelo y aumentar la producción de los distritos de riego mexicanos a través del uso más eficiente del agua y el suelo, por parte tanto del distrito de riego como del usuario individual". Los autores señalan que la intención de las autoridades del Ministerio de Recursos Hídricos fue que estas oficinas se "establezcan permanentemente en los distritos de riego como una parte importante de su organización funcional". Dadas las enormes diferencias en la precipitación anual (ver figura 1), topografía, suelos, clima, cultivos, etc., para la supervisión y control de las oficinas IDRYD, el país se dividió en dos grandes zonas: la zona norte y la zona sur, dividido aproximadamente en paralelo 24o latitud norte.

Amaya Brondo y Robles-Espinosa (1963, 1964) describen en detalle las múltiples funciones planteadas para las oficinas IDRYD, comenzando con la actualización de los estudios agrológicos utilizando los métodos más avanzados en esa época, fotografías aéreas y fotointerpretación, y sobre todo teniendo en cuenta las condiciones de salinidad en la zona norte, donde la escasa precipitación atmosférica promueve la acumulación de sales en los suelos. Las actividades de las oficinas IDRYD no sólo abarcaban la definición de profundidades óptimas y programación de riego para los cultivos principales, sino también mejorar la eficiencia de la gestión del agua de riego, tanto en la red de transporte y distribución como en la aplicación de campo y otros aspectos de la producción agrícola. Las oficinas IDRYD también calculan nivelación de tierras e hicieron recomendaciones para lograr una mayor eficiencia en la aplicación de agua de riego.



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Avances significativos en la modernización de riego se produce en 1967, cuando se creó el "Plan de Mejoramiento Parcelario" (Plan de Mejora de Parcela), más conocido por su acrónimo "Plamepa" (Pasos, 1985). Este plan consta de dos tipos de actividades: la mejora de la operación y distribución de agua, y la asistencia técnica a los agricultores para que un mejor uso del agua en sus campos aumentara la eficiencia de riego y la productividad de sus tierras. Esta asistencia se llevó a cabo en secciones de irrigación donde hubo un uso menos eficiente del agua, de acuerdo con los estudios hidrométricos realizados. El plan era interinstitucional y pidió la participación del Ministerio de Agricultura, en particular el Instituto Nacional de Investigación Agrícola, para hacer recomendaciones no sólo en las técnicas de riego, sino también respecto a la tecnología agrícola en general para los principales cultivos.

Amaya-Brondo (1970) señaló que "por el logro de una mayor eficiencia en la gestión del agua y el uso, 20% de agua desperdiciada podría recuperarse, considerando esto una meta realista en las actuales condiciones de desarrollo de los distritos, meta que puede ser alcanzada sin la necesidad de alinear los canales. Este porcentaje de recuperación se integraría como sigue: aumentar la eficiencia de transporte en 50% de la estimada en el ciclo de cultivos 1965-1966, y la eficiencia del uso del agua en la parcela de 50 a 70%, con lo cual la eficiencia total, estimada en un 25% en ese momento, aumentaría a 45,5%, es decir, el objetivo del 20%. También se informó que este objetivo aparentemente modesto haría posible regar 500 000 hectáreas adicionales". La historia demostraría que estas estimaciones fueron muy optimistas. Sin embargo, un beneficio adicional, bien entendido por los especialistas en irrigación y drenaje, era que la reducción de las pérdidas de agua de riego necesariamente se refleja en una reducción en la recarga de los niveles freáticos y, por lo tanto, en la reducción de los mismos. Con esto, las condiciones de salinidad del suelo también mejorarían.

Plamepa recibió un nuevo impulso en 1972, cuando se firmó un préstamo del Banco Interamericano de Desarrollo (BID) para reforzar el programa. El plan original considera dos etapas, con un costo total de 61.6 millones de dólares. Sin embargo, solo se ejecutó una parte equivalente a 47 millones de dólares. A través de este programa, en un área de más de un millón de hectáreas, se hicieron mapas topográficos de los campos de regadío, para mejorar el lugar y dirigir surcos de riego en las parcelas, utilizando lo que se conoce como "receta de riego". Además, se crearon un gran número de "parcelas demostrativas", en las que las técnicas de riego se probaron en los principales cultivos; 14,387 estructuras de aforo se construyeron para la entrega del agua de riego en volumen; 340.5 km de canales estaban alineados; se adquirieron equipos de laboratorio y se capacitó un gran número de ingenieros y técnicos. Desafortunadamente, Plamepa se suspendió inesperadamente en 1977.

Cabe señalar que las oficinas IDRYD dirigieron sus actividades principalmente hacia la mejora de las técnicas de riego y la productividad agrícola, dejando el estudio de los problemas de salinidad y drenaje en segundo lugar. Sin embargo, es importante tener en cuenta que la mejora en el transporte y la aplicación de agua de riego, al final, también se refleja en la mejora de las condiciones de drenaje y salinidad del suelo.

## Monitoreo de los niveles freáticos y salinidad de suelo

### *Estudios freatimétricos*

El monitoreo de los niveles freáticos se realiza de 4 a 12 veces al año, mediante la medición directa (con una sonda acústica) de la profundidad de los niveles en una red de pozos de observación (fortificados con tubos de PVC de 1 ¾ - 2 pulgadas) alrededor de 3 m de profundidad, con una densidad de 1 pozo cada 100 a 400 ha. La red de pozos de observación se completó durante varios años porque el costo de cada pozo hacía difícil construir toda la red en un solo año. Sin embargo, la operación más costosa y compleja



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en el largo plazo fue la medición sistemática de profundidades freáticas, además de la sustitución de pozos dañados. Como regla general, se recomienda que las mediciones puedan hacerse en uno o dos días. Por esta razón, en algunos de los distritos la totalidad de sus técnicos participaría, incluso los de otras secciones técnicas del distrito de riego (Amaya Brondo y Robles-Espinosa, 1963). En otros casos, hubo una sola brigada que fue responsable de tomar las medidas, lo que, en los distritos más grandes (con más de 200 000 ha), tomaría alrededor de dos meses.

Estas mediciones se representaron gráficamente en mapas dibujados a mano puesto que en ese tiempo los plóters eran escasos. Se elaboraron dos tipos de mapas: iso-profundidad (isóbatas) e iso-elevación (isóbaras) de los niveles freáticos. Estos mapas fueron muy similares a las isolíneas o mapas de isoyetas.

Usando los mapas isóbatas, es posible identificar las zonas más afectadas, mientras que los mapas de isobaras (que, en cierto modo, son líneas equipotenciales) permiten la identificación de las principales direcciones de las corrientes freáticas. Esta información fue utilizada para diseñar las redes de colectores de drenaje.

Los mapas de iso-profundidad a menudo se resumen en un gráfico de "áreas- tiempo", lo que permite la observación de cómo las zonas con diferentes rangos de profundidad de nivel freático varían durante el año y durante varios años. La figura 2 muestra un ejemplo de este tipo de información gráfica en el Distrito de riego No. 41 del Río Yaqui, Son.

Se puede observar que estos mapas permiten "tomar el pulso" del distrito de riego, en términos de problemas con los niveles freáticos. Reflejan los principales cambios que se produjeron en los niveles freáticos como consecuencia de actividades tales como obras de rehabilitación, la entrada en funcionamiento de los pozos de bombeo de agua subterránea, las mejoras en los sistemas de riego y drenaje, etc. En el gráfico de la figura 2, está muy claro cómo las áreas con los niveles freáticos someros disminuyeron (sombreados en gris oscuro) a partir de abril de 1970, cuando una red de pozos comenzó a bombear

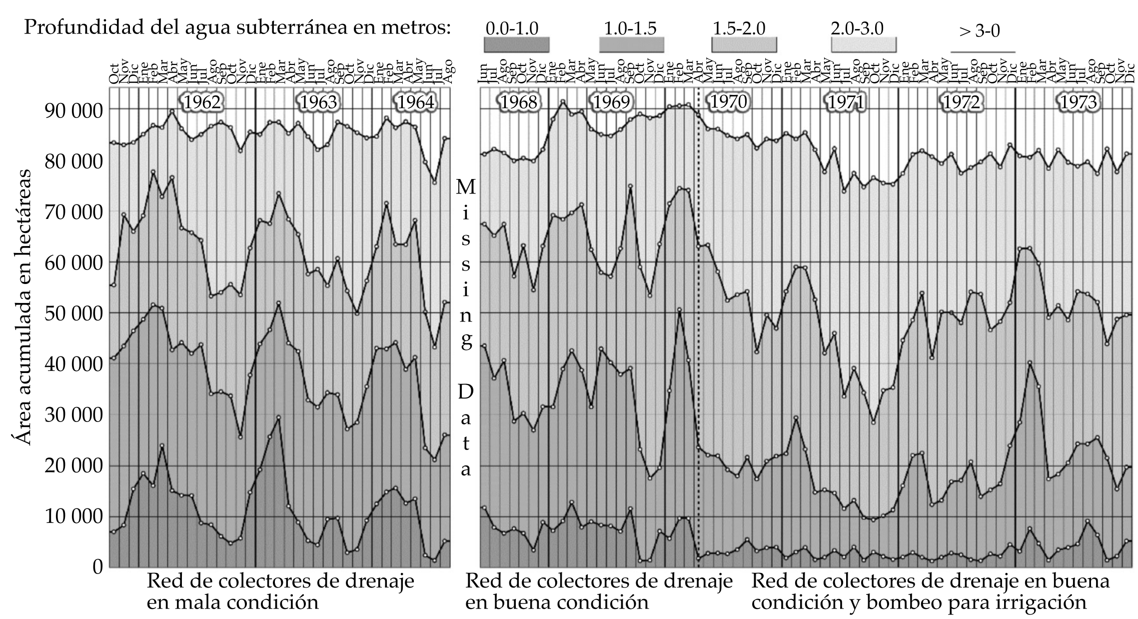


Figura 2. Detalle de un gráfico de "áreas-tiempo", donde la variación tanto intraanual como interanual se puede observar en áreas con diferente rango de profundidad del nivel freático.

agua subterránea, mostrando su enorme efecto como " drenaje vertical". Estadísticamente, estos gráficos eran muy "robustos", ya que se construyeron a partir de una gran cantidad de información. Complementados con información sobre la precipitación, derivaciones para el riego, la extracción del acuífero, etc., estos mapas permitieron la evaluación tanto de los principales componentes del balance de agua como del estado de los suelos del distrito. Es una verdadera lástima que este tipo de gráficos ya no se produzcan en nuestros distritos de riego.

## Estudios de salinidad del suelo

La salinidad del suelo se determinó inicialmente en los llamados "mapas de salinidad aparentes", para los cuales no se toman muestras de suelo ni se llevan a cabo análisis químicos. Estos mapas se construyeron sobre la base de reducciones en la productividad agrícola de los principales cultivos en el supuesto de que la salinidad fue el principal factor en la reducción de los rendimientos de los cultivos. En estos mapas, se diferencian cuatro tipos de afectaciones salinas, que se estiman en función de la reducción observada en las producciones agrícolas:

a) No se ve afectada por la salinidad,
b) ligeramente afectada (reducción de 10 a 15% en la producción media)
c) afectada de forma intermedia (reducción de 15 a 30% en la producción media), y
d) afectada fuertemente (la reducción de más de 30% en la producción media).

El área mínima diferenciable era "una parcela" (o la parte de ella plantada con un solo cultivo), generalmente de unas pocas hectáreas de superficie.

En 1964, se estimó que para los cuatro distritos en los que se iniciaron estos estudios (Culiacán, río Fuerte, río Mayo y río Yaqui) con una superficie total de 610,701 hectáreas, 36% de sus tierras exhibe algún grado de afectación por la salinidad, a partir de la afectación leve para tierras abandonadas debido al alto grado de afectación (Amaya Brondo y Robles-Espinosa, 1964).

Solo en las partes más afectadas que se analizaron se construyeron "mapas de salinidad" sobre la base de muestras de varias capas de suelo (típicamente 0-30 cm, 30-60, 60-90, 90-150, 150-210 y 210-300 cm) y de las determinaciones no solo de conductividad eléctrica del extracto de saturación, sino también de los principales aniones y cationes.

La cuantificación de las áreas "salinas" en un distrito de riego depende básicamente del criterio para definir un suelo "salino". Hacia la mitad del siglo pasado, el Laboratorio de Salinidad del Departamento de Agricultura de los Estados Unidos publicó el conocido Manual 60 "Diagnóstico y rehabilitación de suelos salinos y sódicos" para servir como una guía práctica para resumir la información sobre la "salinidad" y "alcalinidad" de suelos. Cuatro grandes grupos de suelos se diferencian en función de dos parámetros: la conductividad eléctrica (CE) del extracto de saturación del suelo, según si esta era mayor o menor que 4 mmho/cm, y la "tasa de adsorción de sodio" (TAS), conforme a si esta era menor o mayor que 15%. Un suelo se consideraba "normal", sin problemas de sales, si tenía un EC abajo de 4 mmho/cm y una TAS por debajo del 15%. El suelo era "salino" si tenía una CE por encima de 4 mmho/cm y una TAS por debajo del 15%. Y era "sódico" si la CE estaba por debajo de 4 y SAR por encima de 15%. Estos suelos son más difíciles de recuperar porque requieren mejoras. El resto de los suelos son "salino-sódicos". Aplicando este criterio, una gran parte de los suelos de regadío en las regiones áridas se clasificaría como salina. Por esta razón, aunque no en general, otras clasificaciones se establecieron con base en diferentes rangos de valor de la conductividad eléctrica del extracto de saturación de las muestras de suelo. Así, De la Peña estableció las siguientes clases de suelos en función de la salinidad (Llerena-Villalpando, 2011):

a) Primera clase, por debajo de 4 mmho/cm (sin afectación salina).

b) Segunda clase, de 4 a 8 mmho/cm (ligeramente afectados).
c) Tercera clase, de 8 a 12 mmho/cm (intermediamente afectados).
d) Cuarta clase, de 12 a 20 mmho/cm (fuertemente afectados).
e) Quinta clase, por encima de 20 mmho/cm (muy fuertemente afectados).

En la caracterización de la salinidad del suelo, otro problema, sin solución clara y general, fue la determinación de la "adecuada" densidad de muestreo, que en gran medida depende de la magnitud de la zona y el propósito del estudio, ya que no es la misma cosa muestrear una parcela de 20 ha con problemas de salinidad con el objetivo de llevar a cabo una operación de lixiviación del suelo que muestrear un distrito de riego completo de varias decenas de miles de hectáreas para simplemente construir un mapa genérico de la salinidad del suelo. Es esencial el conocimiento confiable de los contenidos y la distribución de sales en el suelo para la correcta planificación de lixiviación de suelos salinos utilizando la menor cantidad posible de agua de riego, una regla ineludible en la medida de que la crisis del agua se haga más grave.

Uno de los primeros intentos para definir la intensidad de muestreo con el fin de realizar la lixiviación de suelos salinos, teniendo en cuenta el costo del agua, el costo de muestreo de suelos y los análisis químicos, así como el costo de perder la cosecha si la tierra fuera sublixiviada, fue llevado a cabo por Llerena- Villalpando y Palacios-Vélez (1979), quienes llegaron a la conclusión de que, por las condiciones de ese tiempo, era necesario tener al menos una muestra por hectárea.

En cuanto al método de interpolación de datos de salinidad del suelo, necesaria para la cartografía de suelo salino, Ramírez Ayala, Palacios-Vélez y Zárate-de-Lara (1979) compararon el método de interpolación de Kriging con ciertas funciones de tendencia para tres series de datos correspondientes a diferentes escalas espaciales. El área de estudio más pequeña tenía datos de salinidad determinada en una cuadrícula de 17 x 17 sitios separados solo por 1.25 m. Una segunda serie de datos se compone de 97 sitios espaciados por una distancia de 40 m. Por último, una tercera escala tenía 395 sitios ubicados irregularmente con una separación media de 2 700 m, pero fluctuando entre 900 y 20 000 m. Como sabemos, el método de Kriging se basa en la definición inicial de un semivariograma. En este punto, con la primera serie de datos, separados 1.25 m, se obtuvo un semivariograma lineal que no define un radio de influencia donde el semivariograma es igual a la varianza. En la segunda serie de datos, con una separación equidistante de 40 m, un ajuste a un semivariograma esférico se obtuvo con un radio de influencia entre 200 y 260 m. Finalmente, en la tercera serie de datos, con una separación irregular de una media de 2700 m, se obtuvo una variabilidad de los datos demasiado amplia para definir un variograma. Este trabajo pone de manifiesto la necesidad de estudiar escalas intermedias entre 40 y 2 700 m. También es importante estudiar la confiabilidad de los diferentes métodos disponibles de interpolación, ya que la confiabilidad de los mapas construidos depende de ello.

En cuanto a la lixiviación y recuperación de suelos salinos, hay que decir que este tipo de estudio se ha llevado a cabo en pocos lugares en México, además del Distrito de Riego No. 41 Río Yaqui, Sonora, ya que la operación requiere el uso de agua de riego sin necesidad de obtener una cosecha durante el período de rehabilitación de estos suelos.

Algunos de los puntos principales a tener en cuenta en la planificación de la recuperación de suelos salinos por lixiviación son:

a) Definir la densidad de muestreo apropiado para determinar con mayor confiabilidad el grado de salinización del suelo y definir correctamente las cantidades de agua necesaria para la lixiviación (y la cantidad de mejoras, si son necesarias).
b) Obtener mapas de distribución de sal en las parcelas que deben recuperarse, con el objetivo de aplicar lixiviación diferencial



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para ahorrar agua (que se puede llamar "lixiviación de precisión").

c) Iniciar a trabajar las parcelas recuperadas con cultivos tolerantes a la salinidad, ya que la recuperación continúa con el exceso de irrigación.

d) Mantener los niveles freáticos en parcelas recuperadas a profundidades de más de 1.5 m para evitar el retorno de sales a la parte superior del suelo mediante el uso de drenaje subterráneo en caso necesario.

### *La decadencia de las Oficinas IDRYD*

Las Oficinas IDRYD comenzaron a recibir menos apoyo durante la década de 1980 y desapareció durante la década de 1990. Las autoridades mexicanas, ante todo preocupadas por la disminución de los gastos del gobierno tanto como fuera posible, consideraron que las Oficinas IDRYD no eran indispensables y que cada agricultor debe cubrir los costos de los estudios realizados en su parcela.

En un intento de hacer una evaluación objetiva de las actividades de las Oficinas IDRYD, tiene que decirse que una gran parte de su trabajo no fue más allá de recomendaciones y las buenas intenciones. El país aún no tenía (ni tiene hoy) las condiciones que harían que el combate decidido contra cualquier tipo de pérdida de agua de riego no solo fuera posible, sino también económicamente atractivo e incluso esencial, algo que requeriría un aumento sustancial en el costo del agua. Parece imposible que los usuarios agrícolas y urbanos estarían dispuestos a hacer un verdadero esfuerzo para conservar este recurso si solo se nos exhortara sin que nuestros bolsillos se vieran directamente afectados.

Por otra parte, la adopción de prácticas de drenaje subterráneo cuando los niveles freáticos salinos se encuentran por encima de 1.5 m de profundidad y/o cuando hay problemas de salinidad del suelo reflejada en la producción agrícola disminuida requerirán programas de apoyo del gobierno para reducir el esfuerzo y la inversión que los agricultores tienen que hacer.

## Situación actual (2014) de los estudios de drenaje y salinidad

Durante la década de 1980, la mayor parte de los distritos de riego fueron transferidos a asociaciones de usuarios de riego (AUR) y, en la fase más avanzada de este proceso, la transferencia fue a sociedades de responsabilidad limitada (SRL) para gestionar las zonas de riego más grandes. Antes de esto, los distritos fueron operados por lo que ahora se conoce como la Comisión Nacional del Agua (Conagua) a través de las oficinas locales de los distritos de riego. Hoy en día, la Conagua solamente opera grandes obras de infraestructura hidráulica, es decir, las grandes presas y la gestión actual (Nacional) de los Distritos de Riego, y tiene más bien una función normativa. Los usuarios asociados en "módulos de riego" tienen la responsabilidad de distribuir el agua de riego, recogiendo el agua de drenaje, resolviendo conflictos internos, realizando la operación y mantenimiento de las estructuras, así como colectando los pagos de las cuotas de riego. Aunque nunca se ha reconocido abiertamente, una de las razones para la transferencia de los distritos de riego a los usuarios fue más por la preocupación del gobierno para la reducción de los subsidios al sector agrícola de regadío que su convencimiento de que la transferencia de los sistemas de riego a los usuarios mejoraría su funcionamiento. Muchas evaluaciones se han realizado sobre los resultados de la transferencia, pero las evaluaciones negativas parecen predominar (Trava-Manzanilla, 2010).

Después de que los distritos de riego fueron transferidos, se implementó un programa de "retiro voluntario" en los distritos de riego durante el inicio de la década de 2000. Como consecuencia, la Conagua ha perdido buena parte de su personal técnico con más experiencia. Esta pérdida se hizo sentir negativamente en la cantidad y calidad de la información hidrométrica, estadística, agroclimatológica, de producción y comercialización, generada en los distritos de riego y que es fundamental para la planificación, operación y conservación, así como para cualquier programa de mejora en el corto, mediano y largo plazo.



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Por lo tanto, a partir de finales de 1980, la elaboración de mapas freatimétricos prácticamente se detuvo, aunque hay algunas excepciones, tales como los correspondientes a Lázaro, Fuentes, Ortega- Escobar, Rendón-Pimentel y Zataráin-Mendoza (2000), quienes hicieron un pronóstico utilizando mapas de profundidades freáticas para diferentes escenarios de políticas de gestión de suelo y de agua en el Distrito de Riego Núm. 076, Valle del Carrizo, Sinaloa. En este estudio, se utilizaron mediciones de niveles freáticos de 1996; estos pueden haber sido las últimas medidas tomadas en este distrito de riego. Del mismo modo, los estudios de salinidad del suelo ya no se llevan a cabo, por lo que ahora no es posible evaluar con precisión la situación de este aspecto que existe ahora en los distritos de riego del país.

## Conclusiones

En la medida que la extracción de agua subterránea ha ido en aumento, los niveles freáticos han ido disminuyendo. La figura 2 muestra esta tendencia con bastante claridad en el caso del Distrito de Riego Núm. 41, Río Yaqui, Sonora. Desafortunadamente, no hay gráficos similares para otros distritos de riego.

En cuanto a la información sobre la salinidad del suelo, nunca ha habido realmente un intento de cuantificar o mapear generalmente las áreas con diferentes grados de afectación. Recientemente, los intentos de monitorear la salinidad del suelo se han hecho utilizando imágenes de satélite Landsat y el sensor electromagnético EM-38 (Pulido, González-Meraz, Wiegand, Infante-Reyes y Delgado, 2010). Los resultados, sin embargo, no parecen ser muy confiable o alentadores porque la aparición espectral de los cultivos no depende solo de la afectación salina, y el sensor EM-38 requiere una mayor calibración con datos sobre la salinidad analizados en el suelo.

Varios autores han estudiado la afectación salina en las zonas de regadío de nuestro país. Fue Llerena-Villalpando (2011) quien, probablemente, ha logrado resumir el alcance más amplio de esta información. Llega a la conclusión de que hay alrededor de 650,000 hectáreas que se ven afectadas en cierto grado por la salinidad, lo que equivale al 10% del área de regadío del país. Cifras similares se han reportado para otros países, como 12.8% en China y 11.9% en la India (Llerena-Villalpando, 2011). Es de gran importancia para tener una cifra precisa e indicar rangos de salinidad para planificar y justificar las medidas de prevención y lucha contra la salinización.

Con respecto a la utilización de tubos de drenaje subterráneos, uno de los medios más eficaces para reducir las capas freáticas salinas y promover la lixiviación y recuperación de suelos salinizados, en el país se ha instalado este tipo de drenaje en solo alrededor de 60,000 ha, es decir, solo el 1% del área irrigada del país. No es fácil explicar que tan minúscula es esta cifra, pero las posibles causas puede estar entre las siguientes: falta de tradición y convicción por parte de los agricultores de la bondad de estos sistemas; las recurrentes crisis económicas que han afectado a los agricultores, y la falta de promoción por parte de la Conagua y de las instituciones de educación superior e investigación relacionada con problemas de agua en la agricultura.

Por último, se espera que cuando, en el futuro, se inicien los estudios sobre el monitoreo de los niveles freáticos y la salinidad del suelo, habrá tecnología moderna para la medición y transmisión de datos, así como sensores de salinidad del suelo perfeccionados que permitirían la medición *in situ* de la salinidad. Cuando toda esta información se procesa en la forma de mapas y gráficos con la ayuda de sistemas de información geográfica y otros programas de cómputo, los costos y el tiempo disminuirán, mientras que la calidad de estos estudios se incrementará.

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# Use of a Water-Saving System to Conserve Ecosystems for Water Resources

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## Abstract

López, G., García, M. M., Gameros, L. A., & De la Rocha, A. P. (November-December, 2015). Use of a Water-Saving System to Conserve Ecosystems for Water Resources. *Water Technology and Sciences* (in Spanish), 6(6), 125-135.

In the northwestern region of Mexico is border between Mexico and the United States (US), it is carried out an evaluation of a possible problem of the small amount of water that Mexico receives from our neighbor to the north, from the Rio Colorado (RC) from United States. Sometimes USA sends contaminated water to Mexico, by chemicals mainly because the hydric resource, comes from soil washing in the United States, from agricultural activities. In addition, USA, proposed a process to coat the All American Canal (CTA), which has resulted in decreased of aquifers Mexicali Valley, generating concern in authorities and the population of Mexico. This has led to damage ecosystems and thus present climate changes that increase the levels of relative humidity (RH) and temperature, and thus causes corrosion in the industry and generates economic losses, which reduces competitiveness in the electronics industry in this region.

**Keywords**: Ecosystems, industrial competitiveness, corrosion, water saving equipment.

## Resumen

*López, G., García, M. M., Gameros, L. A., & De la Rocha, A. P. (noviembre-diciembre, 2015). Uso de un sistema de ahorro de agua para conservar ecosistemas para el recurso hídrico.* Tecnología y Ciencias del Agua, *6(6), 125-135.*

*En la región noroeste de la república mexicana, zona fronteriza entre México y Estados Unidos (EE.UU.), se está evaluando una posible problemática de la escasa cantidad de agua que México recibe de su vecino del norte, proveniente del Río Colorado (RC). En ocasiones, México recibe agua contaminada por agroquímicos debido a que ese recurso hídrico proviene del lavado de tierras estadounidenses. Además, Estados Unidos propuso revestir el Canal Todo Americano (CTA), lo que ha generado una disminución en los mantos acuíferos del valle de Mexicali, generando preocupación en autoridades y la población. Esto ha conllevado a deteriorar ecosistemas y con ello presentarse cambios de clima que incrementan los niveles de humedad relativa (HR) y temperatura, que genera corrosión y pérdidas económicas, y reducción de la competitividad en la industria electrónica de la región.*

***Palabras clave***: *ecosistemas, competitividad industrial, corrosión, equipo de ahorro de agua.*

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## Introduction

An increase in water and electric consumption in northwestern Mexico is due to the increase in relativity humidity (RH) and temperature, even at low indices, such as 1 to 5% and 1 to 2 °C. This affects some of the operations of industries, since it requires maintaining controlled indoor climates and running air conditioners during the summer, particularly from May to August. These measures are taken to prevent electrochemical conditions that quickly damage industrial equipment and machinery, as well as the products manufactured. The cost of the frequent use of air conditioners and the high cost of electric consumption in this region requires companies to adjust their expenses. This sometimes results in less than optimal production levels and decreases competiveness in the electronics industry in this area of the country. In addition, when water levels decrease its cost increases, which also affects the electronics industry and any other type of industry in the region. Based on this, an investigation was performed to design and implement automated control systems (ACS) to create awareness about the need to conserve water and thereby maintain a lower cost for the water needed for human activities in the city and the in the valley of Mexicali. This would be used to irrigate green areas and crops in order to prevent waste and water losses, and conserve the ecosystem. The premise considered is that the lining of the All-American Canal (AAC), which began some of its activities in 2000, would generate a decrease in the water tables/aquifers in the Mexicali valley, and produce an imbalance in ecosystems as well as a decrease in the water resource. This could raise the cost of water, food and industrial, commercial and domestic activities in the cities of Mexicali, Baja California, and San Luis Río Colorado, Sonora.

## The Colorado River

The Colorado River (CR) received its name because it originates in the state of Colorado. Its headwaters are in the Colorado Rocky Mountains in the central part of the United States. The river supplies water to a large portion of the ecosystems in the southwest portion of this country, including the states of Colorado, Utah, Nevada, California and Arizona, as well as the Mexican states of Baja California and Sonora, in northwestern Mexico. The Colorado River is 2 500 km long (Reyes, Guerra, & Ramírez, 2006). It is an important provider of water for the residents in this region and the only source in some of the regions of both countries. The main environments in the region which the river supports are plains, mountains and deserts, with over 400 species of flora. It provides habitats for fish, reptiles, amphibians, birds, rodents and mammals (Aguirre & Torres, 2007). The main activities in these ecosystems, that use water from the Colorado River, are agriculture, livestock, hunting, geothermal operations to supply electricity to large urban and suburban areas in the region, aquaculture, fishing and ecotourism. The geothermal plant is a primary source of electricity for the valley and city of Mexicali, as well as for towns in the United States, including Calexico, El Centro and Brawley. Nevertheless, it pollutes the river with its chemical wastes. An important factor is that the flow of the river has decreased to a large degree over the past 10 years, causing hydrodynamic changes, particularly in the lower basins of this great provider of water. This concerns environmental specialists, government authorities and residents. It has come about from the disproportionate use of land for new human settlements, modifications of the environment by industrial and agricultural operations that salinized the water table/aquifer, as well as the degradation of soil due to natural causes, primarily erosion (Lozano & Romo, 2003). Therefore, the city of Mexicali is vulnerable to water problems in the near future because of the lining of the AAC, a branch of the CR. The CR comes from the state of Colorado, United States, crosses into Mexico through the valley of Mexicali. It provides water for agricultural activities in the valley and for industrial, domestic, government and commercial activities in the city. Therefore, studies are needed in this area of the country that evaluate the possibility of using a basic low-cost automated control system (ACS) (under 100 Mexican pesos) that is easy to manufacture and operate, to conserve water in the operations of this city and valley. Lining the AAC involves placing a plaque-shaped structure in areas in California through which the river flows. This can lead to a lack of water in wells in the valley of Mexicali, which supply water for the agricultural activities in the valley and for domestic, industrial and commercial activities in the city.



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## Cost of Using Water

The deterioration in ecosystems has caused an imbalance in all regions worldwide, with climate changes, resulting from a lack of awareness on the part of the population. This is due to the emissions of pollutants from anthropogenic sources into the air, water and soil, as well as the felling of forests which generates deserts and abandonment of regions that do not have the natural resources needed for survival. Adding to this the inadequate use of water, some regions in the world have worsened to a degree in which vegetable and animal species have disappeared. The lack of water in some parts of the world increases its cost as a result of the need to transport it from other areas. This is particularly true for industrial companies, whose increased expenses cause an imbalance in their finances and a decrease in competitiveness. While this also occurs in developed countries, it is greater in developing countries and those in extreme poverty. In addition, the lack of water causes diseases that are of concern to governments as well as industries because of the demand on their budgets. Currently, developed countries control most of the water (Porter, 1991) and finances, on a scale close to 85% (Sánchez, 2010), with developing countries representing 22%. Water scarcity occurs in the majority of countries in extreme poverty, which is of concern to international organizations such as the World Health Organization (WHO), United Nations (UN), United Nations Food and Agriculture Organization (FAO), and the Organization of American States (OAS) (Lozano & Romo, 2003).

## The Ecosystem on the Mexico-United States Border

The western region on the border between Mexico and the United States contains a large variety of flora and fauna that has adapted to the habitats of the region shared by the two countries. Both vegetation as well as animals have remained there because of the presence of water from the United States, which runs through several parts of northwestern Mexico. This water is highly important to the survival of the species in the region, and an ecological imbalance can occur if the capacity of aquifer water tables, canals and rivers decreases (González, Montoya, & Hernández, 2007). On occasion, the Colorado River has been polluted by agrochemicals and industrial and urban wastes containing liquid, solid and gaseous pollutants, reducing the quality and quantity of the resource. Therefore, the little amount of water that reaches the states in both countries should be managed well in order to prevent scarcity and problems with the environmental, economic and social conditions of the region (Gómez, Rivera, Martínez, & Yánez, 2004).

## Altering of the Environment and Social Conditions

Another important factor that is currently occurring is the process of lining one of the branches of the Colorado River, the All American Canal (AAC), in southeastern United States. In the near future, this will have a negative effect on the supply of water to the border region of both countries, due to reduced levels in the aquifer water tables over a short period of time. A decrease in water will alter the ecosystems in both countries due to the migration of some species to other places in search of water and food that may become scarce in the region (González *et al*., 2007). In addition, agricultural and industrial activities in the valley and the city of Mexical could decrease over a short period of time, reducing agricultural products. This would bring about an increase in the price of food and a loss in jobs from the closing of some types of industries. It could also create health problems due to a lack of nutrients and generate and proliferate diseases, primarily



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respiratory, caused by a dusty region with eroded soil, loosening fine particles and agricultural pollutants from the soil. Under this situation, part of the food change in this ecosystem could be broken or the flora and fauna in the region could be altered (López, Rueda, & Domínguez, 2002).

## Raising Awareness about Conserving the Ecosystem

Environmental experts in both countries believe that the pollution of the CR and its branches and the lining of the AAC will decrease the quality and quantity of water in this border region. Therefore, some type of program to conserve water is crucial, in which the population is conscious of its appropriate use or there is some type of automated system that helps to raise awareness. Analysts of this topic indicate the possibility of a period during which there is little water supply or scarcity (Robles & Torres, 2003). Previous studies indicate that the residents of the city and valley of Mexicali have a low level of awareness about conserving water for agricultural, domestic and industrial activities, which sometimes floods certain areas. This led to the design and development of an automated system to control irrigation in northwestern Mexico.

## Ecological Balance

The adequate use of water guarantees urban development in small and large cities. This strengthens industries, such as in northwestern Mexico where a large number of maquiladora companies exists, which are mostly foreign (United States, Canada, China, Japan, Germany and Italy). The cities of Mexicali, Tijuan and Ensenada, located 100 km from the Mexico-United States, border have grown disproportionately, resulting in the inadequate use of water and, therefore, some areas have problems with the supply of this resource. Thus, the design and manufacture of an automated system was proposed to control the use of the water for agricultural, livestock, domestic, industrial and commercial activities. Adding to the lack of awareness about the use of water, the process of lining the AAC is being considered in the southern California, next to the border region, in order for the United States to obtain more benefit from the water and prevent the precipitation of the water from reaching areas in Mexico near the border. This will create a larger problem, since water is required for the activities mentioned, and therefore the industrial companies in this region of the country are already experiencing economic costs from the lack of water, by not completing operations for some of the products, thereby decreasing the productive capacity and competiveness level.

## Water to Support Life

Experts in the field of water protection believe scarcity in some countries negatively affects human health. The World Health Organization (WHO) indicates that over half of the global population is impacted by water scarcity, which has contributed to climate change in some regions and the generation and propagation of current diseases as well as the development of new ones (Sánchez, Páez, & Flores, 2006). Some regions in Mexico are experiencing water scarcity and a decrease in the productivity of agricultural, commercial and industrial operations. Northwestern Mexico is vulnerable to the negative effects of water scarcity, because of what has been mentioned above (González *et al*., 2007). Specialists on the topic believe that developing environmental and engineering policies are good methods for contributing to water conservation. The scarcity of water generates a decrease in the productivity of vegetables, legumes, fruits, wheat, corn and food for livestock, such as alfalfa, a source of nutrition for humans. In addition, the cost of commercial



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products in this region increases, including those sent to other areas of the country or to the United States, which creates economic problems (Reyes *et al*., 2006). According to a report by Mexico's National Water Commission (Conagua, Spanish acronym), the water quality in this region has declined over the past 20 years and the amount of water in wells located in the valley of Mexicali has decreased. This has damaged roughly 12 000 hectares, making the land infertile for agricultural activities. As a result, commercial and industrial operations have decreased over the past five years. Currently, the valley and city of Mexicali receive water from the Colorado River, but the water that reaches Mexicali is sometimes polluted. This, along with the lining of the canal, will reduce the supply of water by roughly 30% over three to five years, according to experts on the topic. Given that this will severely affect this region of Mexico, it is important to raise awareness about conserving water through social water conservation programs or automated systems that help to prevent the waste of the resource.

## Methodology

Water is the key to the survival of life and essential to the viability and development of any civilization. Analyses have been performed of some of the difficulties and solutions related to supplying water to small and large populations and for agricultural and industrial activities (López, Soriano, Torres, & Zamudio, 2006). Over the past 30 years, scarcity has existed in some parts of Mexico and the water supply is not sufficient for the population. A wide range of actions have been important for preventing damage to sources of water used for human activities (WHO, 2004). For this reason, a study was performed in the city of Mexicali about the problem that could occur in this region of the country, and an evaluation was developed with the objective of implementing a new low-cost automated control system (ACS). Five stages were necessary to perform the analysis, which are described below.

a) Periodic analysis of water quality. According to Conagua, Mexicali is one of the main cities in Mexico that receives water containing agrochemical impurities from parts of the United States. Meanwhile, a large portion of the population is not aware of conserving this resource, allowing the water to run from faucets or hoses and causing areas to flood. Therefore, the water quality in the city of Mexicali was evaluated for the period 2005 to 2012.
b) Evaluation of water consumption in homes. The lining of the AAC will negatively affect this region of the country in the near future, which is cause for great concern. The precipitation of water in the subsoil is known to cause it to decrease, and therefore water levels will decline and it will need to be conserved. The inadequate use of water (which is practiced by a large portion of the Mexicali population) is in the process of causing possible economic, social and environmental chaos. Therefore, it is necessary to develop an evaluation to raise awareness about the adequate use of water by the population.
c) Analysis of deterioration of soil in the valley of Mexicali. Damage from the decrease or possible undersupply of water to fertile land surfaces in the Mexicali valley has increased slightly over the past 10 years. This has reduced the agricultural crops grown in the region, and slightly increased their costs and prices. Thus, the percentage of soil with more deterioration was analyzed.
d) Manufacture of the ACS. The ACS was designed and manufactured to evaluate the differences in water savings from using the system, versus not using it. The automated system is low-cost, with an 85% efficiency, tested for 5 years in Mexi-



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cali and its valley. This helped to conserve water and improve the ecosystem of this region.

e) Microscopic evaluation of the soil. An evaluation was performed in different parts of the region where the ACS was used versus sites where it was not used. The objective was to observe differences using a scanning electron microscope. The analysis enabled performing a detailed analysis of the consequences of the decrease in water in the valley of Mexicali and the possible consequences if an undersupply occurs.

## Results

The quality of water is greatly important for any activity that contributes to the development of healthy communities, and therefore their economic growth. Northwestern Mexico—where the city of Mexicali is located, on the United States-Mexico border— is an area that has grown economically and is very important because of its fertile land, on which cereals and vegetables can be grown, primarily. In addition, a large number of industries have located here, particularly in the automotive, electronics and metal mechanics sectors. Agriculture began nearly 100 years ago and the industrial plants arrived a little over 30 years ago. But the quality of the water received from the CR's AAC has decreased over the past 10 years. This has occurred because of the presence of agrochemicals used in agricultural fields in the United States, which are discharged into the water that flows into Mexico. This resource is used to irrigate crops in the valley of Mexico and for domestic, industrial and commercial activities in the city of Mexicali. The above generates high costs for governments by requiring specialized equipment to obtain good quality water. Nevertheless, the cost of water in Mexicali is low, even with specialized equipment to treat it; that is, around six Mexican pesos per cubic meter. With an average monthly payment of 300 to 500 Mexican pesos, the population and companies waste it or pollute open channels located in the valley of Mexicali, through which the water runs with no treatment whatsoever. Based on this, an analysis was performed of the quality of the water from 2005 to 2012 at the entrance to the valley of Mexicali, with periodic monitoring (not constant). A total of 1 500 measurements were obtained over time, shown in Figure 1. This was developed to determine processes to obtain good quality water for the required activities.

At the beginning of the study, the water quality was indicated to be roughly 75%, and a higher concentration of the water quality levels, 60%, were observed from 2005 to 2007. From 2007 to 2010 this value was 50%, a decrease which required improving specialized equipment to treat and supply it for the required activities. From 2010 to 2012, the quality decreased by 50%, which is serious because of the possibility of generating respiratory and intestinal infections.

## Evaluation of Water Consumption

Since the quality of water received from the United States is low, and the valley and city of Mexicali have grown considerably over the past 20 years, an analysis of the consumption of water in households was performed. One thousand surveys were taken over the seven years of the study, as shown in Figure 2.

The objective of this evaluation was to determine the consumption per household in the city of Mexicali, and thereby estimate future household consumption to correlate it with the low-quality water supplied to the city and valley. This indicates how the water is received and identifies whether it is adequate for household use and irrigation in agricultural areas, where areas are flooded because of a lack of awareness on the part of the population, by letting the water flow and not controlling it. The surveys of the Mexicali residents indicate that from 2005



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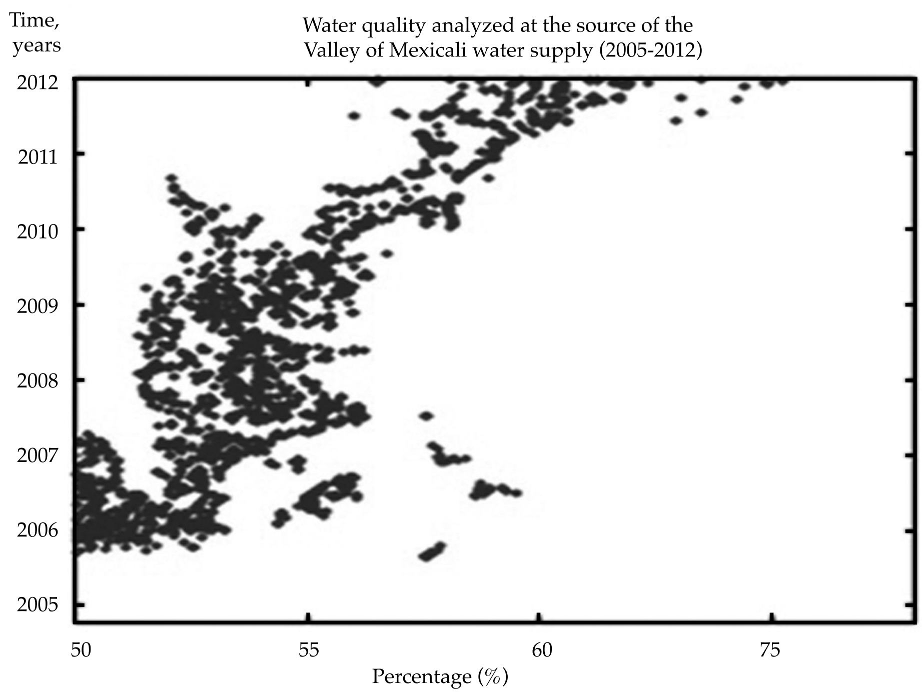


Figure 1. Analysis of the quality of water in the city of Mexicali water supply system.
Source: Evaluated data from experimental studies created by a research project in the valley of Mexicali region (2005-2012).



to 2007, during summer when more water is used, consumption was under 300 m$^3$ per month per household, which is more than the average established by the World Health Organization (WHO) of 150 m$^3$. From 2007 to 2008, consumption increased to 375 m$^3$ and reached 450 m$^3$ by 2012. This is very important because of the high cost of treating low quality water, which is not adequately used. Control of water consumption by the population of Mexicali is crucial given the decrease in the supply which is in progress due to the lining of the AAC and because it tends to be a very productive agricultural, commercial and industrial region where water scarcity is possible. The state authorities of Baja California and the municipality of Mexicali are concerned and it seems the population does not share that perspective and therefore continues to waste the resource.  For roughly 10 years, fines have been considered for persons or institutions that waste water, but these measures have not made a lot of progress.

## Analysis of Soil Deterioration

One of the consequences of an undersupply of water is damage to the land surfaces and portions of ecosystems. This creates economic and environmental losses in every region of the world due to the lack of fertile soil for growing food products for humans and animals, such as bovine, porcine and ovine livestock, primarily. The case of the valley of Mexicali is no exception. The population does not yet understand the possible consequences from the lining of the AAC or from receiving water from the United States that is polluted with agrochemicals, as well as the consequences of not being conscious about conserving water in households, industries and agricultural areas.

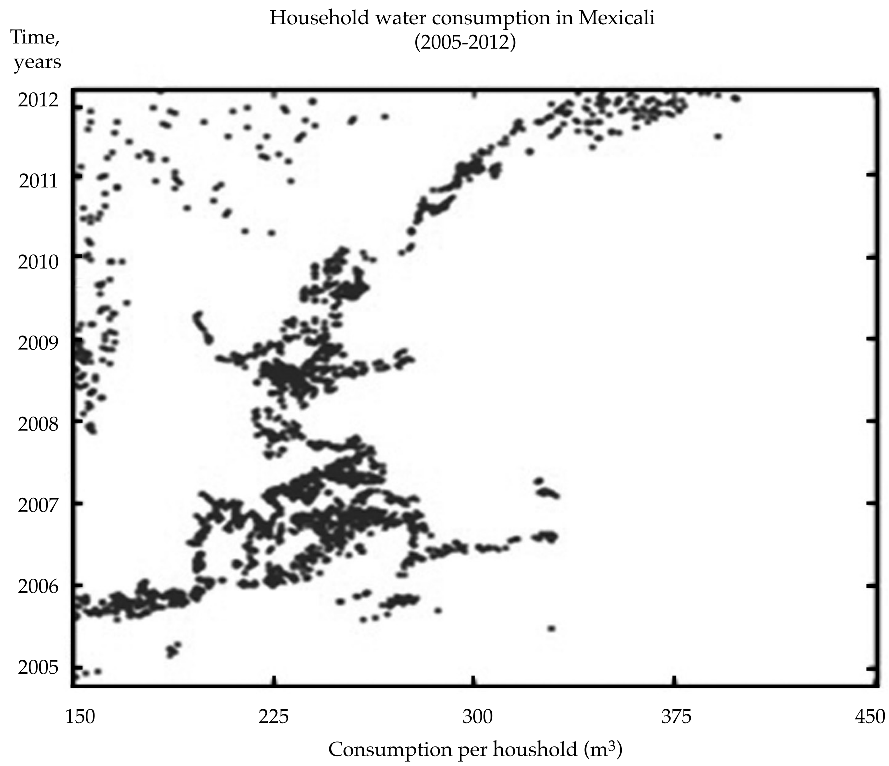


Figure 2. Evaluation of water consumption ($m^3$) in households in the city of Mexicali (2005-2012).
Source: Evaluated data from experimental studies created by a research project in the valley of Mexicali region (2005-2012).

Table 1 shows the analysis of the deterioration in the soil with the various degrees of damage from 2005 to 2012. It also shows the evaluation of water consumption with and without an ACS, which was compared in order to observed the benefit of its use. Land surfaces are created that are infertile for growing crops, causing economic losses and reducing competitiveness. In parallel, a lack of awareness has been observed in terms of managing and conserving water on the part of at least half of the population in this city of nearly 900 000 residents.

## Automated Control of Water

The ACS was designed and manufactured by experts in the area of electronics and the environment, supported by research students from the Technological Institute of Mexicali (ITM, Spanish acronym). After the system was manufactured, it was applied as an experimental test in green areas in the ITM and in households, where it obtained a water savings. The ACS system (Figure 4) and information about consumption from 100 households in the city of Mexicali (Table 2) are shown in Figure 4.

The power source supplies the electricity needed for the automated water flow control system to operate. When there is no moisture or water, the moisture detector sends a signal to start the actuator. The actuator is a pump that supplies water to the areas to be irrigated. Lastly, a light indicates whether the automated system is functioning. When lit, the automated system is operating and when the light turns off it is not operating.

Table 1. Evaluation of the deterioration in the soil in the valley of Mexicali (2005-2012).

| Time, years | Level of deterioration of the soil* | Amount of water used daily in domestic watering, $m^3$ | |
|---|---|---|---|
| | | With ACS | Without ACS |
| 2005 | 2 | 40 | 34 |
| 2006 | 3 | 43 | 31 |
| 2007 | 3 | 47 | 28 |
| 2008 | 4 | 53 | 25 |
| 2009 | 4 | 58 | 25 |
| 2010 | 5 | 64 | 23 |
| 2011 | 6 | 70 | 23 |
| 2012 | 6 | 75 | 22 |
| | * Level of deterioration (0 to 10) where 0 is the lowest and 10 is the highest degree of deterioration. | | |

Table 2 indicates the consumption levels for the years 2011 and 2012 to determine the increase without conserving water. The water flow is controlled by the system in order to decrease costs and achieve more efficient use.

## Microscopic Evaluation of Soils from the Valley of Mexicali

Small increases in the deterioration of fertile land in the valley of Mexicali have highlighted the importance of conserving the ecosystem in the region. While damage to land surfaces has been observed at the macroscopic level, the detailed analysis using a scanning electronic microscope has a greater level of resolution. The micro-analysis shows that the majority of soil remains moist thanks to the automated control system. Figure 4a presents dry soil without the use of the ACS and its comparison during an evaluation time period, when the ACS was used, with which a slight water savings was observed (Figure 4b).

## Conclusions

This study demonstrates that the premise suggested at the beginning, that the lining of the AAC will create losses in the flow of water tables from the United States to Mexico. This is particularly relevant in the valley of Mexicali where the flow of water in the water tables has decreased over the past 10 years, since the beginning of some of the operations related to the lining of the AAC. This is vitally important to the water accord between the two countries, but if no agreement can be reached then awareness about conserving the resource will be needed. Therefore, conserving water is of great interest to both countries and in all regions of the world, since it is essential to conserving and preserving ecosystems. Cases such as this investigation are of great interest since the water resource is not renewable. Therefore programs should be developed to conserve it. The process of lining the AAC, subject of this study, will affect northwestern Mexico. Meanwhile, roughly 50%



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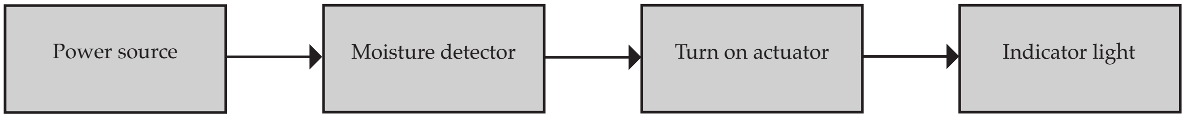


Figure 4. Block diagram of the automated water control system (ACS).

Table 2. Analysis of water consumption in 100 households with and without the ACS (2011-2012).

| | **Water consumption ($m^3$), 2011** | **Water consumption ($m^3$), 2012** |
|---|---|---|
| Without using the ACS | 3 775 | 3 230 |
| With the ACS | 2 685 | 2 345 |

of the population of the city of Mexicali is not conscious whatsoever about the adequate use of water. Areas are being flooded by irrigation activities as a result of letting the water run, considering that there will always be access to quality water in sufficient quantities. The lack of water in this region could greatly affect the daily activities of households, industries, commerce, government centers, agricultural areas and green areas, primarily. This investigation designed and developed an automated system to control water for irrigation activities. It application resulted in a savings of up to 75%. This electronic device has been implemented in educational institutions, households, industries and green areas, and has become of great interest to the Mexicali society and to the city of San Luis Río Colorado in Sonora.

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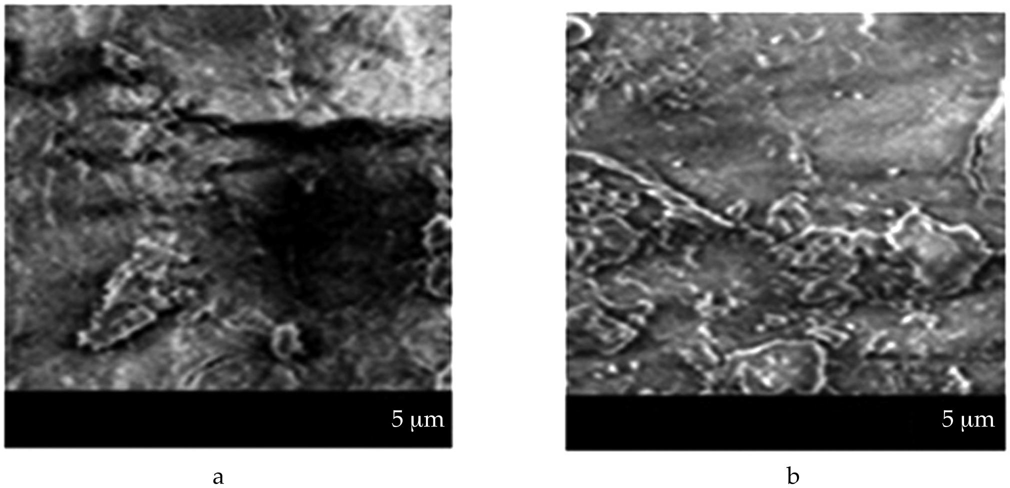


Figure 5. Microscopic analysis of the land surface (a) without using the ACS and (b) with the ACS.

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Nota técnica

# Peligros causados por vegetación incontrolada y mantenimiento inadecuado en presas de tierra

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## Resumen

Escolano-Sánchez, F., & Fernández-Serrano, R. (noviembre-diciembre, 2015). Peligros causados por vegetación incontrolada y mantenimiento inadecuado en presas de tierra. *Tecnología y Ciencias del Agua*, 6(6), 137-145.

Las presas pequeñas, cuyo uso se destina al riego, a menudo son gestionadas por las comunidades de propietarios, responsables de las labores de mantenimiento y de la red del sistema de riego que mana de ellas. Debido a diversos factores sociales —como el envejecimiento de la población en las zonas rurales, que implica merma de las áreas agrarias cultivadas— existen áreas donde la actividad de mantenimiento de la red hidráulica de riego se lleva a cabo de forma defectuosa. Una práctica inadecuada del mantenimiento favorece la colonización de la vegetación no controlada, lo que afecta la estructura de tierra compactada de diferentes maneras. Esta nota muestra de modo gráfico los impactos observados en España, con frecuencia por la vegetación, que en conjunto con la presencia de animales, puede implicar un riesgo. Se proponen conclusiones generales y recomendaciones, a fin de ayudar a los propietarios a mantener sus presas y evitar problemas a largo plazo.

**Palabras clave**: presas pequeñas, vegetación, mantenimiento, impacto negativo.

## Abstract

*Escolano-Sánchez, F., & Fernández-Serrano, R. (November-December, 2015). Hazards Caused by Uncontrolled Vegetation and Inadequate Maintenance Practice in Earth Dams.* Water Technology and Sciences *(in Spanish), 6(6), 137-145.*

*Small dams for irrigation use are often managed by landowner communities. Dam owners are responsible for the routine maintenance actions of each dam and their common irrigation system net. Due to various social factors, like population ageing or farming loss, in areas where there has been a notable decline of agriculture, the maintenance activity of the irrigation hydraulic net is defectively conducted. An inadequate practice of maintenance first allows the growth of vegetation which may develop over the dam embankment surface, affecting to the compacted earth structure. Trees and big shrubs that grow on dam slopes and crest may have a negative impact on certain geotechnical aspects. Apart from vegetation, once that owners neglect their maintenance obligations, animal invasion or human wrong uses go with vegetation growth. The paper shows frequently found vegetation impacts observed in Spain, along with animal or human impacts, which may involve geotechnical problems. General conclusions and recommendations have been proposed in order to help owners to maintain their dams and to avoid long term problems.*

***Keywords****: Small dams, vegetation, maintenance, negative impact.*

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## Introducción

La vegetación en las pequeñas presas de tierra es un problema en relación con un punto de vista geotécnico. El crecimiento incontrolado de la vegetación puede dañar terraplenes y estructuras de concreto y dificultar la inspección periódica. En general, el efecto geotécnico de crecimiento de la vegetación leñosa se ha considerado como factor común que agrava el acrecentamiento y principalmente la contracción y los problemas de subsidencia de tierra con raíces secas causando movimientos en diseño de la cimentación (Biddle, 2001).

Un ejemplo de las pequeñas presas está dado por Pfost y Curry (1996), teniendo en cuenta que control vegetativo es benéfico cuando se controlan erosiones o se rellenan surcos y cárcavas, tratando de mantener un crecimiento vegetativo vigoroso.

Cuando se permite que los árboles y las plantas leñosas crezcan en presas de tierra, pueden obstaculizar las inspecciones de seguridad, interferir con la operación segura o incluso pueden causar la fractura de la presa (Comité para la Seguridad de las Presas Existentes, 1983; FEMA, 2,005). En realidad, debe llevarse a cabo investigación más precisa debe ser llevada a cabo por medio de encuesta de los métodos del estudio de raíces (Böhm, 1979), con el fin de tener una idea de qué tan profundo o dentro del terraplén han penetrado.

La vegetación no es el único problema asociado a la falta de operación de mantenimiento. El mantenimiento adecuado de las presas de terraplén requiere que se impida que los animales de madriguera excaven en la presa y sean erradicados si están presentes en el terraplén de la misma (López-Jimeno, 1999).

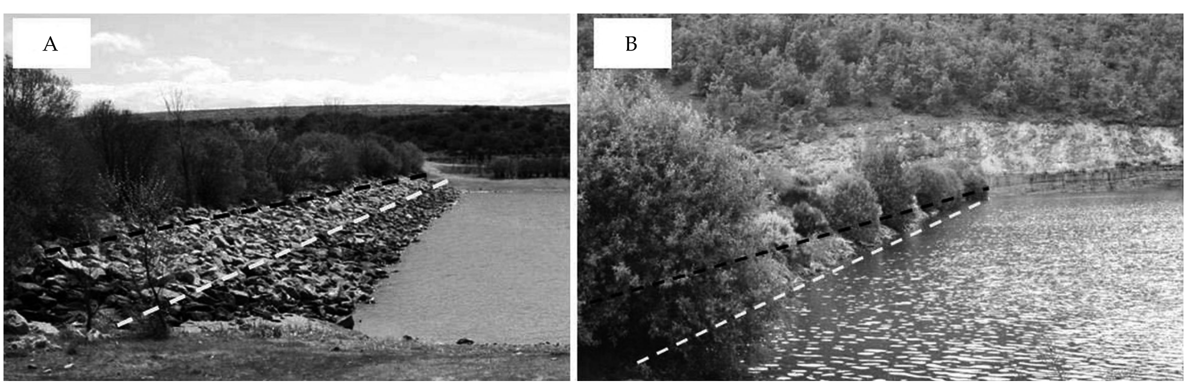
## Crecimiento de la vegetación incontrolada

Los árboles y arbustos no deben ser permitidos en superficies de terraplén o en vertederos conformados de enrocamiento. Los sistemas de raíces extensas pueden proporcionar rutas de filtración para el agua.

Hay una serie de procesos físicos de meteorización que rompen materiales de la tierra; uno muy común se llama acuñamiento raíz, cuando las raíces de las plantas se abren camino en las articulaciones del macizo rocoso. A medida que crecen, las raíces crean presión sobre los lados de la grieta alargándola hasta que la roca se fractura. Este fenómeno común causa inestabilidad de taludes de suelo rocoso abriendo grietas y fisuras, y aumentando gradualmente de tamaño de manera similar a la acción de las cuñas.

### *Vegetación leñosa sobre la cresta presa de la cresta y el talud superior aguas arriba*

Se ha observado que los árboles y arbustos se alinean cuando crecen sobre el talud aguas arriba, en general 2.1 m sobre la línea de saturación en un habitual nivel máximo (embalse). Este comportamiento es un hecho cuando el depósito presenta alto nivel de agua casi todo el año (figuras 1 y 2).




Vista aguas arriba de una presa de enrocado con núcleo de arcilla. (A): La línea blanca es el nivel normal. La línea negra es el alineamiento de los árboles (presa Villagatón, España). (B): La línea blanca es el nivel de suministro máximo. La línea negra corresponde al alineamiento de árboles y arbustos (Presa Santa Lucía de la Sierra, España).



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Figura 2. Árboles detrás de un muro de concreto reforzado, que es un contrafuerte del puente del canal del vertedero. (Presa Santa Lucía de la Sierra, España).

El aspecto más peligroso de crecimiento de los árboles en las crestas de represas y taludes aguas arriba superiores es su desarraigo repentino. Esto puede resultar en el desplazamiento de una cantidad relativamente grande de material del terraplén, lo que baja la cresta de la presa, reduciendo la anchura efectiva de la misma, o facilitando la erosión y la posible filtración.

### *Afectación de vegetación leñosa en elementos estructurales rígidos y canales de la red de drenaje*

Los árboles que crecen en rellenos de pared o cerca de la estructura del canal de agua y otras estructuras de la presa son capaces de empujar las paredes, levantar los cimientos del canal y llegar a ser un obstáculo para la libre circulación de agua (figura 3). En realidad, podría ser difícil que la vegetación creciera lo suficiente como para romper las estructuras de concreto, pero el verdadero problema en relación con el mantenimiento es importante en dos formas diferentes:

Los trabajos de mantenimiento e inspecciones planeadas de la presa se ven afectados de manera significativa o inhabilitados en el peor de los casos. En algunos casos, la concentración de los árboles y la vegetación leñosa sobre un terraplén es tan densa que una evaluación visual de la presa no se puede realizar.

La vegetación invade elementos de drenaje, reduciendo la sección transversal de flujo libre del agua. En otro caso, las raíces elevan el canal reduciendo o invirtiendo el ángulo de descenso, formando charcos (Fig. 4). El problema potencial tiene que ver con el eventual desbordamiento del agua.

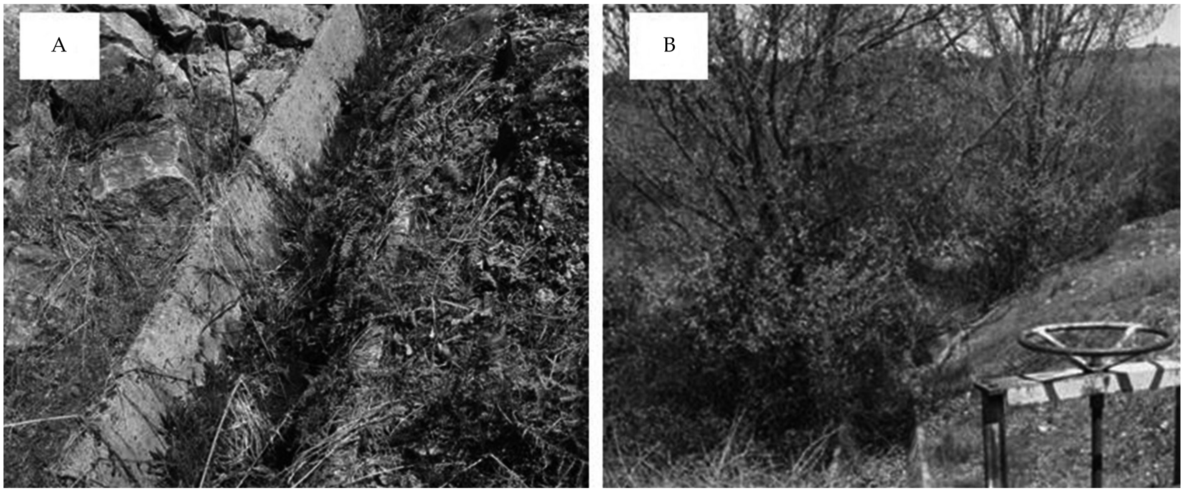


Figura 3. A: Elemento de la red de drenaje de una berma aguas abajo que reduce la sección transversal de flujo de agua. B: Árboles enraizados detrás de un canal de excedentes aguas abajo de una presa de tierra.



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Figura 4. Árboles pequeños que crecen cerca del vertedero de cresta estática de una pequeña presa.

Figura 5. Gran árbol que crece justo debajo de la cresta de la presa en el canal del vertedero de una presa de tierra, bajo el puente de la cresta del vertedero de la presa. El canal continúa con una cubierta de enrocamiento a lo largo del talud de aguas abajo.

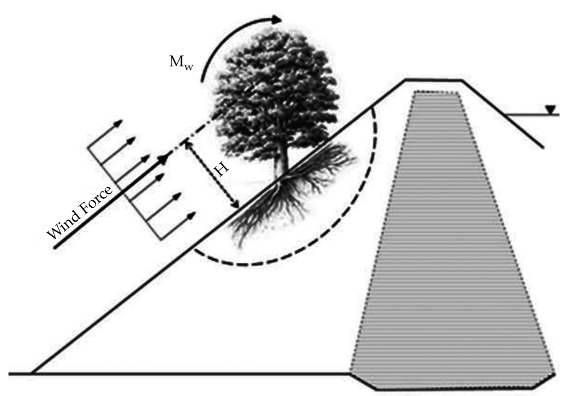


Figura 6. Momento inducido por el viento (MV) que actúa sobre un árbol bien enraizado transferido hacia la parte adyacente del talud. (Coppin y Richards, 1990).

Los vertederos son el elemento de seguridad más importante en las presas, por lo que deben estar siempre limpias de los arbustos y troncos de árboles que pueden impedir el flujo de agua correcto en situaciones normales o de emergencia de la operación de la presa (inundaciones). Los árboles que crecen en el embalse cerca del borde del vertedero son obstáculos para el agua (Fig. 5), y bases potenciales de obstrucción. Para el caso representado en la Figura 6 de un árbol que ha crecido justo en el medio del vertedero, en el lado superior del talud de aguas abajo, debería también removerse para evitar posibles problemas de filtraciones, erosión, animales de madriguera, etc.

### *Vegetación leñosa en el talud de aguas abajo*

Muchos propietarios de presas plantan vegetación leñosa en sus presas de talud aguas abajo para crear paisajes agradables. Cuando es posible, para el caso presas de enrocamiento de cara de concreto aguas arriba, el talud aguas arriba puede volver a crear vegetación mediante geoceldas con el fin de integrar la presa a bellos paisajes.

Para el caso de las presas de tierra, los árboles y arbustos dependen de un sistema de raíces extenso para proporcionar oxígeno, nutrientes y la humedad a medida que crecen. En general, la bola de la raíz se encuentra por debajo del tronco, y el sistema de raíces laterales se extendió hacia el exterior desde el tronco a la "línea de goteo" del follaje de la planta. La gran bola de la raíz y las raíces extendidas de los árboles y arbustos penetran fácilmente en las presas de tierra; mientras que las raíces estabilizan la planta, desestabilizan la presa.

Otra limitación es la sobrecarga por peso y viento. La fuerza del viento ejercida sobre la planta se transfiere hacia la tierra desequilibrando el sistema de fuerzas e induciendo inestabilidad. De esta manera, puede causar la rotación y la inclinación de los árboles, en particular si están expuestos a fuertes vientos (figura 7).

### *Vegetación común de la zona ribereña*

Especies leñosas ribereñas generalmente tienen sistemas de raíces poco profundas, tal vez con raíces laterales superficiales o hundimiento profundo o raíces primarias. Dependiendo de las condiciones locales y la vegetación existente alrededor de la presa, otras especies, no consideradas de ribera, puede crecer sobre una presa

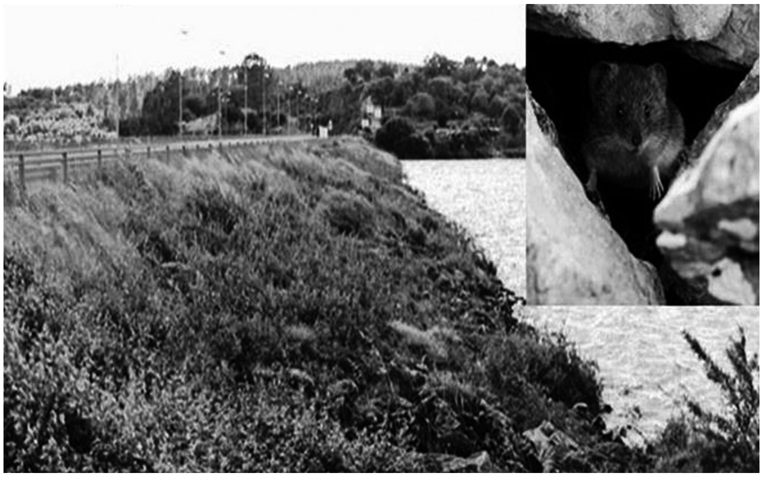

Figura 7. Rata de campo de nieve europea ("Chionomys nivalis"), común en el norte de España, que vive dentro de una presa de tierra. (Presa Horno Tejero, España).

de tierra, como robles o pinos, produciendo sistemas de raíces más profundas.

En cualquier caso, árboles y arbustos se basan en un extenso sistema de raíces para proporcionar oxígeno, nutrientes y la humedad a medida que crecen. Las raíces penetran en el terraplén de acuerdo con las condiciones del agua subterránea, por lo general sin entrar en el suelo compactado saturado, permaneciendo por encima del nivel freático.

## Vegetación asociado con animales de madriguera

Las madrigueras de los roedores en las laderas aguas arriba y aguas abajo pueden alterar drásticamente la forma en una presa controla el agua estancada detrás de la presa. Muchas especies excavan cuevas y madrigueras dentro de las presas de terraplén, causando grandes vacíos que debilitan la integridad estructural de la presa.

Los brotes de ratas de campo en el noroeste de España es un ejemplo de cómo el control de plagas fue necesario con el fin de proteger los cultivos. Aparte de las implicaciones agrícolas, se detectaron ratas de campo en pequeñas presas (Fig. 8).

## Erosión superficial

### *Abarrancamiento y desbordamiento*

El mantenimiento inadecuado de la salida del vertedero puede desarrollar erosión de fondo si la cubierta del canal no ha sido bien diseñada. Este es un problema menor, ya que se puede resolver (por ejemplo) extendiendo un lecho de enrocamiento. El verdadero problema es el desbordamiento incontrolado. El caso de la presa Ontígola (España), una presa construida en 1552, cubierta por la vegetación, es un ejemplo de la erosión de la superficie relacionada con el crecimiento de la vegetación (Fig. 9), mientras que los arbustos impiden observar el desbordamiento incontrolado como el comportamiento hidráulico más peligroso de la presa.

## Discusiones sobre el impacto geotécnico de la vegetación en presas

Es difícil establecer una lista de impactos geotécnicos de la vegetación en presas de tierra, porque no hay suficiente experiencia registrada ni un claro colapso de presa detectado directamente por causa de la vegetación. Algunas ideas sobre el crecimiento de la vegetación se han puesto

Figura 8. Erosión superficial causada por el desbordamiento de una presa de muro construida en 1552 (presa Ontígola, España).



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en orden en relación con los riesgos geotécnicos de pequeñas presas de tierra (Gilbert y Miller, 1991).

## Peligros

Los árboles y arbustos representan un peligro potencial geotécnico cuando crecen y sus raíces penetran fácilmente en presas de tierra. Se ha observado una serie de presas que todavía permanece en servicio en un área de riego residual mostrando posibilidad de abandono. Los efectos adversos se pueden resumir:

- Se puede presentar erosión interna (entubado) inducida por las raíces en descomposición de vegetación leñosa muerta que crea una ruta de filtración cuando muere la vegetación y el sistema de raíces en descomposición puede ofrecer caminos para la filtración y provocar que se produzca el entubamiento.
- Las raíces pueden penetrar las grietas existentes y articularse al suelo/roca de la cimentación.
- Los árboles derribados y desenraizados causan agujeros en la presa. Los árboles grandes podrían derribarse y desenraizarse durante una tormenta. Los árboles desenraizados desplazan a una gran cantidad de suelo y el agujero resultante que deja el sistema de raíces (cepellón) podría romper la presa o acortar la ruta de filtración e iniciar el entubamiento.
- La capacidad de los vertederos podría reducirse cuando la caída de árboles mezclados con los arbustos se atascan en la sección transversal de flujo de agua. La vegetación en los canales de vertedero o de descarga de la presa reduce su caudal hidráulico y su capacidad de trabajo y drenaje.
- Obstrucción sistemas de drenaje.
- Grietas de apertura en las juntas del cimiento o estribo entre la presa y terreno natural.
- La vegetación leñosa ensombrece el terraplén y reduce la cobertura de la hierba densa, lo que puede ser útil para prevenir el abarrancamiento.

## Prevención y soluciones de riesgos

En presas en operación es un requisito inspeccionar y evaluar los problemas con los árboles y arbustos que crecen sobre estas presas. Los arbustos y árboles deben ser removidos e impedir su crecimiento en el cuerpo de la presa. Los animales de madriguera pueden causar filtraciones a través de una presa, lo que puede conducir a la falla de la misma.

## Tratamiento de la vegetación para protección de la erosión de la superficie

La erosión de los escurrimientos de la superficie es uno de los problemas de mantenimiento más comunes de las estructuras del terraplén. Si se espera que la erosión de superficie o las precipitaciones formen zanjas barrancos en el talud aguas abajo, algunos propietarios de presas determinan la siembra de algún tipo de cobertura vegetal (generalmente hierba) en las laderas para proporcionar protección contra la erosión disponible actualmente (por ejemplo, geomembranas, geoceldas-sistemas de confinamiento celular, etc.). En este caso un mantenimiento cuidadoso de las plantas puede ser considerado y planeado.

US FEMA (2005) considera que la cubierta de hierba debe mantenerse a una altura máxima de aproximadamente 10-15 cm para permitir una inspección adecuada del terraplén.

## Vegetación leñosa que afecta a la presa

La mejor situación para una inspección geotécnica de la presa es siempre el talud “desnudo”. Esto ayuda a la a la vigilancia y el mantenimiento, la identificación de los parches de presas, causada por la eventual filtración, grietas, hundimientos, caída, desviación del asentamiento, y otros signos de la patología.

Aunque una protección de la superficie es deseable en regiones áridas o semiáridas, en



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las que puede estarse formado zanjas por las fuertes lluvias, el crecimiento de vegetación libre puede causar la indeseable vegetación de raíces profundas, tales como grandes arbustos y árboles, cuando el mantenimiento es un hecho secundario, que es el principal problema en el interior.

El mejor enfoque para árboles en la cresta, los taludes, y al lado de la presa es cortarlos antes de que alcancen un tamaño significativo. No se recomienda la liberación de herbicidas en el tratamiento de la cara aguas arriba porque debe evitarse el contacto contaminante con el embalse.

### *Daños de animal asociados con la vegetación*

Los animales de madriguera se deben evitar en las presas porque hacen nidos y pasadizos. Estos pasos pueden causar fallos de erosión interna si se conectan al talud aguas abajo del embalse o acortan las vías de filtrado a través de la presa.

Medidas de mitigación de la fauna típicamente incluyen la modificación del hábitat, la captura, fumigantes, agentes tóxicos, espantar, repelentes o disparos, utilizado individualmente o en combinación. Sin embargo, si se aplica de forma indiscriminada, los métodos de mitigación pueden afectar negativamente l ambiente presa, las especies silvestres protegidas e incluso a las poblaciones humanas.

## Conclusiones

La administración pública debe planear inspecciones programadas con el fin de comprobar que los propietarios llevan a cabo una buena actividad de mantenimiento. La inspección y gestión rutinarias de la presa junto con las campañas de información del propietario de la presa son las normas básicas de prevención.

Todos los tipos de de vegetación leñosa y arbustos con raíces profundas que crecen en los terraplenes de presas o en el vertedero se consideran un problema y deben ser controlados. Es conveniente eliminar con anticipación la vegetación antes de que se vuelva una parte crítica del mantenimiento de la presa.

No solo debe controlarse el cuerpo de la presa, sino también los elementos hidráulicos. La operación del vertedero es fundamental para la seguridad de la presa junto con el resto de los canales de descarga y la red de sistema de descarga, que deben considerarse como partes de la presa.

La penetración de las raíces de la vegetación leñosa es una muestra de la ocurrencia de los riesgos de las presas de tierra. Dicha situación inestabiliza la masa de suelo, crea una condición más favorable para la penetración del agua de la superficie y  la falla del talud, y obliga a que se hagan acciones de control para proteger la erosión de superficie.

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- The maximum length of the discussion is 4 journal pages (approximately 10 cuartillas, including figures and tables).
- The figures and tables presented by the commentator shall be progressively marked with Roman numbers and when citing those generated by the author the original numeration should be respected.
- The editors will suppress data that does not pertain to the subject of the discussion.
- The discussion will be rejected if it contains topics addressed by other sources, promotes personal interests, is carelessly prepared, raises controversy involving already established facts, is purely speculative or falls outside the purpose of the journal.
- The discussion will be published along with commentaries from the author or authors to which it refers.
- The discussion will be directed by the editor in chief.

# Guide for Collaborators

The journal ***Water Technology and Sciences*** invites specialists to collaborate with original, unpublished technical articles or notes **related to water, resulting from investigations and provide original contributions**, based on the disciplines of hydrology, hydraulics, water management, water and energy, water quality, and physical, biological and chemical sciences as well as political and social sciences, among other disciplines, according to the guidelines stated below.

## PREPARATION OF THE ARTICLE

### *FORMAT*

**Font:** Palatino throughout the entire document (body of text, tables and figures).

**Font Size:** Use 8, 9, 10 and 20 points, according to the following table:

| 8 points (Palatino) | 9 points (Palatino) |
|---|---|
| • Tables.<br>• Figures.<br>• Acknowledgements. | • Name of authors.<br>• Institution of authors.<br>• Abstract.<br>• *Abstract* and *keywords*.<br>• Institutional address of the authors. |
| **10 points (Palatino)** | **20 points capital letters (Palatino)** |
| • Body of the text.<br>• Title of the work in Spanish. | • Title of the work in English. |

**Line Spacing:** double-spaced.

**Page Numbers:** all pages shall be numbered.

**Length**

***Technical article*:** **30 pages** (numbered), including figures and tables.

***Technical note*:** **10 pages** (numbered), including figures and tables.

### *CONTENS*

**Title**

The article shall present significant contributions to scientific and technological knowledge pertaining to the specialty. It shall be based on finished works or those that have completed a development cycle. It shall show results from a series of experiences over 1 year or more of investigations and be supported by an adequate bibliographical review. **The basic structure of the text shall contain an introduction, the development and the conclusions**. The classic layout is preferable: abstract, introduction, methodology, results, discussion, conclusion and references.

**Title**

The title, **written in Spanish and English**, shall be informative and not exceed 12 words.

**Abstract**

The abstract, **written in Spanish and English**, shall be concise and provide a broad overview of the investigation (objective, method, results and conclusions) without exceeding 250 words.

**Key Words**

Eight words or key phrases (maximum) shall be provided **in Spanish and English** that facilitate the identification of the information.

**Footnotes**

Not admitted. The information is to be incorporated into the text.

**Acknowledgements**

To be included after the text and before the references.

**Tables**

- One page for each table.
- A list of all the tables cited shall be presented after the references.

**Figures**

- One page for each figure.
- All the names of the figures shall be included after the tables.
- They should be high-resolution (300 dpi).

*Note:* When the article is approved by the publication, the author shall send each figure in JPG format with high-resolution (300 dpi).

**References**

- The entire bibliography must be referenced in the main body of the text.
- In the case of addressing scientific and technological topics that are common domain, works that denote the knowledge of the authors about the state-of-art shall be cited.
- Avoid self-citations to the extent possible
- APA format shall be used as a basis.

Some examples of references in APA format are:

***Complete Books***

Last name, A. A. (Year). Title of work. city published: Publisher.

Last name, A. A. (Year). Title of work. Consulted at http://www.xxxxx

Last name, A. A. (Year). Title of work. doi:xxxxx

Last name, A. A. (Ed.). (year).City published: Publisher.

**Book Chapters**

Last Name, A. A., & Last Name, B. B. (Year).. Title of chapter or entry. In A. Last Name, B. Last Name & C. Last Name (Eds.), Title of book (pp. xxx-xxx). Place: Publisher.
Last Name, A. A., & Last Name, B. B. (Year).. Title of chapter or entry. In A. Last Name, B. Last Name & C. Last Name (Eds.), Title of book (pp. xxx-xxx). Consulted at http://www.xxxxxxx

**Newspaper Article or Note Consulted Online**

Last Name, A. A., & Last Name, B. B. (Year). Title of article. Title of publication, issue (number), pp. Consulted at http://www.xxxxxxx

**That is**: Last Name, A. A., & Last Name, B. B. (Year). Title of article. Title of publication, 1(2), 5-17, pp. Consulted at http://www.xxxxxxx

**Printed Newspaper Article or Note**

Last Name, A. A., & Last Name, B. B. (Year). Article Title. Title of publication, 8(1), 73-82.

**Newspaper Article Publication with DOI**

Last Name, A. A., & Last Name, B. B. (Year). Article Title. Title of publication, 8(1), 73-82, doi:xxxxxx

**Conferences or Symposiums**

Collaborator, A. A., Collaborator, B. B., Collaborator, C. C., & Collaborator, D. D. (Month, year). Title of collaboration. In E. E. President (Presidency), Title of symposium. Symposium held at the conference by Name of Organization, Place.

## Language

Spanish or English

## Separation of numbers and use of decimal points

In *Tecnología and Ciencias del Agua*, the separation between thousands is denoted with a blank space. A decimal point is used to separate whole numbers from fractions. In this regard, refer to Diccionario panhispánico de dudas, edited by the Real Academia Espyearla and the Asociación de Academias de la Lengua Espyearla, in 2005, with respect to numeric expressions: "**the Anglo-Saxon use of the period is accepted, normal in some Hispano-American countries…: π = 3.1416.**".

## Delivery of Article

Send the article in *Word* with the name of the authors and institutional address to **revista.tyca@gmail.com**, with copy to Elizabeth Peña Montiel, elipena@tlaloc.imta.mx.

## General Information

The review process will begin once the material is received, during which time the manuscript could be rejected. If the text is suitable for review, having fulfilled the Editorial Policy and the Editorial Committee having determined so, it will proceed to the review stage.

Depending on the review process, the text may be accepted without changes, with minor changes, with extensive changes or rejected.

Once a work is published, the main author has the right to two journals and ten offprints free of charge.
In there are any questions, please write to Helena Rivas López, hrivas@tlaloc.imta.mx or Elizabeth Peña Montiel, elipena@tlaloc.imta.mx

**Citations within the body of the text**

| Type of citation | First appearance in text | Subsequent appearances | Format in parenthesis, first citation in text | Format in parenthesis, subsequent citing in text |
|---|---|---|---|---|
| Work by one author | Last name (Year) | Last name (Year) | (Last name, year) | (Last name, year) |
| Work by two authors | Last name and Last name (Year) | Last name and Last name (Year) | (Last name & Last name, Year) | (Last name & Last name, Year) |
| Work by three authors | Last name, Last name and Last name (Year) | Last name *et al.* (Year) | (Last name, Last name, & Last name, year) | (Last name of first author *et al.*, year) |
| Work by four authors | Last name, Last name, Last name and Last name (Year) | Last name *et al.* (Year) | (Last name, Last name, Last name, & Last name, year) | (Last name of first author *et al.*, year) |
| Work by five authors | Last name, Last name, Last name, Last name and Last name (Year) | Last name *et al.* (Year) | (Last name, Last name, Last name, Last name, & Last name, year) | (Last name of first author *et al.*, 2008) |
| Work by six or more authors | Last name of first author *et al.* (Year) | Last name of first author *et al.* (Year) | (Last name of first author *et al.*, Year) | (Last name of first author *et al.*, year) |
| Groups (easily identified with abbreviations) such as authors | Complete name of institution (Acronym, year) | Acronym (Year) | (Complete name of institution [acronym], year) | (Institution, year) |
| Groups (without abbreviations) such as authors | Complete name of institution (year) | Complete name of institution (year) | (Complete name of institution, year) | |

# Editorial Policy

## Mission

Disseminate scientific and technical knowledge and advances related to water through the publication of previously unpublished articles and technical notes that provide original contributions.

## Our Principles

- Impartiality
- Objectivity
- Honesty

## Our Values

- Knowledge
- Experience
- Thematic expertise

## Contents

Interdisciplinary, composed of previously unpublished articles and technical notes related to water, that result from research and provide original scientific and technological contributions or innovations, developed based on the fields of knowledge of diverse disciplines.

## Topics Covered

Interdisciplinary, related to water, with priority topics in the following knowledge areas:

- Water and energy
- Water quality
- Physical, biological and chemical sciences
- Hydro-agricultural sciences
- Political and social sciences
- Scientific and technological development and innovation
- Water management
- Hydrology
- Hydraulics

## Type of Contributions

***Technical article***: scientific document that addresses and communicates, for the first time, results from a successful investigation or innovation, whose contributions provide and increase current knowledge about the topic of water.

***Technical note***: text that addresses advances in the field of hydraulic engineering and professional practices in the field of water, while not necessarily making an original contribution in every case it must be a previously unpublished work.

Some of the articles submitted to the review process can result in being published as notes and vice versa. This will occur through a proposal and process of mutual agreement between the authors and the editor responsible for the topic. The article and the note have nearly the same structure (abstract, introduction, methodology, results, discussion, conclusion, references).

## Review Process

The journal is governed by a rigorous review process which establishes that each article be analyzed separately by three reviewers who recommend its acceptance, acceptance with minor changes, acceptance with extensive changes, rejection or acceptance as a technical note with the required changes.

At least one of three reviewers will be sought from a foreign institution.

The reviewers may not belong to the same institution as the authors proposing the article for publication.

When the decisions are opposing or inconsistent, the involvement of other reviewers or the members of the Editorial Committee may be requested.

On occasion, the approval of an article will be decided by two reviewers in addition to the opinion of the editor of the corresponding topic or, the editor in chief.

A rejected article will not be accepted for a new review process.

The review process will be performed in such a way that neither the authors nor the reviewers know the names of the other party.

The review process is performed by high-level specialists and experts who are national and internationally renowned in their professional fields and have the ability to reliably evaluate, in a timely manner, the quality as well as the originality of contributions, in addition to the degree of scientific and technological innovation in the topic under which it is submitted for possible publication.

This participation is considered a professional contribution and will be performed as a courtesy.

The reviews have a "Guide for the Reviewer" provided by the journal's Editorial Department.

## Final Ruling

The ruling resulting from the review process is not subject to appeal.

## Authors

Works are published from authors of any nationality who present their contributions in Spanish; nevertheless, we all accept works in Spanish or English.

## Responsibility of the Authors

Submitting a proposal for the publication of an article commits the author not to simultaneously submit it for consideration by other publications. In the event an article has been submitted to another media for eventual publication, the author agrees to do so with the knowledge of the Editorial Department, which will suspend the review process and inform the Editorial Committee of the decision by the authors.

Collaborators whose articles have been accepted will formally cede the copyright to ***Tecnología y Ciencias del Agua***.

The authors are responsible for the contents of the articles.

The author is responsible for the quality of the Spanish used. If the writing is deficient the work will be rejected. ***Water Technology and Sciences*** will only be responsible for the editorial management.

The author commits to making the changes indicated by the editor of the topic in the time frame establish by the editor. In the event these indications are not met, the article will be removed from the review process and be classified as rejected.

The author shall be attentive to resolving the questions and proposals presented by the editors and the editorial coordinator.

Each author shall approve the final printed proofs of their texts.

It is suggested that authors consult the "Guide for Collaborators."

## Readers

Academics, investigators, specialists and professionals interested in the analysis, investigation and search for knowledge and solutions to problems related to water.

## Reception of Articles

The reception of articles and notes is ongoing.

## Time period

Bimonthly, appearing in the second month of the period.

## Subscription and Distribution

The journal is distributed through paid and courtesy subscriptions.

## Open Access

***Water Technology and Sciences,*** previously ***Hydraulic Engineering in Mexico***, provides a digital version of all the material published since 1985.

## Special editions and issues

***Water Technology and Sciences*** will publish special numbers independently or in collaboration with other journals, professional associations or editorial houses with renowned prestige and related to water resources.

In addition, it will publish articles by invitation, acknowledging the professional advances of prominent investigators.

In both cases, the quality of the technical continents and scientific contributions will be reviewed.

***Water Technology and Sciences*** is registered in the following national and international indices and abstracts:

• Thomson Reuters Science Citation Index® (ISI) • Expanded Thomson Reuters Research Alert® (ISI) • Índice de revistas mexicanas de investigación científica y tecnológica del Consejo Nacional de Ciencia y Tecnología (Conacyt) (2013-2018) • Sistema de Información Científica Redalyc (Red de Revistas Científicas de América Latina y El Caribe, España y Portugal), Universidad Autónoma del Estado de México • EBSCO (Fuente Académica Premier NISC; Geosystems, como Marine, Oceanographic and Freshwater Resources) • ProQuest (Cambridge Scientific Abstracts) • Elsevier (Fluid Abstracts: Process Engineering; Fluid Abstracts: Civil Engineering) • CAB Abstracts, CAB International • Latindex (Sistema Regional de Información en Línea para Revistas Científicas de América Latina, el Caribe, España y Portugal), Universidad Nacional Autónoma de México • Periódica (Índice de Revistas Latinoamericanas en Ciencias), Universidad Nacional Autónoma de México • Catálogo Hela (Hemeroteca Latinoamericana), Universidad Nacional Autónoma de México • Actualidad Iberoamericana, CIT-III, Instituto Iberoamericano de Información en Ciencia y Tecnología.

## Other Sources

The journal can also be found archived in Google scholar.