The potential for water hyacinth to improve the quality of Bogota River water in the Muña Reservoir: comparison with the performance of waste stabilization ponds

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Abstract The potential application of Water Hyacinth (Eichhornia crassipes) in organic matter degradation, sedimentation, nutrient and heavy metal absorption and sulfur reduction in the Muña Reservoir has been tested in experimental lagoons. The lagoons were operated at hydraulic retention times (HRT) of 6, 9 and 15 days. One lagoon was covered with Water Hyacinth, which is naturally growing in the Muña Reservoir, while another lagoon was operated as a conventional oxidation pond. The Water Hyacinth lagoon had better removal efficiencies for almost all parameters measured: BOD$_5$, total suspended solids, COD, nitrogen, phosphorus and heavy metals. The oxidation lagoon was facultative for HRT of 9 and 15 days, and anoxic when operated at 6 days HRT. At HRT of 15 days the water quality in the effluent of the covered lagoon corresponded to 12 mg/l of BOD, 6 mg/l of suspended solids and 0.8 mg/l of hydrogen sulfide. Hydrogen sulfide levels in the Muña reservoir can be substantially reduced at HRT higher than 15 days in both lagoons. The uncovered lagoon had better hydrogen sulfide removal during the day but presents high levels at night. If the hydraulic retention time in the Muña reservoir is increased, the water quality of the Bogota river can be substantially improved for all the HRTs tested in the pilot units. HRT seems to give a better prediction of overall effluent water quality than surface loading. More research is needed in order to define the optimum water hyacinth density in the Muña reservoir to determine its influence on the water quality of the effluent. The influence is expected to be negative due to an internal increase of BOD, solids, nutrients and metals loads due to plant decay.

Keywords Constructed lagoons; eutrophication; hydraulic retention time; nutrient removal; organic loading; reservoir management; wastewater treatment; Water Hyacinth

Introduction The Muña Reservoir, 24 km to the south of Bogotá city in Colombia, South America, was built in 1948 for electric energy generation. The reservoir is located in the Andes mountains at 2700 m above sea level, with an average ambient temperature of 16°C all year round. Bogotá River, the main contributor to Muña Reservoir, receives raw sewage and industrial discharges from the City, equivalent to ten million population equivalent of organic load. The presence of high concentrations of heavy metals, organochlorines, organophosphates, hydrocarbons, detergents, oil, greases, chemicals, organic matter and pathogens in Bogotá River and consequently in Muña Reservoir, is of national concern. Muña reservoir discharges return to Bogotá River after electric power generation. The Reservoir has gradually become eutrophic and consequently Water Hyacinth has developed over the last 15 years.

The reservoir has a surface area of 1000 hectares, and potentially the water retention time could be greater than 15 days, however, due to severe hydraulic bypasses, the water retention time in the reservoir is only 4 hours. As a result water quality improvement in the reservoir is also very limited. Improvement of the hydraulic water retention time could substantially increase removal of contaminants in the reservoir.

A 3000 m$^2$ scale model was built in order to study several options to improve water circulation in the reservoir. Tracer studies demonstrated that water retention time could be...
significantly improved by implementing some baffles in the reservoir that would redirect the influent water from the river.

This paper presents the results from a pilot scale lagoon system that was built next to the reservoir and operated at different hydraulic retention times with water from the Bogota River in order to simulate the potential improvement in water quality in the Muña reservoir. The necessity of harvesting the Hyacinth has also been studied.

**Methods**

Two pilot lagoons were constructed and one was operated with a cover of Water Hyacinth, while the other was operated as a conventional oxidation lagoon. Removal efficiencies of parameters like BOD$_5$ (biological oxygen demand), COD (chemical oxygen demand), TSS (total suspended solids), VSS (volatile suspended solids), sulfides, total phosphorus and total nitrogen were measured for different hydraulic retention times. All parameters were analysed according to *Standard Methods*.

The pilot lagoons were constructed such that conditions similar to those of Muña Reservoir were obtained with respect to depth, HRT, bottom sediment characteristics, water quality, temperature, solar radiation, wind speed, and influent water quality. Both lagoons were 12 metres long, 6 metres wide and 2 metres in depth and divided in three compartments connected in series (Figure 1). The water level was kept constant at 1.85 m from the bottom of the lagoon. The effective area of the model was 11.7 m$^2$ x 11.7 m. The bottom area was 8 m x 8 m and the water volume of each lagoon was 92.9 m$^3$.

Water Hyacinth growth was monitored in a Lymnocorral which was placed inside the Muña Reservoir.

Both sections of the pilot lagoon (Figure 2) were operated equally for three different HRT (6, 9 and 15 days) to compare behavior of the Water Hyacinth and oxidation lagoon under different contaminant loads. The retention times were shorter than the theoretically calculated HRT in the Reservoir for an eleven-year period (1987–1998), to guarantee at least the same efficiencies for the Reservoir. During the operation period, the calculated HRT for the reservoir was longer than 20 days for 82% of the time, and longer than 10 days for 97% of the time.

![Figure 1 Schematic diagram of the two pilot lagoons. Numbers 1 to 5 refer to sampling points](https://iwaponline.com/wst/article-pdf/45/1/103/424656/103.pdf)
Table 1 shows the characteristics of the pilot lagoon operation with respect to inflow rate, operation dates and number of days for each HRT condition. Steady-state conditions were obtained for each HRT. Sampling was done for both sections twice a week during the entire operation period for each HRT. Sampling locations can be seen in Figure 1. Once steady-state conditions were reached, for each HRT, an intensive sampling programme was implemented. Parameters analysed included dissolved oxygen concentration, pH and temperature measurements for different depths in the three channels of each lagoon at different times in the day. Grab samples were taken from the water column at different times of the day and analysed for total and soluble BOD₅, sulfides, nitrates, and ammonia. Compound samplings for day and night were done for total and soluble COD, total suspended solids, volatile suspended solids, total phosphorus, total Kjeldahl nitrogen, calcium, magnesium and copper.

The lymnocorral technique by López (1995) was used for measuring growth rate and densities of the Water Hyacinth in Muña Reservoir. The lymnocorral was divided into four sections of 1 m² each and placed in the reservoir. Young and healthy plants were added in
each section to obtain initial densities of 1 kg wet weight/m². The highest densities measured in the Reservoir were 60 kg/m². López (1995) recommended to use plants with 3 to 5 leaves each. Biomass density was assessed at regular intervals by removing all the water hyacinth from each quadrant, removal of excess water and taking the wet weight (Figure 3).

Results and discussion

The biological oxygen demand (BOD₅) entering the pilot lagoons was 64 mg/L, 129 mg/L and 105 mg/L for the hydraulic retention times of 6, 15 and 9 days, respectively. The average surface load was 196, 159 and 216 kg/ha.d, respectively. These loads were in all cases, greater than the average load the Reservoir receives which is 151.4 kg/ha.d. Therefore, it can be expected that Muña reservoir could achieve better removal efficiencies than those obtained in the pilot lagoon.

Water temperature in the lagoons varied within the day but differences were observed between the lagoons. Variations were greater in the uncovered lagoon, which showed a daily range in temperature of 6°C. In the Water Hyacinth lagoon the temperature change within the day was only 1°C. The main consequence of this temperature behavior would be a greater degree of mix in the Hyacinth covered lagoon and a greater degree of thermal stratification in the uncovered lagoon.

The value of pH in the uncovered lagoon during the day was more alkaline than in the Hyacinth lagoon due to the algae photosynthesis which elevated the pH to 7.8–8.5 in the surface water for all the hydraulic retention times. The pH was influenced by photosynthesis only in the first 40 cm of the water column from the surface. During the night pH values descended to less than 7 in the uncovered lagoon. The pH in the Hyacinth lagoon was more constant in its values during the day and averaged 6.5.

High concentrations of dissolved oxygen were measured during the day in the uncovered lagoon during periods of high radiation due to high photosynthesis rates. During the period of 6 day HRT the uncovered lagoon was almost anoxic, with dissolved oxygen concentrations between 1.5 and 2 mg/L. For the retention time periods of 15 and 9 days, dissolved oxygen concentrations were as high as 20 mg/L and 10 mg/L, respectively, in the surface water. Dissolved oxygen was higher than 6 mg/L at 20 cm depth. At night, the oxygen concentrations in both lagoons were less than 1 mg/l for all the HRT tested.

With respect to the effluent quality, the Water Hyacinth covered lagoon achieved better removal efficiencies for almost all parameters. Longer HRT resulted in improved effluent quality of both lagoons for all parameters. BOD₅ removal efficiencies of 90% with effluent BOD₅ of 13 mg/L, were achieved in the covered lagoon at 15 day HRT (Figure 4). For the 9 day HRT, the BOD₅ effluent concentration was 29 mg/L, while at 6 days HRT, BOD₅ concentration in the effluent was 47 mg/L.

Total suspended solids removal was also effective in the covered lagoon. Effluent concentrations of 5.5 and 20.4 mg/L were achieved for hydraulic retention times of 15 and
9 days, respectively. Sulfide concentrations in the effluent of the uncovered lagoon were 0.65, 1.88 and 2.37 mg/L for HRT of 15, 9 and 6 days, respectively. Concentrations in the covered lagoon were higher at 0.90, 3.5 and 4.6 mg/L for HRT of 15, 6 and 9 days, respectively (Figure 5). Sulfide concentrations in the lagoons are of great importance since they define effects associated with bad odors and corrosion in electric generation infrastructure. For HRT of 9 and 15 days, a day-night effect in sulfide concentration occurred in the uncovered lagoon. Sulfides increase at night due to anaerobic conditions and bad odors could occur (data not shown). Although average concentrations of sulfides in the uncovered lagoon were lower than average concentrations in the Hyacinth lagoon, occasional higher values occurred in the uncovered lagoon at night.

Comparison with results from previous studies

Effluent parameters obtained for the water hyacinth pilot lagoon built at Muña Reservoir site were plotted together with results obtained in earlier studies. Figure 6 shows BOD$_5$ effluent concentrations as a function of HRT for primary and secondary effluents. Bogotá river quality can be considered somewhere in between. BOD$_5$ effluent concentration sharply decreases at longer HRT. The results from this study indicate the strong effect that the HRT has on the performance of water hyacinth lagoons. Similar effects were observed for total suspended solids (Figure 7). Total suspended solids concentration in the effluent would be close to 10 mg/L for HRT of 10 days and would diminish with longer retention times. As from HRT 15 days there are marginal improvements in water quality with further increases in retention time.

The relationship between BOD$_5$ effluent concentration and BOD$_5$ surface load is shown in Figure 8. Concentrations are higher at higher loading rate. Considering the average BOD$_5$ load to the Muña Reservoir (150 kg/ha/d) effluent concentrations around 27 mg/L are expected. For this study HRT showed a better correlation with lagoon performance than surface load.

Total phosphorus in the effluent increases as a function of volumetric load of total phosphorus (kg/m$^3$.d). Since the volumetric load is inversely related with HRT, there is also a good correlation with hydraulic retention times (Figure 9).
A good logarithmic correlation (89%) exists between total effluent Kjeldahl nitrogen concentrations and inflow volumetric load for the data from previous studies. However, the results obtained in our study do not confirm this trend (Figure 10). Effluent concentrations measured in the Water Hyacinth pilot lagoon were high considering the inflow volumetric load of 0.01 kg/m$^3$.d. However, the analysis of effluent nitrogen concentrations with respect to HRT (Figure 11), show similar values to those obtained in previous studies. These data seem to confirm that HRT is a better design parameter for water hyacinth lagoons than surface load.

The results presented above were obtained for relatively low densities of water hyacinth in the lagoons. In the Muña reservoir the average of 25 measurements performed indicate an extremely high water hyacinth density of 60 kg/m$^2$. At such high density, growth and death of plants are balanced, and therefore the additional BOD load from decaying water hyacinth biomass would affect negatively the effluent quality from the lagoon.

**Logistic equation for the water hyacinth growth**

The following equation was used to describe the growth of water hyacinth in the Muña reservoir:

$$W_t = \frac{K}{1 + e^{a-rt}}$$

$W_t$ is the density in kg/m$^2$, $K$ is the system’s maximum load capacity, $r$ is the growth rate in days, $t$ is the time in days and $a$ is a constant. The equation was adjusted to biomass data measured in the lymnocorral. Maximum load capacity was considered to be 60 kg/m$^2$ (maximum found in the Reservoir). The constants $r$ and $a$ were obtained, corresponding to the slope and y-axis cut value of the line equation. The correlation was 95%, growth rate was 0.03 days$^{-1}$ and the constant was 3.69. In Figures 12 and 13 the observed and adjusted data for productivity and growth rates are shown.
The fastest growth rates occur close to day 136 and are approximately of 0.43 kg/m².d. The corresponding density is 33 kg/m². The measured maximum growth rate was 0.4 kg/m².d. If the Water Hyacinth was to be harvested totally, harvesting should be done at higher rates than the maximum to be able to eradicate it from the Reservoir. Maximum growth rates for Water Hyacinth of 0.1–0.2 kg/m².d have been found in temperate regions (Dinges, 1982), which are lower than the ones observed in this study. In tropical regions growth rates are expected to be higher because of higher temperatures throughout the year. During rainy periods growth rate might decrease due to reduced radiation.

It is not clear which could be the optimal water hyacinth density for operation of the Muña reservoir. Tchobanoglous et al. (1989) suggest to harvest up to 40% of the lagoon area covered each week during summer. However, whichever density is selected, harvesting the biomass, and disposing of it could prove to be a difficult task. If the biomass is not harvested, subsequent input of BOD, nutrients, and metals, will most likely diminish the improvement in water quality that could be obtained under growth controlled conditions. This is the principal weak point of the project, since water hyacinth harvesting will be extremely difficult.

Conclusions
The following conclusions can be obtained from the results of this study.

- A water hyacinth covered pilot lagoon showed better removal efficiencies for BOD, suspended solids, nitrogen, phosphorus, and heavy metals, when operated at HRT of 5, 9 and 15 days, compared to an uncovered pilot lagoon.
- At HRT of 15 days the water quality in the effluent of the covered lagoon was 12 mg/l of BOD, 6 mg/l of suspended solids and 0.8 mg/l of hydrogen sulfide.
- Hydrogen sulfide levels in the Muña reservoir can be substantially reduced at HRT higher than 15 days in both lagoons. The uncovered lagoon had better hydrogen sulfide removal during the day but presents high levels at night.
- The hydraulic retention time seems to be a better predictor of overall effluent water quality than surface loading.
- More research is needed in order to define the optimum water hyacinth density in the Muña reservoir to predict its influence on the water quality of the effluent. The influence is expected to be negative due to an internal increase of BOD, solids, nutrients and metal loads due to plant decay.

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