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Treatment of Municipal Wastewater by Subsurface Flow Wetlands Modified to Rural Communities in Mexico

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Authors' contributions

This work was done in collaboration with all authors. Author IDBQ designed the study, is responsible of the project, performed experimental methodologies and did interpretation of results, along with the author LJOB who also handled experimental strategies, wetland design calculations and performed hydrological simulations with IBER software. Authors HESC, MGM and JTGG supported with sampling, physicochemical and chemical analysis as well as plant sowing, wetland maintenance and interpretation of results. All authors read and approved the final manuscript.

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ABSTRACT

In this work, efficiency and quality of water by artificial wetland with subsurface flow were obtained. This wetland is 12.15 m long and 8 m wide with three channels. Its substrate bed consists of volcanic rock ("tezontle"), with three particle size (5-10, 10-15 and 15-20 cm), where the influence of porosity and its relation to hydraulic conductivity were determined, both parameters were related to Manning and Darcy equations for obtain water flow behaviour in each channel of wetland. The system was planted with *Phragmites australis* and *Typha latifolia*. For input to each channel were designed curved shapes with slope of radius 2.67 m, to avoid short circuits, with 6% minimum

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curvature, 1% slope, 0.5 m/min minimum velocity, and 2 L/s of flow (expense). Quality parameters of treated water were evaluated and with IBER software was modelled the hydrodynamic from wetland. It was concluded from results that curves sloped forms in channels improve treatment, achieving more efficiency. Furthermore the result of hydrodynamic modelling indicates that flow between channels is homogeneous, continuous and short circuits are avoided.

Keywords: Hydrodynamics modeling; porosity beds; slope curves; short circuits; wetland.

1. INTRODUCTION

Natural wetlands are systems in which predominantly natural processes such as marshes and mangroves, whether natural or artificial, permanent or temporary, stagnant or flowing, sweet, brackish or salty, including extensions of sea water whose depth at low tide does not exceed six meters [1]. Together, they combine biological, physical and chemical characteristics, which give them a high self-purifying potential. Wetlands are transition zones between terrestrial and aquatic environment and serve as a dynamic link between the two. These are complex ecosystems that act as an interface between terrestrial and aquatic habitats [2]. They are rich in biodiversity, high productivity environmental and lots of nutrients. Also serve as spawning, development of invertebrates and fish [3], nesting areas for birds [4] and provide environmental services such as control of coastal erosion and flooding, production fishery resources, and as tourist attraction [5,6]. Wetlands are capable of purifying water, eliminating large amounts of organic matter [7], solids, nitrogen, phosphorus and, in some cases, toxic chemicals [8,9].

So a new system for the treatment of waste water has been developed based on the behaviour of the natural wetlands, representing great potential that does not require external energy to function, called artificial or constructed wetland, which represent low cost systems [10]. These wetlands are shallow ponds, consisting of channels or shallow lagoons of less than one meter with plants of a hydrophilic nature and in which decontamination processes take place through the interactions between water, solid substrate, microorganisms, vegetation and fauna that may be present. They are divided according to the type of water circulation, in surface flow or subsurface flow wetlands, the latter in turn can be horizontal flow or vertical flow [11,12], and [13].

In subsurface flow wetlands, water circulation is of subterranean type through a granular medium and in contact with roots and rhizomes of plants [14,15]. The depth of the water sheet is usually 0.3 to 0.9 m [16]. Biofilm that grows attached to granular medium, to roots and rhizomes of plants, plays a fundamental role in water decontamination processes [16], if there is sufficient ground, it can be an alternative low cost, for example in rural areas. Another aspect of interest about wetlands is to provide habitat for wildlife [17], and are aesthetically pleasing to the eye. Two critical processes dominate performance in treatment of wetlands, microbial dynamics and hydrodynamics. Microbial processes are crucial in removal of nutrients, where these are fundamental mechanism of wastewater treatment. As for hydrodynamics, wetlands operate at almost flow rates constant, depending on operation.

Parameters such as velocity, flow distribution and retention time will depend of hydraulic conductivity [18,19]. In construction of artificial wetlands it is of vital importance to establish the vegetation in appropriate density. Macrophytes plants are extensive used due to physical conditions offered by wetlands, however use of hydrophyte species is preferred because they are plants that regularly inhabit water bodies. Major benefit these plants is transfer of oxygen to root zone, their physical presence in system (stems, roots, and rhizomes, allows oxygen to be transported more deeply into the substrate of what diffusion would allow. Within hydrophytes, helotophytes plants are preferred. Most frequently used in sewage treatment are Enea (*Typha*), Reeds (*Phragmites*), Totoras (*Scirpus*) and Sinonimia (*Carex*), among other species [20,9].

Climatic parameters such as: temperature, solar radiation and evapotranspiration are determining factor in efficiency of treatment [14], which tends to vary during one year. According to [14], in temperate zones drastic changes in temperature can affect the removal of BOD and therefore COD, while in warm and tropical areas, these parameters vary in a smaller interval than in temperate zones. The effects of evapotranspiration are not obvious to the naked eye, but can be measured in reductions in the outflow as well as in the increase of the concentration of BOD and/or COD in the course of a season. These impacts on hydrological behaviour appear to be smaller compared to those produced in the concentration, for example in COD.

Is presented in this paper, results of municipal wastewater treatment from a constructed subsurface flow wetland with horizontal flow, which is located in Campus Azcapotzalco of University Autonoma Metropolitana in Mexico City, Mexico; whose dimensions are 12.15 m long and 8 m wide with three channels present. The substrate consists of three layers of volcanic stone ("tezontle") with different particle size: 5-10, 10-15 and 15-20 cm respectively. In wetland were planted *Phragmites australis* and *Typha latifolia* [20]. The objective of designing a horizontal flow subsurface wetland was due, on the one hand, to the commitment of a future macro level construction for wastewater treatment in a rural community in the Lerma River Basin in Mexico, Mexico containing High loads of organic matter (OM), so it has been necessary in the wetland of the present article its optimization with curves that contain slopes to avoid short circuits and therefore dead zones, as has happened in the construction of subsurface wetlands in the state of Michoacán, Mexico by Rivas et al [15] and Rivas [14].

The main objective in this paper is mainly oriented to the hydrodynamic behaviour of water flow through three channels, to which were modified for each channel, change curve shapes with slope to homogenize the hydraulic flow and also minimize and even eliminate short circuits and dead zones in the wetland. System monitoring was performed weekly measuring the parameters: temperature, pH, OPR, OD, COD and total solids suspended (TSS), in order to optimize and evaluate the capacity of wastewater treatment by the subsurface wetland system of horizontal flow, after built. Porosity and its relation to hydraulic conductivity were studied, related with Manning and Darcy equations for obtain water flow behaviour in each channel of wetland. Later, hydrodynamics study was performed using IBER software [21], consisting in modelling in two-dimensional of water flow for shallow water, using transport-reaction equations of physical and physicochemical parameters [22], Which can also be used to transport pollutants through good calibration and evaluation [23,24].

2. MATERIALS AND METHODS

2.1 Constructed Wetland

Subsurface flow horizontal wetland system was built in 2015 in University Autonomous Metropolitan, Campus Azcapotzalco in Mexico City, Mexico, for the treatment of domestic sewage generated by nearby communities the pre-treated water comes from a treatment plant: El Rosario (Tlalnepantla, State Mexico). In this system studies are under way to support hydraulic, hydrological, biological and environmental investigations in the graduate program in Environmental Science and Engineering of the Division of Science and Engineering. They were designed for input on each channel, curved shapes with slope with radii 2.67 m to prevent short circuits and dead zones, considering a minimum camber of 6%, with 1% slope (Fig. 1c), and 0.5 m/min of velocity.

Also necessary hydraulic connections were installed with a previous clarifier, a sand trap, with 12 water shedders in triangular form for influent and a design flow Q of 2 L/s (Fig. 2).

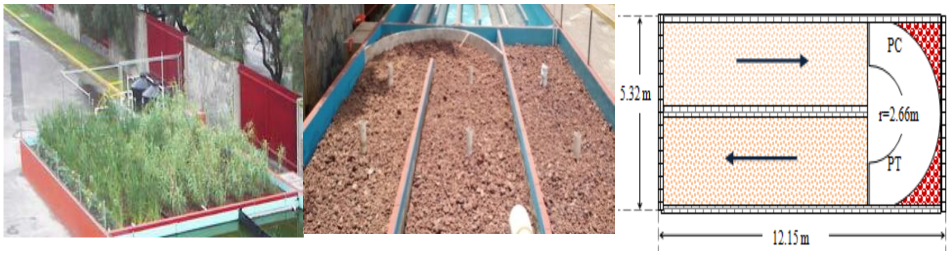
In Fig. 2 is presented total treatment system consisting first of an anaerobic pre-treatment system with following order: The raw wastewater passes to two grids allowing retain sand and/or coarse settleable solids; after this water passes a regulation tank where it is accumulates and flow rate is controlled for system rest.

The next step is to bring water to two serially septic tanks where anaerobic digestion is performed to remove a portion of organic matter; for finally the wastewater enters to wetland through 12 water shedders.

2.2 Sampling and Analytical Techniques

For this study, water samples were taken in each of sections marked in red (Fig. 3a), where in each section were built sampling ports (Fig. 3b).

For samples collection a sampler Bailers was used. In each sampling following parameters were analysed: COD which was determined through Hach method 8000 with equipment Hach Model DR-2400 with reactor 2400COD HI839800 HANNA Instruments E4. Other parameters as temperature, pH, conductivity, dissolved oxygen (DO), redox potential (ORP), were monitored and



(a) (b) (c)

Fig. 1. a) View Wetland with plants. b) Details of curve instead in channels. c) View curves shapes with slope

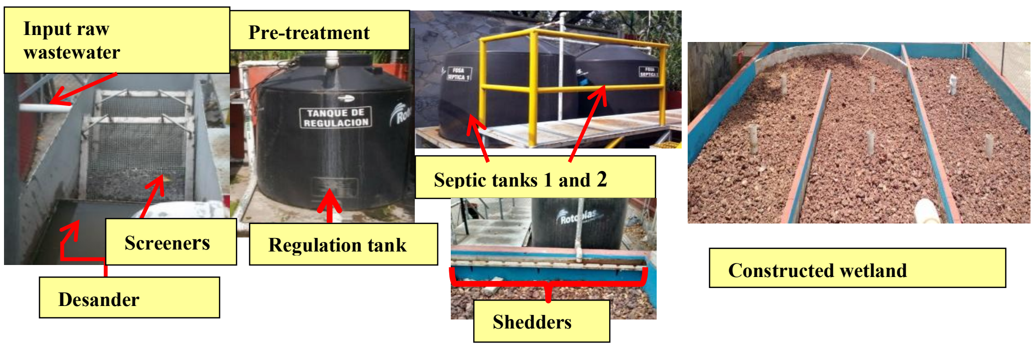


Fig. 2. Different parts of municipal wastewater treatment system by a constructed wetland

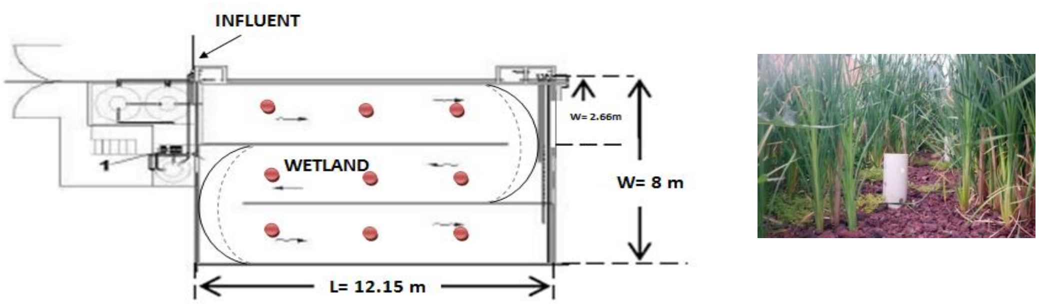


Fig. 3. (a) Outline of treatment system by subsurface wetland of horizontal flow (b) Sampling port

measured using a Vernier Lab Quest with HI 98150 sensor and interface HI 1618 Hanna. Total solids Suspended (TSS) were measured by standard methods technique 2540B [25].

2.3 Determination Grain Sizes of Support Beds

An important aspect in construction of this wetland was the previous studies through a 1:20 scale system to determine the porosity of the grain sizes used in the three support beds, Fig. 4, the measurements of empty spaces in each material, as well as the fraction of void volume over total volume.

With Equation 1, apparent porosity (Pa) was determined for each strata with the data obtained from corresponding material.

$$Pa = \frac{s-w}{s-i} \text{ X } 100 \qquad (1)$$

Where:

s= dry weight
w= wet weight
i= weight immersed in water

With Equation 2, porosity along the bed considering the three grain sizes was obtained.

$$Pl = \frac{\sum(Pai*bi)}{B} \quad (2)$$

Where:

Pl = porosity along the bed
Pai = porosity in each stratum
bi = width of each stratum.
B = total Bed Width

As product of volcanic activity, "tezontle", which was material used, is quite hard and resistant despite being a porous stone. Its resistance makes it an ideal material for support the hydrophyte species. Also worth mentioning that it is a light material with density ranging from 1.2 to 1.6 g/cm^2. For void fraction, effective particle size in wet weight of each tezontle grain sample, and weight of each sample submerged in water were analysed. Vessel used to immerse the samples was constructed of glass 6 mm thick with dimensions of 15 x 20 x 16 cm with a volume of 4800 cm^3. After obtaining the porosity in whole bed, considering three strata, it was possible to perform approximation of hydraulic conductivity (ks), using Table 1 data [26], which was used for the operation of wetland of horizontal flow, since it is the movement of the water through the porous spaces and fractures, where it is related to hydraulic gradient and conditioned by the level of saturation and the permeability of the material.

For geometric and hydraulic design it took into account the Manning Equation (3) to define behaviour of flow in each channel. The equations used considered a non-permanent flow.

$$v = \frac{1}{n} y^{2/3} s^{1/2} \quad (3)$$

Where:

v = Flow velocity, m/s
n= Manning coefficient, s/m
y= depth of water in wetland, m
s= hydraulic gradient m/m

Manning coefficient (n) is related to parameters previously indicated where resistance that produces emergent vegetation is important for water flow in each channel, so that was considered Equation (4) and values are indicated in the Table 2.

$$n = \frac{a}{y^{1/2}} \quad (4)$$

Where:

a = resistance factor, s.m

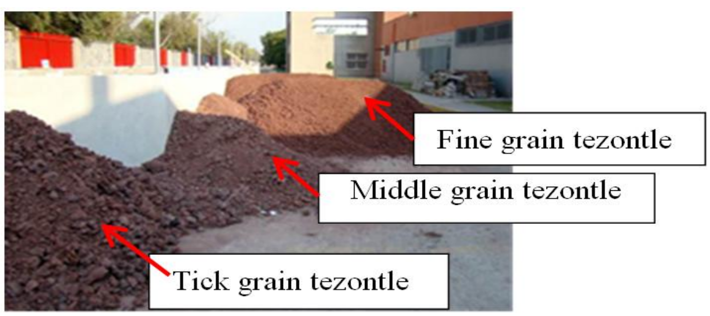


Fig. 4. Selection of three grain sizes for substrate of built wetland

Table 1. Typical media characteristics for subsurface wetlands

Type of material	Effective size (D) (mm)	Porosity (n) (%)	Hydraulic conductivity (ks) (m^3/m^2/d)
Coarse sand	2	28-32	100-1000
Heavy sand	8	30-35	500-5000
Fine gravel	16	35-38	1000-10,000
Middle gravel	32	36-40	10,000-50,000
Thick rock	128	38-45	50,000-250,000

Table 2. Resistance factors according to the density of vegetation

α	y	Vegetation
0.4	<0.4	Limited
1.6	0.3	Moderately dense
6.4	≤0.3	Very dense

With the Darcy Equation (5) was considered the porosity of each substrate:

$$v = k_S * s \qquad (5)$$

Where:

k_s: hydraulic conductivity of a wetland unit area perpendicular to the flow direction, $m^3/m^2/d$
s: hydraulic gradient, m/m (It was considered the height of inlet flow between outflow)
v: Darcy velocity, m/d

To obtain hydraulic Q of system, we used Equation (6)

$$\mathrm{Q = k_S . Ac. s} \qquad (6)$$

Where

Ac= wetland area

2.4 Wetland Hydrodynamic Modelling

Previously treated wastewater, as indicated above in Fig. 2, enter to wetland, where hydrodynamics modelling is important; IBER software [21] is used to modelling water flow in each channel from wetland. With Numeric Method is obtained the hydraulic parameters variation, also transport of total solids (TS), latter to relate effect of inertia and gravity forces acting on water flow. Modelling was conducted in two dimensions, where advection-dispersion effects and particle sizes of three substratum layers (beds) in wetland were considered, because both factors are important in calculating of Manning Coefficient. Water flow simulation was done through each wetland substrate layer, considering also particle size of each layer (Fig. 5).

IBER Software was used to input the water flow in each substrate layer, considering an approximation of 2 L/s, with a slope of 1 %, which is corresponding to geometry of each curve. Also were considered in calculations, the roughness of walls and bottom of all the wetland, since it was built of porous block. Other, parameters considered in calculations was suspended solids (TSS). For water flow behaviour and velocity in wetland it took into account friction related with: vegetation, soil, TS, hydraulic gradient, and height or depth of each substrate bed. The aim of this modelling was also highlight water flow path through the banked curves sections. The factors taken into account for speed calculating in the simulation were:

- Manning number, implicitly dimensionless coefficient "n", considering: water depth, water surface slope, hydraulic gradient, substrate material and density of vegetation.
- Topography: In calculations of each channel, slopes and curves were used with elevations, so that the simulation is as close as possible to wetland system.
- Flow: One boundary condition that resembles a constant discharge at entrance of system, with an expenditure of design Q= 2 L/s was performed.

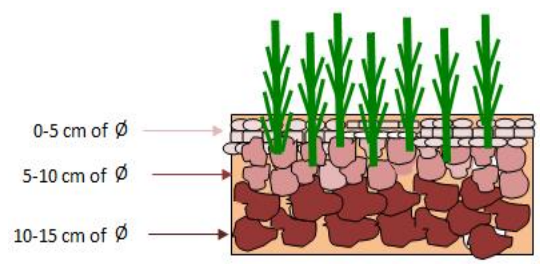


Fig. 5. Substrates beds grain size distribution in the wetland

3. RESULTS AND DISCUSSION

3.1 Tests of Porosity and Hydraulic Parameters

In Fig. 6a, 6b and 6c, values of dry weight (w), wet weight (s) and weight of submerged material in water (i) are shown for different particle sizes.

Results of apparent porosity (Pa) are presented in Table 3.

Table 3. Values of apparent porosity (Pa)

Layer	Thickness (m)	Particle size (m)	Pa %
Top	0.20	< 0.015	30.96
Middle	0.30	From 0.015 to 0.06	26.81
Bottom	0.30	From 0.06 to 0.16	22.13

For porosity in whole layer, Equation 2 was applied, obtaining average result of three substrates with a value equal 26.09.

$$Pl = \frac{\sum((30.96*0.20)+(26.81*0.30)+(22.13*0.30))}{B} = 26.09$$

Finally with Equation 5 and ks (Table 1), it was obtained Q= 1.56 Lps (135.49 m^3/d) and considering v = 0.034 m/s.

3.2 Physicochemical Parameters Results

The variation of physicochemical parameters is presented in the next Figs. with growing plants [27,28]. It can be seen in Fig. 7, temperature at each sampling during the first stage (February) was lower in sites H0, H1, H2, H3 and H4 with respect at the same points in the second stage (April).

H5 and H6 sites were slightly higher in stage 1 that in stage 2. Values H7 and H8 sites coincided; H9 site was lower in stage 1. It can be considered that temperatures ranged between 17°C and 23°C, which depended of hours sampling, which was between 11:00 and 14.00 hours in both stages. In order to obtain accurate measurements, it was important to consider that the hours of temperature measurement were the same in the two sampling stages.

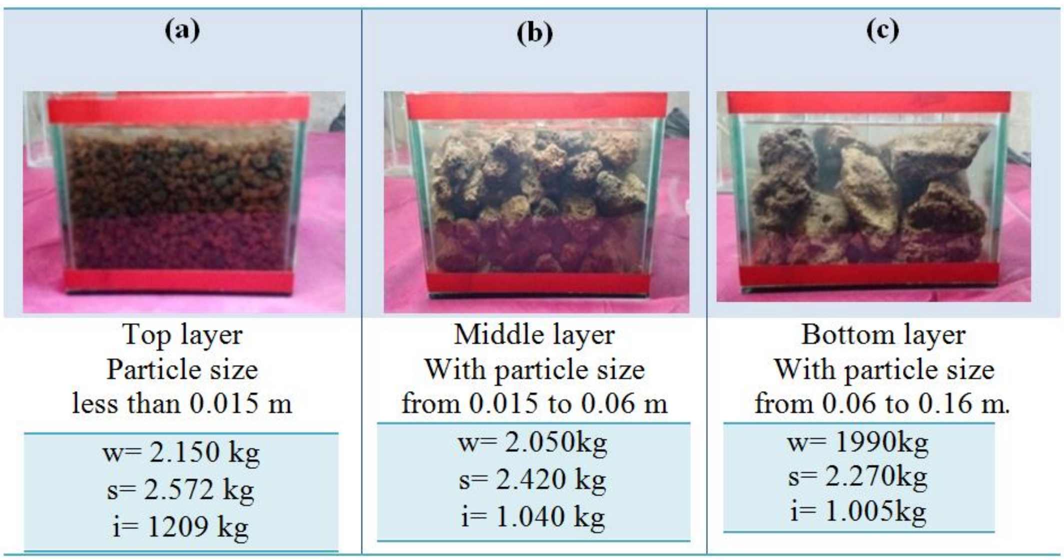


Fig. 6. (a) Material porosity fine tezontle. (b) Material porosity intermediate tezontle. (c) Material porosity thick tezontle

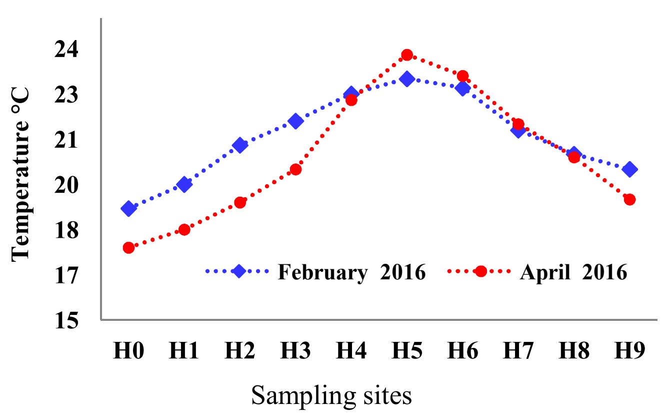


Fig. 7. Temperature variation in wetland in two sampling periods

For pH, Fig. 8 a similar profile was observed in each stage, H0 site at the entrance of the system was 8.4 and 8.2 in each stage, decreasing along the system, and finally a better stabilization is obtained in H8 and H9 sites. In second stage, although there is a tendency to lower values these generally remained above those measured in the first stage, mainly in the H7, H8 and H9 sites where there seems to be a tendency towards stabilization.

Probably *Phragmites australis* plant begins organic matter treatment and in H3 site onwards, *Typha latifolia* plant continues with treatment. In addition, there is the possibility that some hydrolysis process may be present.

In Fig. 9 shows average conductivity values; there is an increase in these values at sites H3 and H6 in the two sampling stages, which corresponding to input flow in each slope curve in each channel of the wetland where there is a higher concentration of ions that decreases to outlet from each curve and along of each channel until wetland exit.

Fig. 10 shows average results of total solids suspended (TSS) concentration in mg/L, where a clear trend of decreasing in solids concentration is observed with a slight increase in inlet flow in each curve.

Fig. 11 shows an improvement in redox potential (OPR) values as water flow progresses along the system in the two stages until the wetland exit, a similar behaviour is observed in both profiles at sites H3 and H4, which is the input of the water flow in the curves, there is an increase, where organic matter (OM) accumulates, this parameter is related to the dissolved oxygen (DO) required.

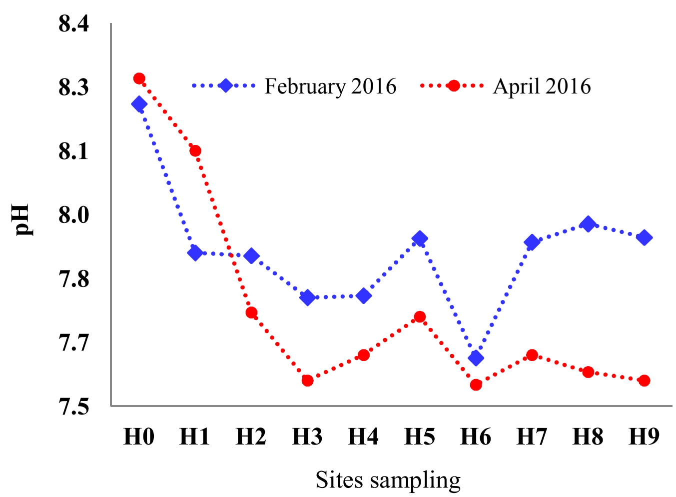


Fig. 8. pH variation in wetland in two sampling periods

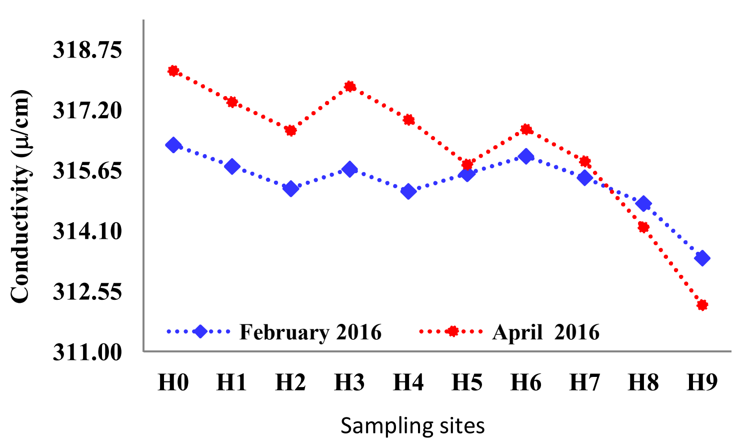


Fig. 9. Conductivity variation in wetland in two sampling periods

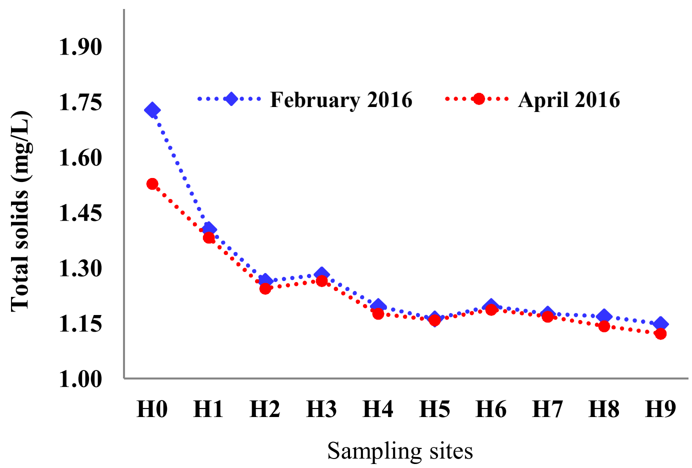


Fig. 10. TSS variation in wetland in two sampling periods

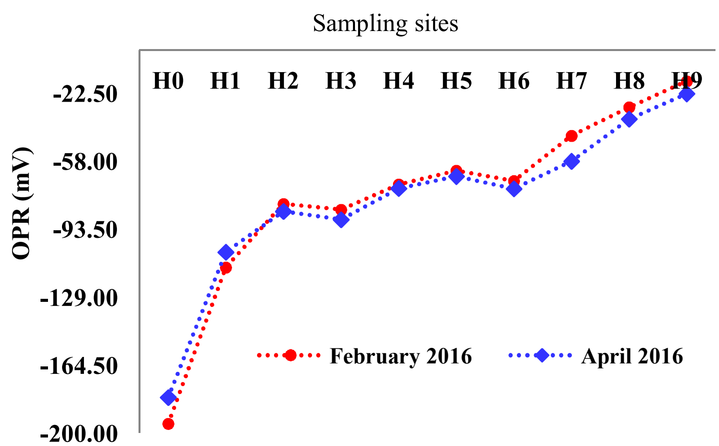


Fig. 11. OPR variation in wetland in two sampling periods

At sites H3 and H4, which is the input of water flow in curves of each channel, there is an increase of conductivity, where OM accumulates, this parameter is related to required DO (Fig. 12) to oxidize OM and also can related to COD (Fig. 13). In the channel changes at the H3 and H6 sites a decrease of oxygenation mainly in the second stage (Fig. 12).

In these sites a greater amount of oxygen is required for OM oxidation on the one hand, and on the other this adds to benefits of curve shapes with slope, which by its shape allow better aeration in sites H7 to H9, there is a stabilization of DO, where is observed also in first stage.

In Fig. 13, similar profiles with downward trend of COD improving in second stage, where COD at input of system had a higher value. In channel changes a slight increases of COD was presented, since more amount of accumulated OM exists at the beginning of the curvature due to reduction of water speed.

3.3 Analysis System through the Software IBER

Under the above conditions mentioned was conducted three runs for different particle sizes, in Fig. 14a, 14b and 14c is presents the behaviour of flow velocity of water in three layers of wetland substrate, which is illustrated by a scale (Fig. 14d). Velocity increased as the grain size was coarser, being faster in the layer with granulometry 10-15 (Fig. 14c) and lower speeds in the layer 0-5 and 10-15 cm (Fig. 14a and 14b).

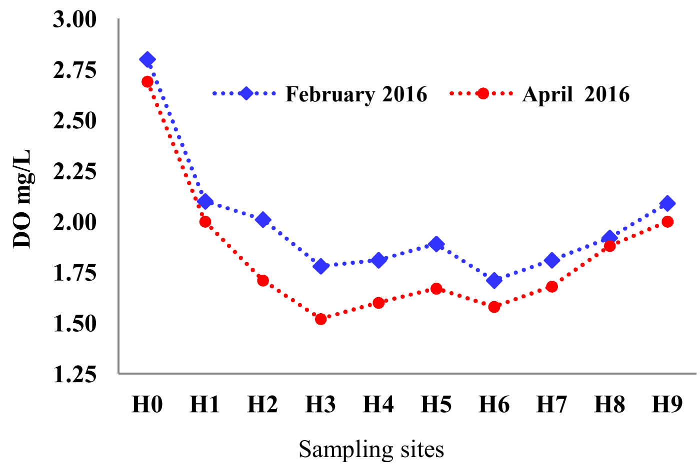


Fig. 12. DO variation in wetland in two sampling periods

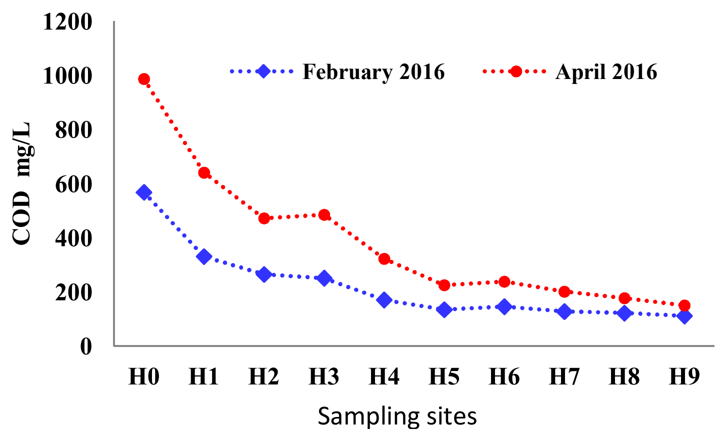


Fig. 13. COD variation in wetland in two sampling periods

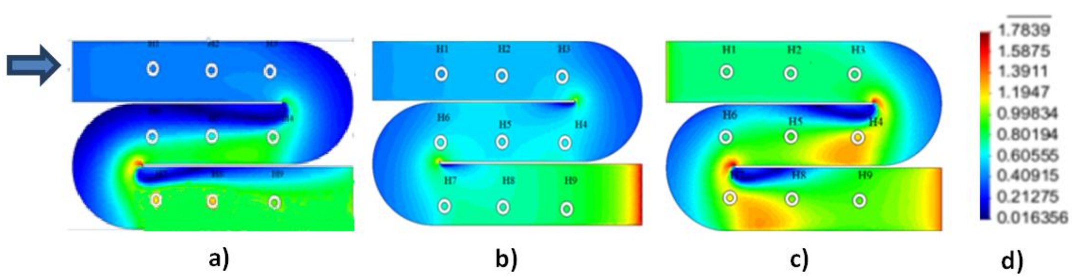


Fig. 14. Modelling results of water flow velocity. (a) Size particle of 0-5 cm. (b) Size particle of 5-10 cm. (c) Size particle 10-15 cm. (d) Scale, [27]

3.4 Transport of Total Suspended Solids (TSS)

In Fig. 15a, 15b and 15c is observed the route of TSS in each substrate of wetland. It is noted that at this stage colours do not mean same as in above descriptions, here when colour tends towards red in the colour scale, it means higher solids concentration [27]. In Fig. 15a, corresponding to upper layer (0-5 cm diameter), it is observed that practically interacts with the material, adsorbing part on surface of the porous material and other part is absorbed through the pores and plant roots. In curves shapes one

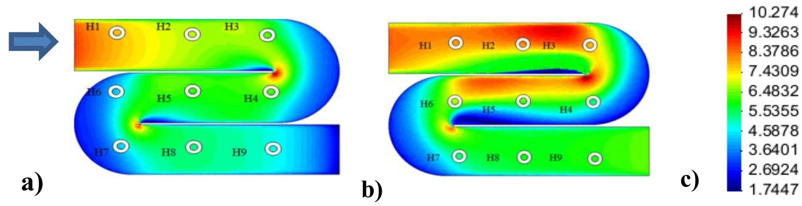


Fig. 15. (a) Results of TSS transport modelling grain size 0-5 cm. (b) Results of sediment transport modelling grain size 5-10 cm, [27]

slight accumulation is observed. In Fig. 15b a similar behaviour is observed, with a path of SST toward second substrate layer with grain size of 5-10 cm where is greater solids accumulation and is most noticeable prior to entry of curves (sites H3 and H6), which is due to change of section, where flow velocity decreases, allowing that solids concentrate.

In Figs. 16a y 16b for deeper layer, with grain size of 10-15 cm, final destination of TSS is observed, also show tendency very similar to the others in previous layers. Results show that in first and second channel most solids removed. Unlike the above from H2 accumulation starts where it seems that there is a vertical flow leading to solids into the interstices of the previous layers. It is also noted that there is more tendency to accumulate in the H3 and H5 sites, in the beginning of curves shapes with slope and a little in downhill sections. All strata present in exits don't carry solid material. It is important this diagram colour, because allows knowing the area most susceptible to the higher concentration of solids, mainly larger ones which form an important part of bottom sediment in wetland, besides indicating their participation in compaction that influencing much with vegetation.

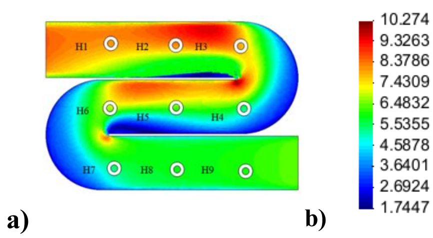


Fig. 16. (a) Results of sediment transport modelling, grain size 10-15 cm. (b) Scale, [27]

4. CONCLUSIONS

Then conclusions of this work are indicated, where, the volcanic rock (tezontle) due to its physical characteristics has been a good substratum for the layers in the subsurface wetland, in addition by good its porosity, it was possible to achieve acceptable values of hydraulic conductivity; since it has spaces between grains where hydraulic gradient allows a saturation and permeability for flow through each layer of wetland.

This type of volcanic rock has also allowed the Phragmites australis, planted in the first channel and part of the second, as well as the Typha latifolia planted in the rest of channels to function with great capacity as hydrophytes in the wetland reinforcing the capacity of the treatment.

Through the IBER software, areas susceptible to saturation due to sedimentary material were observed in the wetland. These are sections before the curves with slope between the channels. Also through this software, it was possible to visualize that these curves allow more homogeneous flows between the channel changes, which minimizes the short circuits and avoided dead zones that cause stagnant areas and the presence of vermin.

Using the IBER software, the result of the variation of the hydraulic flow velocity in the channels was presented in a colour scale to understand this variation; where it was observed that the hydraulic jump is produced by the slope of each curve, favouring that the flow has a correct movement in the in the direction change, improving in turn the elimination efficiency of pollutants and most importantly, to avoid dead zones. The results could be verified through the measured parameters, COD, TSS, DO, ORP and, conductivity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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