Treatment for small polluted rivers: Design and performance of an experimental structure

N Ramírez-Baca[1], R Saucedo-Terán[2], LI Manzanares-Papayanopoulos,[1] J Carrazco-Palafox[3] and GV Nevárez-Moorillón[3]*

[1] *Centro de Investigación en Materiales Avanzados, S. C. (CIMAV), Miguel de Cervantes No. 120. Complejo Industrial Chihuahua, Chihuahua, Chihuahua México*

[2] *Campo Experimental La Campana-INIFAP, Ave. Homero No. 3744 Fracc. El Vergel Chihuahua, Chihuahua México*

[3] *Universidad Autónoma de Chihuahua, Facultad de Ciencias Químicas, Campus Universitario. Apdo. Postal 1542-C, Chihuahua, Chihuahua, Mexico*

Abstract

In view of the economic reality of developing countries, it will not be possible to build all the necessary wastewater treatment plants (WWTP) needed to control the pollution of their rivers in the next 20 years. Therefore, low-cost alternative technologies must be developed to restore the water quality of polluted rivers. It is well-known that the self-purification cycle in nature uses several biotic and abiotic processes to restore polluted water to its former pristine quality. This cycle has been surpassed in many rivers due to continuous discharges of wastewater into them. A low-cost structure that will enhance the water quality in small polluted rivers is proposed and can be constructed *in situ*, based on three conditions: Disruption of plug flow, flow velocity and support material for bacterial growth. The design of the experimental stage of this structure can control slope, water flow, length, support material and the number of locks. Two 175m-long experimental models were constructed; both models were filled with crushed, washed and screened 10 to 12 mm diameter river stone. A mixture of primary and secondary effluents from a WWTP was used to test the models, with a chemical oxygen demand of COD ≈50 and 100 $mg \cdot \ell^{-1}$ respectively. For a uniform 0.5% slope, the maximum flows achieved were 27 and 30 $\ell \cdot min^{-1}$ with and without locks. The system worked efficiently breaking the plug flow, mixing the water flow and allowing stable aerobic microbial communities of 5.58 and 8.86 log $UFC \cdot g^{-1}$, and COD reductions ranging from 90.27 to 555.2 $mg \cdot min^{-1}$ depending on the pollutant concentration.

Keywords: freshwater contaminants, self-purification, alternative technology, microbial communities

Introduction

The natural process of self-purification of rivers has allowed the transport and transformation of most of the anthropogenic wastes discharged into them. Nevertheless, the self-purification capacity of many rivers has been exceeded by far, and they now serve as wastewater collectors in many cities of the world. Even though with available technology for wastewater treatment water quality can be restored totally before it is discharged into rivers or creeks, this technology is not generally employed in most of the so-called "developing countries" and the "less developed countries". This will last for at least 10 or 20 more years due to the economic, political and social conditions of these countries (Palupi et al., 1995; Australia and World Affairs 1995; WHO-UNICEF, 2000; Josephson, 2001). In Mexico alone, ranked in the top 20 world economies, 82.26% (196.6 $m^3 \cdot s^{-1}$) of domestic raw sewage produced is discharged into rivers, creeks and agricultural fields (Semarnat/CNA, 1999). In addition, 159 $m^3 \cdot s^{-1}$ of industrial wastewater are produced and only 15% undergo biological treatment (Sanchez-Santillan et al., 2002).

Agricultural practices in many countries still use flood irrigation and an uncontrolled use of pesticides and fertilisers. This combination leads to the production of non-point source discharges that increase the concentration of these compounds in rivers. All the conditions mentioned above imply problems for large- (Dynesius and Nilsson 1994; Gore and Shields 1995) or medium-sized rivers, but are especially critical for small rivers.

The so-called small-sized rivers (5 to 12 m wide), low depth (0.3 to 0.7 m) and wide river beds (8 to 20 m) have slow and structured plug flows. These characteristics result in a slow oxygen transfer from the upper layer to the middle and to the one in contact with bottom sediments. Nutrients from the river basin, from river edges or from rain runoff are introduced into the rivers as part of the natural cycle. These nutrients allow the survival of bacteria and algae that will transform the organic matter into inorganic compounds, integrating them into the trophic cycle. Rivers under the conditions stated above are in equilibrium (Ostroumov, 1999). Anthropogenic activities disturb this equilibrium by continuously discharging wastes into rivers, like domestic and industrial raw wastewater or agricultural non-point sources, producing a decomposition zone, followed by a septic zone, a recovery zone and finally a clean zone. The length of each of these zones depends on the water flow rate, quantity and kind of bacteria (free or attached), nutrient transport and transformation, temperature, oxygen uptake and quality and quantity of anthropogenic contaminants (Barillier and Garnier, 1993; Stoodley et al., 1997; Crump et al., 1999; Burns and Ryder, 2001). Degradation of contaminants is especially slow in small-sized rivers due to low-flow velocity and few free bacteria in the water column. Therefore, the different zones are longer than those in the bigger-sized rivers (Edeline and Lambert 1979; Gantzer et al., 1988).

* To whom all correspondence should be addressed.
☎+52 (614) 414-4492; e-mail: vnevare@uach.mx
Received 19 April 2004; accepted in revised form 6 October 2004.

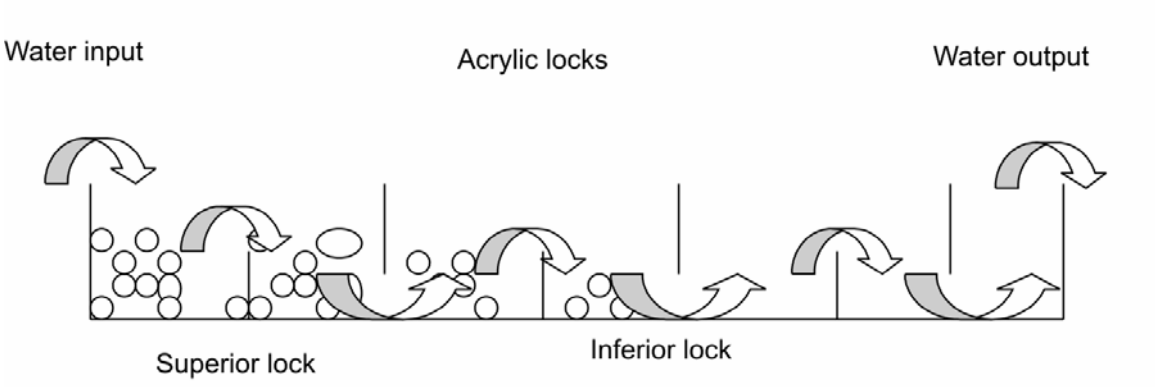

Figure 1
Experimental design treatment for small-sized polluted rivers: Basic design

In this work a structure is proposed to improve the water quality of those rivers that continuously receive wastewater. This structure requires no pumps (utilises the natural flow impulse), is constructed *in situ*, and makes use of the riverine portion along its course and its natural slope to maintain the required water flow. The structure intends, under controlled flow conditions, to promote:

- Homogeneous oxygen and pollutant concentration in the water column
- Reduction of pollutants by attached biofilm growth
- Continuous ejection of bacteria from the system to avoid clogging
- Reduction of pollutants by sessile bacteria downstream.

In order to evaluate a structure with the above-mentioned characteristics, an experimental model was constructed and evaluated under controlled conditions.

Methods

Structure design

To probe the performance of such a structure, an experimental prototype was designed for laboratory tests. The basic design of the experimental structure (Fig. 1) was a trapezoidal-shaped channel, 175 m long, formed by independent sections. These sections were made up of thermoformed plastic, 1.15 m in length, 0.10 m wide at the base, 0.11 m wide at the top, closed at both ends to 0.05 m height (superior locks). Each piece was slotted every 0.1 m to insert removable acrylic locks at various distances. One hundred and fifty sections were joined with two stainless steel clamps per section and sealed with silicon. Two models were constructed to compare different water-flow and pollutant concentration.

The inferior locks or flow barriers were made of acrylic trapezoidal plates, 4 mm thick (105 mm wide at the base, 100 mm height, 115 mm wide at the top), open at the bottom with a rectangular section (100 mm wide, 20 mm height). These plates, combined with the connection of two sections, functioned as inferior and superior locks.

Hydraulic performance

Hydraulic performance of the experimental structure was evaluated using a uniform 0.5% slope and tested for two flows (10 and 15 $\ell \cdot min^{-1}$) under varying conditions:

- With superior locks
- With superior and inferior locks
- With superior and inferior locks with stone

The dispersion produced by the locks was measured with a 50 mℓ high concentration dye discharge, injected at the first section and its dispersion was measured every 15 m. The capacity of the system to continually expel the excess of biomass was evaluated using sludge from a WWTP. The sludge was introduced into the structures and uniformly dispersed into the system. After the sludge was deposited, the inferior locks were introduced into the centre slot of each section. Re-suspension of the sludge was visually evaluated.

Biological performance

To assess the system efficiency for biological removal of contaminants, the structures were evaluated under four different conditions:

- V1C1 V1 = water flow 15 $\ell \cdot min^{-1}$ and C1 = contaminant concentration measured as 50 $mg \cdot \ell^{-1}$ COD
- V1C2 V1 = as stated above and C2 = contaminant concentration measured as 100 $mg \cdot \ell^{-1}$ COD (100% higher related to condition C1)
- V2C1 V2 = water flow 10 $\ell \cdot min^{-1}$ (with 50% reduction related to V1) and C1 = as stated above
- V2C2 V2 = as stated above and C2 = as stated above.

The results reported as COD removal efficiency were established by the differences between the inflow and outflow COD concentrations in each structure. All conditions were evaluated with inferior and superior locks, and with support material. The support material, river stone, for bacterial growth was washed, crushed and screened five times (12 mm diameter). Each set of conditions was monitored for 22 d continuously and the experiments were done in duplicate.

Laboratory techniques

Every 5 d, five stones were taken from a section in the middle portion of the system, then put into a container with 50 mℓ of distilled water. The microbial biomass was detached from the stones by homogenisation and the supernatant was used for biological analysis. From this wash-water, 1 mℓ samples were diluted by decimal serial dilution to a final concentration of $1x10^{-7}$. Microbiological analysis for total aerobic mesophilic micro-organisms (*Standard Methods*, 1975) were done in duplicate using the pour-plate technique and

incubated for 48 to 72 h at 28°C. Results were expressed as log colony forming units per gram of biomass (logCFU·g^{-1} biomass).

Another set of samples was collected every third day from the influent and effluent to measure chemical oxygen demand (COD), total solids (TS) and turbidity (T). COD tests were done by digestion at 150°C for 2 h in a HACH reactor (Mod 45600). Samples were cooled for 2 h to room temperature for stability and COD concentration was measured with a HACH colorimeter (Mod. DR890) and TS was determined by the *Standard Methods* (1975) technique. Turbidity was determined with a portable HACH turbidimeter with a capacity ranging between 0.1 and 400 NTU and 0.1 NTU accuracy. Data were analysed by ANOVA using SAS v8 (SAS, 2003).

Visual evaluation of microbial communities

At the end of the 22 d of continuous operation in each experimental set of conditions, a photographic record of each section was taken and visually examined for the growth of visible different microbial communities. In those sections in which the stone surface was observed, microbial communities were considered scarce; in those where the surface of the support material was completely covered by the microbial mat it was considered as regular microbial growth; and in those sections where the microbial mat of one kind of micro-organism formed blankets that covered more than two stones and edges of each were not visible, the microbial community was considered abundant. Microbial communities were considered as follows: brown-coloured microbial mats were formed mainly of bacteria; white films were mainly formed of filamentous cells resembling algae when observed under the microscope at 40X (Olympus BX 41) and the green-coloured mats were formed mainly of algae.

Results

The hydraulic performance of the structure permitted maximum flows for the slope used before overflow of 27 and 30 ℓ·min^{-1} with and without inferior locks respectively (Table 1). The initial dispersion of the concentrated dye was 80 mm long, and the coloured section was enlarged as the flow travelled trough the structure. At the 175 m mark of the structure's length, the dispersion obtained under the different flows (10 and 15 ℓ·min^{-1}) was 18 and 24 m. When the activated sludge from the WWTP was introduced into the structure, and uniformly dispersed into the system without the inferior locks, the sludge that flowed settled in the bottom of the second half in each section. At this point the inferior locks were introduced into the centre slot of each section and the sludge was uniformly resuspended into the water column and expelled from the structure. This condition was maintained throughout the structure for the water flow (V2=10 ℓ·min^{-1} and V1=15 ℓ·min^{-1}), previously selected. The models achieved total retention times (effective contact) of 138 and 98 min at such water-flow velocities.

Mesophilic aerobic bacterial counts showed a one unit log difference (log CFU·g^{-1} biomass) between pollutant concentrations (50 and 100 mg·ℓ$^{-1}$); however, no significant difference was observed with either, low or high water flow velocity (Fig. 2). Bacterial counts defined a stable bacterial community with a rapid growth in the first three days and uniform counts thereafter.

The COD graph (Fig 3) showed removal rates ranges from 90.27 to 555.2 mg·min^{-1}. It was noticed that the range observed was due to changes in pollutant concentration but not to the water flow velocities used. The results showed that the tendency of COD removal was consistent under all conditions, except for one point in Fig. 3b.

TABLE 1
Hydraulic conditions obtained with 0.5% slope (IL, inferior locks)

Parameter	Flow 10 (ℓ·min^{-1})		Flow 15 (ℓ·min^{-1})	
	With IL	Without IL	With IL	Without IL
Velocity (cm·s^{-1})	2.78	2.85	3.41	3.69
Retention time (min)	113	108	93	85
	Models packed with river stone			
Velocity (cm·s^{-1})	2.26		3.02	
Retention time (min)	131		98	

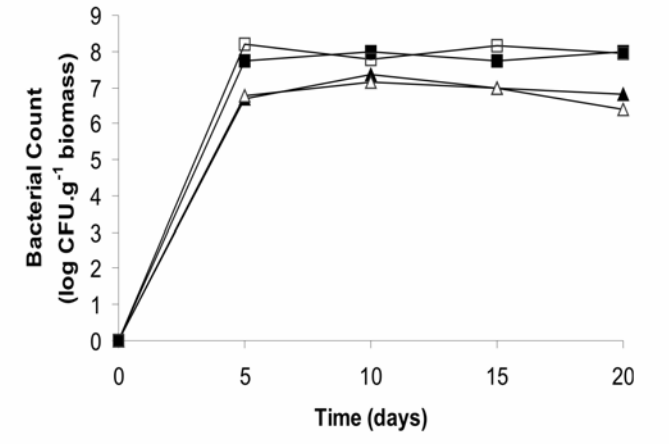

Figure 2
Total mesophilic count of micro-organisms during the complete duration of the experiments. Samples were taken every 5 d from 60th section. ▲ COD concentration of 50 mg·ℓ$^{-1}$ water flow velocity 15 ℓ·min^{-1}; △ COD concentration of 50 mg·ℓ$^{-1}$ water flow velocity 10 ℓ·min^{-1}; ■ COD concentration of 100 mg·ℓ$^{-1}$ water flow velocity 15 ℓ·min^{-1}; □ COD concentration of 100 mg·ℓ$^{-1}$ water flow velocity 10 ℓ·min^{-1}

Total solids (TS) differences between inflow and outflow of the system ranged between 600 and 500 mg·ℓ$^{-1}$ (Fig. 4). Negative numbers indicated that a higher amount of solids were being expelled from the system than those that had been introduced. The TS differences showed a similar behaviour at each pollutant concentration, except for two points under high-water flow velocity and low concentration (Fig. 4a). During the initial stage, the structure could be considered as a biofilter, and later on its performance was related to the amount and activity of the biomass generated and removed from the system.

Turbidity reduction ranged between 10 and 81% in the four different experimental conditions (Fig. 5). Reduction in turbidity increased over time, slowly and consistently under all conditions evaluated.

Microbial communities evaluated at the end of each experimental run, showed a succession of micro-organisms along the structure differentiated visually by their predominance of a brown-coloured bacterial mat, a white floating biofilm with predominance of filamentous cells, and green algae. It is worth mentioning that

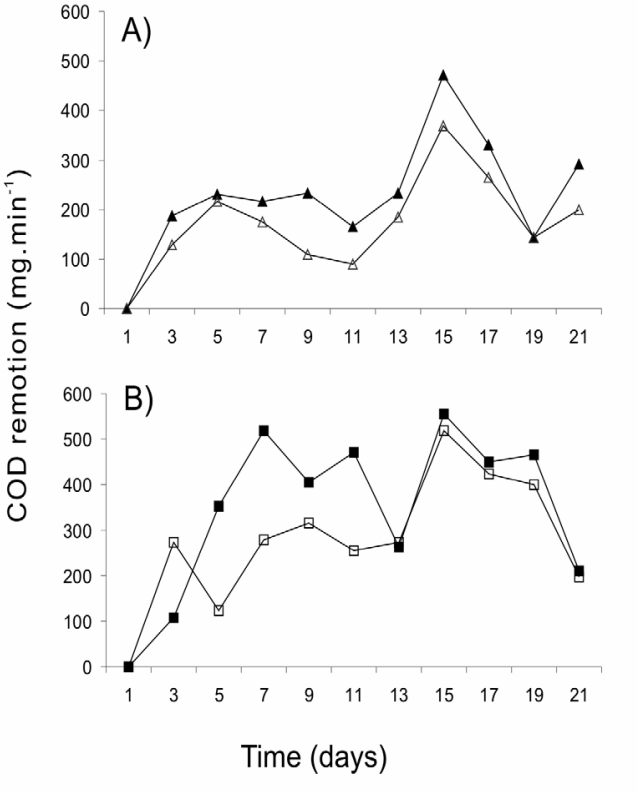

Figure 3

Chemical oxygen demand reduction. Samples were taken every third day. A) low concentration of pollutants; B) high concentration of pollutants. . ▲ COD concentration of 50 mg·ℓ-1 water flow velocity 15 ℓ·min-1; △ COD concentration of 50 mg·ℓ-1 water flow velocity 10 ℓ·min-1; ■ COD concentration of 100 mg·ℓ-1 water flow velocity 15 ℓ·min-1; □ COD concentration of 100 mg·ℓ-1 water flow velocity 10 ℓ·min-1

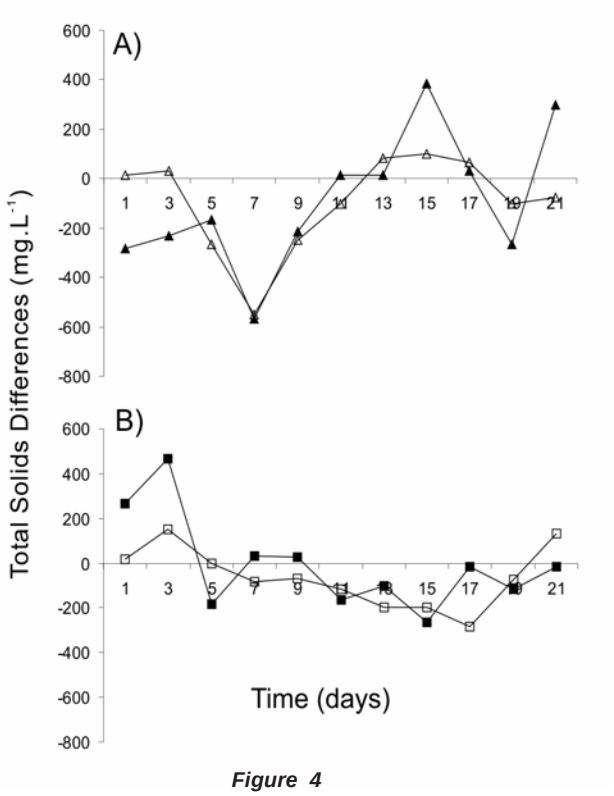

Figure 4

Total solids differences content. Samples were taken every third day. A) low concentration of pollutants; B) high concentration of pollutants. . ▲ COD concentration of 50 mg·ℓ-1 water flow velocity 15 ℓ·min-1; △ COD concentration of 50 mg·ℓ-1 water flow velocity 10 ℓ·min-1; ■ COD concentration of 100 mg·ℓ -1 water flow velocity 15 ℓ·min-1; □ COD concentration of 100 mg·ℓ -1 water flow velocity 10 ℓ·min-1.

velocity greatly influenced the length of the structure that had poor or nil microbial communities, as observed in Fig. 6.

Discussion

The model efficiently handled varying flows under varying conditions and obstacles: superior and inferior locks, with and without river stone. In the typical plug flow of a river, the water column runs stratified in three layers, each one with varying velocities, and the slower velocity being in contact with the bottom sediments (Welch and Lindel, 1992). The DO concentration depended mainly on the atmospheric contact and its uptake by the superior layer (Laenen and Dunnette, 1997). The dynamic exchange between the various layers in the water column depended on the extent of stratification and on the flow velocity. When the oxygen and pollutant concentrations were uniformly distributed, the mineralisation by native bacteria occurred more efficiently (Barillier and Garnier 1993).

The locks designed to break the stratified flow were tested with a high- concentration dye in a single discharge. With each lock, the expected turbulence and velocity modification (Naudasher, 1999) increased the dispersion of the dye, enlarging the area of coloured water. The enlargement of the coloured sections produced, confirmed that stratified flow was altered constantly, thus a uniform concentration of pollutants and oxygen content in the water column was expected. When the activated sludge was injected and left undisturbed for 1h, it settled uniformly after reaching the midpoint in every section of the structure. Therefore, the whirl energy produced by the superior lock was enough to suspend the sludge in the water column and transport it for approximately 600 mm until it settled again. With the insertion of the inferior lock right after the onset of sedimentation, the sludge settled at the bottom was resuspended and ejected from the structure. This behaviour prevents one of the main problems of the self-purification process in nature: the stratified flow and the rapid microbial sedimentation. It also assured that the structure was not clogged during its performance and that the inferior and superior locks operated efficiently, mixing the water column and keeping the pollutants and oxygen concentrations homogeneous.

As a result of the visual inspection, sequential changes were observed along the 175 m, in quality and quantity of the microorganisms present in the structure. These changes were more obvious when the first and last section of the structure in each experiment were compared. For low pollutant concentration conditions (COD 50 mg·ℓ-1), the support material in the first section was totally covered with a typical brown coloured mat. For the same conditions, the last section of the structure showed the water column totally clear and the support material covered with green algae exclusively. For high pollutant concentration conditions (COD 100 mg·ℓ-1), the first section showed a very turbid water column, the support material was totally covered by a film with predominantly algal cells and floating bacterial flocs. For the same conditions, the water column in the last section was totally clear, green algae were present and traces of the white film remained.

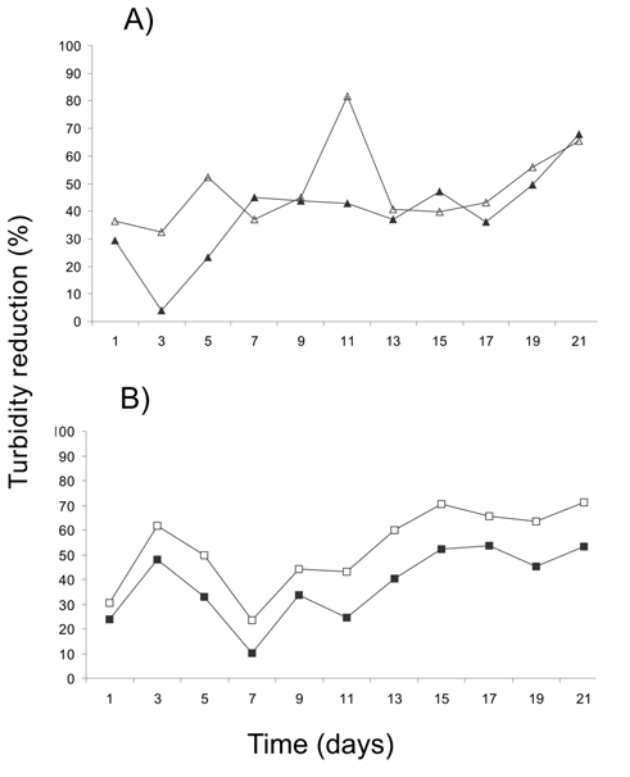

Figure 5

Turbidity reduction. Samples were taken every third day. A) low concentration of pollutants; B) high concentration of pollutants. ▲ COD concentration of 50 mg·ℓ $^{-1}$ $^{-1}$ water flow velocity 15 ℓ·min^{-1}; △ COD concentration of 50 mg·ℓ $^{-1}$ water flow velocity 10 ℓ·min^{-1}; ■ COD concentration of 100 mg·ℓ $^{-1}$ water flow velocity 15 ℓ·min^{-1}; □ COD concentration of 100 mg·ℓ $^{-1}$ water flow velocity 10 ℓ·min^{-1}

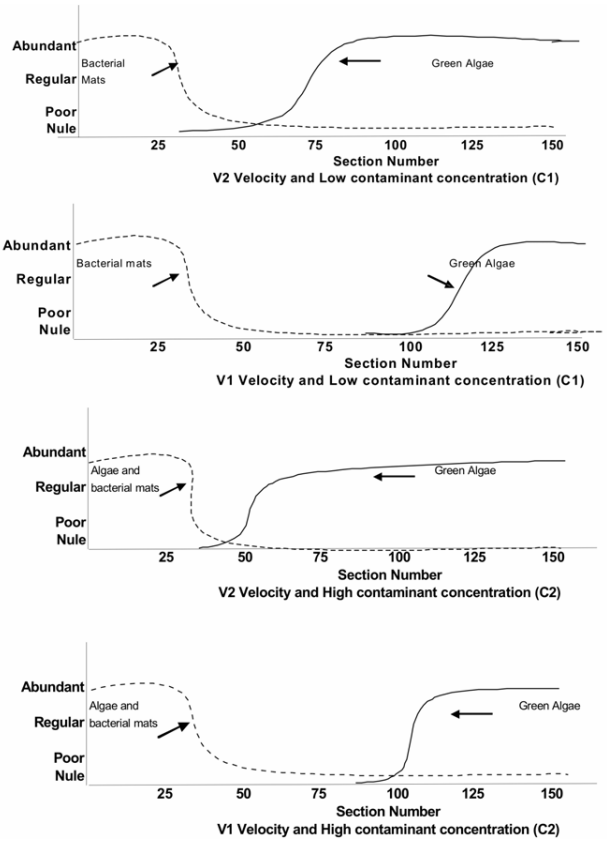

Figure 6

Microbial community succession in the experimental structure as observed by visual inspection

It has been widely reported (Characklis and Trullear, 1982; Srinanthakumar and Amirtharajah, 1983; Fleming, 1993; White, 1995; White, 1998) that attached bacteria in different media are more efficient for the degradation of pollutants than detached bacteria. Besides, attached biofilm promotes the growth of diverse bacterial communities with different metabolic capacities where every species uses its neighbour's metabolic abilities and products (Davey and O'Toole, 2000). Consequently, a support material with enough surface areas to promote biofilm growth, capable of reducing and transforming pollutants, was provided. The structure demonstrated that enhanced compact attached bacterial growth could be obtained without the system being clogged. The community's tendency is toward stabilisation depending on nutrients and oxygen present in the system, showing differences due to pollutant concentration, as expected (Srinanthakumar and Amirtharajah 1983; Brummer et al., 2000).

From the analyses of the four conditions, it can be observed that COD reductions were highly significant for both water flow ($F=12.59$, $p<0.01$) and pollutant concentrations ($F=18.26$, $p<0.01$). However, COD reduction was more influenced by pollutant concentration than by water flow, as can be observed in Fig. 3. Comparing the four conditions, the system was shown to be more efficient under high water flow (15 ℓ·min^{-1}) and high COD (100 mg·ℓ$^{-1}$) conditions. If COD reduction is related to microbiological growth (Fig. 2) the stable microbial conditions are reflected in a stable COD removal (Fig. 3) under every condition.

When TS results of the influent and effluent are analysed, they look erratic; nevertheless, comparing the difference between input and output TS, the results showed a defined behaviour (Fig. 4). This may be attributed to a cycled detachment and expulsion of bacteria from the structure, keeping the biotic system balanced based on nutrient and oxygen availability. The predictable clogging problem in a system with stratified flow was avoided with the locks installed as superior and inferior locks, because the whirls produced promote enough detachment of biofilm.

The experimental design was tested under four different conditions and with a fixed slope. It was shown that the system performed as expected both hydraulically and biologically, under laboratory-controlled conditions. It is recommended to:

- Measure the COD in the effluent after a 15 min period of settling time, to avoid inclusion of the expelled bacteria, in order to obtain an accurate description of the system's efficiency on COD removal.
- Measure the seasonal impact on the microbial community developed in the system, due to the sensitivity of microorganisms to temperature gradients that occur during the year (Pignatello et al. 1985; Gram et al. 1999).
- Study its behaviour using industrial wastewater or agricultural runoff for its efficiency to develop specialised bacteria (Molin 1992).

In addition, other natural processes such as denitrification can be characterised in the system (White 1995; Garcia-Ruiz et al., 1998), under the various conditions of water flow and concentrations that the structure allows.

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