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Implementation of a Best Management Practice (BMP) System for a Clay Mining Facility in Taiwan

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The present paper describes the planning and implementation of a best management practice (BMP) system for a clay mining facility in Northern Taiwan. It is a challenge to plan and design BMPs for mitigating the impact of clay mining operations due to the fact that clay mining drainage typically contains very high concentrations of suspended solids (SS), Fe-ions, and $[H^+]$ concentrations. In the present study, a field monitoring effort was conducted to collect data for runoff quality and quantity from a clay mining area in Northern Taiwan. A BMP system including holding ponds connected in series was designed and implemented and its pollutant removal performance was assessed. The assessment was based on mass balance computations and an analysis of the relationship between BMP design parameters such as pond depth, detention time, surface loading rate, etc. and the pollutant removal efficiency. Field sampling results showed that the surface-loading rate is exponential related to the removing rate. The results provide the basis for a more comprehensive and efficient BMP implementation plan for clay mining operations.

Key Words: Best management practices; Holding ponds; Surface loading rate; Clay mining drainage.

INTRODUCTION

The Masu River watershed lies at the northeast corner of Taiwan (Fig. 1). The upper half of the river drains relatively undeveloped lands, which includes

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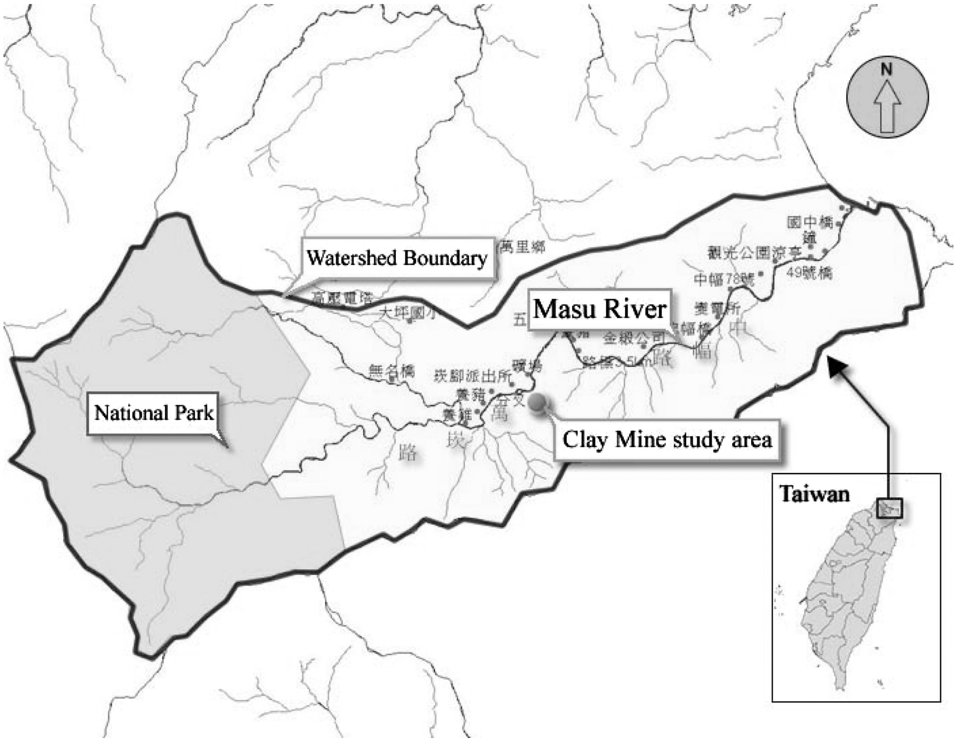

Figure 1: The Masu river watershed and the clay mine study area.

a national park. The lower half of the river is impacted by wastewater and stormwater runoff from a clay mining operation; a number of hog and chicken farms, and a few villages and towns. The Masu River has a drainage area of 29 square kilometers and is a major drinking water source for people living in the watershed. Water quality in the Masu River is generally good. However, there is concern regarding the untreated wastewater and runoff during storm events from the clay mine operation, which might cause the deterioration of water quality and lead to damage to the ecosystem.

The clay mine is a 32-hectare operation with a maximum wastewater flow of 0.3 cubic meters per day (CMD), which is held in holding ponds below the mining areas. During storm events, runoff from the mining site is collected and discharged into the Masu River. Part of the runoff flows through a series of sediment traps and the balance flows through the same holding ponds for the wastewater before entering the Masu River.

Constructed wetlands have for some years been used in the United States for treating mining wastewater containing trace metals.[1] A number of literature studies have examined the basic mechanisms of pollutant removal.[2] Because mining wastewater normally contains a high level of solids, the main mechanism for removing trace metals is gravitational settling, with vegetative uptake and intercept also contributing to the overall removal.[3]

Reports published by the US EPA indicated that an ALD (anoxic limestone drain) could be used to increase the pH value and to improve the rate of precipitation of iron.[4] Dissolved iron could be removed through oxidation, but it could also lead to the liberation of iron from iron hydroxide to achieve a stable and balanced system.[5]

However, little research was done to examine the use of only the holding ponds to remove dissolved iron. Although some studies[6] pointed out that alkaline materials released by plants could cause the precipitation of metal-oxides, such literature studies are still scarce. Other researches indicated[7,8] that the pH value and the alkalinity of water have a very strong influence on the creation and precipitation of iron hydroxide. The increased export of alkalinity from soil as a result of heavy rainfall could also affect the efficiency of treatment.[9] Manyin et al.[10] reported that concentrations of F_e-ions in BMP treated effluent correlated positively with that of the influent and flow rate, while the effluent pH value correlated negatively with influent iron concentration and flow rate.

Manyin further suggested that under variable pH-value situations, the influent surface area-loading rate be used as the main BMP design parameter for mining operations. Tarutis et al.[11] also suggested that BMP removal efficiency is related to the surface area of the BMP. In Taiwan, mining operations are few, but clay mining is still of significant. It is therefore important to examine the use of BMPs such as ponds and constructed wetlands for treating clay mine drainage in order to mitigate its impact on receiving waters.

The main objective of the present study is to (i) develop and implement an inflow and outflow mass balance model to predict the BMP efficiency, (ii) monitor the application of such a model, (iii) discuss the results and BMP design implications, and (iv) develop a pollution control plan for the clay mining operation.

MATERIALS AND METHODS

Background Water Quality Sampling

Sampling and Analyses. Background water quality samples were taken at the mining site during both dry and wet weather. Dry weather samples were taken on 3/20/2003 at the eight sampling locations shown in Figure 2, and on 3/27/2003 at sampling point No. 2 and No. 6. The results show that pH and suspended solids (SS) are of concern, with values of 3.0 and 97 mg/L, respectively.

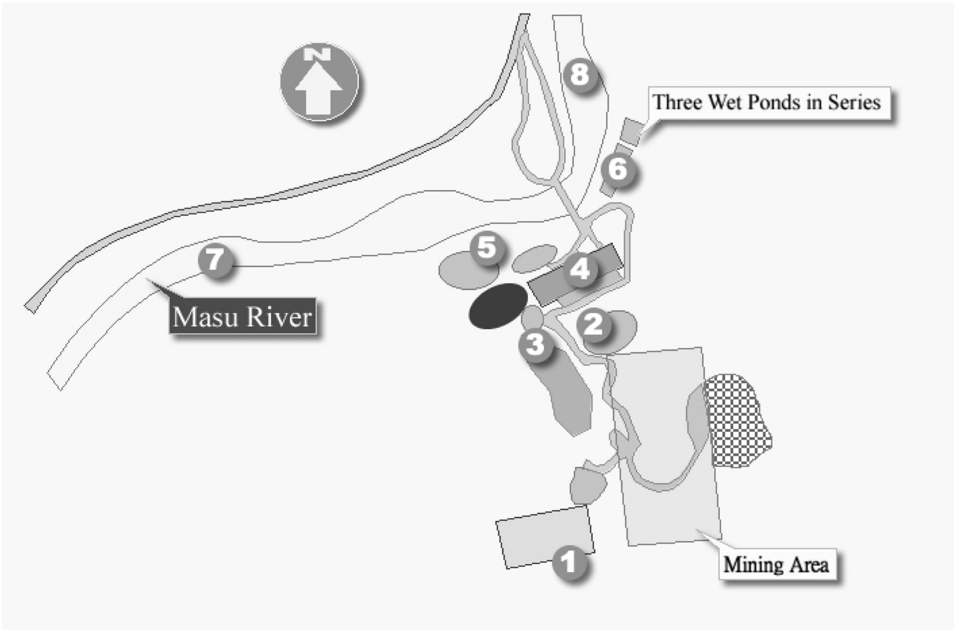

Figure 2: Short-term BMP placement plan and baseline sampling locations.

Wet weather samples were taken on 4/3/2003 and 4/26/2003 at sampling point No. 6, which represents the inflow stormwater runoff water quality at the holding pond. Results for 4/3/2003 are given in Table 1. Similar results were obtained for the 4/26/2003 storm. The results in Table 1 show that SS concentrations during storm events cab be exceedingly high (>20,000 mg/L). This indicates a severe erosion problem for the mining site. Although some of the sediment loads are removed by the sediment traps and holding ponds, a substantial amount would be discharged into the Masu River. The higher

Table 1: Stormwater runoff sampling results (4/3/03).

Time	pH	TSS (mg/L)	Time	pH	TSS (mg/L)
05:31	6.4	922	09:31	4.9	868
05:51	6.1	1,980	10:01	5.5	1,360
06:11	6.2	1,940	10:31	5.2	362
06:31	6.3	2,100	11:31	6.5	3,380
06:51	4.9	862	12:31	6.5	2,000
07:11	6.2	2,890	13:31	6.5	10,100
07:31	5.3	1,320	14:31	5.3	714
08:01	6.2	1,100	15:31	4.9	188
08:31	6.4	2,320	16:31	4.9	384
09:01	6.3	24,100	17:31	5.0	1,060
Average	pH = 5.8;	TSS = 2997.5 mg/L			

pH values observed during storm events might be the result of dilution effects associated with larger volumes of water

Pollution Control Strategy

Characteristics of the Clay Mine Drainage. Mine wastewater is the main source of pollution during dry weather. During wet weather, the disturbed areas and the clay storage areas become potentially major sources of pollution as a result of erosion, chemical reaction and washoff processes induced by stormwater runoff.[12,13] According to studies done in the United States,[14] mine drainage typically would contain high levels of acidity and metal ions, which poses a significant threat to the receiving waters. An example[15] of the chemical reaction between iron and water to cause elevated levels of acidity is shown below in Eq. (1).

$$4FeS_2 + 15Fe^{3+} + 14H_2O \rightarrow 4Fe\left(OH\right)_{3(s)\downarrow} + 8H_2SO_4 \tag{1}$$

Planning and Implementation of Control Measures. The dry and wet weather sampling results suggested that the main concern for potential water quality impact on the Masu River is the high sediment loads during storm events and to a lesser extent, the acidity problem. The research team proposed a short-term and a long-term solution for mitigating the impact of the mining operation on the Masu River water quality.

Short-Term Pollution Control Strategy

A short-term pollution control strategy was devised, which called for the use of the existing control practices and making modifications to them so the pollutant removal efficiency of these existing facilities would be enhanced. The facilities in question are the three holding ponds in series located at the exit point from the mining site to the Masu River, indicated as Point #6 in Figure 2. The modifications made to the ponds included the following:

(i) The first pond is modified to have a shallow sediment forebay with an average water depth of 2.5 m. The pond is trapezoidal in shape with a length to width ratio of 3.5 to 1 and a total volume of 493 cubic meters. Emergent wetland plants are placed at the inlet point and floating lotus and hyacinth are placed in the pond. Coral rocks are also used to increase the pH value.

(ii) The second pond is made into a deeper pond with an average water depth of 1.0 m. The pond is roughly rectangular in shape with a length to width ratio of 2 to 1, and a volume of 172 cubic meters. Two gabions filled with small rocks, each 1.2 m thick and 1.7 m tall, are placed across the pond width so that the pond is divided into three compartments. The gabions

Table 2: Design parameters for the modified pond system.

	Function	Area (m^2)	Depth (m)	Volume (m^3)	Hydraulic residence time (hrs)
First Pond	Sedimentation/Vegetative Uptake/pH Adjustment	207	2.50	493	4
Second Pond	Filtration/Vegetative Uptake	172	1.00	172	1.5
Third Pond	Filtering/Vegetative Uptake	360	0.05–1.50	262	2

would reduce the flow velocity and therefore enhance the detention time. They also provide some pollutant removal by acting as filters. Emergent wetland plants are planted at the top of the gabions to provide water quality benefits.

(iii) The third pond is modified so that the first half of the pond bottom is transformed into zigzagged shallow grassed ditches. Runoff water would first flow through the ditches and then enter the pond, which has an average water depth of 1.5 m. The grassed swale has a length of about 20 m and a depth of 0.5 m. The pond has a length to width ratio of 3 to 1 and a volume of 262 cubic meters. Both emergent and floating plants are placed in the pond.

The modifications are listed in Table 2. A schematic of the pond treatment train system is shown in Figure 3. These modifications provided a significant increase in the total storage volume for the pond system and a longer hydraulic residence time. With the addition of the gabion filter, the coral rock and the various vegetation the system was expected to have higher pollutant removal efficiency than the existing ponds and help mitigate the water quality impact of the mine drainage on the Masu Creek.

Long-Term Pollution Control Strategy

The long-term pollution control strategy for the clay mine operation involves the use of various BMPs placed at strategic locations, some of them in series, in order to achieve a high degree of treatment of the wastewater as well as stormwater runoff from the site. The placement of various BMPs is shown in Figure 4.

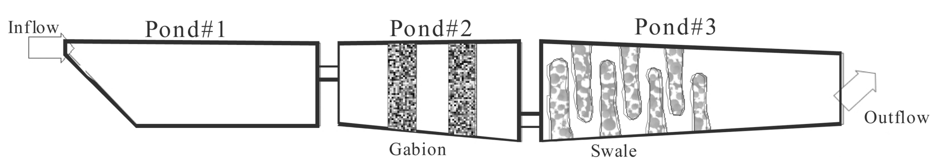

Figure 3: Plan view of the three-pond treatment train system.

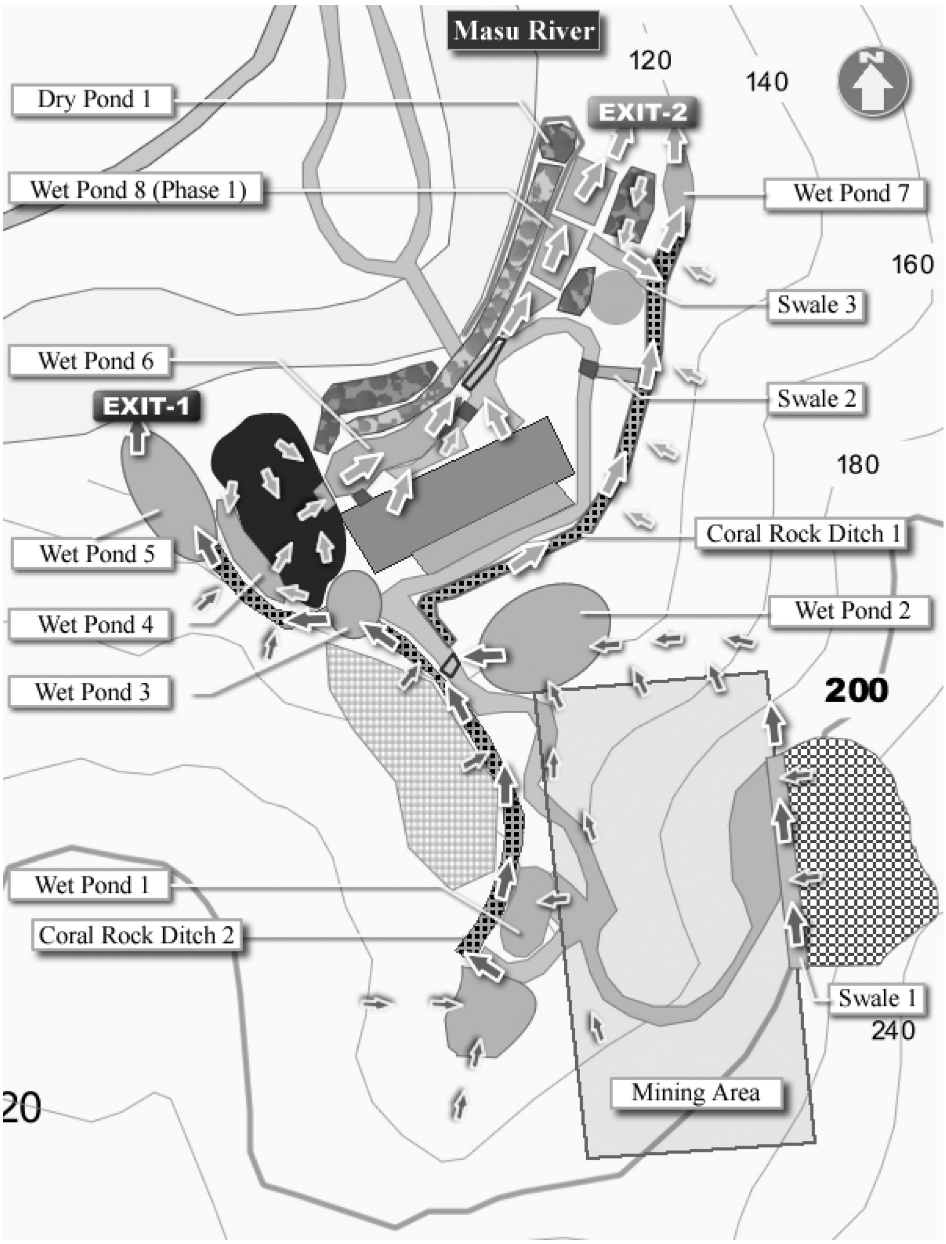

Figure 4: Long-term BMP placement plan.

Moldeling Analysis of the Pond Treatment Train System

A time-varying, one-dimensional formulation, based on mass balance and plug-flow principles, was used to describe the pollutant fate and transport through the holding pond system.[16] The longitudinal, unsteady-state mass balance equation for pollutant transport is described in the following equation:

$$\frac{\partial C}{\partial t}\Delta V = (QC)|_x - (QC)|_{x+\Delta x} + kC\Delta V \tag{2}$$

Under steady-state assumptions, $\partial C/\partial t = 0$, Eq. (2) can be solved to obtain:

$$\frac{C_o}{C_i} = e^{-k\cdot\left(\frac{A\cdot D}{Q}\right)} \tag{3}$$

where C_i is inflow concentration, C_o is outflow concentration, Q is flow rate, V is pond volume, t is time, x is distance along the pond length, and k is the reaction coefficient, A is surface area of pond, D is depth of pond.

BMP pollutant removal efficiency is frequently calculated based on comparing the inflow and outflow event mean concentrations, i.e., removal $= (C_i - C_o)/C_i \times 100$. However, an approach that incorporates a BMP design parameter into the computation of the removal efficiency is also widely used.[1,11,17] The theoretical basis for such an approach is the classical particle-settling algorithm, which relates the removal to the "surface-loading rate," or $L_s = |\Delta C| \cdot Q/A$. For a constant Q, $\Delta C(= C_{x+\Delta x} - C_x)$ is the change of pollutant concentration over a BMP with surface area A.

Substituting Q/A with (L_s/delta C) into the mass balance Eq. (3) we obtain:

$$\frac{C_o}{C_i} = e^{-\left(\frac{K_a\cdot\Delta C}{L_s}\right)} \tag{4}$$

in which $k_a = kD$ is the area reaction coefficient.

Equation (4) can be used to estimate BMP pollutant removal efficiency. With data on pollutant concentrations and when Q, V, k_a, D are fixed, a relationship between the surface loading rate L_s and the percentage removal rate $\delta(\%)$ can be established:

$$\delta = 1 - e^{-\left(\frac{K_a\cdot\Delta C}{L_s}\right)} \tag{5}$$

However, due to the limit of self-purification processes, the concentration of pollutants in constructed wetlands would not keep decreasing with time but will approach a fixed value.[18,19] The fixed value could be viewed as the background concentration value in the holding ponds. If the background concentration is defined as C^* and f is defined as in Eq. (6), then substituting Eq. (4) into Eq. (6) will result in Eq. (7) as the relationship describing the fate of a pollutant in the pond system.

$$\frac{C_o - C^*}{C_i - C^*} = f \cdot \frac{C_o}{C_i} \tag{6}$$

$$\frac{C_o - C^*}{C_i - C^*} = f \cdot e^{-\frac{K_a\cdot\Delta C}{L_s}} \tag{7}$$

Table 3: The minimum, maximum, mean and standard deviation (S.D.) of pollutant concentrations at influent points of the detention pond system.

	Influent concentration (mg/L)			
	Min	Max	Mean	S.D.
Pond 1				
TSS	12.50	1084.50	212.37	310.63
total Fe	0.34	24.92	3.93	5.47
(H+)	1.17E-04	2.95E-07	2.49E-05	3.41E-05
Pond 2				
TSS	4.00	59.00	13.20	16.60
total Fe	0.10	7.33	1.53	1.90
(H+)	4.79E-07	3.16E-04	6.34E-05	8.40E-05
Pond 3				
TSS	6.00	37.00	8.51	10.52
total Fe	ND	7.75	2.05	2.37
(H+)	2.29E-04	3.16E-07	7.76E-05	8.72E-05

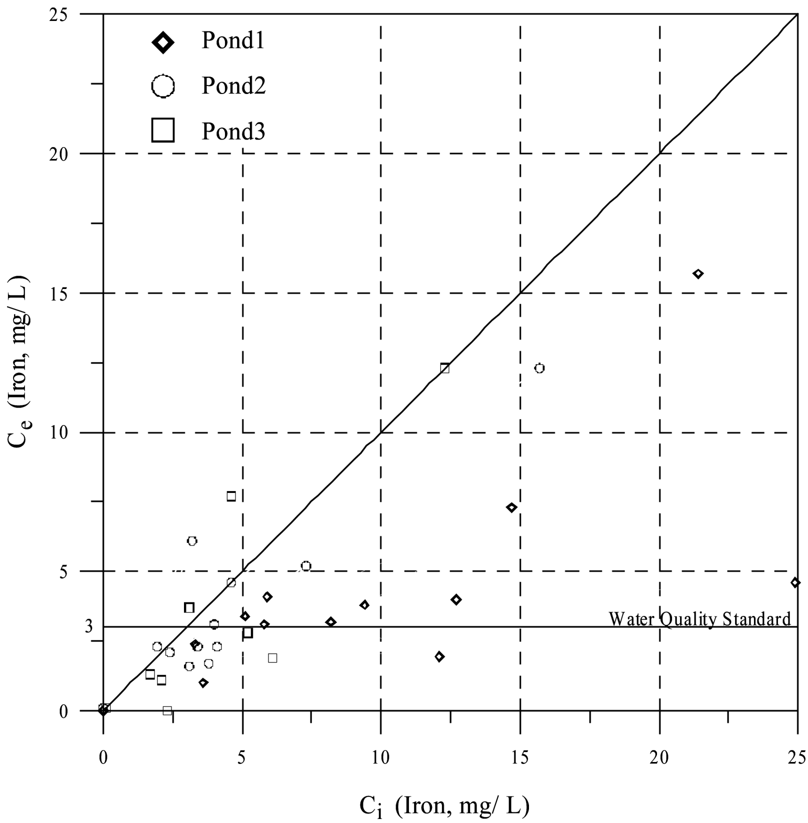

Figure 5: Inflow vs. outflow iron concentrations for the 3-pond system.

RESULTS AND DISCUSSION

The short-term strategy was implemented in 2003. A monitoring program of the completed system was initiated in 2003 and continued into summer of 2004 to collect the necessary data for evaluating the performance of the BMP system. A total of 12 sets of samples were taken at the entry and exit points of the holding pond system. Parameters analyzed include F_e-ion, SS and pH value. The results showed a wide range of values for the influents into the three ponds. The maximum, minimum, mean value and standard deviation of the observed parameters are listed in Table 3. Most suspended solids data tend to be very high.

Figures 5 and 6 illustrate the relationship between the inflow and outflow Fe-ion and suspended solids concentrations, respectively, obtained from the field data. These data can be used to estimate the overall pollutant removal efficiency of the three-pond system. The results and some observations are summarized below:

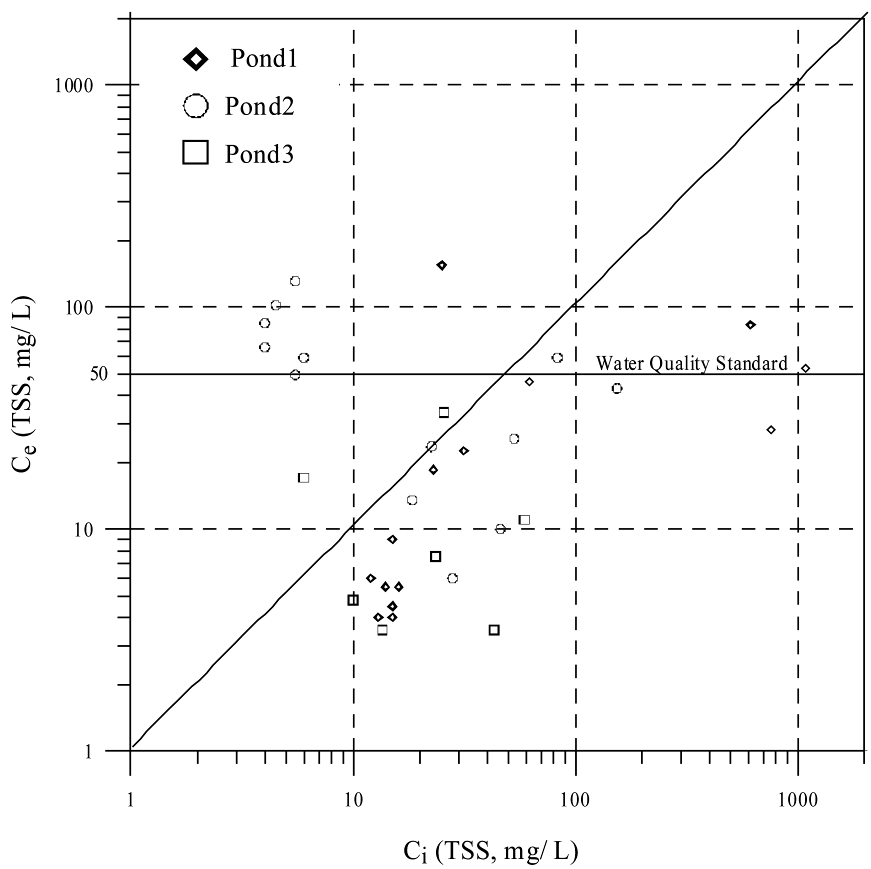

Figure 6: Inflow vs. outflow TSS concentrations for the 3-pond system.

(i) Referring to Figure 6, for Pond #1, all twelve events show positive pollutant removal. For suspended solids, the removal rate ranged from 10% to more than 96%, with an average efficiency of 70%.

(ii) It is interesting to note that, when influent SS concentration is 500 mg/L or more, the removal rate averaged 92%. However, for the group of data with influent SS concentration less than 60 mg/L, the removal rate drops to an average of 48%.

(iii) For Pond #2, seven events showed positive and five showed negative SS removal, indicating possible resuspension of sediment. The overall average when the negatives are taken as zero gave a 30% efficiency.

(iv) For Pond #3, only eight data points were obtained, of which two showed negative and one zero efficiency. The five positive data points ranged from 55% to 84%, with an overall aggregate average of 18%.

(v) The data showed an overall SS removal efficiency of 83% for the three-pond system. A higher overall removal was obtained for the F_e-ion (Fig. 5).

CONCLUSIONS

The Taiwan clay mine drainage contained high levels of pollutant that could adversely impact the river downstream. A pollution control strategy based on the use of various BMPs was devised for the clay mine. A short-term strategy, which involves the use of three existing holding ponds in series, was implemented t the mine site. Results obtained at the pond system show very significant removal of suspended solids, but not as good the increase in pH values. Analysis also showed that using the surface-loading rate as the design parameter was an appropriate approach.

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