J. ENVIRONMENTAL SYSTEMS, Vol. 33(1) 71-86, 2011

A FREE WATER SURFACE CONSTRUCTED WETLAND IN TREATING SUGARCANE WASTEWATER*

DOORCE S. BATUBARA

DONALD DEAN ADRIAN

Louisiana State University, Baton Rouge

ABSTRACT

A free water surface constructed wetland stabilized sugar cane wastewater which had received preliminary treatment. About 568 L/s of sugar cane wastewater flowed through a sedimentation basin, then through a canal toward the 5.2 km^2 wetland which contained eight controlled outlets. Wetland waters were monitored near six of the eight outlets for the 65 days of the grinding season and for an additional 4 months. Wastewater pH entering the wetland was about 5.5 and soon increased to the neutral pH. At the end of the factory operating season 95% of each of the mass of TSS and BOD entering the wetland had been removed and then more TSS and BOD were removed after the factory operation ended. Part of the BOD content was from suspended solids, which were susceptible to being trapped in the wetland vegetation and being removed from the water column by sedimentation.

INTRODUCTION

The term wetlands under the Clean Water Act in EPA Regulations listed at 40 CFR 230.3(t) means "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." Crites, Middlebrooks, and Reed define

*Financial support was provided by Audubon Sugar Institute.

doi: 10.2190/ES.33.1.e
http://baywood.com

wetlands as land where the water table is at (or above) the ground surface long enough to maintain saturated soil conditions and the growth of related vegetation [1]. Natural and constructed wetlands with a complex of saturated substrates, emergent and submergent vegetation, animal life, and water have the ability to purify wastewater. Some of the functions of water plants in the wetland ecosystems [2] are to be major storage sites for carbon and nutrients; to generate large amounts of organic carbon (through photosynthesis); and to conduct gases to and from the sediments. Haberl, Grego, Langergraber, Kadlec, Cicalina, Dias, et al. pointed out that the organic constituents produced as the result of dead plant degradation in wetland can act as an additional carbon source [3].

Not all natural wetlands can serve as part of a wastewater treatment system because of the lack of control at their boundaries. For example, a natural wetland, riparian to a stream which serves as a source for a municipal drinking water supply, is unlikely to be suitable for use in a wastewater treatment system. Perhaps enclosing a portion of a natural wetland by building a dike around it will still preserve its function as a water purification system as well as maintaining its characteristics as natural wetlands [4, 5]. Three types of constructed wetlands are described [3, 6-8] as free water surface (FWS), subsurface flow (SF) and vertical flow (VF). Meanwhile Crites et al. categorize wetlands as natural marshes and constructed wetlands with two types: free water surface (FWS) and subsurface flow (SSF) [1]. Free water surface wetlands where water flows on the top of the wetland is the closest type of wetland to the diked wetland in this study.

A wetland may be appropriate to serve as a means to achieve secondary treatment of wastewater, the minimal level of municipal and industrial treatment required in the United States before discharge to most receiving waters. BOD_5 and TSS concentrations of treated wastewater should be less than 30 mg/L with minimum reduction of 85% [9]. Natural treatment systems have been used widely for wastewater improvement but they are particularly attractive for rural areas in developed countries and for general use in developing countries [10].

The performance of wetlands in treating wastewater depends on the physical, chemical, and biological reactions in the wetland water as well as on and within the soil matrix. Water pH would affect wetland water chemistry and biology. Water pH in wetlands can be increased or lowered due to several mechanisms going on in the wetlands. It should be kept within certain ranges of pH for the microorganisms to thrive because many of the treatment processes in wetlands depend upon microorganisms living on and around the aquatic plants. Microbial biomass is a major sink and repository for some nutrients [2] and organic matter which decomposes is deposited as sediment where it builds up at extremely slow rates.

Vegetated free water surface constructed wetlands produce effluent waters with pH just above neutrality whether the incoming water is acidic or basic [9] but there are exceptions for influent wastewaters containing mineral acids. The Roberts wetland treatment system and the Indian Creek wetland treatment system, reviewed by Witthar [11], are among examples of systems used to treat very acidic water; however the water pH of 3 of acid mine drainage entering the wetlands increases only to above 6 when the water leaves the wetlands. The acid mine drainage may have pH as low as 2 and the net change in pH of water being treated in wetland treatment system between inflow and outflow is typically within two units. Acidity is increased due to the oxidation of ferrous iron to ferric iron and subsequent hydrolyzation to ferric hydroxide and its soluble forms, carbonate and bicarbonate [12].

THE WETLAND SYSTEM

A south Louisiana bottom land hardwood diked natural wetland with eight controlled outlets, as seen in Figure 1, has been utilized as part of a wastewater treatment system for a sugar factory in stabilizing the wastewater. Many emergent and submergent types of plants existed in this wetland. The typical emergent plants in natural wetlands in the United States, bulrushes (*Scirpus*) and cattails (*Typha* sp.) are also present in this wetland; the hardwood type present in this wetland is mangrove. Just a few plants are reported to grow in the wastewater which has high nutrient concentrations and BOD; among these plants are bulrushes and cattail [13]. There were also some floating plants living on this system. The types of major wetland plants that are used in wastewater treatment system can be seen in Table 1.

The area of the diked natural wetland used for the wastewater treatment is 5.2 km^2 and it does not fall exactly into any type of wetlands but it is much closer to free water surface (FWS) type of wetland. The wastewater flowed on the surface of the wetland and was kept in the wetland for several days before discharge through outlets in the dikes to the receiving water close to the system. The sugar factory was operated for 65 days, for 24 hours a day, with about 568 L/s of water used to wash mud and plant debris from sugarcane at the wash table. The authors found that the wash water discharge from the sugar factory as wastewater typically has high BOD and TSS. The wastewater (wash water) flowed to a sedimentation basin first, then through a canal to the diked wetland.

During the cane washing process some sugarcane juice, which is one of the BOD sources, is lost from the cane stalk to the wash water stream. The amount of sucrose in the sugarcane juice lost at the wash table during the washing process may differ from one mill to another mill and from day to day. This variation could be due to how long the sugarcane has been left at the mill before being washed, and also how far the sugarcane field is from the mill; thus, BOD values may also vary from one mill to another. According to UNEP [14] the BOD concentration from sugarcane mills in Louisiana is 81 to 562 mg/L and according to Middlebrooks wash water from sugar mills may have BOD values of 6 to 1190 mg/L [15]. Meanwhile the BOD_5 of the wash water from the sugarcane mill in this study was between 360–876 mg/L. Data reported by Sutherland for

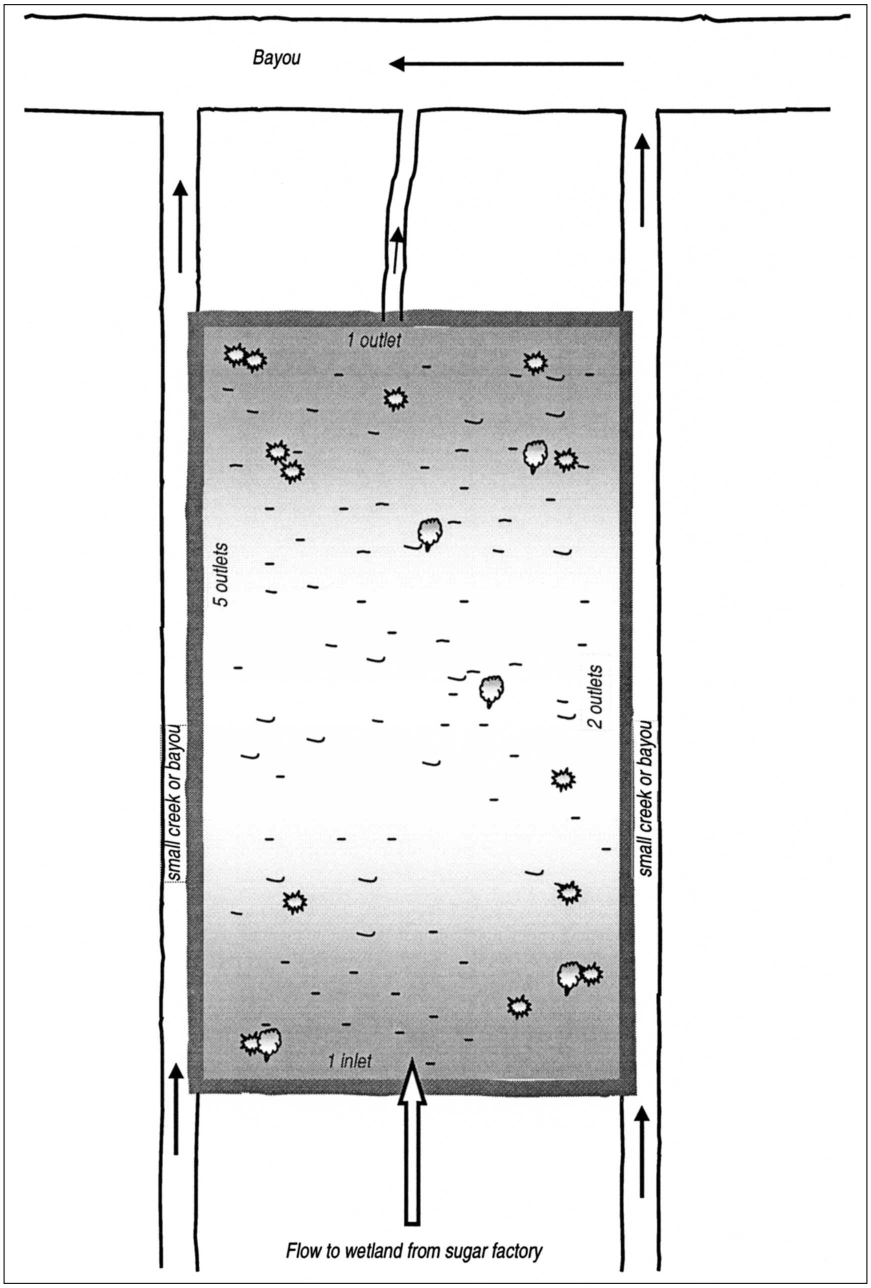

Figure 1. Free water surface constructed wetland for wastewater treatment from a sugarcane factory.

a raw sugar factory in Louisiana which recycled all of its wash water through a treatment system before returning the flow to the wash table showed that the wash water reached a BOD_5 value of 3340 mg/L by the end of the milling season [16].

There is an irregular man-made ditch which directs the wastewater away from the inlet on a path through the interior of the diked wetland toward the middle of one side of the wetland. About 2 weeks after the wastewater discharges to the wetland began, the ditch filled and overflowed to flood other parts of the wetland. The water depth at the end of the grinding season was about 0.40 m to 1.40 m, depending on the topography since the diked wetland bottom is not level. The average depth of the water was about 0.60 m. Wastewater samples were grabbed at the inlet and near the accessible outlet pipes whenever the wastewater was available at the depth of about 0.20 m to 0.50 m. The wastewater was taken to the laboratory for pH, BOD, and TSS measurements. The pH of wastewater was measured as soon as the samples arrived in the laboratory to avoid pH changes due to microbial and chemical activities. The samples for laboratory analyses were carried out according to Standard Methods [17].

The minimal level of municipal and industrial treatment required in the United States before discharge to most surface receiving waters is secondary treatment with BOD_5 and TSS concentrations less than 30 mg/L with minimum reduction of 85% [9]. Evaluation of the grab samples provided data to determine not only whether the system meets the requirements of its discharge permit but also whether it can be improved in treating the wastewater effluent from the sugarcane factory.

REMOVAL MECHANISMS IN WETLAND

Many contaminants from wastewater such as biochemical oxygen demand (BOD), suspended solids (SS), nitrogen, phosphorus, trace metals, and pathogens can be reduced in concentration in wetlands during treatment [18]. The performance of any type of wetland in treating wastewater depends on the physical, chemical, and biological reactions in the wastewater as well as on and within the soil matrix. The quiescent condition in free water surface systems promotes very rapid removal of settleable organic solids in wetlands.

BOD is the most common parameter that is evaluated in stream pollution control where organic loading must be limited to maintain the desired dissolved oxygen levels. In addition, BOD is a useful test that gives the amount of biologically oxidizable organic matter in a wastewater. This test can be used to determine the rates at which oxidation occurs although complete biological oxidation of organic matter theoretically requires infinite time. In many cases of domestic and industrial wastewater, it has been found that the 5-day BOD value is about 70 to 80% of the total BOD [19]. The settled organics (BOD) can undergo either aerobic or anaerobic decomposition, depending on the dissolved oxygen status at the point of deposition [1].

Table 1. Types of Wetland Plants Used for Water Treatment [1]

Types of plants	Names of plants	Notes
Larger trees	Cypress, ash, willow	Often pre-exist on natural bogs, strands, and "domes."
Emergent species	Cattail – *Typha angustifolia* (narrow leaf cattail) – *Typha latifolia* (broad leaf cattail)	Worldwide distributed, optimum pH is 4 to 10, can be permanently inundated at > 0.3 m but can also tolerate drought. Commonly used for FWS and SSF.
	Bulrush – *Scirpus acutus* (hardstem bulrush) – *Scirpus cypernius* (wool grass) – *Scirpus fluviatilis* (river bulrush) – *Scirpus robustus* (alkali bulrush)	Worldwide distributed, optimum pH is 4 to 9, can be permanently inundated—hardstem up to 1 m, but most others 0.15 to 0.3 m, some can tolerate drought.
	Reeds Typical varieties are *Phragmites australis* (common reed)	Worldwide distributed, optimum pH is 2 to 8, can be permanently inundated up to 1 m and also very drought resistant; used very successfully at constructed wetlands in the United States.

	Rushes – *Juncus articulates* (jointed rush) – *Juncus balticus* (Baltic rush) – *Juncus effuses* (soft rush)	Worldwide distributed, optimum pH is 5–7.5, some rushes can tolerate permanent inundation up to 0.3 m but they prefer dry-down periods; rushes are suited well as a peripheral planting for habitat enhancement.
	Sedges – *Carex aquatilis* (water sedge) – *Carex lacustris* (lake sedge) – *Carex stricata* (tussock sedge)	Worldwide distributed, optimum pH is 5–7.5, some types can sustain permanent inundation, others require dry-down period; sedges are suited well as a peripheral planting for habitat enhancement.
Sub-merged species	– *Ceratophyllum demersum* (coontail or hornwart) – *Elodea* (waterweed) – *Potamogeton pectintus* (sage pond weed) – *Potamogeton perfoliatus* (redhead grass) – *Ruppia maritime* (widgeongrass) – *Vallisneria Americana* (wild celery) – *Myriophyllum* spp. (watermilfoil)	These species are worldwide distributed, optimum pH is 6 to 10, can tolerate continuous inundation with the depth of acceptable water being a function of water clarity and turbidity as these plants depend on penetration of sunlight through the water column.
Floating species	– *Lemna* (duckweed)	Occur accidentally in FWS wetlands; the presence can be beneficial (algae is suppressed) and detrimental (the reduction of transfer of atmospheric oxygen at the water surface because of the duckweed mat.

Oxygen dissolved in the wetland water is required in order to hasten the oxidation and the degradation of contaminants in the wetland. Dissolved oxygen in the wetland is supplied through at least three pathways; i.e., atmospheric or natural reaeration (via diffusion), photosynthesis which adds oxygen during algae production, and by leakage to soils or water from macrophyte roots [20]. Wetland plants play an important role in relation to wastewater treatment, especially in transferring oxygen to the rhizomes and roots. According to Brix the metabolism of macrophytes in wetlands such as plant uptake and oxygen release affects the wastewater treatment process [21]. The oxygen release from roots depends on three things: the internal oxygen concentration, the oxygen demand of the surrounding medium, and the permeability of the root walls [22]. As long as there is some demand of oxygen for contaminant assimilation around the roots, the oxygen may be released to the surroundings of the roots. Among the available mechanisms, atmospheric reaeration at the water surface is the major source of oxygen for the FWS wetland [1]. The release of oxygen from plant roots can be neglected [3] compared to the amount of oxygen transferred by atmospheric reaeration. Therefore, dissolved oxygen concentration in wetland waters cannot be used as the only measure for BOD removal since many microbial and chemical activities in wetlands use dissolved oxygen.

RESULTS

The pH of sugar cane wastewater entering the wetland (see Figure 2) was around 5 with one outlier above 11. The relatively low pH at the inlet is likely to be due to microbial activity during the flow of the wastewater to the wetlands. The high pH outlier came from some lime spilled while facilities were being washed at the end of the sugar mill operation season, so the flowrate of wastewater to the wetland was only a small fraction of the flowrate while the mill operated. Extremes in pH can exert stress conditions or kill aquatic life; the most favorable condition for living organisms occurs with a near neutral pH. In biological treatment systems, pH must be controlled within a range favorable to the particular organisms involved; most bacteria can work in the range of $4.0 < pH < 9.5$ [23].

The diked wetland stabilized the wastewater pH in a few weeks to values which fluctuated between 6.5 and 7.5. This pH behavior correlated to the consequences promoted by an aerobic soil being flooded and the water pH being checked before 10 AM. The presence of algae in wetland may change the water pH in a diurnal cycle. During daytime photosynthesis algae in the wetland utilizes carbon dioxide and produces oxygen shifting the carbonate-bicarbonate-carbon dioxide to a higher equilibrium pH. During night time hours algal respiration uses oxygen, produces carbon dioxide, and lowers the pH. However the annual trends in FWS pH reviewed by Kadlec and Wallace are typically quite weak. They reviewed the annual cyclic trend in daily effluent pH from the Titusville, Florida, FWS wetland

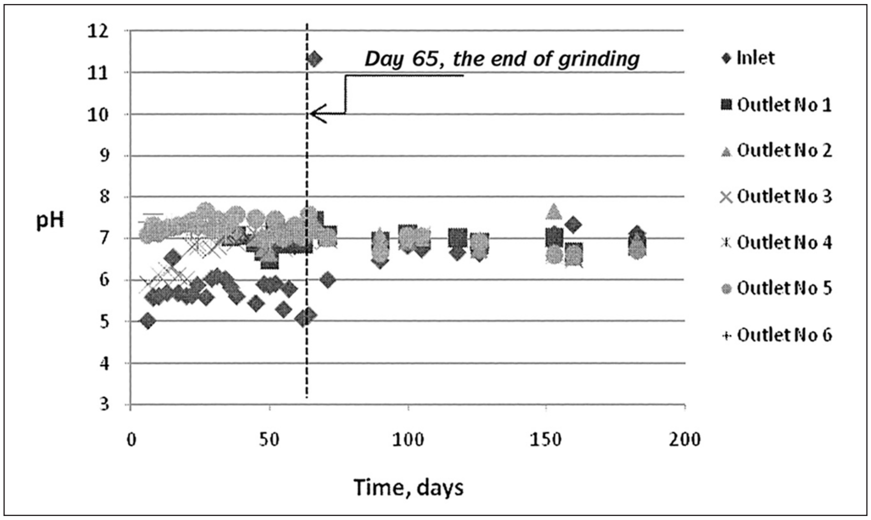

Figure 2. The water pH in the free water surface wetlands at the inlet and close to some outlets.

and reported there is a mid-summer minimum pH but the amplitude of the cycle is only 0.13 pH units [9].

Since the wastewater from the sugarcane factory is not very acidic, the diked wetland can neutralize it quickly. Based on monitoring during this study, algae were not often present which produced small water pH variation in the wetland between night and day. Therefore, this type of wetland to treat sugarcane wash water is excellent in terms of pH stabilization.

BOD_5 of sugarcane wastewater which had received primary settling treatment and then entered the wetland system was in the range of 360 mg/L to 876 mg/L (Figure 3). The high BOD_5 values were typical for wastewater from a sugar factory processing sugarcane harvested mechanically. One high reading for BOD_5 of 3270 mg/L (not shown in the figure) was taken after the day the mill was being washed at the end of the milling season so was associated with a minimal wastewater flowrate to the wetland. BOD in the wetland dropped significantly mostly by settlement during the impounding period of the water. The high BOD_5 value, 140 mg/L, in the wetland during the impoundment period might be due to not enough settlement because of the turbulence of the wastewater. The cumulative BOD_5 which entered the diked wetland was high compared with the remaining BOD_5 at the same time. At the end of the sugarcane factory operation period the accumulated BOD_5 added to the wetland was more than 2,000 tones while on the same day the remaining BOD_5 in the water of the diked wetland was found to be only about 105 tones. Based on these two figures, more than 90%

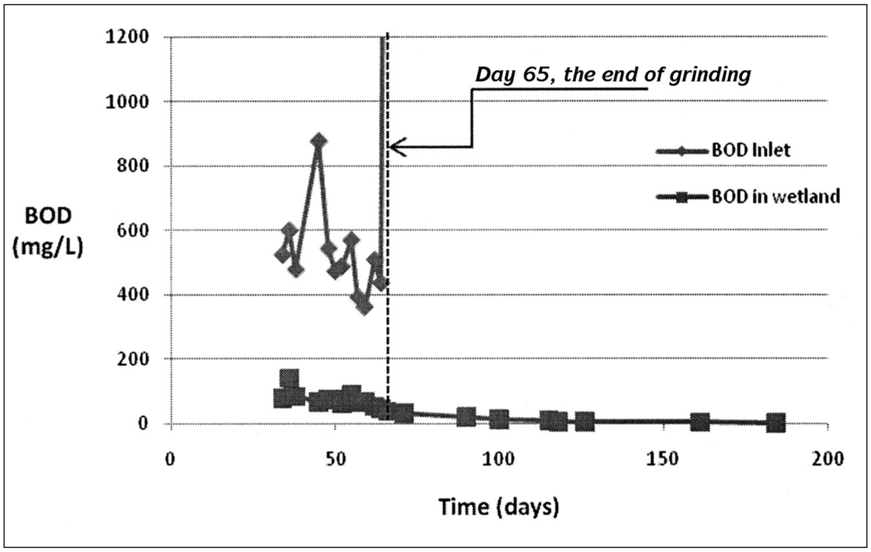

Figure 3. Performance of the free water surface constructed wetlands to remove BOD of sugarcane washwater.

of BOD_5 was removed by the end of the day the mill ceased operation for the season. The water in the wetland was then released slowly to the receiving waters.

BOD_5 concentration in the wetland was 36 mg/L on the last day of the mill operation for the season. Then the BOD_5 concentration in the wetland decreased; about 4 months after the operation ended the wetland BOD_5 concentration reached 1.5 mg/L. This removal was relatively slow compared to the removal during the first 2 months of the operation.

The sugarcane wastewater, which was analyzed weekly, entered the wetland with a TSS concentration around 200 mg/L during the first 2 weeks and then increased to the range of 700 mg/L to almost 900 mg/L in the following weeks (see Figure 4). The solids content of wastewater arriving in the wetlands varied as it depends on how much solids were removed in the settling ponds. There was also a trend of increasing TSS concentration entering the wetland; this might be due to wash water recycling in the factory.

The suspended and volatile suspended solids determinations are also used to evaluate the strength of the wastewater. Suspended solids often contain 80% volatile matter. Solids formerly in suspension are damaging to the life in the water when they settle to form sludge deposits on the bed of the wetland. Furthermore, deposits containing organic materials may deplete bottom oxygen supplies and may produce noxious or undesirable gases such as hydrogen sulfide, carbon dioxide, and methane. The wetland removed about 95% of the suspended solids; most of it by sedimentation.

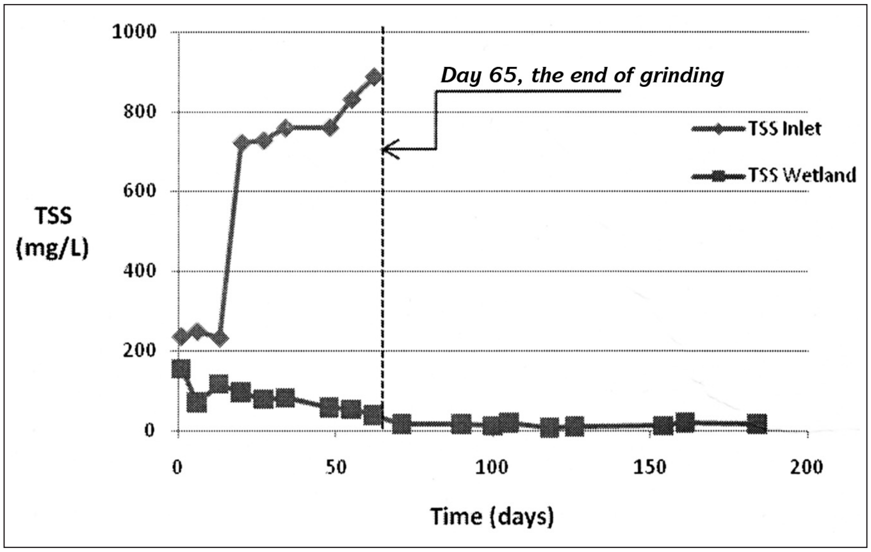

Figure 4. Performance of the free water surface constructed wetland to remove suspended solids of sugarcane washwater.

EVALUATION AND DISCUSSION

The performance of the free water surface constructed wetland system in stabilizing the wastewater pH and reducing BOD and TSS concentrations was excellent. The system was able to produce effluent that met the requirements for discharge to the receiving waters in the United States, i.e., BOD_5 and TSS should be less than 30 mg/L. The seasonal sugarcane factory milling season running from October to December was compatible with the use of this constructed wetland to treat the sugarcane factory wastewater. The diked wetland stored and treated the wastewaters for a short duration, thereby avoiding prolonged flooding which could clog wetland soils and kill the aquatic life in the wetland.

Natural wetlands are effective systems to stabilize the typical wastewater from a sugarcane factory which has pH around 5. This relatively low pH does not affect the function of many wetland plants because many typical wetland plants can stand a wide range of pHs. For example, the optimum pH for bulrushes is 4 to 9 and for cattails is 4 to 10 [1]. Some microorganisms may be sensitive to low pH; however as mentioned in [23] most bacteria can work well in the range of $4.0 < pH < 9.5$. Since the sugarcane wastewater pH entering the wetland fell in this range, microorganisms and wetland plants were still able to perform well in stabilizing the organic matter.

BOD and TSS were removed very rapidly in the wetland despite the low concentration of dissolved oxygen in the wetland waters, which was frequently less than 2 mg/L. It was assumed that most of the oxygen transferred to the wetland was through atmospheric reaeration [1] and was consumed as soon as transferred. Therefore, the biodegradation of organic matter was supposed to be faster in sparse vegetation regions of the wetland which allowed more water area exposed to the atmosphere. Oxygen production through reaeration may exceed respiration in sparse vegetation regions resulting in oxygen surplus but it may not occur in dense vegetation [24]. However, the trend of BOD removal performance was about the same in shaded area or not-shaded areas. The different trend of removal was only between the BOD concentrations present in the wetland. The BOD removal from high concentration wastewater (the first several weeks of flow to the wetland) is more rapid compared to the removal of BOD in low concentration wastewater (after the loading ended). At the end of the sugarcane factory milling season wastewater loading to the wetland, monitoring data showed the BOD and TSS already reached the treatment goal (concentrations for both parameters are 30 mg/L or less).

A small amount of BOD from the wetland plants is contributed to the wetlands. After several months of inundated conditions in the wetlands some plants may die. Some soft tissues of wetland plants decompose very quickly when their emergent portions die back in fall or even in a mild frost. This decomposition results in an increase in BOD [1, 3]. Then whenever dissolved oxygen was available the BOD later was biodegraded by wetland microorganisms. However, BOD in wetlands naturally never reaches zero because of its function in the production of carbonaceous material [3]. As mentioned by Kadlec, in most cases BOD is found in all wetlands having an equilibrium concentration of about 5 mg/L [25].

The following discussion relates to the area of wetland that may be needed in treating wastewater. Determining the size of a wetland involves the wastewater flow rate and hydrology factors which should be considered in wetland systems to maximize microbial access to dissolved organic matter.

The important question in designing a wetland as a treatment system is the amount of wetland area required to achieve a specified BOD_5 or other criterion. Crites et al. suggest the following equation $A_{fws} = (k)(Q)$ to achieve an effluent having less than $BOD_5 = 10$ mg/L, TSS = 10 mg/L, Total N < 10 mg/L (during warm weather), and P > 5 mg/L in a FWS wetland with a depth of 0.3 m, where: A_{fws} = site area for FWS in ha; (k) = factor (4.31×10^{-3}, SI units); and Q = Design flow in m^3/d [1]. The detention time is assumed to be 7 days. Based on this equation and given Q = 568 L/s (49,054 m^3/day), the site area of FWS required is about 211 ha.

The 5.2 km^2 FWS wetland seemed larger than what is required. Given the flow rate of about 49,054 m^3/day the hydraulic loading rate is 1 cm/day; while studies by Wile, Miller, and Black suggested that a hydraulic loading rate of some

2 cm/day and a detention time of seven days will provide maximum treatment efficiencies [26]. The wetland itself has depths which varied from 0.3 to 1.5 m with an average of around 0.6 m. The whole wetland could hold the 65 days of wastewater from the sugarcane mill for several days but when it rained the treated water has to be released, otherwise the water will overflow the dike and may cause it to fail. Sometimes part of the water in the wetland was released due to concern that prolonged flooding may harm some of the wetland plants which may be less flood tolerant even though most of the wetland plants can stand extended flooding conditions. Hydroperiod, the seasonal shift in surface and subsurface water levels, directly affects the stability of particular wetlands [27]. Cattails and bulrushes which are typical of wetland plants can be permanently inundated at the depth of water more than 0.3 m [1]. They can also tolerate drought conditions. These two emergent plants are suggested by Baker and Revel to be used in constructed wetlands in treating wastewater [28]. In addition, cattails and bulrushes are two kinds of the few plants that thrive in high-nutrient and high-BOD wastewater [13]. If detention time in this system could be kept for 7 days then the area needed for the wastewater would be less than half of the available area.

The successful performance related to hydraulic conditions in a wetland refers to how a system can have uniform flow conditions so the wastewater becomes distributed evenly and the wastewater constituents have good contact with organisms responsible for treatment. The wetland treatment system in this study has only one inlet and a ditch to bring the wastewater to the middle of the wetland so that after the ditch fills the water flows to other parts of the wetland. However, the wetland bottom is not even so the wastewater flows first to the deepest parts, then to other parts. One side of the wetland has deeper parts and this side has more outlets than other sides. Wetland plants also play their roles in regulating flow in the wetland: the physical presence of leaves, stems, roots, rhizomes, and detritus helps to slow and regulate water flow [1].

Even though this free water surface constructed wetland system had good performance in stabilizing the wastewater from a sugar factory, soil clogging should be one consideration in order to avoid un-optimal uses of the wastewater treatment system. Having wastewater well distributed in the wetland can avoid clogging. If the system were to be used throughout the whole year, distribution of water can be achieved by having some inlets distributed around the wetland, or having some parallel cells to let the water flow in parallel. However, this idea increases the costs of the wetland, besides it is not practical to have more than one inlet. Thus, having one inlet may not be a problem with this free water surface wetland that is used only in a relatively short time during the whole year when the sugarcane factory is operating.

This type of wetland that falls in the FWS wetland category is usually self-maintaining if biomass is created quickly enough to fixate metal concentrates in sediments. Dike maintenance is required in this type of wetland treatment system to ensure the dike is strong enough to hold the water and can be used as an access route to monitor the system. Harvesting the emergent wetland plants to remove some nutrients permanently from the wetland may be done also because the emergent plants in the wetland also take up nutrients and other wastewater constituents. However, the major purpose of emergent wetland plant harvesting is to have enough surface for transferring oxygen through the atmosphere to the wetland, not removing nutrients. As reviewed by Crites et al., harvesting of the plant material from a constructed wetland provides a minor nitrogen removal pathway as compared to biological activity in the wetland [1]. In addition, aged plants need to be removed from the wetlands as they are lower in utilizing the sunshine as a source of energy in photosynthesis process.

CONCLUSION

1. BOD and TSS of the sugarcane wastewater were removed significantly from the wastewater in the free water surface wetland.
2. BOD and TSS were removed effectively as they were added to the free water surface constructed wetland. About 95% removal of the total accumulative loading of each of these parameters was achieved at the end of the grinding season.
3. Removal performance tends to be higher in higher concentration.

ACKNOWLEDGMENT

The authors acknowledge Paul Cancienne, Patrick Cancienne, and Freddie Martin for their support in this research project.

REFERENCES

1. R. W. Crites, E. J. Middlebrooks, and S. E. Reed, *Natural Wastewater Treatment Systems,* CRC Press Taylor & Francis, Boca Raton, Florida, 552 pp., 2006.
2. R. G. Wetzel, Constructed Wetlands: Scientific Foundations are Critical, in *Constructed Wetlands for Water Quality Improvement*, G. A. Moshiri et al. (eds.), Lewis Publishers Inc., Chelsea, Michigan, pp. 3-7, 1993.
3. R. Haberl, S. Grego, G. Langergraber, R. H. Kadlec, A. R. Cicalini, S. M. Dias, J. M. Novais, S. Aubert, A. Gerth, H. Thomas, and A. Hebner, Constructed Wetlands for the Treatment of Organic Pollutants, *Journal of Soils and Sediments, 3*:2, pp. 109-124, 2003. doi: 10.1007/BF02991077
4. C. D. Martin, G. A. Moshiri, and C. C. Miller, Mitigation of Landfill Leachate Incorporating In-Series Constructed Wetlands of a Closed-Loop Design, in *Constructed Wetlands for Water Quality Improvement*, G. A. Moshiri et al. (eds.), Lewis Publishers Inc., Chelsea, Michigan, pp. 473-476, 1993.
5. R. K. Bastian and D. A. Hammer, The Use of Constructed Wetlands for Wastewater Treatment and Recycling, in *Constructed Wetlands for Water Quality*

Improvement, G. A. Moshiri et al. (eds.), Lewis Publishers Inc., Chelsea, Michigan, pp. 59-74, 1993.
6. H. Brix, T. Koottatep, and C. H. Laugesen, Wastewater Treatment in Tsunami Affected Areas of Thailand by Constructed Wetlands, *Water Science and Technology, 56*:3, pp. 69-74, 2007. doi: 10.2166/wst.2007.528
7. A. Ghermandi, D. Bixio, and C. Thoeye, The Role of Free Water Surface Constructed Wetlands as Polishing Step in Municipal Wastewater Reclamation and Reuse, *Science of the Total Environment, 380*:1-3, pp. 247-258, 2007. doi: 10.1016/j.scitotenv.2006.12.038
8. P. Gui, R. Inamori, M. Matsumura, and Y. Inamori, Evaluation of Constructed Wetlands by Wastewater Purification Ability and Greenhouse Gas Emissions, *Water Science and Technology, 56*:3, pp. 49-55, 2007. doi: 10.2166/wst.2007.517
9. R. H. Kadlec and S. Wallace, *Treatment Wetlands* (2nd Edition), CRC Press Taylor & Francis, Boca Raton, Florida, 1016 pp., 2009.
10. A. P. Kruzic and S. K. Liehr, Natural Treatment and Onsite Systems, *Water Environment Research, 80*:10, pp. 1206-1224, 2008. doi: 10.2175/106143008X328608
11. S. R. Witthar, Wetland Water Treatment Systems, in *Constructed Wetlands for Water Quality Improvement*, G. A. Moshiri et al. (eds.), Lewis Publishers Inc., Chelsea, Michigan, pp. 147-156, 1993.
12. J. T. Watson, S. C. Reed, R. H. Kadlec, R. L. Knight, and A. E. Whitehouse, Performance Expectations and Loading Rates for Constructed Wetlands, in *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*, D. A. Hammer (ed.), Lewis Publishers. Chelsea, Michigan, pp. 319-351, 1989.
13. W. J. Mitsch and J. G. Gosselink, *Wetlands* (4th Edition), John Wiley & Sons, Inc., Hoboken, New Jersey, 582 pp., 2007.
14. UNEP, *Environmental Aspect of the Sugar Industry—An Overview,* Industry and Environment Office, United Nations Environment Programme, 1982.
15. E. J. Middlebrooks, Sugar Refining, *Industrial Pollution Control*, John Wiley and Sons Inc., New York, pp. 133-177, 1979.
16. C. W. Sutherland, *pH Control and Odor Problems Associated with Sugar Mill Wash Water,* MS thesis, Louisiana State University, Baton Rouge, Louisiana (unpublished), 1992.
17. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, *Standard Methods for the Examination of Water and Wastewater* (18th Edition), 1989.
18. J. T. Watson, S. C. Reed, R. H. Kadlec, R. L. Knight, and A. E. Whitehouse, Performance Expectations and Loading Rates for Constructed Wetlands, in *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*, Donald A. Hammer (ed.), Lewis Publishers Inc., Chelsea, Michigan, pp. 319-351, 1989.
19. C. N. Sawyer and P. L. McCarty, *Chemistry for Environmental Engineering* (4th Edition), McGraw-Hill, New York, 658 pp., 1994.
20. K. K. Moorhead and K. R. Reedy, Carbon and Nitrogen Transformations in Wastewater during Treatment with Hydrocotyle umbellate L, *Botany, 37*, pp. 153-161, 1990.
21. H. Brix, Do Macrophytes Play a Role in Constructed Treatment Wetlands? *Water Science and Technology, 35*:5, pp. 11-17, 1997. doi: 10.1016/S0273-1223(97)00047-4

22. H. Brix, Macrophyte-Mediated Oxygen Transfer in Wetlands: Transport Mechanisms and Rates, in *Constructed Wetlands for Water Quality Improvement*, G. A. Moshiri et al. (eds.), Lewis Publishers Inc., Chelsea, Michigan, pp. 391-398, 1993.
23. L. Metcalf and H. P. Eddy, *Wastewater Engineering: Collection, Treatment, Disposal*, McGraw-Hill, New York, 782 pp., 1972.
24. C. D. Sculthorpe, *The Biology of Aquatic Vascular Plants*, E. Arnold, London, 610 pp., 1985.
25. R. H. Kadlec, Wetlands for Water Polishing: Free Water Surface Wetlands, in *Global Wetlands: Old World and New*, W. J. Mitsch (ed.), Elsevier, Amsterdam, Netherlands, pp. 335-349, 1994.
26. I. Wile, G. Miller, and S. Black, Design and Use of Artificial Wetlands, in *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*, P. J. Godfrey, et al. (eds.), Van Nostrand Reinhold, New York, pp. 26-37, 1985.
27. M. Scholz, *Wetland Systems to Control Urban Runoff*, Elsevier, Amsterdam, Netherlands, 333 pp., 2006.
28. J. G. Baker and R. D. Revel, Vegetation Establishment in an Urban Constructed Wetland: Result from a Canadian Pilot Project, in *Wetlands and Remediation: An International Conference*, J. F. Means and R. E. Hinchee (eds.), Battelle Press, Columbus, Ohio, pp. 59-66, 1999.

Direct reprint requests to:

Donald Dean Adrian
Louisiana State University
3513 E.
Patrick F. Taylor Hall
Baton Rouge, LA 70803
e-mail: dadrian@lsu.edu