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Treatment of domestic wastewater in a pilot-scale natural treatment system in central Mexico

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Abstract

There is severe degradation of the water quality of the Texcoco River in central Mexico as a result of discharges of raw sewage from communities into the watershed. Constructed wetlands may be appropriate technologies for treating the domestic wastewater generated by small communities in central Mexico. To assess the removal of pollutants from wastewater, we constructed a pilot-scale treatment wetland in the small community of Santa María Nativitas in the Rio Texcoco watershed. The system, consisting of sedimentation terraces, stabilization pond, subsurface flow wetland (SSFW) and vertical flow wetland (VFW), removed >80% of TSS, COD and nitrate from domestic sewage. Removal of ammonium was less efficient at about 50%. This study also showed that ornamental flowers with high economic value planted in the SSFW performed as well as cattail (*Typha angustifolia*) in removing TSS and nitrogen. The treated water was suitable for irrigation, which could help to alleviate the scarcity of water in the Rio Texcoco watershed. Modeling exercises indicated that the pilot-scale wetland could be readily adapted to treat sewage from six families.

Keywords: Natural treatment systems; Treatment wetlands; Domestic wastewater; Ornamental plants; Developing countries; Mexico

1. Introduction

Water suitable for human consumption and irrigation is a scarce resource in the densely populated region of central Mexico. A monitoring study of pollution of the Rio Texcoco watershed in central Mexico showed that the main source of pollution is the discharge of raw domestic sewage into the river (Belmont and Metcalfe,

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2002). Wastewater treatment and reuse of the treated water are potential solutions for addressing the problems of poor quantity and quality of water in this region. To promote the treatment and re-use of domestic wastewater as a water management solution in the Rio Texcoco watershed, we constructed a pilot-scale treatment wetland in the small community of Santa María Nativitas. Constructed wetlands for wastewater treatment are an inexpensive and technologically appropriate solution for wastewater treatment in developing countries (Denny, 1997; Haberl, 1999; Kivaisi, 2001). The pilot-scale wetland was constructed to evaluate the best design features for wastewater treatment and to promote the development of similar systems throughout the watershed. The location for construction of the pilot-scale wetland in the community of Santa María Nativitas was based on the positive response of the community to the project, the prior construction of a common sewer line which serves approximately 500 homes and discharges wastewater into the Texcoco river, and community willingness to provide the land for the site.

Early in the development of this pilot project, a decision was made to construct a subsurface flow wetland for treatment of domestic wastewater. The gains in vegetation biomass in constructed wetlands can provide economic returns to communities when harvested for biogas production, animal feed, fiber for paper making, and compost (Lakshman, 1987). Economic benefits from constructed wetlands are an important consideration in developing countries where additional incentives are required to encourage communities to maintain treatment wetlands. At present, the most common aquatic plants used in subsurface wetlands are bullrush (*Scirpus* sp.), cattail (*Typha* sp.) and reeds (*Phragmites* sp.). However, there is potential to use other types of moisture-tolerant plants in constructed wetlands. Ornamental plants could function as an important part of a wastewater treatment system and could also provide economic benefits to the community. Ornamental plants are not consumed and would not be a health risk if contaminated by toxic compounds in a wetland.

Wolverton (1990) reported that calla lily (*Zantedeschia aethiopica*), canna lily (*Canna flaccida*), and three other ornamental plant species planted in a rock filter used to treat septic tank effluents were able to add oxygen and increase biological activity in the septic bed. Neralla et al. (1998) concluded from greenhouse experiments that ornamental plants, including canna lilies, were as effective as cattails in improving the quality of effluents from septic tanks, but noted that cattails yielded 200% more water loss through evapotranspiration in comparison to the flowers. In our previous greenhouse studies (Belmont and Metcalfe, 2003), calla lilies were effective at reducing total suspended solids, chemical oxygen demand and nitrogen from an artificial wastewater. There have been no previous reports of the use of ornamental flowers in larger scale constructed treatment wetlands.

This pilot-scale study was directed at determining the effectiveness of a subsurface flow wetland for the treatment of domestic sewage generated by the small community of Santa María Nativitas in the Rio Texcoco watershed in central Mexico. Various design features in the wetland, including a terraced sedimentation pond and a vertical flow wetland were evaluated for effectiveness. The potential for using ornamental plants in the wetland was evaluated by comparing the treatment efficiency in a subsurface flow treatment cell planted with calla lilies and canna lilies to the efficiency in a cell planted with bullrushes.

2. Methods and materials

2.1. Study area and water management issues

The Rio Texcoco watershed is located in central Mexico, approximately 60 km to the northeast of Mexico City (Fig. 1). The Rio Texcoco river originates in the Sierra Nevada mountains and passes by several small communities before discharging into the central valley of Mexico near the city of Texcoco (Fig. 1). The community of Santa María Nativitas (Nativitas) is located at approximately the midway point in the watershed at a mean altitude of 2380 m above sea level (Lopez-Vega et al., 1998). A population of 1881 people was reported in the community in 1995 (INEGI, 1995), and agriculture and floriculture are the main economic activities (Flores-Sánchez, 2000). Approximately 80 farmers are involved in floriculture. The most cultivated species is *Chrysanthemum cinerariaefolium*, but there is also some cultivation of roses. The main markets for the flowers are local cities in the watershed and nearby Mexico City (Flores-Sánchez, 2000). The community has experienced tensions over the lack of potable water,

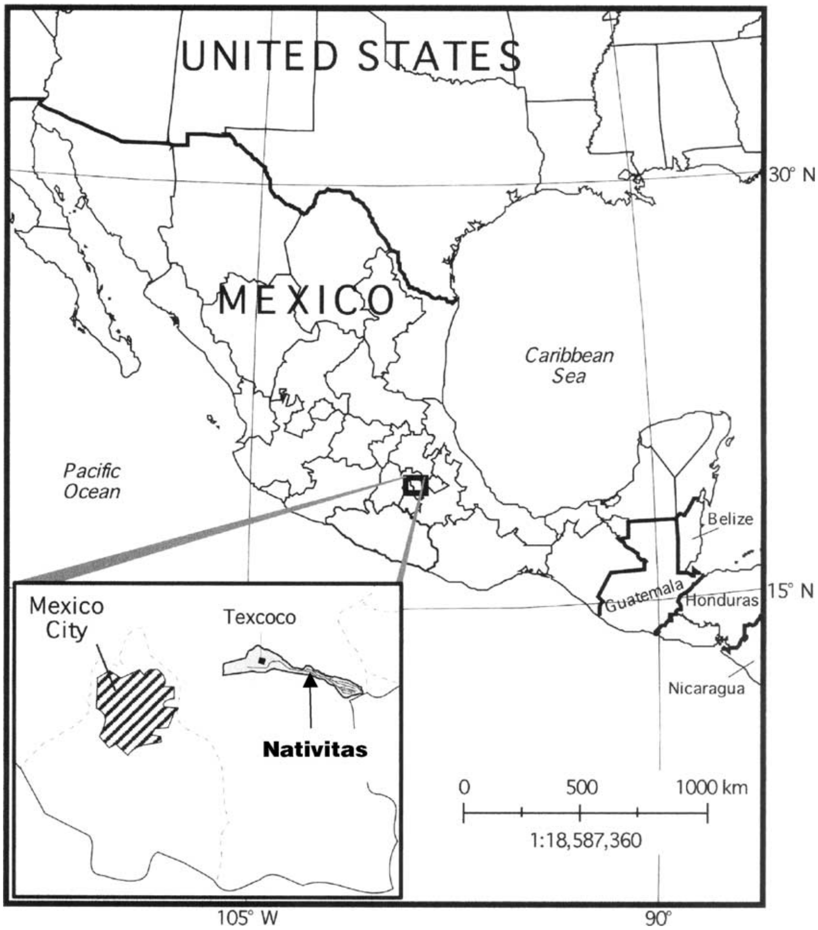

Fig. 1. Location of Santa María Nativitas.

involving disputes between homeowners and the farmers that own greenhouses over the large amounts of potable water used for floriculture.

A sewer line for the collection of domestic sewage was constructed in Nativitas in 1994 and according to INEGI (1995), it presently services 90% of the houses in Nativitas. Although the flow of sewage was not monitored extensively, flow rates determined in isolated sampling periods were in the range of 250–350 m^3/min, with large variations in sewage flows throughout the day. The wastewater collected by the sewer is discharged directly into the Rio Texcoco river since the community did not receive support from the municipal government to build a treatment plant. The community has identified land to be donated for a treatment plant and has communicated a willingness to use the treated water for irrigation (Lopez-Vega et al., 1998).

2.2. Design and construction of the treatment wetland

The configuration and dimensions of the pilot-scale wetland constructed in the community of Nativitas are shown in Fig. 2. A diverting valve directs a small fraction of the raw sewage into three sedimentation terraces (not shown) to trap large suspended solids and sand. The sewage then passes to a stabilization pond through a valve that regulates the inflow of wastewater, and then passes into two subsurface horizontal flow wetlands (SSFW) connected in parallel. The influent flows

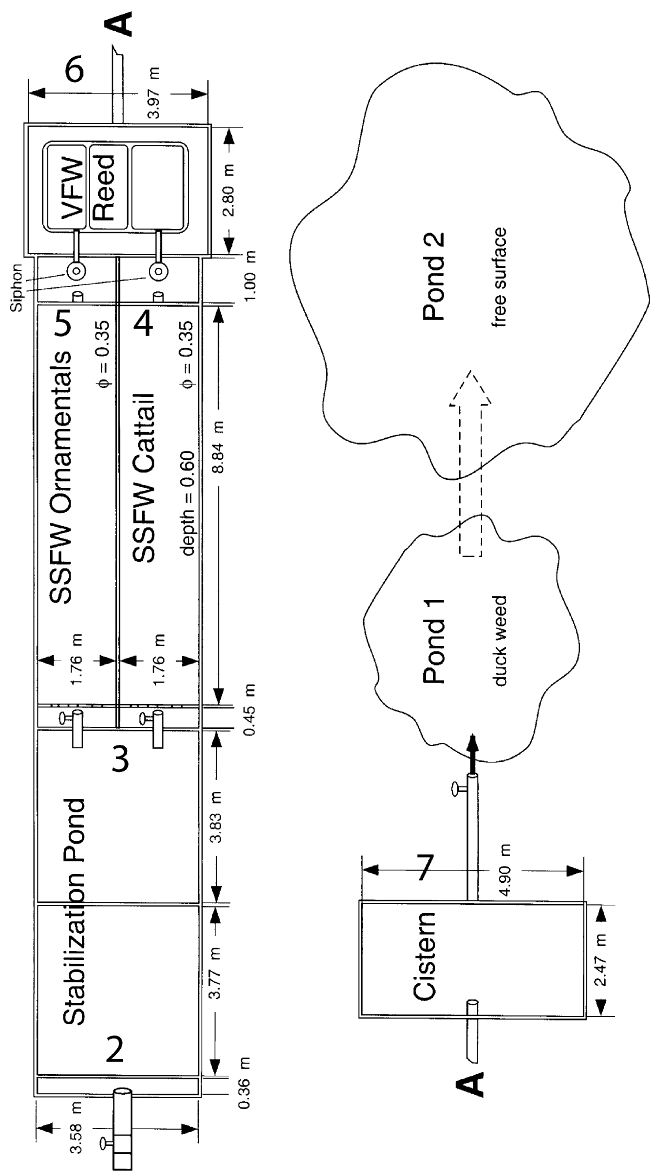

Fig. 2. Pilot-scale wetland constructed at Santa María Nativitas, Mexico. The sedimentation terraces and sampling site 1 are not shown. Numbers 2–7 mark the location of sampling sites for monitoring of water quality parameters.

to the SSFWs are controlled by PVC valves, which are adjusted to maintain equal flows in each cell. Following the SSFW, the water passes into a vertical flow wetland (VFW) via two siphons that feed the VFW intermittently. The effluent (A in Fig. 2) is then stored in a cistern and the overflow from the cistern is directed into two ponds connected in series. The final holding ponds with surface areas of approximately 30 m^2 and 100 m^2, respectively, were constructed using displaced soil to form the banks of the ponds. Infiltration occurs from the ponds, which contributes to recharge of groundwater. The floating plant species duckweed (*Lemna* sp.) was seeded into the first pond to provide surface cover and contribute to water treatment.

The terraces were built in a few hours using rocks from the immediate area and by shaping the soil. The stabilization pond was constructed by excavating the rock and soil overburden to a depth of approximately 1.4 m and constructing cinder brick walls to a height of approximately 2 m. The average depth of the water in the stabilization pond is 1.7 m. The SSFW are 0.6 m in depth and the water level is kept 10 cm below the gravel surface (i.e., 0.5 m water depth). The substrate in the cells consists of coarse gravel of 3–5 cm in diameter ($\phi = 0.35$). One SSFW cell was planted with cattail and the other with the ornamental plants, calla lily and canna lily. In the VFW, the substrate consists of coarse sand, which was planted with the common reed *Phragmites communis*. The walls of the stabilization pond, SSFW, VFW, and cistern were constructed of cinder brick. The floor of these parts of the system was constructed from poured concrete.

The treatment system was operated at a flow of 2 L/min in order to have a flow of 1 L/min into each SSFW, which corresponds to a hydraulic retention time (HRT) of 2.3 days in each SSFW. The average volume of wastewater treated daily was 2.88 m^3/day. This flow represents approximately 1% of the total daily flow of domestic sewage from Nativitas.

The purpose of the pilot scale treatment system was to produce reclaimed water useful for agriculture and to facilitate the calculation of the removal rate constants. Therefore, the VFW was located after the SSFW in the treatment system because the objective was to transform organic nitrogen (org-N) into NH_4 and NO_3 for crop fertilization as the reclaimed water is used for irrigation. Concrete was used to maintain appropriate geometry and zero infiltration to facilitate the calculation of the removal rate constants; in a full-scale system, the use of berms and lining would be recommended.

2.3. Sampling and analysis

After construction of the treatment wetland, the system was allowed to stabilize and plants were allowed to grow for a period of approximately 9 months. During this period, proper maintenance of the wetland was sporadic and there were episodes of blockage of sewage flows. Beginning in October 2000, the system was stabilized and intensive monitoring of the wetland began on 15 January, 2001 and continued to 16 October, 2001. Over this period, samples of sewage were collected approximately every 2 weeks ($n = 21$) at seven points within the water treatment facility (Fig. 2), including the input of untreated sewage, the outputs of each component of the system and the water stored in the cistern. Dissolved oxygen was also monitored in the final retention ponds. Note that nitrate analyses were conducted over a shorter monitoring period, from 3 September to 26 October, 2001.

The parameters that were measured to assess the performance of the wetland are listed in Table 1. The analytical techniques used are described in the Standard Methods for Water and Wastewater Analysis (APHA, 1998). Concentrations of $N\text{–}NH_4^+$, $N\text{–}NO_3^-$, and $N\text{–}NO_2^-$ were measured using Orion ion-selective electrodes (model number 9512BN, 9707BN, and 9746BN, respectively). The calibration curves were done using standards of ammonium chloride, sodium nitrate and sodium nitrite, respectively (1 ppm, 10 ppm, and 100 ppm for ammonium and nitrate, and 0.1 ppm, 1.0 ppm and 10 ppm for nitrite). Total nitrogen was

Table 1
Analytical techniques used to monitor water quality parameters in the pilot-scale wetland in Nativitas, Mexico

Parameter	Method	Reference
pH	Electrode	APHA (1998)
Temperature	Probe	APHA (1998)
Eh	Pt electrode	APHA (1998)
Total suspended solids	Filter dried at 110 °C	APHA (1998)
Ammonia	Ion selective electrode	APHA (1998)
Nitrate	Ion selective electrode	APHA (1998)
Nitrite	Ion selective electrode	APHA (1998)
Total nitrogen	Hach kit, Method No. 10071	Darula (2000)
Chemical oxygen demand	Closed reflux method (photometric)	APHA (1998)
Dissolved oxygen	Membrane electrode	APHA (1998)

measured using a Hach Kit, Method No. 10071 (Darula, 2000). The calibration curves were done with ammonium chloride standards of 1 ppm, 10 ppm and 20 ppm. Dissolved oxygen (DO) was quantified using a YSI oxygen meter, with the instrument calibrated against air. Eh and pH, were measured with Orion electrodes, model numbers 9778BN and 9107BN, respectively. The meter was calibrated using buffers of borax (pH 9.2) and phthalates (pH 4.0) for analysis of pH, and Zo Bell's solution for analysis of Eh, as described in APHA (1998). Total suspended solids (TSS) were determined by filtering 4 L volumes of water through preweighed glass–fiber filters (Whatman GF/C, 42 mm diameter, 1.2 m pore size), drying at 110 °C, and weighing the dried filters to four decimal places. Chemical Oxygen Demand (COD) was analyzed, rather than Biological Oxygen Demand (BOD_5) because of the relative ease of analysis. COD was analyzed by the closed reflux photometric method using commercial kits (BioScience Inc., Cat. No. 174-318). The COD standard curves were prepared using standards of potassium biphthalate of 50 mg/L, 125 mg/L, 250 mg/L and 500 mg/L.

2.4. Data analysis

Statistical analysis was performed using Microsoft Excel 2000, to calculate the 95% confidence intervals using Student's *t* distribution and to perform ANOVAs.

3. Results and discussion

3.1. Plant growth

The cattails planted in the SSFW were able to thrive and increased in root depth and emergent biomass. They showed periods of dormancy in the growth of emergent vegetation throughout the study period. During the winter months (i.e. January and February), the calla lilies planted in the SSFW did not grow well because of nighttime air temperatures that fell below 10 °C. This species was also affected by the strong sunlight because of the elevation at >2000 m. However, the canna lilies were much hardier and once they had grown high enough to protect the calla lilies from the sun and wind, both species grew well throughout the rest of the experiment. It was possible to harvest flowers from both species throughout the study period. The root zones of both the cattails and ornamental flowers extended down into the full subsurface depth (i.e., 0.5 m).

3.2. Water temperature, dissolved oxygen, Eh and pH

The mean temperature recorded for the input wastewater was 18.2 ± 0.2 °C and the water temperature in the treatment system was between 15 °C and 16 °C (Table 2). This range of temperature is adequate

Table 2
Mean concentrations and percent removal rates (±95% confidence limits) for water quality parameters ($n = 21$) monitored from January to October 2001 at seven points in a pilot-scale wetland in Nativitas, Mexico

Parameter	Input	Terraces	Stabilization pond	SSFW cattail	SSFW flowers	VFW	Cistern
NH_4^+ (mg N L^{-1})	66.3 ± 4.5	44.4 ± 2.5	43.8 ± 1.9	42.4 ± 1.1	39.3 ± 1.6	21.6 ± 1.6	22.9 ± 4.5
%NH_4^+ removal	–	13.9 ± 10.4	19.3 ± 7.6	20.6 ± 7.8	25.9 ± 8.0	54.8 ± 7.0	53.9 ± 8.4
NO_3^- (mg N L^{-1})	28.4 ± 7.3	14.3 ± 4.3	11.2 ± 2.8	6.6 ± 1.3	6.5 ± 1.4	5.5 ± 1.2	5.2 ± 0.9
%NO_3^- removal	–	49.6 ± 15.0	60.7 ± 9.8	76.7 ± 4.6	79.7 ± 5.0	80.7 ± 4.3	81.7 ± 3.1
Total N (mg N L^{-1})	162.9 ± 14.3	85.3 ± 5.1	70.0 ± 3.2	66.5 ± 3.5	63.1 ± 4.1	57.1 ± 4.9	44.6 ± 4.5
% Total N removal	–	40.3 ± 4.9	51.8 ± 3.2	54.7 ± 3.2	58.3 ± 2.9	62.3 ± 3.2	71.7 ± 2.6
COD (mg/L)	1569.2 ± 81.2	954.5 ± 48.5	643.1 ± 24.2	324.2 ± 12.8	289.5 ± 12.1	206.2 ± 10.2	223.3 ± 13.2
% COD removal	–	32.3 ± 3.6	54.8 ± 2.2	77.0 ± 1.3	79.8 ± 1.1	85.6 ± 0.8	83.9 ± 1.1
DO (mg/L)	1.9 ± 0.2	0.7 ± 0.2	0.9 ± 0.5	0.5 ± 0.1	0.5 ± 0.1	3.4 ± 0.7	5.3 ± 0.8
Eh (mV)	−45.5 ± 13.6	−161.4 ± 16.8	−192.1 ± 17.5	−184.4 ± 19.5	−182.2 ± 18.1	37.0 ± 15.4	50.8 ± 11.6
TSS (mg/L)	406.1 ± 33.4	154.0 ± 9.4	64.4 ± 3.5	22.4 ± 3.4	24.7 ± 5.5	16.4 ± 2.9	58.6 ± 5.3
pH	8.2 ± 0.1	7.5 ± 0.1	7.7 ± 0.1	7.6 ± 0.0	7.5 ± 0.0	7.6 ± 0.0	7.7 ± 0.1
T (°C)	18.2 ± 0.2	15.0 ± 0.5	15.1 ± 0.4	15.6 ± 0.5	15.7 ± 0.5	16.1 ± 0.5	15.9 ± 0.5

Note: that nitrate was only monitored from September to October 2001 ($n = 9$).

for efficient removal of nutrients and pathogens (Kadlec and Knight, 1996).

The mean DO concentration in the raw sewage was 1.9 ± 0.2 mg/L and this concentration dropped to 0.7 ± 0.2 mg/L in the sedimentation terraces as a result of oxygen demand from the decomposition of organic matter (Table 2). In the rest of the treatment wetland, these suboxic conditions persisted until the VFW, where the mean DO increased to 3.4 ± 0.7 mg/L. This pattern was expected since oxygenation is the main feature of intermittent VFWs. The SSFW did not increase the DO because of the high oxygen demand in the wastewater. The DO increased in the cistern and in the ponds because of surface aeration and possibly because of the proliferation of algae. The DO in the final retention pond was 7.1 ± 0.8 mg/L, which indicates that this water could support the oxygen requirements of aquatic organisms.

The oxidation–reduction potential (Eh) decreased throughout the treatment wetland, but increased after the VFW (Table 2). These results are consistent with the DO data and show that the water was suboxic in the terraces, the stabilization pond and the SSFWs, and the conditions became aerobic after the VFW. The pH of the raw sewage was 8.2 ± 0.1, and the system reduced the pH to values close to 7.5 (Table 2). These results are consistent with the behavior of pH in other treatment wetlands (Kadlec and Knight, 1996). There was no significant difference between the pH in the SSFW cells planted with cattail and with flowers.

3.3. Chemical oxygen demand

The mean COD in the raw sewage was 1887 ± 167 mg/L (Table 2). There was high variation in COD concentrations over the sampling period. The COD of the raw sewage is very high in comparison to the range of COD values reported in the literature for domestic wastewater; including representative concentrations reported by Metcalf & Eddy Inc. (1991) of 250 mg/L, 500 mg/L, and 1000 mg/L for weak, medium and strong wastewater, respectively. This indicates that the sewage from Nativitas is very "concentrated" relative to sewage analyzed from cities and towns in industrialized countries that have more advanced sanitation systems.

The whole treatment system reduced COD by an average of 84.9 ± 1.3% (Table 2). Most of the reduction occurred in the first three steps of the treatment, as the terraces reduced COD by 29.5 ± 4.3%, the stabilization pond to 52.9 ± 3.2%, and the cattail-planted and flower-planted SSFWs to 76.4 ± 1.7% and 80.0 ± 1.1%, respectively. The VFW reduced COD slightly (i.e., 4%) but significantly ($p < 0.001$), relative to the SSFW. There was no significant difference between the COD removal of the SSFW cell planted with calla lily and the one planted with cattail ($p = 0.195$). This result is consistent with the literature that reports no difference in BOD and CODs removal in SSFW containing different plants species (Kadlec and Knight, 1996; Tanner, 2000).

3.4. Total suspended solids

The concentration of total suspended solids (TSS) in the untreated sewage was 406.1 ± 33.4 mg/L (Table 2). This value is high compared with the typical value of 350 mg/L reported in North America for strong wastewater (Metcalf & Eddy Inc., 1991). There was a very large reduction of TSS in the sedimentation terraces, from 406.1 ± 33.4 mg/L to 154.0 ± 9.4 mg/L (Fig. 3), which represents a 53.3 ± 5.0% reduction (Table 2). It is interesting that the terraces accounted for such a large fraction of TSS removal, since this is a very simple and inexpensive system. The stabilization pond reduced TSS further to 64.4 ± 3.5 mg/L. At this point, the system had removed 81.0 ± 1.7% of input TSS. The cattail SSFW reduced TSS to 22.4 ± 3.4 mg/L and the flower SSFW to 24.7 ± 5.5 mg/L, with no significant difference between the two SSFW cells (Fig. 3). Finally, the VFW reduced the TSS to 16.4 ± 2.9 mg/L.

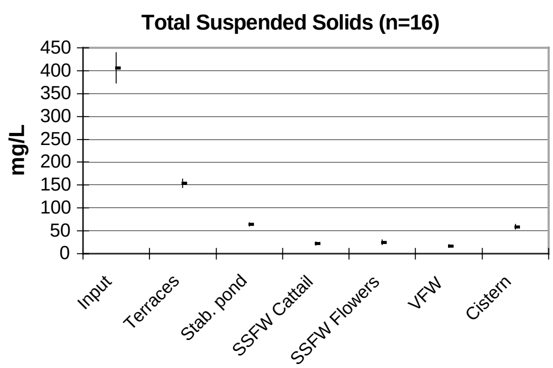

Fig. 3. Mean concentrations of total suspended solids ($n = 16$, ±95% confidence intervals) in mg/L in pilot-scale constructed wetland.

The system achieved a total reduction of 95.9 ± 0.6% of TSS, but the TSS in the cistern increased slightly to 58.6 ± 5.3 mg/L; probably due to growth of algae.

3.5. Nitrogen

The ammonium concentration in the raw sewage was 80.5 ± 5.5 mg/L (Table 2). This concentration is high compared with the usual values observed in domestic wastewater, which are 25 mg/L for medium strength wastewater and 50 mg/L for strong wastewater (Metcalf & Eddy Inc., 1991). This result indicates that it is necessary to use a treatment system with high performance for ammonium reduction. The terraces removed a large proportion of the ammonium from 80.5 ± 5.5 mg/L to 53.9 ± 3.0 mg/L (Fig. 4). In the stabilization pond, there was a very small reduction of ammonium, to 53.2 ± 2.3 mg/L. A further small reduction occurred in the SSFWs; to 51.5 ± 1.4 mg/L in the cattail SSFW and 47.7 ± 2.0 mg/L in the flower SSFW (Fig. 4). There was no statistically significant difference between ammonium reduction in flowers and cattail cells ($p > 0.303$). A more noticeable removal of ammonium occurred in the VFW, which reduced the concentration to 26.2 ± 1.9 mg/L. This was probably due to the elevated concentrations of dissolved oxygen in this part of the system, since high DO promotes oxidation of ammonium to nitrate. According to the literature, VFWs have higher rates of removal of ammonium relative to SSFW (Platzer, 2000).

Nitrate analysis data were collected between 3 September, 2001 and 26 October, 2001 ($n = 9$) because of very high transient concentrations that occurred in grab samples earlier in the monitoring period. The mean concentration of nitrate in the raw sewage was very high at 125.8 ± 32.3 mg/L. Since nitrate is typically absent in domestic sewage (Metcalf & Eddy Inc., 1991), these results indicate sources of nitrate other than domestic waste. It is hypothesized that the abnormally high concentrations of nitrate are related to the disposal of fertilizers used in floriculture. Fertilizers are applied for floriculture in the area up to two or three times a week (personal communication). When these farmers wash their equipment and the containers used to apply the fertilizers, the rinse water goes directly into the sewer.

There was a substantial reduction of nitrate concentrations in the terraces, from 125.8 ± 32.3 mg/L to 63.4 ± 18.9 mg/L (Fig. 5), for a total reduction of 49.6 ± 15.0% (Table 2). As shown in Fig. 5, the stabilization pond further reduced nitrate to 49.5 ± 12.3 mg/L (60.7 ± 9.8% reduction). The cattail SSFW reduced nitrate to 29.3 ± 5.7 mg/L (76.7 ± 4.6% reduction), while the flower SSFW reduced this to 28.8 ± 6.3 mg/L (79.7 ± 5.0% reduction), with no significant difference in nitrate removal between the two SSFW ($p = 0.97$). The VFW did not contribute significantly to further nitrate removal (Fig. 5). The nitrate concentration in the cistern was essentially the same as in the output of the VFW (Fig. 5). Thus, the main nitrate removal occurred in parts of the system where the dissolved oxygen concentration (DO) was low. This

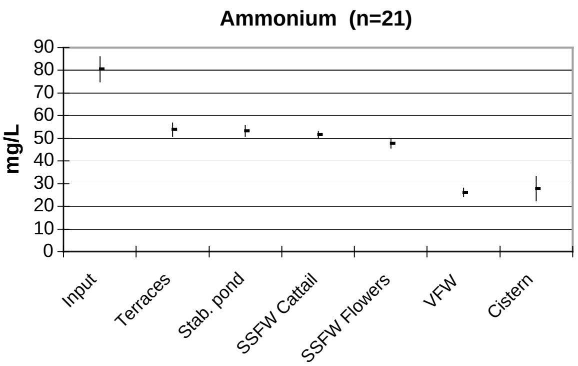

Fig. 4. Mean concentration of ammonium ($n = 21$, ±95% confidence intervals) in mg/L in pilot-scale constructed wetland.

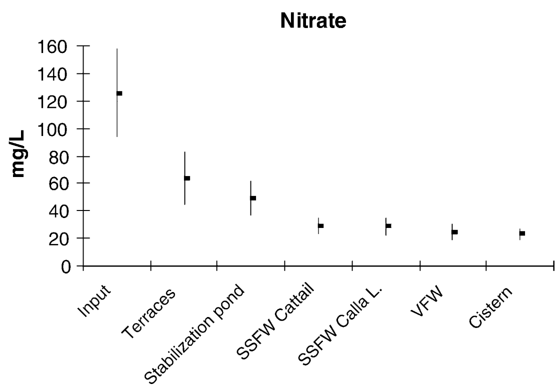

Fig. 5. Mean concentration ($n = 9$, ±95% confidence intervals) in mg/L in pilot-scale constructed wetland.

is probably due to the fact that denitrification requires anaerobic conditions and a carbon source. The final nitrate concentration of 23.1 ± 3.9 mg/L is low enough in the treated water to support aquatic life or to be used for irrigation purposes or for livestock (SEMARNAP, 1996; CNA, 1989).

According to Kadlec and Knight (1996), concentrations of nitrite in treatment wetlands are typically very low in comparison to concentrations of nitrate and ammonium. Analysis of nitrite was conducted only twice in September and October of 2001 and the results were consistent with the literature. Concentrations of nitrite in the raw sewage were in the range of 0.20–0.34 mg/L and the concentrations never exceeded 0.32 mg/L at any point in the wetland. Since these concentrations are negligible compared with other forms of nitrogen, nitrite was not extensively monitored in the constructed wetland.

Total nitrogen (TN) concentrations in the raw sewage were very high at 162.9 ± 14.3 mg/L (Table 2). The greatest proportion of nitrogen removal occurred in the sedimentation terraces, where 40.3 ± 4.9% of nitrogen was removed (Table 2). This indicates that removal was primarily from the sedimentation of organic nitrogen. The stabilization pond further reduced total nitrogen to 51.8% of the content in raw sewage (Table 2). The SSFWs reduced the TN slightly to a total percent removal of 54.7 ± 3.2% (cattail) and 58.3 ± 2.9% (flowers). There was no significant difference in nitrogen removal between the two SSFWs. The VFW removed only a small additional amount of the total nitrogen to 62.3 ± 3.2%.

Organic nitrogen was estimated by subtracting the concentration of ammonium and nitrate from total nitrogen. The organic nitrogen concentration was higher than ammonium in the raw sewage, but between that point and the VFW, organic nitrogen levels were lower than ammonium. Sedimentation of organic nitrogen in the terraces probably contributed to this change. It is also probable that there was ammonification of the organic nitrogen in the system, which was promoted by the suboxic conditions. There was an increase in org-N in the VFW; possibly due to periodic clogging. As was explained before, the elevated DO in the VFW may have promoted nitrification of ammonium to nitrate. However, although reduced ammonium concentrations were observed at this location, there was no increase in nitrate concentration. Possibly, denitrification was occurring and that is the reason for the observed reduction in total nitrogen and no increase in nitrate concentration. However, these conclusions have to be interpreted with caution because the operation of the VFW was irregular due to periodic clogging. Further studies are needed in the VFW to evaluate the nitrogen dynamics in this part of the system. These tests should be done with a smaller organic loads and periods of

Table 3
Comparison of the water quality parameters for input and output water from the pilot-scale constructed wetland in Nativitas and the Mexican water quality guidelines for various water uses

	Guidelines related to use of water				Soil	Construction wetland input	Construction wetland output
	Indirect irrigation[a]	Urban public use[a]	Aquatic life protection[a]	Livestock[b]	Direct irrigation[a]		
T (°C)	N.A.	40	40	N.A.	N.A.	18.2 ± 0.2	16.1 ± 0.5
TSS (mg/L)	150	75	40	N.A.	N.A.	406.1 ± 33.4	16.4 ± 2.9
BOD_5 (mg/L)	150	75	30	N.A.	N.A.	–	–
Total N (mg/L)	40	40	15	N.A.	N.A.	162.9 ± 14.3	57.1 ± 4.9
NO_3^- (mg/L)	N.A.	N.A.	N.A.	90	N.A.	125 ± 32.3	24.3 ± 5.4
NO_2^- (mg/L)	N.A.	N.A.	N.A.	10	N.A.	<1	<1
NH_4^+ (mg/L)	N.A.	N.A.	0.06[b]	N.A.	N.A.	80.5 ± 5.6	26.2 ± 1.9
DO (mg/L)	N.A.	N.A.	5.0[b]	N.A.	N.A.	1.9 ± 0.2	3.4 ± 0.7
pH	5–10	5–10	5–10	4.5–9.0	5–10	8.2 ± 0.1	7.6 ± 0.0
Fecal coliforms (MPN)	1000	1000	1000	1000	2000	–	–

N.A.: not applicable.
[a] SEMARNAP (1996).
[b] CNA (1989).

filter recovery to avoid clogging (Platzer and Mauch, 1997).

3.6. Quality of the treated water and feasibility for reuse

Table 3 shows the acceptable values for several water quality parameters established by Mexican environmental legislation (SEMARNAP, 1996; CNA, 1989) for the discharge of treated wastewater. The Mexican water quality guidelines do not coincide in all cases with those established by environmental agencies in the USA, Canada and the World Health Organization (Jiménez et al., 1999). For comparison, Table 3 also shows the water quality parameters for the untreated sewage and treated water sampled from the constructed wetland at Nativitas. The guidelines in Table 3 indicate that under Mexican law, the untreated wastewater from Nativitas does not meet the water quality guidelines for discharge into surface water. This community, and probably others in the watershed are illegally discharging their untreated wastewater into the Rio Texcoco river.

According to water quality guidelines in Mexico (Table 3), treated water has to be of higher quality if it is to be discharged into a river or a lake than if it is to be used for immediate irrigation. The only restrictions under Mexican regulations for treated water that is to be used for immediate irrigation are for pH, fecal coliforms (FC) and the content of grease and oil. The acceptable pH range is 5–10, the limit of FC is 2000 coliforms/100 mL, and the grease and oil content has to be lower than 15 mg/L for the monthly average and 25 mg/L for the daily average. The FC removal efficiencies in treatment wetlands are usually greater than 90% (Kadlec and Knight, 1996). Although FC and grease and oil content were not analyzed in this study, it is probable that the treated water from the Nativitas constructed wetland was of sufficient quality for reuse in irrigation. It is also possible that the treated water in the final retention ponds could be used as a source of water for livestock, according to Mexican water quality guidelines (Table 3).

Under Mexican guidelines, if receiving waters are to be protected for the preservation of aquatic life, ammonium levels in treated water are restricted to <0.06 mg/L. However, the Rio Texcoco is currently a heavily impacted aquatic ecosystem and the water is used mainly as a source of irrigation water for agriculture. In Table 3, the term “indirect irrigation” refers to a case where the treated water is discharged into a river or lake and this water is then used for irrigation. Under this scenario, there are no regulatory restrictions for the treated water related to concentrations of nitrate or ammonium. The TSS concentrations in the treated water are below the accepted limit. The total nitrogen in the output of the treatment system was 57.1 ± 4.9 mg/L; slightly higher than the limit of 40 mg/L established in the guidelines. The water therefore, could be discharged into the river for subsequent use in agricultural irrigation if the removal of TN was improved slightly. It is not possible to directly evaluate Biological Oxygen Demand limits, since this parameter was not measured. However, the measured COD in the treated water was 244.3 ± 27.6 mg/L. It is expected that the BOD_5 in the treated water would be comparable to the 150 mg/L level established in the guidelines since BOD_5 is always lower than COD (Kadlec and Knight, 1996).

The main regulatory restriction affecting the discharge of treated water into the Rio Texcoco is the total nitrogen content. It was also observed that the raw sewage and the treated water had high nitrate content. If a full-scale treatment system was developed, it should be designed and operated with a focus on nitrate removal, and this would also reduce total nitrogen and BOD_5.

According to Mexican regulations, raw sewage can be used for agricultural irrigation (SEMARNAP, 1996), with restrictions on the crops that can be grown and the periods of irrigation. However, this represents a health risk to the farmers because of waterborne pathogens and it requires monitoring and enforcement to assure that only permitted crops are being cultivated. Irrigation with treated wastewater from a constructed wetland is a preferred solution for generating water for irrigation. Further work should be done to assess the reduction of waterborne pathogens in this treatment wetland.

3.7. Design considerations

The SSFW planted with calla lilies and canna lilies were equally as efficient as the SSFW planted with cattails for treating domestic sewage. It is possible to use SSFW planted with these ornamental plants for simultaneous water treatment and production of commercial

Table 4
Rate constants, k (in m/year) calculated for removal of various water quality parameters in the SSFW of the pilot-scale wetland, as calculated by the k–C^* model described by Kadlec and Knight (1996)

Location	TSS	TN	NH_4–N	NO_3–N	Org-N	COD
Cattail SSFW	54.26	1.77	1.10	17.72	4.23	25.27
Flower SSFW	47.59	3.59	3.69	18.30	3.24	29.63
Average k	50.93	2.68	2.39	18.01	3.74	27.45

flowers. The floriculture activities in the treatment wetland would not sacrifice treatment performance, nor would they require a large extra investment. To improve harvesting of good-quality flowers, it would be necessary to study the culture of calla lily in SSFW under greenhouse conditions, since controlled growing conditions would increase the flower yield and quality.

The most cost-effective part of the treatment wetland at Nativitas was the sedimentation terraces. The terraces were inexpensive and simple to construct and they significantly reduced concentrations of TSS and nitrogen. If communities in developing countries cannot afford to construct or to maintain full-scale systems for treating domestic sewage, sedimentation terraces are a valuable method for achieving partial treatment. However, they still require periodic maintenance to remove accumulated sediment. The SSFW also contributed significantly to the treatment of wastewater. While the VFW further reduced concentrations of TSS and COD and increased DO in the treated water, this part of the wetland required the most maintenance to avoid clogging and was the most expensive to construct, due to the installation of siphons to produce intermittent flows. If VFW are included in wetlands for the treatment of wastewater with a high organic content, tandem systems should be designed so that flows can be shunted back and forth; allowing periodic drying out and regeneration of the VFW.

It is possible to scale up this pilot-scale wetland to treat the domestic sewage generated by an entire community, but the cost of construction, the need for a large wetland area and the maintenance requirements could be prohibitive. A more practical solution for sewage treatment in this region of Mexico may be to collect wastewater from a small number of homes and to treat this wastewater in systems that are coupled with floriculture or agriculture activities. Based upon the assumption of designing a treatment wetland for the domestic wastewater from six families, it was estimated that the average flow to be treated is: 6 families × 5 people/family × 157 L wastewater per person per day = 4620 L/day. The dimensions of the terraces and stabilization ponds were calculated by comparing the flow in the proposed system (4.62 m^3/day) with the average flow in the pilot-scale wetland (i.e., 2.88 m^3/day). Based upon extrapolation from the pilot-scale wetland, the proposed treatment wetland should have three sedimentation terraces of 5 m length × 4 m width × 1 m depth in parallel, followed by a stabilization pond of 10 m length × 4 m width × 1.5 m depth.

The design of the SSFW in this system was based on the k–C^* model described by Kadlec and Knight (1996). The physicochemical parameters used for the design of this part of the treatment system were calculated from monitoring data collected during the operation of the pilot scale system in Nativitas. The input concentration of the pollutants used in the calculation of the SSFW was the same as those observed in the effluent of the stabilization pond in the pilot scale wetland. Table 4 presents the calculated removal rate constants using the k–C^* model. The flow (Q) used for the calculations was 1 L/min, which corresponds to an HRT = 2.3 days. The rate constants were calculated for a system temperature of 15.7 °C, which was the average temperature of the water in the SSFWs.

Based upon this model, the minimum SSFW area was estimated as 369.7 m^2, which is the area required to achieve a predicted total nitrogen concentration <40 mg/L in the effluent in order to comply with the Mexican guidelines for irrigation water. It is proposed that two SSFW be constructed, each 50 m length × 4 m width × 0.6 m depth, which corresponds to a wetland area of 400 m^2 and a hydraulic retention time of 16.3 days (Table 5). This design is conservative since it incorporates a slightly higher area than the minimum area of 369.7 m^2. Predicted total nitrogen concentrations in the SSFW effluent would be 38.2 mg/L, and this system would also be predicted to significantly reduce COD,

Table 5
Summary of design parameters for the SSFW calculated with the k–C^* model for a treatment wetland scaled to 6 families to produce water suitable for irrigation, and predicted concentrations of water quality parameters in the influent (i.e., after sedimentation pond) and effluent from the SSFW

Subsurface flow wetland; k–C^* model	
Design flow (m^3/day)	4.6
Wastewater production (L/person per day)	157
Population equivalent	30 people
Hydraulic retention time	16.3
SSFW dimensions	Two cells of 50 m × 4 m each
Length (m)	100
Width (m)	4
Depth (m)	0.55
Area (ha)	0.040
Slope (%)	<0.055

	COD	BOD[a]	TSS	FColi[a,b]	TN[a]	NH_4^+	NO_3^-	Org-N[a]
Estimated influent concentration (mg/L)	643.1	400.0	64.4	10^5	70.0	53.2	49.1	16.8
Predicted effluent concentration (mg/L)	1.1	24.7	11.9	10	38.2	30.5	0.7	7.9
Predicted % reduction	99.8	93.8	81.6	>99.9	45.4	42.7	98.5	52.9

[a] Estimated from typical influent concentration in domestic wastewater (Metcalf & Eddy Inc., 1991).
[b] Fecal coliforms: cfu per 100 mL.

BOD, TSS, and fecal coliforms (Table 5). Further treatment in VFW or retention ponds would improve water quality.

A retention pond should be constructed to store the treated water exiting the SSFW for later distribution to field crops and greenhouses. Duckweed could be grown in this pond to avoid mosquitoes and algae growth (Reed et al., 1995). The duckweed mat may promote suboxic conditions in the pond, which would further reduce nitrate, COD and suspended solids. However, ammonia will not be further reduced under these conditions. Nitrogen removal has also been observed in duckweed ponds due to plant uptake. Reed et al. (1995) established that harvesting of duckweed every 4 days would yield 22,000 kg/(ha year) (dry weight) of harvested material. At 5% nitrogen and 1% phosphorous content, the harvested material could be composted to yield 880 kg/(ha year) of nitrogen and 220 kg/(ha year) of phosphorous that could be used for soil improvement.

In the community of Nativitas, floriculturists receive a rationed amount of water equivalent to 1 m^3 of water per greenhouse per week. A small treatment wetland for six families designed to treat 4.6 m^3 of wastewater per day could meet the irrigation demands of up to 30 floriculture greenhouses. Any excess production could be used for irrigation of agricultural crops. Duckweed produced in the storage pond could be used for compost. It is also possible to design more efficient systems that can produce water of suitable quality for aquaculture or for consumption by domestic animals. Small SSFW planted with ornamentals plants could also be adapted for wastewater treatment in urban settings, such as for small hotels, office buildings or businesses.

4. Conclusions

A pilot-scale wetland designed to treat approximately 1% of the flow of domestic sewage from the community of Santa María Nativitas in central Mexico effectively reduced concentrations of TSS, COD and nitrogen in the wastewater. Sedimentation terraces were the simplest and most cost-effective part of the system for improving water quality. The subsurface flow wetlands (SSFW) also performed well in the water treatment. There were no differences in the performance of SSFW planted with cattail and ornamental flowers. A vertical flow wetland (VFW) further reduced TSS and COD, but did little to reduce nitrogen levels. The VFW was the most expensive component of the system and frequently clogged as a result of the buildup of organic material in the substrate. A constructed wetland able to treat the domestic wastewater for approximately six families in this region of Mexico is a viable solution for reducing discharges of raw sewage into watersheds.

This type of wastewater treatment system would be successful in Rio Texcoco watershed because it could reduce satisfactorily the level of pollutants and be a source of acceptable irrigation water. Therefore, it would provide economic benefits to families through the culturing of ornamental flowers, generation of water suitable for irrigation and the production of biomass for composting.

This low cost wastewater treatment system studied here demonstrates an ecotechnology that can be applied not only in developing countries but also in rural areas in developed countries that do not have direct access to sewer services. This wastewater treatment system is especially attractive in arid regions because of the production of water suitable for irrigation.

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References

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Waterworks Association, Washington, DC, USA.

Belmont, M.A., Metcalfe, C.D., 2002. Contaminación del agua en la cuenca del río Texcoco. In: Proceedings of the International Conference: IMBAKUCHA 2002. The First Intercultural Conference on the Integrated Management of Human Settlements within Watersheds, May 28–31, Otavalo, Ecuador.

Belmont, M.A., Metcalfe, C.D., 2003. Feasibility of using ornamental plants (*Zantedeschia aethiopica*) in subsurface flow treatment wetlands to remove nitrogen, chemical oxygen demand and nonylphenol ethoxylate surfactants–A laboratory-scale study. Ecol. Eng. 21 (4–5), 233–247.

CNA (Comisión Nacional del Agua), 1989. Criterios Ecológicos de la Calidad del Agua. Diario Oficial de la Federación, December 13, p. 8.

Darula, K.E., 2000. Total Nitrogen Test 'N Tube™ Reagents. Hach Company. P.O. Box 389, Loveland CO 80539, USA, p. 5.

Denny, P., 1997. Implementation of constructed wetlands in developing countries. Wat. Sci. Tech. 35, 27–34.

Flores-Sánchez D. 2000. Biodiversidad, gestion de sistemas de cultivo y patrimonio: Estudio de caso Cuenca del Rio Texcoco. M.Sc. Thesis. Colegio de Postgraduados. Montecillo, Estado de Mexico, Mexico.

Haberl, R., 1999. Constructed wetlands: a chance to solve wastewater problems in developing countries. Wat. Sci. Tech. 40, 11–17.

INEGI, 1995. Conteo General de Poblacion y Vivienda. Instituto Nacional de Geografia, Estadistica e Informatica, Mexico.

Jiménez, B., Ramos, J., Quezada, L., 1999. Analysis of water quality criteria in Mexico. Wat. Sci. Tech. 40, 169–175.

Kadlec, R.H., Knight, R.L., 1996. Treatment Wetlands. CRC Press, Lewis Publishers, Boca Raton, FL, p. 893.

Kivaisi, A.K., 2001. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecol. Eng. 16, 545–560.

Lakshman, G., 1987. Ecotechnological opportunities for aquatic plants, a survey of utilization options. In: Reddy, K.R., Smith, WH. (Eds.), Aquatic Plants For Water Treatment and Resource Recovery. Magnolia Publishing Inc., Orlando, FL, pp. 49–68.

Lopez-Vega, M., Vargas-Morales, F., Zarazua-Escobar, J.A., 1998. Recuperacion de suelos degradados con el uso de sabila proponiendo un beneficio economico, Proyecto de Servicio Social: Desarrollo Comuitario de Texcoco, Universidad Autonoma Chapingo, p. 12.

Metcalf & Eddy Inc., 1991. Wastewater Engineering, Treatment, Disposal, and Reuse, third ed. McGraw-Hill Inc., New York, p. 1333 (revised by Tchobanoglous, G. and Burton, F.L.).

Neralla, S., Weaver, R.W., Lesikar, B.J., 1998. Plant selection for treatment of septic effluent in subsurface wetlands. In: Sievers, D.M. (Ed.), On-site Wastewater Treatment. American Society of Agricultural Engineers, pp. 247–253.

Platzer, C., 2000. Development of reed bed systems – a European perspective. In: Proceedings of the International Conference on Wetland Systems for Water Pollution Control, vol. 1, November 11–16, Orlando, FL, USA, pp. 23–27.

Platzer, C., Mauch, K., 1997. Soil clogging in vertical flow reed beds – mechanisms, parameters, consequences and . . . solutions? Wat. Sci. Tech. 35, 175–181.

Reed, S.C., Crites, R.W., Middlebrooks, E.J., 1995. Natural System for Wastewater Management and Treatment, second ed. McGraw-Hill Inc., New York, 433 pp.

SEMARNAP (Secretaria de Medio Ambiente, Recursos Naturales y Pesca), 1996. Norma Oficial Mexicana: NOM-001-ECOL-1996.

Tanner, C.C., 2000. Plants as ecosystem engineers in subsurface-flow treatment wetlands. In: Proceedings of the International Conference on Wetland Systems for Water Pollution Control, vol. 1, November 11–16, Orlando, FL, USA, pp. 13–22.

Wolverton, B.C., 1990. Aquatic plant/microbial filters for treating septic tank effluent. In: Hammer, D.A. (Ed.), Constructed Wetlands for Wastewater Treatment. Lewis Publishers, NY.