Experimental results on constructed wetland pilot system

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Abstract Research into a constructed wetland for wastewater treatment using M.H.E.A. (Hierarchical Mosaic of Artificial Ecosystems) pilot system was carried out over a vegetative period in 8 different flow and vegetable composition series. The system consisted of a free water pond as a first step working as primary treatment followed by a zone with *Typha* sp. and surface flow and finally a woody zone with a subsurface flow and planted with ligneous species (*Salix* sp., *Populus* sp., *Fraxinus* sp. and *Alnus* sp.).

Removal efficiency in the study reflects an optimal result: 80–99% total suspended matter removal, 82–98% organic matter removal, 70–98% nutrients removal and up to 99.9% faecal bacterial disinfecting. Effluent characteristics were in accordance with European Union legislation criteria for wastewater treatment systems.

Keywords Constructed wetlands; experimental sewage treatment; pilot system; removal efficiency; wastewater

Introduction

Wastewater treatment plant viability is a pressing problem, especially for small communities in regions characterised as "sensible" for eutrophication. It is therefore necessary to develop new low installation and operation cost technologies; these must efficiently remove organic and nutrient loads, allowing for water reuse and biomass utilisation in order to reduce operating investments. In most cases, the economic costs should cover the proposed objectives, such as the inclusion of tertiary treatment for sensitive designated zones, is economically unapproachable for small villages in rural areas. In Spain wastewater is reused for irrigation in many areas.

The European Union Directive 91/271/EEC (ECOD, 1991a) established a series of requirements for wastewater treatment plant effluents and removal efficiency, which must be applied before the end of December 2005 for populations between 2,000 to 15,000 equivalent inhabitants. Nutrients must therefore be removed in rural areas in the north-west of Spain where wastewater is very diluted (BOD_5 between 20 and 50 mg/l in 70% of the villages), but with moderate to high concentration of Nitrogen (N) and Phosphorus (P) due to use of fertilisers (González and Cabo, 1998).

The province of León localities with less than 10,000 inhabitants come to about 97%, and those with less than 2,000 inhabitants represent 82.5% of the total population of the province. Most of these small localities are located in disperse zones or in mountain and riverside zones, many of them being catalogued as eutrophication sensitive and consequently will require tertiary treatment (nutrients elimination). In another case, these localities are on the Spanish meseta, but very tied to agricultural or cattle-raising activities and they are equally conditioned to treat their wastewater to tertiary level according to European legislation EU 91/676 (ECOD, 1991b).

It has been widely demonstrated in Spain that conventional (activated sludge) treatment systems applied to small rural municipalities have many operational and management problems, which is at present greatly inactive or abandoned. As an alternative to the conventional treatment systems, low-cost and natural systems are increasingly applied in

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central Spain, where stabilisation ponds are one of the most adequate and applied systems. Constructed wetlands have not up to now been considered as a treatment option by the administration but mainly due to the absence of previous experiences on pilot plants. The aim of this work was to study the applicability of this system to the wastewater and climatic conditions of the region and to know the parameters for the design of a full-scale process.

Materials and methods

An M.H.E.A. (*Hierarchical Mosaic of Artificial Ecosystems*) model developed by Michel Radoux at Fondation Universitaire Luxembourgeoise, (Radoux and Kemp, 1982; Radoux *et al.*, 1995) in Viville (Belgium), was followed up by the experimental pilot plant design situated in the Northwest of Spain.

Eight series of three glass fibre basins of 0.85 × 1.3 × 0.55 m, were installed with a capacity of 0.6 m^3 and a surface of 1.1 m^2 each basin. They were preceded by a pond like primary treatment (WSP) with a detection time of 24 hours. First basins on series were filled to 25 cm high with 6–8 mm diameter gravel bed. Water is over 20 cm of gravel. Effective volume was reduced to 0.29 m^3. These basins had a superficial flow and they were planted with 30 units of *Typha latifolia* collected from their natural system (Ansola *et al.*, 1995a, 1995b).

Two following steps in the series were totally filled with inert gravel, they had a subsuperficial flow and were planted with 15 units/m^2 of *Salix atrocinerea*, *Alnus glutinosa*, *Populus alba* or *Fraxinus excelsior*, each being one year old. The different series, each composed of a surface of 4.4 m^2, were as follows (Table 1).

Raw wastewater was taken and pumped directly from a municipal sewer to supply the system and distributed to the series basins by peristaltic pumps in continuous action. The hydraulic load differed between series. For the series 1, 5 and 7 the operative water-flow was 160 l/d for a surface of 4,4 m^2. The series 2, 6 and 8 had a water-flow of 250 l/d with the same surface. There were two special series, 3 and 4 that represented the experimental operations designed flows as a reply to the minimum and maximum flow of the full-scale pilot plant constructed in Bustillo de Cea (León, Spain) (Ansola *et al.*, 1998).

Physico-chemical and microbiological analysis in the influent, pond effluent and final effluent were carried out for a vegetative period (March to October) in the pilot scale experimental system. The analysis was based on *Standard Methods* (1989).

In Table 2, we show the European Union established elimination removal levels and limited effluent values of different parameters proceeding of wastewater treatment plants. There is no legislation which refers to microbiological parameters or the treatment removal efficiency with regard to this topic.

Results and discussion

Influent characteristics

The average electrical conductivity detected was 436 μS/cm, which corresponds to a typically domestic wastewater (Metcalf and Eddy, 1991) and low mineral composition (Henze *et al.*, 1997), with a maximum of 498 μS/cm and a minimum of 412 μS/cm. Concentration of total suspended solids (TSS) varied between 287 mg/l and 124 mg/l, the

Table 1 Configuration of experimental series and their designed water-flow

Series 1	Pond-*Typha-Salix-Salix*	P-T-S-S	Water-flow = 160 l/d
Series 2	Pond-*Typha-Salix-Salix*	P-T-S-S	Water-flow = 250 l/d
Series 3	Pond-*Typha-Salix-Salix*	P-T-S-S	Water-flow = 80 l/d
Series 4	Pond-*Typha-Salix-Salix*	P-T-S-S	Water-flow = 200 l/d
Series 5	Pond-*Typha-Alnus-Populus*	P-T-A-P	Water-flow = 160 l/d
Series 6	Pond-*Typha-Alnus-Populus*	P-T-A-P	Water-flow = 250 l/d
Series 7	Pond-*Typha-Fraxinus-Fraxinus*	P-T-F-F	Water-flow = 160 l/d

DIRECTIVE (91/271/EEC)	Units	Maximum daily concentration	Removal (%)
Biochemical Oxygen Demand (BOD_5 at 20°C)	mg O_2/l	25	70-90
Chemical Oxygen Demand (COD)	mg O_2/l	125	75
Total Suspended Solids (TSS)	mg/l	35	90
Total Phosphorus	mg/l P	2*	80
Total Nitrogen	mg/l N	10 or 15**	70–80

* populations higher than 100,000 eq. inhab. The value will be 1 mg/l
** 10 ppm for populations of higher than 100,000 eq. inhab. and 15 ppm for those between 10,000–100,000

average concentration was 164 mg/l, all these values less them of 350 mg/l, which allowed for the quantification of this wastewater as weak concentration (Metcalf and Eddy, 1991) or diluted wastewater type (Henze *et al.*, 1997). The organic load also expressed as the total Chemical Oxygen Demand (COD) varied between 271 and 112 mgO_2/l, with average concentration of 156 mgO_2/l, which also confirms its classification as weak concentration wastewater since the average concentration for this parameter in the typical domestic wastewater (Henze *et al.*, 1997) is located between 250 and 500 mgO_2/l for very diluted types. Biochemical Oxygen Demand (BOD_5) varied between a maximum of 93 mgO_2/l and a minimum of 72 mgO_2/l, with an average concentration for the study time of 83 mgO_2/l and values below 110 mgO_2/l for very diluted wastewater types (Henze *et al.*, 1997).

Nutrients concentrations showed the same dilution effect of the wastewater used as an influent. Nitrate presented a range of variation, with a maximum of 3.9 mg/l and a minimum of 2.4 mg/l, below the typical domestic wastewater (15–29 mg N/l; Metcalf and Eddy, 1991). The total nitrogen concentration in the influent, measured as Total Kjeldahl nitrogen (TKN), had a maximum of 19.6 mg/l and a minimum of 7.8 mg/l, below the 20 mg/l described (Henze *et al.*, 1997) for very diluted wastewater types. With regard to phosphorus concentrations, (TP) was presented with a minimum of 4.2 mg/l and a maximum of 5.0 mg/l, close to 4 mg/l for very diluted types (Henze *et al.*, 1997). Average concentration and the standard deviation of the different parameters measured are shown in Table 3.

This very diluted influent is a common pattern in the north of Spain owing to the infiltration of ground water into the sewage (González and Cabo, 1998).

Pond effluent

The effect of pond treatment as a first step into the series, operating as a sedimentation tank with only one day of hydraulic detention time, reduced the average concentration levels of solids up to 31 mg/l for TSS and 26 mg/l for TVS. The organic load was reduced to 47 mg/l

Table 3 Average influent concentration and standard deviation for the measured parameters

Parameters (units)	Average concentration	Standard deviation
Temperature (°C)	7.5	0.1
pH	16.6	1.8
Conductivity (µS/cm)	463	22.9
DO (mg O_2/l)	2.1	0.4
TSS (mg/l)	164	40.1
TVS (mg/l)	145	19.2
COD (mg O_2/l)	156	39.1
BOD_5 (mg O_2/l)	83	7.0
Nitrate (mg NO_3^-/l)	3.4	0.4
Ammonia (mg NH_4^+/l)	5.1	0.9
TKN (mg/l)	14.6	2.6
TP (mg P/l)	4.7	0.3
Faecal coliform (col./100 ml)	600285	257602

average concentration for COD, but it was not sufficient in BOD_5 with an average concentration of 38 mg/l.

The average concentration levels of nutrients after pond treatment were insufficient for the requirements according to European legislation. Thus, we obtained average concentrations of 4 mg/l for ammonia, 2 mg/l for nitrate, and with regard to total nutrients forms, 11 mg/l for total nitrogen and 3 mg/l for total phosphorus were obtained.

Disinfecting efficiency, owing to the short detention time applied, was insignificant depending on waste stabilisation pond possibilities, though an average concentration of 169,044 col/100 ml was obtained.

Final effluent

Values of concentration for the most important parameters in the final effluent are given in Table 4; showing good results obtained for the final effluent quality and they agree with the requirements of the European Council legislation.

Removal efficiency

Average removal efficiencies obtained in the study are shown in Figure 1, these results show a high reduction level in all the series for the different analysed parameters.

The suspended solid removal (Figure 1a) was high in the first pond stage with an average removal of 81% in TSS. An average removal between 97% of series 4 (PTSS-200) and 99% of series 8 (PTFF-250) was obtained in the final effluent of the series. This last series, which was operating with the higher water-flow, is significantly different to others applying a statistical "t" test for independence variables (significant level of 95%), except with series 6 (PTPA-250), for the solids removal efficiency. Suspended (TSS) and volatile (TVS) solids concentration in the influent and the effluent have positive correlation, therefore the degree of removal found for each one of these parameters does not vary.

Organic matter removal efficiency (Figure 1b) was represented for the obtained elimination in COD and BOD_5. In the pond stage an average removal of 69% to COD and 54% to BOD_5 was obtained. These results are not sufficient. Treatment in the following stages showed a high removal efficiency and was more efficient with higher assayed hydraulic detection time. Thus removal levels varied between 91% in series 6 (PTPA-250) to 95% in series 1 (PTSS-160) for the COD average elimination and between 98% in series 7 (PTFF-160) to 99% in case of BOD_5. According with the "t" test assayed for the variables independence of results obtained in COD reduction. Series 1 (PTSS-160) is significantly independent of the rest also occurs with the series 3 (PTSS-80).

Table 4 Average effluent concentration for the main parameters in the different series tested

Parameters (units)	Effluent							
	Series 1 PTSS 160 l/d	Series 2 PTSS 250 l/d	Series 3 PTSS 80 l/d	Series 4 PTSS 200 l/d	Series 5 PTPA 160 l/d	Series 6 PTPA 250 l/d	Series 7 PTFF 160 l/d	Series 8 PTFF 250 l/d
pH	7.38	7.45	7.36	7.30	7.39	7.44	7.39	7.32
DO (mg O_2/l)	3.8	3.5	5.8	3.4	3.8	3.9	3.7	3.7
Conductivity (µS/cm)	366	355	364	368	359	360	358	353
TSS (mg/l)	3.4	3.6	4.9	5.0	3.7	2.5	3.3	1.9
COD (mg O_2/l)	7.8	10.9	9.4	11.0	12.2	13.2	9.9	12.0
BOD_5 (mg O_2/l)	1.1	1.2	0.9	1.3	1.1	0.9	0.7	1.1
Nitrate (mg NO_3^-/l)	0.3	0.3	0.1	0.1	0.3	0.5	0.2	0.5
Ammonia (mg NH_4^+/l)	0.4	0.7	0.1	2.0	0.2	1.0	0.1	0.2
TKN (mg N/l)	0.4	1.4	0.3	2.2	0.5	0.9	0.2	0.9
TP (mg P/l)	0.2	0.2	0.1	0.4	0.2	0.3	0.04	0.3

... was more adequate than other species. However, with regard to the DBO_5 removal, the use of *Fraxinus excelsior* had a greater efficiency, although significant differences were not detected between the data of this parameter.

Nutrients (N and P) removal (Figure 1c and 1d) is very low in the pond stage, obtaining 25% for the TP and 23% for TN; with regard to the nitrogen forms studied, an average removal of ammonia of 29% and 30% in the case of nitrate was obtained in the first stage.

The nitrate assimilation in the series was produced with greater hydraulic detention times and fundamentally in the case of series that used *Salix* sp. as woody species, a maximum average removal in series 3 (PTSS-80) of 98% was obtained. All the results obtained for this parameter were found to be 85% of average removal (minimum in series 6 PTPA-250 and series 8 PTFF-250).

The removal of ammonia reached maximum average levels in larger used surfaces (99% in the case of series 3 PTSS-80) and it was minimal in greater applied water flow (81% in the case of series 6 PTPA-250). Significant differences for this parameter were not found in the different flows tested with the series of *Fraxinus* sp. (series 7 and 8) or between those which used the minor flow of *Salix* sp. series (series 3).

In total nutrients forms (TN and TP), the use of *Fraxinus* sp. in series with the lowest water flow applied (series 7 PTPP-160) obtained the best average results (98% for TN and 99% for TP), these results are significantly different to the other series studied, except for TN with series 3 (PTSS-80) and series 1 (PTSS-160) which obtained 98% in TN removal and 97% in TP removal for series 3, and 97% for TN and TP removal in series 1.

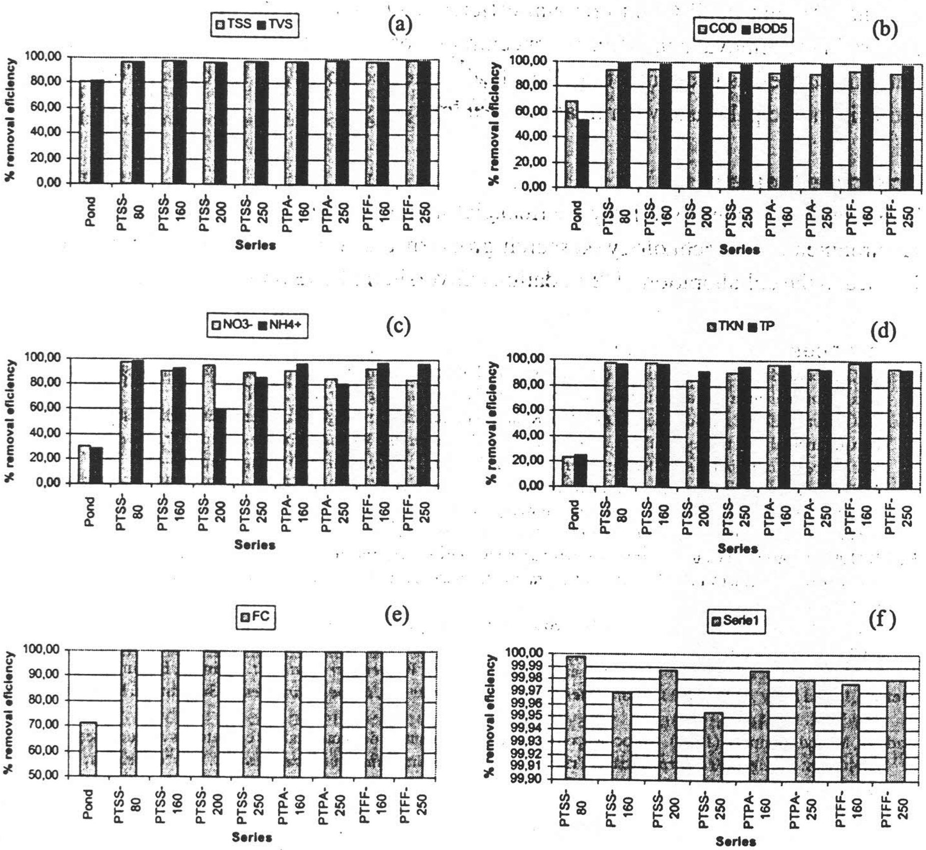

Figure 1 Removal efficiency in series for different parameters studied. a) Total solids; b) Organic matter; c) Nitrogen species; d) Total nutrients; e) Faecal coliform disinfecting; f) Detail of faecal coliform disinfecting in assayed series

Disinfecting (Figure 1e) in the pond stage obtained average results of 71%. The use of macrophytes and woody species notably improves the results, with average disinfecting from faecal coliform bacteria (Figure 1f) in all the series studied up to 99.9% being obtained. The maximum results for disinfecting were obtained with the lowest flows tested, with 99.99% maximum being observed in the series 3 PTSS-80 (99.99%), however there did not seem to exist a preference for the disinfecting in the use of one or another kind of woody species.

Conclusions

Wastewater characteristics used as an influent in the study reflected a weak concentration. However this kind of water is common in rural areas of north west Spain.

Removal of solids from the diluted wastewater was satisfactorily obtained with any of the following operational strategies and selected species in the study. If the objective for the application of this model at full scale is solids removal, we could reduce the surface to system establishment. Organic matter removal was obtained with high efficiency levels and is procured in a significantly superior way to more commonly used surfaces and with the use of *Salix* sp. a woody species at the end of the system.

The removal efficiency of nutrients was accomplished with statistical significance at higher hydraulic detection times. Statistical differences observed with the use of *Fraxinus* sp. as a third system stage made it possible to reduce the surface requirements as opposed to the use of *Salix* sp., with equal results. The hydraulic detention time is very significant, with disinfecting being higher at greater times.

Final effluent quality and removal efficiency obtained in the study are highly satisfactory in the removal and effluent concentration of suspended solids, organic matter, and nutrients as well as in disinfecting. Results obtained comply with European Council legislation in municipal wastewater treatment requirements.

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