Scientific Research and Essays Vol. 6(28), pp. 6001-6022, 23 November, 2011
Available online at http://www.academicjournals.org/SRE
DOI: 10.5897/SRE11.1605
ISSN 1992-2248 ©2011 Academic Journals

Full Length Research Paper

Proposed design of anaerobic wetland system for treatment of mining waste water at former tin mining catchment

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Accepted 18 October, 2011

This research provides an approach for designing a constructed wetland system for treatment of tin contaminated wastewater from mining catchment. Initially, physico-chemical characteristics and concentration of heavy metals in the soil and ponds were evaluated. It was found that the soil and water quality of the area is highly degraded. This study will help for the design of the wetland for wastewater treatment. Design of wetland was mostly based on the review of scientific literature, theoretical modelling and verification of performance via a pilot system. The wetland system comprises of three compartments in series: an 'inflow' pond receiving untreated tailings water overflowing into a wetland compartment which in turn overflows into an 'outflow' pond receiving the now treated water. Waterproof baffles in each wetland compartment serve to increase the flow path of the water, thereby increasing the potential for sulphate retention. On site a computer connected to the pumps regulates the flow of tailings water through the systems. The wetland compartment of each system is filled with approximately 50 cm depth of a mixture of the cattle manure as (25%) and municipal waste compost (75%) as substrate. This mixture has good permeability with optimal growth of plants. Additionally 30 tonnes of limestone will be deposited at the far end of the wetland to facilitate final pH adjustment if it should be required. At the bottom of the inflow and outflow ponds in each system, a layer of about 25 cm of a 1:6 mixture of cattle manure and municipal compost is deposited to provide a substrate for the invertebrate species that spontaneously inhabit the systems. The planting density chosen is based on similar research on constructed wetlands. Proposed anaerobic wetland is first of its kind introduced for mining waste water treatment in Malaysia.

Key words: Water quality, heavy metals, soil, water, constructed wetland, wastewater treatment, anaerobic system.

INTRODUCTION

Wetlands are defined as having a water table above or at the soil surface for a significant proportion of the year which is a determining factor in their make-up of the ecosystem, an emergent vegetation characteristic of wet biotopes (often containing a large proportion of helophytes) and a soil characteristic of wet biotopes (anoxic, chemically reduced) (Mitch and Gosselink, 1986). In treatment wetlands, contaminated water flows through soil, where biological and physical reactions remove contaminants (Kadlec and Alvord, 1989). Traditionally, treatment wetlands have been used to remove organic and inorganic pollutants from wastewater (Brovelli et al., 2010), so most research pertaining to pollutant removal has been concerned with the biodegredation of organic and inorganic compounds. A wetland is a more or less engineered system, designed to enhance the interaction between vegetation, fauna, soils and microorganisms for the primary purpose of pollutant removal from agricultural wastewaters (for example parlour washings), runoff (for example field, road, farmyard) or sewage (Hammer, 1992; USDA et al.,

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1995a, b; US EPA, 2000; CRAPL, 2007; Carty et al., 2008a). In wetland systems, water flows vertically or/and horizontally through a porous substrate (for example gravel, sand) planted with macrophytes. Normally wetlands are composed of one or more shallow, several cells of variable depth and characteristics, (depths 30 to 40 cm) through the vegetation, made of submerged, emergent or floating-leaved plants which is designed to receive and treat contaminated surface water runoff from mining lakes and ponds, in such a manner that any discharge from the wetland will not pollute the water environment" (Carty et al., 2008b; Scottish Government, 2008b). Wetlands are attractive as an endpoint in the rehabilitation of mine wastes such as tailings and tailings water for two reasons. First, pollutants originating from mining activities such as metals and sulphur are relatively immobile when present under waterlogged conditions (Gambrell, 1994). Secondly, pollutants are retained by the wetlands from water passing through the wetlands (Hammer, 1989; Dunbabin and Bowmer, 1992). Both characteristics are largely due to the same processes. Permanently waterlogged wetland soils are generally anaerobic because of the relatively low diffusion rate of oxygen through water compared to air. In addition, micro-organisms present in such soils respire using terminal electron acceptors other than oxygen. Such organisms can, for example reduce ferric iron to its ferrous form or reduce sulphate to sulphide. The formation of highly insoluble sulphide from soluble sulphate in particular is important. Not only does that process lead to the precipitation of sulphur, but also co-precipitation of metals including iron, zinc, lead and cadmium. Once metal sulphides have precipitated, they are stable and insoluble providing the soil remains anaerobic (McIntire and Edenborn, 1990; Dvorak et al., 1992). Wetlands can therefore be used in several aspects of rehabilitation of mine wastes. Firstly, mine tailings can be revegetated under wetland conditions using wetland plants, and secondly, the quality of water originating from mining operations can be improved by passing it through wetlands, whether they are naturally-occurring or constructed specifically for that purpose (Hammer, 1989).

Constructed wetlands have several advantages if properly designed (Hammer, 1992; USDA et al., 1995a, b; Cooper et al., 1996; Cronk, 1996; Kadlec and Knight, 1996; IWA, 2000; Braskerud, 2002a, b; Mason, 2002; Poe et al., 2003; Carty et al., 2008a, b): they can provide high and consistent level of treatment for nutrients, pathogens and hydrocarbons, contribute to runoff and flood management if built large enough, act as long-term carbon stores, are easy to manage, require little maintenance and energy use and are cheaper than alternative methods for farm runoff disposal. They minimize odours produced by agricultural wastes due to their dense plant cover and shallow surface flow, are aesthetically pleasing if designed in a sensible manner, bring additional value to farmland and enhance habitat and biodiversity. They can be used as contingency measures against accidental spillages, for irrigation if large enough and they reduce the need for dirty water storage, decrease land area needed for application and allow better timing of land spreading. Constructed wetlands have some limitations: their construction requires relatively large areas in comparison with conventional treatment systems and they can be costly and in the long-term and may be reduced when pollutants enter rapidly and in large amounts, and they require a minimum of water to maintain ecosystem function (USDA et al., 1995b; Kadlec, 1999; US EPA, 2000). Moreover, the creation and mismanagement of wetlands may alter existing wetlands or local hydrology, for example creating a pathway between the farm and water body where it was previously inexistent can introduce invasive species, disrupt and intoxicate plant and animal communities (Verhoeven et al., 1990; SEPA and Pond Action, 2000; US EPA, 2000; Bruyère and Questel, 2001; Johansson et al., 2004; Van de Weg et al., 2008). Wetlands performance varies strongly spatially and temporally, and wetlands may act as sinks or sources of contaminants depending on their age, location, design, wastewater characteristics, loadings, retention time, hydrological conditions, season, biological activity and management (IWA, 2000; Woltemade, 2000; Dunne et al., 2005a; Scholz and Lee, 2005).

Vegetation in wetlands (*Phragmites australis, Typha latifolia* or *Scirpus* spp.) has overall positive impact on treatment efficiency: it stabilizes the surface of the wetland, reduces flow velocity and facilitates sedimentation, takes up nutrients from sediment and stores them in green parts or other organs (roots, tubers), adsorbs metals, provides fixation sites for microorganisms, conducts oxygen to sediment, produces aerobic conditions which enhance nitrification, and provides wildlife with habitat and food (Mitchell and Williams, 1982; Brix, 1994; IWA, 2000; Lambers and Colmer, 2005). Plant nutrient uptake is not the major pathway for N and P removal but can contribute 16 to 75% removal of total nitrogen and 12 to 73% removal of total phosphorus (Reddy and DeBusk, 1987). An appropriate plant selection can improve wetland efficiency: plants should be native, perennial and highly productive for rapid nutrient uptake, produce rhizome or storage organs, and be tolerant to high pollutant loads and anaerobic conditions (Langergraber, 2004). However, dying plants and accumulation of debris might increase BOD, decrease dissolved oxygen or release nutrients and affect treatment performance (Langergraber, 2004). Vegetation removal can be a way to export nutrients from the wetland, but it is costly, time-consuming and may disturb wetland function and decrease efficiency (Mason, 2002). Heavy metals (for example from oil spillages, mining) may be removed or stored by sedimentation, adsorption to plants and sediment, plant uptake, biological assimilation, decomposition, chemical transformation and volatilisation, these processes being mainly influenced by temperature, pH, redox potential and availability of adsorption sites (Sinicrope et al., 1992; Eger, 1994; Crites et al., 1997; Mitsch and Wise, 1998; Walker and Hurl, 2002).

The variability in the design, use and performance of wetlands, and the lack of detailed studies investigating simultaneously the hydrology, ecology and economics of individual systems justifies the necessity to explore the efficiency, limitations and sustainability of the particular design used in Malaysia until now.

Wetland plants for vegetation of mine tailings

In Malaysia the approach for revegetation of mine tailings has not yet been applied, but has been proposed for the Bestari Jaya catchment. Malaysia has a net precipitation level greater than the evapotranspiration level, therefore the supply of water for the establishment of wetlands should not pose a problem. However, characteristically, data shows that mine tailings have low nutrient content and high concentrations of potentially toxic metals and sulphur compounds, both of which can be problematic for the successful establishment of plants. Nutrient supply to the plants can be improved by adding fertiliser. Alternatively, plants that have low nutrient re- quirements can be used. The latter solution is more attractive as it reduces the cost of the reclamation process. In addition, plants that are used for revegetation purposes can survive higher metal concentrations than plants that are not accustomed to such conditions. Beining and Otte (1996) observed that the amphibious floating sweet grass (*Glyceria fluitans*) was growing very well on tailings in a pond near the abandoned lead–zinc mine at Glendalough, Co. Wicklow. This was the first time that this species was reported to grow under such conditions and a study was initiated to investigate whether the species was suitable for revegetation purposes (McCabe, 1998). Some results have been published already (McCabe and Otte, 1997), while other data are intended for publication (McCabe et al., 1997).

Filtering of metals from contaminated water passing through a 'volunteer' wetland

Wetlands can also be used for quality improvement of contaminated water (Brix and Schierup, 1989; Hammer, 1989). Biogeochemical and physical processes, as well as uptake by plants lead to reduced concentrations of contaminants including nitrogen, phosphorus and metals as the water passes through the wetlands. Naturally occurring, so-called 'volunteer' wetlands, as well as constructed wetlands can be used for the treatment of polluted water. Many studies have shown the effectiveness of such systems in reducing concentrations of contaminants in water, but the question still remains as to how the system itself and its longevity are affected by the accumulation of toxic substances (Walski, 1993). If treatment wetlands deteriorate within a relatively short period of time (10 to 20 years) then this approach would not be attractive for municipal and industrial purposes. Most constructed treatment wetlands are younger than fifteen years and, therefore, have not been active long enough for an accurate assessment of the impact of accumulation of pollutants on their longevity. Natural, volunteer wetlands may have been receiving pollutants for a much longer period of time.

A key objective of this feasibility study was to design a treatment system that would be inexpensive in terms of both initial installation costs and long-term operating and maintenance costs.

Study area

Bestari Jaya catchment is located at 3°, 24' 40.41" N and 101° 24' 56.23" E. It is a part of Kuala Selangor district, located in Selangor, biggest state of the country. District Kuala Selangor has three main towns namely: Mukim Batang Berjuntai, Mukim Ulu Tinggi and Mukim Tg.karang. Bestari Jaya is located in Mukim Batang Berjuntai. Tin mining activities has ceased from the last ten years, now sand mining. The catchment has a total of 442 small and big mining lakes and ponds (Figure 1). Bestari Jaya has a tropical, humid climate with very little variations in temperature throughout the year. The average temperature of the area is 32°C during day and 23°C at night (Ashraf et al., 2010). The Bestari Jaya catchment is strongly impacted by mining pollution which affects Selangor River as mining water flows freely without treatment to the river via small connecting River Ayer Hitam. The protection of the River Selangor is a high priority due to its high ecological value and economic importance, in particular for drinking purposes and fishing which represents a significant local source of income and employment. In order to address mining pollution in the Bestari Jaya Catchment, the construction of wetlands was suggested and promoted by the writer.

MATERIALS AND METHODS

Sampling

A total of 92 hectors of downstream part of the catchment were sampled, starting from north-eastern side of catchment to Sungai Ayer Hitam that meets Sungai Selangor at the Jalan Timur Tambahan road junction. Water samples were taken from two ex-mining ponds at the junction of Sungai Ayer Hitam and at the junction of Sungai Selangor and soil samples were taken at the embankment of the river and ponds and the area nearby. Global positioning system (GPS) was used to determine the actual coordinates of the sampling sites and to reconfirm the location of the sampling site during subsequent sampling periods. Soil and water investigation consists of ten locations, in order to determine

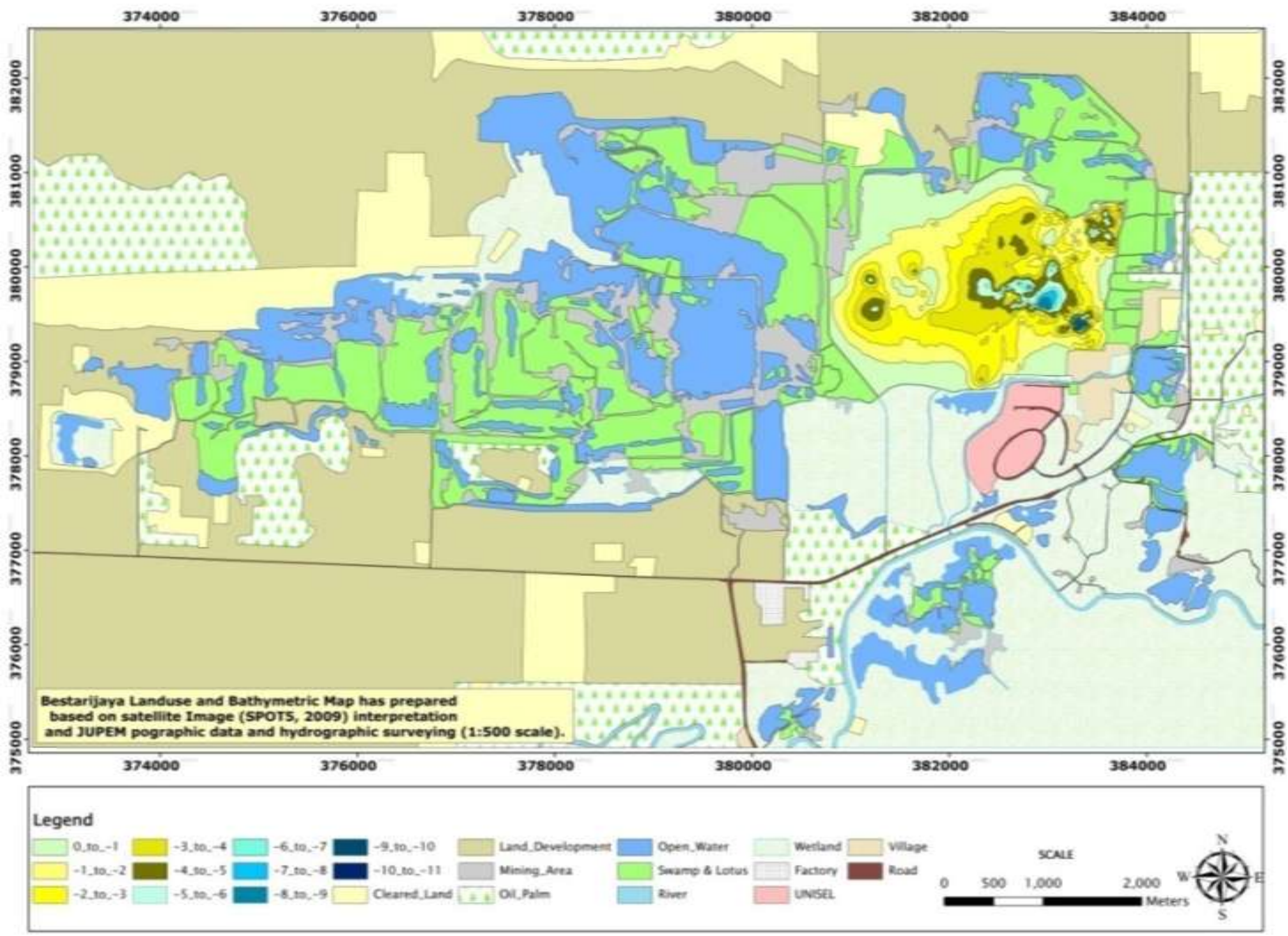


Figure 1. Bestari Jaya catchment showing selected ponds (Yellow) for wetland development.

and to provide ground information for subsequent detailed planning of the future work. For soil sampling, multiple sub samples were taken from each location and then samples were homogenized into composite sample with stainless spoon and then sub sampled by spoon into each sample container to get accurate results. For *ex-situ* analysis, soil samples were collected from first 20 cm of the soil in polythene bags and water samples were collected 10 cm below the surface water using HDPE bottle 500 ml (APHA, 1998). The water samples were preserved by few drops of nitric acid (70%) and stored in an icebox and transported to laboratory for analysis.

Water investigation

Two ponds P1 and P2 at downstream of the catchment investigated for physio-chemical parameters and heavy metals analysis. Physio-chemical parameters were analysed by instrument Hydro lab HACH MS5 while colour of water is measured by true colour units (TCU). For quantitative estimation of heavy metals, samples were digested by acid digestion method (ASTM D 5198-09) and analyzed by atomic absorption spectrophotometer.

Soil investigation

Soil physico-chemical parameters measured were soil texture, temperature, hydraulic conductivity, moisture content, soil pH and soil grain size. Texture is determined by Bouyoucos method (Bouyoucos, 1936), soil temperature by soil thermometer, hydraulic conductivity by (ASTM D5084 – 03) method, moisture content by gravimetric method, soil pH was measured by potentiometrically (Duddridge and Wianwright, 1981) and Soil grain size was measured by ASTM D422 method. For estimation of heavy metals, the samples were air dried, crushed in a mortar pestle and sieved up to 0.5 mm mesh sieve and then digested by wet digestion method and analysed by a Perkin Elmer Analyst 800 atomic absorption spectrophotometer.

RESULTS AND DISCUSSION

Water quality parameters for 15 sampling stations are shown in Tables 1 and 2. Results show that there is variation in water quality at all sampling stations. Water

Table 1. Construction materials quantities and estimated costs for the Bestari Jaya wetland.

Material	Quantity/duration	Estimated cost RM
Pulverised fuel ash PFA	614 t	10000
Cattle manure[a]	60 t	2000
Municipal waste compost	49 t	2000
Lime stone	31 t	3000
Pea gravel	11 t	1000
Broken stone	10 t	1000
Pipe working/building material	-	5000
Top soil	64 t	5000
Design engineering/consultation	6 months	8000
Plant hire and operation	7 weeks	20000
Total		57000 RM

[a]The cost solely for transport.

quality parameters of sampling station WS15 are: colour 9 TCU, temperature 32.51°C, pH 5, conductivity 1756 µmhos/cm, salinity 0.30%, turbidity 0.22 NTU, dissolved oxygen 6.82 mg/L, total dissolved solids 2998 mg/L while at WS1 (Junction of Sungai Ayer Hitam and Sungai Selangor) water quality parameters are: colour 5 TCU, temperature 32.19°C, pH 6.47, conductivity 1640 µmhos/cm, salinity 0.26%, turbidity 0.12 mg/L dissolved oxygen 6.59 mg/L and total dissolved solids 2654 mg/L. This shows that variation trends at all sampling stations are from upstream to downstream. Possible factors involved in this variation may include formation of wetlands, palm oil plantation and the dilution factor of water. Acidic pH and low DO is the characteristic of peat swamp water (flowing into the catchment) and also by metal and sand mining activity. The high conductivity values represent high concentration of total dissolved solids. The main source of high TDS value is the recent sand mining activity going on in the study area. This study shows that the water quality is degraded in the area (Tables 3 and 4); Graph 1 shows the physico-chemical properties of soil. Table 3 shows that average contents of the soil are gravel 37.3% with diameter 3 to 6 mm, sand 57.20% with diameter 0.1 to 2 mm, silt 2.9% with diameter 0.008 to 0.4 mm and clay 2.46% with diameter 0.0008 to 0.0014 mm that is kind of medium textured sandy soil. Sandy soils have low clay and organic matter contents and aggregation is very weak to non existent. The structure is called single grained. Such kind of soil cannot retain so much water and can drain quickly. Single drained soils required frequent irrigation and fertilization for plants roots to penetrate. Table 4 indicates that the average moisture content of soil is 6.36% of soil, temperature 22.0°C, pH 5.64 and hydraulic conductivity is 13.7 cm/day. This shows that soil temperature and hydraulic conductivity is feasible for plant growth but low pH due to high cations in soil and moisture content due to sandy structure depress plant growth.

Metal concentration of water and soil are good indicators of degree of contamination (Table 5); Graphs 2 and 3 shows the concentration of heavy metals in water of the area under investigation. At the sampling station, WS1 are as follows: lead 38 mg/L, zinc 88 mg/L, nickel 2.5 mg/L, cobalt 1.0 mg/L, arsenic 30 mg/L, copper 59 mg/L, iron 06 mg/L, manganese 44 mg/L and tin 85 mg/L while at sampling station WS15 concentration of heavy metals are as follows: lead 96 mg/L, zinc 121 mg/L, nickel 2.8 mg/L, cobalt 1.8 mg/L, arsenic 77 mg/L, copper 80 mg/L, iron 16 mg/L, manganese 48 mg/L and tin 250 mg/L. Same variation trends of decrease in metal concentration are at all sampling stations from upstream to down stream. According to Meterological Department, Malaysia, Bestari Jaya is a flooding area with average rainfall of 2670 mm, annual precipitation 1800 mm and average wind speed up to 10 km/h so the possible causes of this decrease in metals concentration are natural aeration, natural precipitation, other possible causes of decrease in metal concentration are formation of wetlands, palm oil plantation and the dilution factor of water as it flows downstream (Table 4). Graphs 4 and 5 shows heavy metals concentration in soil. Concentration is even higher in soil as compared to water. Comparison of metal concentration in water and soil with Interim National Water Quality Standards Malaysian (INWQS) shows that the heavy metals concentration falls above class 4 so it shows that the study area has a high pollution impact on the environment.

Wetland development conceptual model

In designing a treatment wetland for heavy metals removal, processes within three compartments must be considered: 1) water, 2) media and 3) biota (Rai, 2008; Sheoran and Sheoran, 2006; Vymazal and Kröpfelová, 2008). As outlined in Figure 2, water is the most essential

Table 2. Physio-chemical parameters of surface water in the study area.

Sample No.	Location	Coordinates	Colour (TCU)	Temperature (°C)	pH	Conductivity (µS/cm)	Salinity (%)	Turbidity (NTU)	Dissolved oxygen (mg/l)	Total dissolved solids (mg/l)
WS1	Junction of Sungai Selangor + Sungai Ayer Hitam	3° 24' 28.04" N; 101° 25' 54.89" E	5	32.19	6.47	1640	0.27	16	6.83	2654
WS2	Junction of Sungai Ayer Hitam + Sungai Udang	3° 24' 30.96" N; 101° 25' 54.08" E	7	32.62	6.27	1680	0.28	18	6.65	2784
WS3	Sungai Ayer Hitam water flow	3° 24' 36.54" N; 101° 25' 59.96" E	7	32.52	6.27	1686	0.28	18	6.70	2797
WS4	Sungai Ayer Hitam at bank of UNISEL	3° 24' 56.68" N; 101° 25' 59.18" E	7	32.51	6.29	1686	0.28	18	6.72	2800
WS5	Sungai Ayer Hitam at bank of UNISEL	3°25' 06.69" N; 101° 26' 08.14" E	7	32.98	6.29	1688	0.28	19	6.15	2812
WS6	Junction of Pond 1 to Sungai Ayer Hitam	3° 25' 16.57" N; 101° 26' 09.24" E	7	32.90	6.28	1690	0.28	18	6.42	2864
WS7	Pond 1	3^0 25' 13.37" N; 101° 26' 04.66" E	7	32.75	5.78	1704	0.29	19	6.34	2900
WS8	Pond 1	3° 25' 15.56" N; 101° 26' 0.79" E	7	32.50	5.20	1744	0.29	20	6.00	2934
WS9	Junction of Pond 1 to another Pond	3° 25' 13.87" N; 101° 25' 55.35" E	7	32.44	5.32	1734	0.29	19	6.42	2924
WS10	Junction of Sungai Ayer Hitam to Pond 2 at north-eastern boundary UNISEL	3° 25' 20.92" N; 101° 26' 12.06" E	7	32.28	5.41	1694	0.28	18	6.39	2887
WS11	Junction of Sungai Ayer Hitam to Pond 2	3° 25' 22.11" N; 101° 26' 6.66" E	9	32.32	5.34	1710	0.28	20	6.28	2912

Table 2. Contnd.

WS12	Pond 2	3° 25' 22.54" N; 101° 26' 0.94" E	9	32.12	5.22	1724	0.29	22	6.87	2920
WS13	Pond 2	3° 25' 22.05" N; 101° 25' 58.38" E	9	32.57	5.39	1732	0.29	24	6.45	2922
WS14	Pond2	3° 25' 23.71" N; 101° 25' 52.42" E	9	32.29	5.28	1738	0.29	22	6.59	2956
WS15	Junction of Pond 2 to another Pond	3° 25' 33.21" N; 101° 25' 51.34" E	9	32.51	5.00	1756	0.30	22	6.82	2998
Mean		$\bar{X}$	7	32.5	5.71	1707	0.28	0.19	6.50	2870
Standard deviation		σ	1.18	0.24	0.52	30.83	0.007	2.13	0.25	87.26
Variance (standard deviation)		σ^2	1.40	0.06	0.27	950.78	0.00006	4.552	0.06	7615.49

Table 3. Grain size analysis of the soil.

Sample No.	Location	Coordinates	Gravel		Sand					Silt		Clay	
					Course to medium		Fine						
			Particle diameter (mm)	%	Particle diameter (mm)	%	Particle diameter (mm)	%	Total %	Particle diameter (mm)	%	Particle diameter (mm)	%
SS1	Junction of Jalan Timur Tambahan + Sungai Selangor.	3° 24' 29.80" N; 101° 25' 55.08" E	4	37.66	1	32.01	0.1	25.34	57.35	0.04	2.81	0.0014	2.18
SS2	Bank of Sungai Ayer Hitam + Sungai Udang.	3° 24' 32.03" N; 101° 25' 54.75" E	5	37.98	2	30.45	0.2	26.73	57.18	0.02	2.40	0.0009	2.44
SS3	Bank of Sungai Ayer Hitam.	3° 24' 36.29" N; 101° 25' 57.34" E	3	35.44	1	29.48	0.1	27.52	57.00	0.02	3.88	0.0008	3.68

Table 3. Contnd

SS4	South-eastern boundary of UNISEL.	3° 24’ 54.73” N; 101° 26’ 0.48” E	6	38.41	2	30.18	0.3	27.36	57.54	0.04	2.57	0.0016	1.48
SS5	Wetlands developed by overflow of Pond 1.	3° 25’ 09.78” N; 101° 25’ 59.41” E	5	36.98	1	31.24	0.3	25.57	56.81	0.01	2.88	0.0016	3.38
SS6	Bank of Pond 1.	3° 25’ 11.54” N; 101° 26’ 07.44” E	4	37.52	2	31.12	0.2	26.60	57.72	0.009	2.67	0.0019	2.09
SS7	North-eastern boundary of UNISEL.	3° 25’ 13.40” N; 101° 26’ 11.64” E	3	37.84	2	30.52	0.2	25.92	56.44	0.02	3.13	0.0018	2.59
SS8	Wetlands developed by overflow of Pond 1.	3° 25’ 59.18” N; 101° 25’ 56.90” E	4	36.85	2	29.92	0.2	26.34	56.26	0.008	3.98	0.0019	2.91
SS9	Junction of Sungai Ayer Hitam with pond 1 on north-western side.	3° 25’ 19.80” N; 101° 26’ 13.07” E	5	35.94	2	30.74	0.1	26.40	57.14	0.1	3.76	0.0016	3.16
SS10	Junction of Sungai Ayer Hitam with pond 1 on south-western side.	3° 25’ 22.79” N; 101° 26’ 11.06” E	5	37.72	2	29.12	0.1	27.86	56.98	0.3	2.81	0.0008	2.49
SS11	Wetland between Ponds 1 and 2.	3° 25’ 20.64” N; 101° 25’ 54.37” E	4	37.44	1	31.19	0.3	27.15	58.34	0.4	2.21	0.0008	2.01
SS12	Embankment of Pond 2.	3° 25’ 27.52” N; 101° 25’ 53.89” E	3	37.74	1	32.92	0.2	25.47	58.39	0.2	2.10	0.0009	1.77
SS13	Embankment of Pond 2.	3° 25’ 22.86” N; 101° 25’ 51.67” E	6	37.54	2	31.44	0.4	26.13	57.57	0.2	2.56	0.0014	2.33
SS14	Embankment of Pond 2.	3° 25’ 34.95” N; 101° 25’ 49.93” E	3	37.75	2	30.88	0.3	25.71	56.59	0.3	3.12	0.0016	2.54

Table 3. Contnd

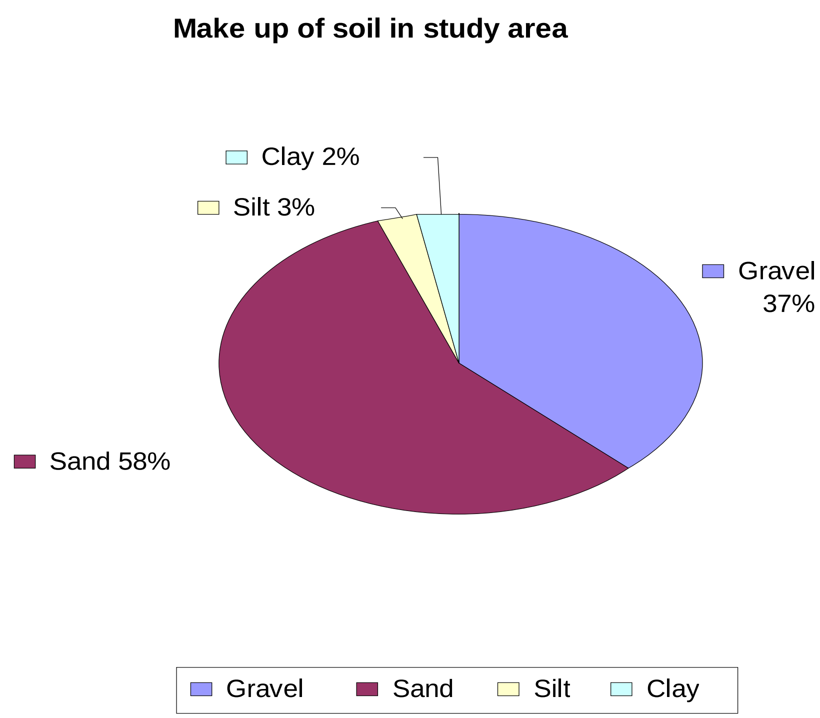
SS15	Embankment of Pond 2.	3° 25' 36.24" N; 101° 25' 52.14" E	5	37.58	1	31.12	0.2	26.76	57.88	0.009	2.62	0.0018	1.92
Mean		$\bar{X}$	4.33	37.35	1.6	30.82	0.2	26.45	57.20	0.11	2.9	0.0013	2.46
Standard deviation		σ	1.04	0.77	0.50	0.95	0.09	0.78	0.63	0.13	0.57	0.0004	0.61
Variance (standard deviation)		σ^2	1.09	0.60	0.25	0.91	0.008	0.61	0.40	0.01	0.33	0	0.37

Table 4. Physio-chemical parameters of soil in the study area.

Sample No.	Location	Coordinates	Moisture content % by weight	Temperature (°C)	pH	Hydraulic conductivity (cm/day)
SS1	Junction of Jalan Timur Tambahan + Sungai Selangor.	3° 24' 29.80" N; 101° 25' 55.08" E	6.23	21.22	5.7	14.3
SS2	Bank of Sungai Ayer Hitam + Sungai Udang.	3° 24' 32.03" N; 101° 25' 54.75" E	6.24	22.84	5.5	12.4
SS3	Bank of Sungai Ayer Hitam.	3° 24' 36.29" N; 101° 25' 57.34" E	6.38	21.44	5.3	15.2
SS4	South-eastern boundary of UNISEL.	3° 24' 54.73" N; 101° 26' 0.48" E	6.43	22.19	5.3	12.9
SS5	Wetlands developed by overflow of Pond 1.	3° 25' 09.78" N; 101° 25' 59.41" E	6.52	22.92	5.4	13.8
SS6	Bank of Pond 1.	3° 25' 11.54" N; 101° 26' 07.44" E	6.18	21.14	5.8	12.5

Table 4. Contnd.

SS7	North-eastern boundary of UNISEL.	3° 25' 13.40" N; 101° 26' 11.64" E	6.34	22.81	5.7	13.6
SS8	Wetlands developed by overflow of Pond 1.	3° 25' 59.18" N; 101° 25' 56.90" E	6.48	22.45	5.8	13.7
SS9	Junction of Sungai Ayer Hitam with pond 1 on north-western side.	3° 25' 19.80" N; 101° 26' 13.07" E	6.44	21.91	5.8	14.1
SS10	Junction of Sungai Ayer Hitam with pond 1 on south-western side.	3° 25' 22.79" N; 101° 26' 11.06" E	6.30	21.65	5.8	14.5
SS11	Wetland between Ponds 1 and 2.	3° 25' 20.64" N; 101° 25' 54.37" E	6.38	22.24	5.4	14.8
SS12	Embankment of Pond 2.	3° 25' 27.52" N; 101° 25' 53.89" E	6.41	21.14	5.8	13.8
SS13	Embankment of Pond 2.	3° 25' 22.86" N; 101° 25' 51.67" E	6.28	22.34	5.1	12.9
SS14	Embankment of Pond 2.	3° 25' 34.95" N; 101° 25' 49.93" E	6.39	21.87	5.8	14.6
SS15	Embankment of Pond 2.	3° 25' 36.24" N; 101° 25' 52.14" E	6.43	22.39	5.7	13.3
Mean		$\bar{X}$	6.36	22.0	5.6	13.7
Standard deviation		σ	0.09	0.61	0.23	0.84
Variance (standard deviation)		σ^2	0.009	0.37	0.05	0.71



Graph 1. Soil profile in the study area.

compartment; all the processes of heavy metals removal within the other compartments are encompassed within the water compartment. Metal transport is dependent upon water movement which transports the heavy metals throughout the system. The water causes the saturation of the media, allowing reduction of the redox value in order for treatment processes to occur within the media and related biota. Each is dependent upon the other, with water as the most important compartment. The media compartment consists of any substrate used to contain both the water and the biota. For metals removal, the media used must act as an adsorbent for metal species. The ability of the media to adsorb heavy metals is dependent upon its chemical make-up and the species of arsenic present. Media within a treatment wetland can be selected to treat different concentrations or volumes of heavy metals. The media also sustains the biota, providing water and nutrients to both plants and microorganisms. The biota compartment consists of both plants and microorganisms. Biota can uptake heavy metals and alters the redox of the environment by several means. The biota is also a source of organic matter for the media used to better adsorb arsenic (Sheoran and Sheoran, 2006). Biota used within a treatment wetland can be altered to best suit the conditions present.

Proposed design for Bestari Jaya wetland

Wetland system was proposed on the grounds of the Bestari Jaya mine tailings. The system comprises of three compartments in series- an ‘inflow’ pond receiving untreated tailings water overflowing into a wetland compartment which in turn overflows into an ‘outflow’ pond receiving the now treated water (Figure 3). Waterproof baffles in each wetland compartment serve to increase the flow path of the water, thereby increasing the potential for sulphate retention. On site a computer (ACS Pentium PC) connected to the pumps regulates the flow of tailings water through the systems. Also, connected to the computer are four permanent industrial-grade electrodes (Rosemount Solu Cube® Analyser Model 2700), one situated in each of the four ponds. These facilitate continuous and simultaneous monitoring of conductivity and temperature. Data are logged into a database every ½ h for the initial two months, thereafter every 3 h, 24 h a day and can be accessed remotely via a portable modem. This makes it possible to monitor the performance of the systems from our laboratory at the University of Malaya using pc anywhere 32 software.

Reference pond 1

Wetland is developed, by following the treatment volume approach and comprises five ponds (referred to as P1, P2, P3, P4 and P5) lined by compacted clay and separated by shallow vegetated areas submerged in wet conditions. Reference Pond is located at 3° 26’ 11.10 N, 101° 26’ 20.32 E, elevation 7 m. This pond is 0.8 km from

Table 5. Heavy metals concentration in the surface water of the study area.

			Element concentration [mg/l (ppm)]									
Sample No.	**Location**	**Coordinates**	**Pb^{2+}**	**Zn^{2+}**	**Ni^{2+}**	**Co^{2+}**	**As^{3+}**	**Cu^{2+}**	**Fe^{2-}**	**Mn^{2+}**	**Sn^{2+}**
WS1	Junction of Sungai Selangor + Sungai Ayer Hitam.	3° 24’ 28.04” N; 101° 25’ 54.89” E	38	88	2.5	1.0	30	59	06	44	85
WS2	Junction of Sungai Ayer Hitam + Sungai Udang.	3° 24’ 30.96” N; 101° 25’ 54.08” E	46	86	2.5	2.1	35	78	10	46	100
WS3	Sungai Ayer Hitam water flow.	3° 24’ 36.54” N; 101° 25’ 59.96” E	45	86	3.1	2.0	32	68	12	46	150
WS4	Sungai Ayer Hitam at bank of UNISEL.	3° 24’ 56.68” N; 101° 25’ 59.18” E	51	87	3.6	1.9	36	76	15	47	150
WS5	Sungai Ayer Hitam at bank of UNISEL.	3° 25’ 06.69” N; 101° 26’ 08.14” E	51	86	2.9	2.0	52	69	13	49	155
WS6	Junction of Pond 1 to Sungai Ayer Hitam.	3° 25’ 16.57” N; 101° 26’ 09.24” E	60	88	7.5	2.9	78	71	10	49	200
WS7	Pond 1.	3° 25’ 13.37” N; 101° 26’ 04.66” E	58	88	8.1	2.5	91	60	12	48	225
WS8	Pond 1.	3° 25’ 15.56” N; 101° 26’ 0.79” E	89	90	6.2	2.8	88	80	15	49	268
WS9	Junction of Pond 1 to another Pond.	3° 25’ 13.87” N; 101° 25’ 55.35” E	67	90	4.3	3.0	67	75	20	48	227
WS10	Junction of Sungai Ayer Hitam to Pond 2 at north-eastern boundary UNISEL.	3°25’ 20.92” N; 101° 26’ 12.06” E	80	92	3.4	2.7	91	70	14	48	199
WS11	Junction of Sungai Ayer Hitam to Pond 2.	3° 25’ 22.11” N; 101° 26’ 6.66” E	89	94	5.9	2.9	69	78	18	49	134

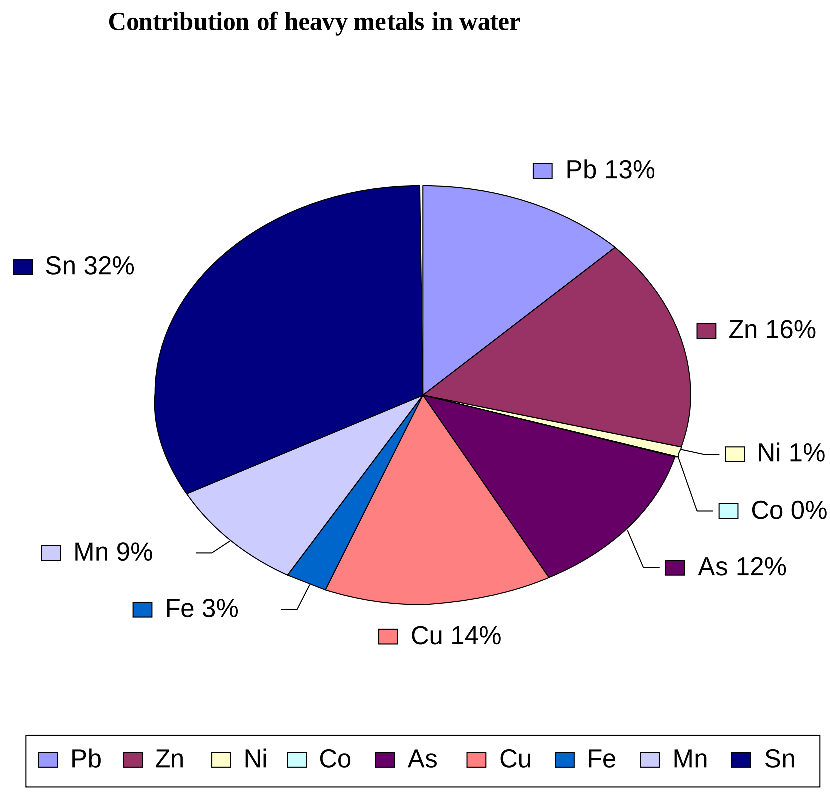
Table 5. Contnd

WS12	Pond 2.	3° 25' 22.54" N; 101° 26' 0.94" E	91	132	8.1	1.8	90	95	19	51	155
WS13	Pond 2.	3° 25' 22.05" N; 101° 25' 58.38" E	87	110	6.2	2.1	89	81	20	50	190
WS14	Pond 2.	3° 25' 23.71" N; 101° 25' 52.42" E	94	122	5.5	2.5	71	88	18	49	198
WS15	Junction of Pond 2 to another Pond.	3° 25' 33.21" N; 101° 25' 51.34" E	96	121	2.8	1.8	77	80	16	48	250
Mean.		$\bar{X}$	69.46	87.8	4.8	2.2	66	75	14	48	179
Standard deviation.		σ	20.70	31.96	2.06	0.55	23.36	9.56	4.10	1.75	52.53
Variance (standard deviation).		σ^2	428.55	1021.7	4.24	0.30	546.11	91.45	16.83	3.06	2760

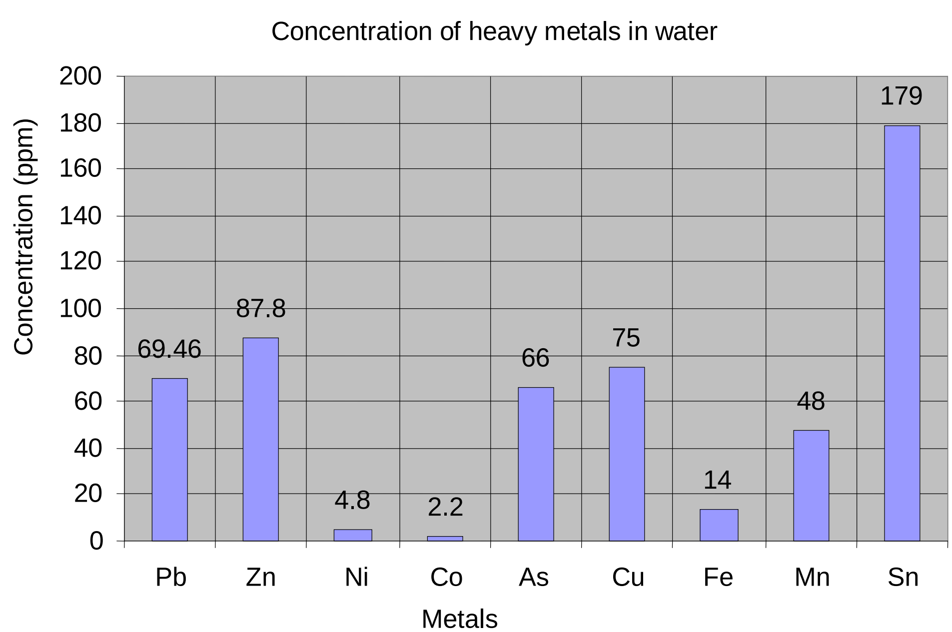
the UNISEL and Bestari Jaya Town and was selected according to its position with reference to Selangor River and water flow from the catchment. The pond has an area of 2200 m^2, a maximum depth of 8.5 m in the centre and volume of 1500 m^3 (Figure 4). Pond is estimated to receive 105 m^3 ha^{-1} (that is a Vt of 1840 m^3) runoff water from mining area including tin tailing and sand mining water with high TDS and TSS. Wastewater from the mining ponds and runoff from tin tailings will discharge into a swale (45 m long) from two pipes (50 and 80 cm in diameter) over paving slabs to minimise erosion. Water leaves reference pond P1 runs through a long shallow vegetated area (c. 40 m long, 15 m wide) and through a series of three ponds (P2: 115 m^2, P3: 105 m^2, P4: 190 m^2, up to 1 m deep) separated by short (c. 20 m) shallow vegetated (grass or watercress) areas. Flow then enters a large and deep pond (P5, c. 2500 m^2, up to 1.5 m deep, vegetated) (Figures 5 and 6). Finally, under normal conditions, water will leave pond P5 through an inlet located on the south-east corner of the pond and flows into a ditch transferring treated water to River Ayer Hitam that ultimately fed up into river Selangor. The wetland compartments will be planted with *T. latifolia* (four plants per m^2) and *P. australis* (nine plants per m^2). *G. fluitans* (seven plants per m^2), bulbs of *Iris pseudacorus* (five plants per m^2, rhizomes of *T. latifolia* (six plants per m^2) *Juncus effusus* (seven plants per m^2), *Phalaris arundinacea* (nine plants per m^2) and *Cyperus rotuduss L.* (nine plants per m^2). Flow rates were set at 300 to 500 ml min^{-1}. These rates were adapted to fit the size of the systems based on the values given for other operational systems as described by Crites (1994).

The theoretical residence time for the systems is 52 days, but the applicable value has yet to be confirmed. Here we report a selected number of parameters measured, namely: volunteer species (invaders), pH, redox potential, conductivity and sulphate concentrations in water. The site was visited on a monthly or bi-weekly basis and some parameters were monitored continuously. The pH was measured using a glass combination electrode connected to a pH meter (WTW pH90). Redox potential was measured using a platinum electrode connected to a mV meter (WTW pH90).

Conductivity was measured using the industrial



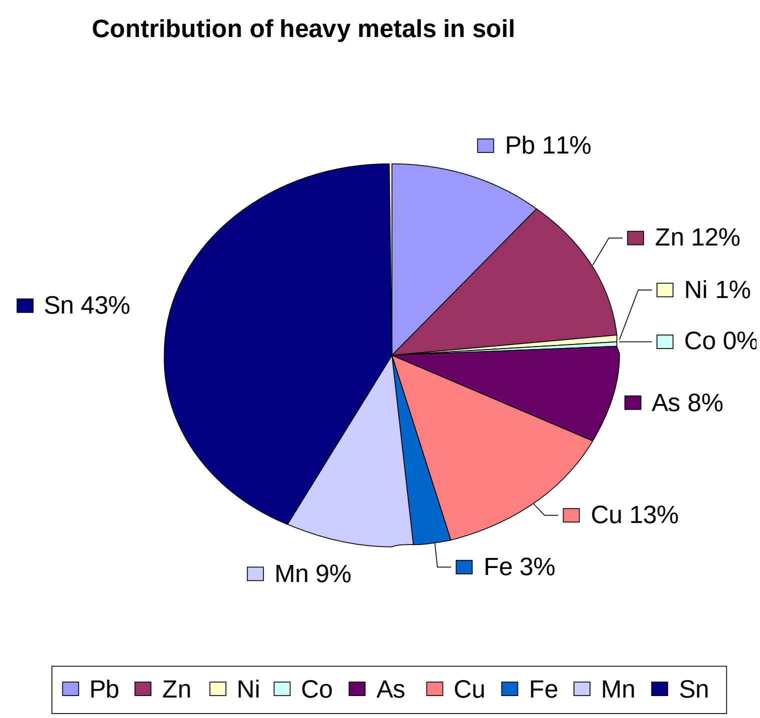
Graph 2. Contribution of heavy metals in water.



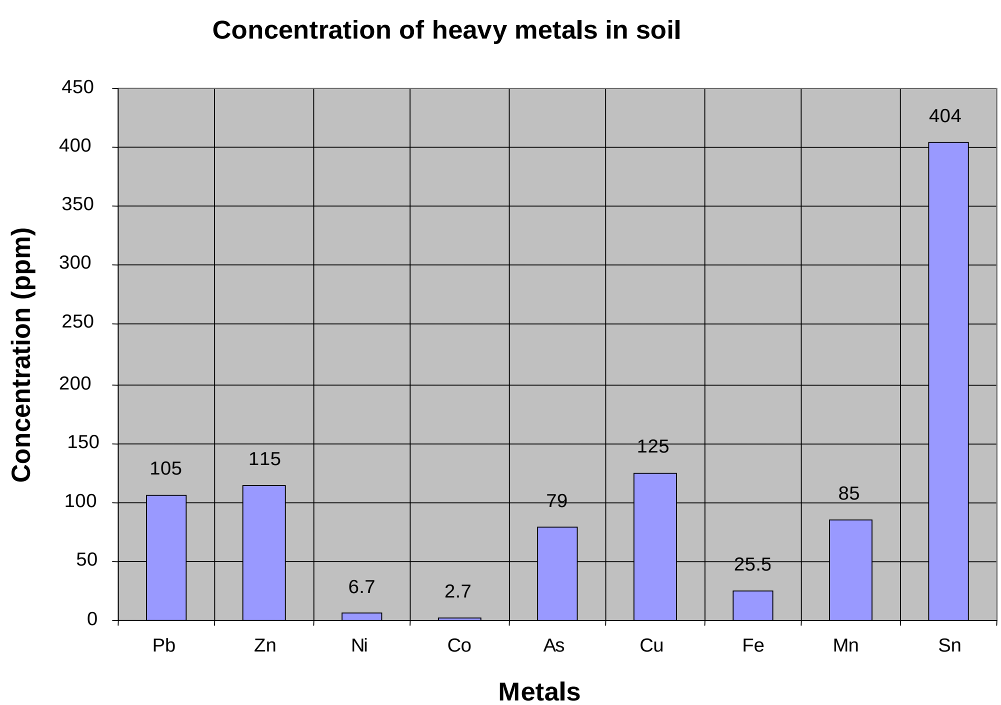
Graph 3. Concentration of heavy metals in water.

electrodes mentioned earlier. For the analysis of sulphate, a Dionex ion chromatograph was used.

Invading flora will be identified using the standard key of the Malaysian Botanical Society. The wetland compartment



Graph 4. Contribution of heavy metals in soil.



Graph 5. Concentration of heavy metals in soil.

of each system is filled with approximately 50 cm depth of a mixture of cattle manure (25%) and municipal waste compost (75%). This mixture was chosen because literature shows that it combined good permeability with

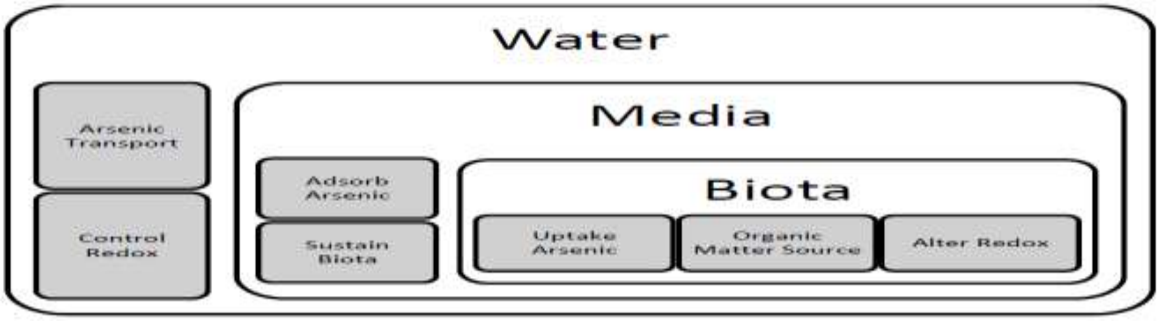


Figure 2. Diagram noting the three compartments of a treatment wetland: water, soil and biota.

Figure 3. View of reference Pond 1. The end of inlet swale is visible in the foreground; the outlet is located on the opposite bank.

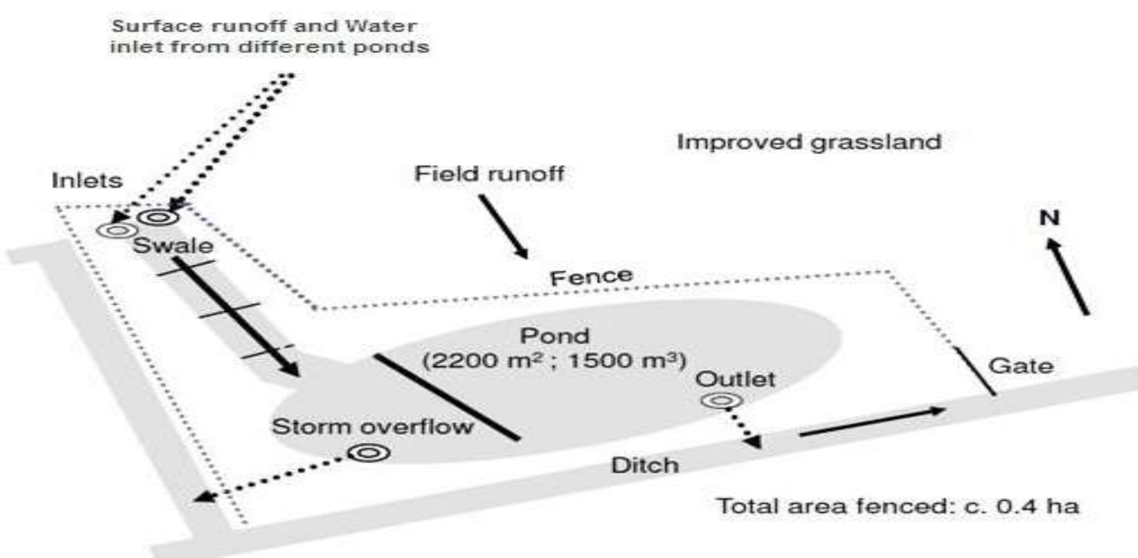


Figure 4. Proposed sketch of reference Pond 1 (not to scale), dashed arrows represent flow in subsurface pipes and full arrows represent surface flow.

optimal growth of plants. At the bottom of the inflow and outflow ponds in each system, a layer of about 25 cm of a 1:6 mixture of cattle manure and municipal waste compost was deposited to provide a substrate for the

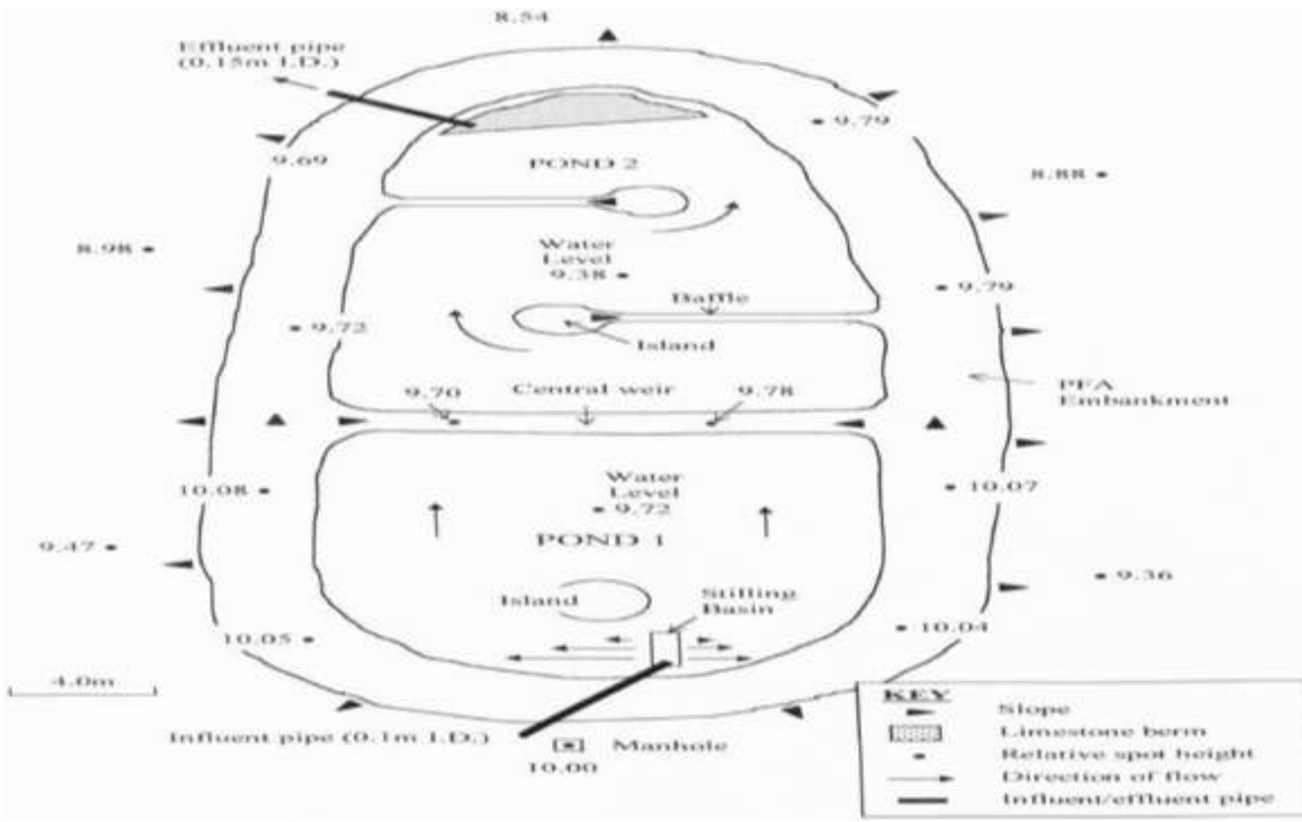


Figure 5. Proposed structure with construction materials for Pond 1 and Pond 2.

invertebrate species that spontaneously inhabit the systems. The planting density chosen was based on similar research on constructed wetlands (Szczepanska and Szczepanska, 1982; Kadlec and Alvord, 1989). Additionally 30 tons of limestone is deposited at the far end of the wetland, to facilitate final pH adjustment if it should be required. Figure 5 shows placement of limestone at the far end of the treatment system. The system was designed such that the compost depth in the wetland would be 0.30 to 0.50 m. An additional 0.30 m of freeboard is allowed for accumulation of material on the substrate surface. The total area of substrate surface is 440 m^2. To generate additional hydraulic head, a concrete wall is constructed across the culvert from which the discharge emanates. Two sections of 100 mm diameter pipe were built into this wall. The first carries water underground to the influent point of the wetland, discharging into a basin from where the water is distributed across the wetland. The second section of pipe allows overflow back into the original watercourse when flow rates exceed approximately 400 L/min. Because pollutant concentrations are lower at higher flow rates due to dilution, and because of further dilution of the overflow water by the effluent from the wetland, the impact of this water on the receiving watercourse is minimal.

The water outlet structure was originally a section of 150 mm diameter plastic pipe buried into the retaining embankment. A movable 90° bend on the wetland-side of this pipe allowed the water level in the wetland to be adjusted (although typically the water level has been maintained approximately 50 to 100 mm above the surface of the substrate (Figures 5 and 6). Because the site slopes downwards slightly (away from the proposed influent point to the wetland), a central weir was incorporated in the design in order that the wetland could be constructed on two levels, the second cell being 0.4 m lower than the first cell. In this way savings were made in terms of both materials costs and land area used for the embankment. The quantities of materials used and the overall estimated cost for the development of wetland at Bestari Jaya is given in Tables 1 to 6.

Conclusions

The preliminary result obtained from this study is alarming. The results of water quality trends clearly show that majority of water quality parameters are quite high and fall in class 3 in terms of Malaysian Interim Water Quality Standards. The picture is more severe if we talk in terms of heavy metals concentration in the area. It falls

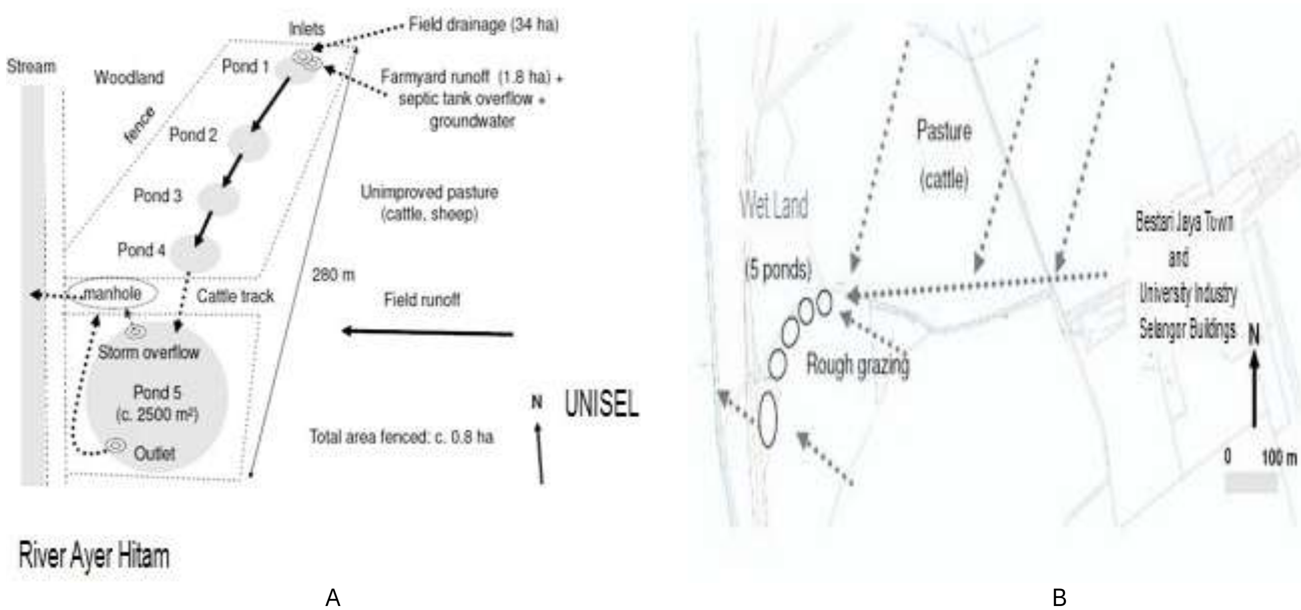


Figure 6. Proposed sketch of wetland ponds (not to scale) at two different angles. Dashed arrows represent underground piped flow and full arrows represent surface flow.

above level 4 in INWQS. After comparison of different parts of study area it is concluded that Bestari Jaya catchment has high pollution risks on environment, Sungai Ayer Hitam recipient of catchment water is highly polluted river that ultimately ends into Sungai Selangor, is vulnerable and sensitive ecosystem especially to metal pollution. Therefore lot of research needs to be carried out to access the pollution impact of the area on the environment and for the rehabilitation and reclamation steps to be taken. Wetlands have a strong capacity for the retention of pollutants, including those originating from mining activities. The establishment of a wetland cover over tailings provides a promising alternative to the more traditional dry land option. Critics of both applications frequently doubt the longevity of these systems. Where the use of wetlands for treatment of polluted water is concerned, the answer is simple-size matters. If a wetland is built sufficiently large to manage the input of pollutants, then it should be functional for many decades (Beining and Otte, 1996, 1997). Restriction in the use of wetlands for treatment of wastewater is therefore determined by the available space for construction of such a system.

Revegetation of tailings with wetlands should be sustainable for indefinite periods of time. The vegetation component provides the source of organic matter needed to drive the chemical reduction of sulphides and the subsequent precipitation of metal sulphides. Through these processes, the metals and sulphates are returned to the form they were derived from originally in the mining process, as many metal ores are sulphide in nature.

Therefore, wetlands can be used to complete the recycling of mine wastes from sulphides back to sulphides.

1) The proposed wetland at Bestari Jaya is comparatively small in engineering terms and is unique in the sense that the proposed wetland will play an important role in guiding the design of such systems for mining sites in Malaysia in future.
2) The wetland built is an anaerobic (compost) surface flow system. In engineering terms the decision to construct such a system was based on the limited hydraulic head available across the site.
3) 640 tons of pulverised fuel ash (PFA) were used for the construction of the retaining embankments, which are keyed into the *in situ* soil to a depth of approximately 0.2 m. Extensive excavation of the *in situ* soil was not possible as it was found to be heavily contaminated with metals from former mining operations. The substrate of the wetland is a combination of horse manure, cow manure and municipal waste.
4) It is unclear whether temperature is the direct cause of changes in removal efficiency or whether perhaps temperature changes influence microbial activity, which in turn affect metal removal efficiency. In either case this observation has some important implications. In particular, it suggests that wetland systems operating under cold climate conditions may be less effective, at least in terms of aluminium removal.
5) Three methods are currently in use for assessing constructed wetland performance:

a) Treatment efficiency (%),

Table 6. Heavy metals concentration in the soil of the study area.

			Element concentration (mg/kg)								
Sample No.	**Location**	**Coordinates**	**Pb^{2+}**	**Zn^{2+}**	**Ni^{2+}**	**Co^{2+}**	**As^{3+}**	**Cu^{2+}**	**Fe^{2-}**	**Mn^{2+}**	**Sn^{2+}**
SS1	Junction of Jalan Timur Tambahan + Sungai Selangor.	3° 24' 29.80" N; 101° 25' 55.08" E	110	120	8.5	3.0	70	120	22	84	425
SS2	Bank of Sungai Ayer Hitam + Sungai Udang.	3° 24' 32.03" N; 101° 25' 54.75" E	96	113	5.5	2.8	75	112	24	91	400
SS3	Bank of Sungai Ayer Hitam.	3° 24' 36.29" N; 101° 25' 57.34" E	110	132	6.1	2.0	82	128	25	72	390
SS4	South-eastern boundary of UNISEL.	3° 24' 54.73" N; 101° 26' 0.48" E	115	110	6.6	2.9	86	135	25	84	350
SS5	Wetlands developed by overflow of Pond 1.	3° 25' 09.78" N; 101° 25' 59.41" E	120	122	7.9	2.0	62	140	25	89	355
SS6	Bank of Pond 1.	3° 25' 11.54" N; 101° 26' 07.44" E	102	121	7.5	2.9	78	137	25	81	338
SS7	North-eastern boundary of UNISEL.	3° 25' 13.40" N; 101° 26' 11.64" E	108	100	8.1	2.5	91	125	26	79	325
SS8	Wetlands developed by overflow of Pond 1.	3° 25' 59.18" N; 101° 25' 56.90" E	99	120	6.2	2.8	88	100	26	86	368
SS9	Junction of Sungai Ayer Hitam with pond 1 on north-western side.	3° 25' 19.80" N; 101° 26' 13.07" E	97	102	7.3	3.0	67	125	28	98	387
SS10	Junction of Sungai Ayer Hitam with pond 1 on south-western side.	3° 25' 22.79" N; 101° 26' 11.06" E	120	112	6.4	2.7	91	120	25	98	399
SS11	Wetland between Ponds 1 and 2.	3° 25' 20.64" N; 101° 25' 54.37" E	85	100	5.9	2.9	69	128	26	81	434

Table 6. Contnd

SS12	Embankment of Pond 2.	3° 25' 27.52" N; 101° 25' 53.89" E	99	132	8.1	2.8	90	125	25	83	455
SS13	Embankment of Pond 2.	3° 25' 22.86" N; 101° 25' 51.67" E	97	110	6.2	2.1	89	130	28	90	490
SS14	Embankment of Pond 2.	3° 25' 34.95" N; 101° 25' 49.93" E	110	122	5.5	3.5	71	128	24	81	498
SS15	Embankment of Pond 2.	3° 25' 36.24" N; 101^0 25' 52.14" E	110	121	5.8	2.8	77	130	29	86	450
Mean.		$\bar{X}$	105	115	6.7	2.7	79	125	25.5	85	404
Standard deviation.		Ơ	9.81	10.24	1.02	0.41	9.80	9.94	1.76	6.92	53.46
Variance (standard deviation).		$Ơ^2$	96.31	105	1.05	0.14	96.20	98.98	3.12	47.98	2858

b) Area-adjusted removal rates ($g/m^2/d$),
c) First-order removal constants (m/d).

To make useful comparisons between constructed wetland systems, a performance indicator must be independent of differences in influent pollutant concentration (Tarutis et al., 1999). A new method of wetland performance assessment proposed by Tarutis et al. (1999) based on first-order removal of contaminants appears to be a far better method of assessment.

RECOMMENDATIONS

Much can be drawn from the design of Bestari Jaya wetland and these lessons may be of considerable use for future constructed wetland projects:

1) A thorough characterisation of the quantity and quality of mine water to be treated proved essential in this project. There is no doubt that a similar familiarity should be encouraged for all such projects, since mine waters commonly exhibit fluctuations in both quantity and quality.
2) A key objective of the feasibility study was to design a treatment system that would be inexpensive in terms of both initial installation costs and long-term operating and maintenance costs. Investigation of the variety of construction materials available is therefore to be encouraged. Almost 50% of the total expenditure of this project is on plant hire and operation. Typically costs are incurred even when machinery is not operating due to inclement weather conditions.
3) Establishing the exact removal mechanisms operational within the Bestari Jaya wetland will require detailed and long-term biogeochemical research which was beyond the scope of this particular study. From the results of this work it would seem that particular emphasis needs to be placed on establishing the main mineral phases within the wetland substrate, and ascertaining the role of iron and sulphur cycling in the vicinity of the water-sediment interface.
4) If contaminant removal is rate dependent, as the weight of evidence suggests it to be, then it is crucial to have accurate indications of residence times to properly understand the removal mechanisms operating within constructed wetlands. Tracer tests, using a conservative ion such as lithium should be undertaken to achieve this. However, multiple tests would be required to establish residence times at different influent flow-rates. The use of automatic sampling equipment would be of great use in this regard.
5) The first-order removal model of assessment

proposed by Tarutis et al. (1999) appears to be the most appropriate method for comparing wetland performance. This being the case, future constructed wetlands may be more effectively designed on the basis of the first-order removal model. However, as Tarutis et al. (1999) point out, if this is to be, possible future research must be undertaken to gather values for the first-order removal constant at constructed wetlands already operational.

6) The anaerobic wetland treatment appear to be a very promising new treatment technology, particularly for remediation of marginally polluted mine water discharges.

Previously, no research has been undertaken to determine the mineral phases accreting to the media within the reactors. Such work would certainly assist in ascertaining the exact removal mechanisms operational in these treatment units. It appears that at full-scale a very efficient water distribution system would be required for the system to operate effectively.

7) Wetland/passive treatment of other waste streams may be feasible and in some cases has been successfully undertaken. Elements of the research presented here may be applicable to other water pollution issues and an investigation of such possibilities might prove fruitful. In particular the following types of wastes may be suitable for passive treatment of landfill drainage, airport/runway drainage and sewage effluent and railway runoff etc.

ACKNOWLEDGEMENTS

The work reported in this paper is a basic research work carried out at Analytical Laboratory, Department of Chemistry and partially at Department of Geology, University of Malaya. I take this opportunity to express my gratitude to Ministry of Higher Education, Malaysia to provide me scholarship to complete my higher studies in Malaysia. Thanks also go to Institut Pengurusan Dan Pemantauan Penyelidikan, (IPPP) University of Malaya to provide me enough funding (Project No. PS355/2009C) for the completion of this valuable research.

REFERENCES

American Public Health Association (APHA).(1998). Standard Methods of Water and Waste Water analysis, 20th ed. Washington, D.C.

Ashraf MA, Maah MJ, Yusoff I (2011). Heavy metals accumulation in plants growing on former tin mining catchment.Int. J. Environ. Sci. Tech., 8(2): 401-416.

ASTM D422 – 63. 2007. Standard Test Method for Particle-Size Analysis of Soils.

ASTM D5084 – 03.2007. Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter

ASTM D 5198-09. (2007). Standard Practice for Nitric Acid Digestion of Solid Waste.

Beining BA, Otte ML (1996). Retention of metals from an abandoned lead–zinc mine by a wetland at Glendalough, Co. Wicklow, Ireland. Biology and Environment: Proc. Royal Ir. Acad., 96B(2): 117-26.

Beining BA, Otte ML (1997). Retention of metals and longevity of a wetland receiving mine leachate. In J.E. Brandt, J.R. Galevotic, L. Kost and J. Trouart (eds), Proc. of the Four. Ann. Nat. Meet. Visi. 2000: An Environmental Commitme., Austin, Texas. Am. Soc. Surface Min. Reclamat., pp. 43-46.

Bouyoucos GJ (1936). Directions for Making Mechanical Analysis of Soils by the Hydrometer Method. Soil Sci., 3(1): 42-47.

Braskerud BC (2002a). Factors affecting nitrogen retention in small constructed wetlands treating agricultural non-point source pollution. J. Ecol. Eng., 18: 351-370.

Brix H, Schierup H (1989). The use of aquatic macrophytes in water-pollution control. *Ambio,* 18(2), 100-107.

Brix H (1994). Functions of macrophytes in constructed wetlands. Water Sci. Technol., 29(4): 71-78.

Brovelli A, Carranza-Diaz O, Rossi L, Barray DA (2010). Design methodology accounting for the effects of porous medium heterogeneity on hydraulic residence time and biodegradation in horizontal subsurface flow constructedwetlands. Ecological Engineering, in press.

Bruyère F, Questel Y (2001 Study of ponds and canals in Guadeloupe. Regional Department of the Environment Guadeloup (DIREN) , France, P. 65.

Carty A, Scholz M, Heal KV, Gouriveau F, Mustafa A (2008a). The universal design, operation and maintenance guidelines for farm constructed wetlands (FCW) in temperate climates. Biores. Technol., 99: 6780-6792.

Carty A, Scholz M, Heal KV, Keohane J, Dunne EJ, Gouriveau F, Mustafa, A (2008b). Farm constructed wetland design manual for Northern Ireland and Scotland. Department of Environment (Northern Ireland) and Scottish Environment Protection Agency, UK, p.61.

Cooper PF, Job GD, Green MB, Shutes RBE (1996). Reed Beds and Constructed Wetlands for Wastewater Treatment. Water Research Centre, Swindon, UK, p. 184.

CRAPL (Regional Chamber of Agriculture of the Pays Loire), (2007). Effluent treatment lightly loaded. Choose a treatment system for your farm to manage the lightly loaded effluents. Angers, France, P. 64.

Crites RW. (1994) Design criteria and practice for constructed wetlands. Water Sc. Technol., 29: 1-6.

Crites RW, Dombeck GD, Watson RC, Williams CR (1997). Removal of metals and ammonia in constructed wetlands. Water Environ. Res., 69(1): 132-135.

Cronk JK (1996). Review article: constructed wetlands to treat wastewater from dairy and swine operations: a review. Agric. Ecosys. Environ., 58(3): 97-114.

Duddridge JE, Wianwright M (1981). Heavy Metals in River Sediments-Calculation of Metal Absorption Maximum Using Langmuir and Freundlch Isotherms. Environ. Poll. Series., 2: 131-136.

Dunbabin JS, Bowmer KH. (1992) Potential use of constructed wetlands for treatment of industrial wastewaters containing metals. Sci. Total Environ., 111: 151-68.

Dunne EJ, Culleton N, O'Donovan G, Harrington R (2005a). Constructed wetlands to retain contaminants and nutrients, specifically phosphorus from farmyard dirty water in southeast Ireland. In: Dunne EJ, Reddy KR, Carton OT (eds.), Nutrient Management in Agricultural Watersheds: a Wetlands Solution. Wageningen Academic Publishers, The Netherlands, pp. 144-156.

Dvorak DH, Hedin RS, Edenborn HM, McIntire PM (1992). Treatment of metal-contaminated water using bacterial sulfate reduction: results of pilot-scale reactors. Biotechnol. Bioengg. 40**,** 609–16.

Eger P (1994). Wetland treatment for trace metal removal from mine drainage: the importance of aerobic and anaerobic processes. Water Sci. Technol., 29(4): 249-256.

Gambrell RP (1994). Trace and toxic metals in wetlands—a review. J. Environ. Qual., 23: 883-891.

Hammer DA (1989) Constructed wetlands for wastewater treatment: municipal, industrial and agricultural. Chelsea, MI. Lewis Publishers.

Hammer DA (1992). Designing constructed wetland systems to treat agricultural nonpoint source pollution. Ecol. Eng., 1: 49-82.

IWA (2000). Constructed wetlands for pollution control. Processes, performance, design and operation. Scientific and Technical Report No. 8. TJ International (Ltd), Padstow, Cornwall, UK, p.156.

Johansson AE, Gustavsson AM, Öquist MG, Svensson BH (2004).

Methane emissions from a constructed wetland treating wastewater: seasonal and spatial distribution and dependence on edaphic factors. Water Res., 38: 3960-3970.

Kadlec RH, Alvord H (1989) Mechanisms of water quality improvement in wetland treatment systems. In D.W. Fisk (ed.), Wetlands: concerns and successes, Florida. Am. Water Resour. Assoc., pp. 489-498.

Kadlec RH, Knight RL (1996). Treatment Wetlands. CRC Press LLC, Lewis Publishers, Boca Raton, New York, USA, p. 893.

Kadlec, RH (1999). The limits of phosphorus removal in wetlands. Wetlands Ecol. Manage., 7: 165-175.

Lambers H, Colmer TD (2005). Root physiology: from gene to function. Preface. Plant Soil, 274: 7-15.

Langergraber G (2004). The role of plant uptake on the removal of organic matter and nutrients in subsurface flow constructed wetlands: a simulation study. In: IWA, ASTEE, Cemagref and Agence de l'Eau. Wetland Systems, Volume 2. Proceedings of the ninth International Conference on Wetland Systems for Water Pollution Control, Avignon (France), 28th September 2004, pp. 491-498.

Mason C (2002). Biology of Freshwater Pollution, Fourth Edition. Pearson Education Ltd, Edinburgh Gate, Harlow, Essex, UK, p. 387.

McCabe OM, Otte ML (1997). Revegetation of mine tailings under wetland conditions. In J.E. Brandt, J.R. Galevotic, L. Kost and J. Trouart (eds), *Proceedings of the Fourteenth Annual National Meeting— Vision* 2000: *An Environmental Commitment*, Austin, Texas. American Society for Surface Mining and Reclamation. pp. 99-103.

McCabe OM, Johnson MS, Otte ML (1997). Tailings revegetation in Ireland. In T.C. Richmond (ed.), *The principles and practices of tailings revegetation*. Baltimore, MD. John Hopkins University Press.

McIntire PE, Edenborn HM (1990). The use of bacterial sulfate reduction in the treatment of drainage from coal mines. Proc. Mining and Reclam. Confer. Exhibit., Charlestown, WV, April, 23(6): 409-415.

Mitch WJ, Gosselink JG. (1986) Wetlands. New York. Van Nostrand Reinhold.

Mitchell BD, Williams WD (1982). The performance of tertiary treatment ponds and the role of algae, macrophytes and zooplankton in the waste treatment process. Occasional, , Australian Government Publishing Service, Canberra, Australia, 2: 90.

Mitsch WJ, Wise KM (1998). Water quality, fate of metals, and predictive model validation of a constructed wetland treating acid mine drainage. Water Res., 32: 1888-1900.

Poe AC, Pichler MF, Thompson SP, Paerl HW (2003). Denitrification in a constructed wetland receiving agricultural runoff. Wetlands, 23: 817-826.

Rai PK (2008). Heavy metal pollution in aquatic ecosystems and its phytoremediation using wetland plants: and ecosustainable approach. Int. J. Phytorem., 10(2): 33-60.

Reddy KR, DeBusk WF (1987). Nutrient storage capabilities of aquatic and wetland plants. In: Reddy, K.R. and Smith, W.H. (eds.). Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing, Orlando, Florida, USA, pp. 337-357.

Scholz M, Lee BH (2005). Constructed wetlands: a review. Int. J. Environ. Stud., 62: 421-447.

Scottish Government, 2008b. Treat run-off of pollutants: farm wetlands. http://www.scotland.gov.uk/Topics/Rural/SRDP/RuralPriorities/Packages/ReducingDiffuseolluti o/Treatmentofrunoffsofnutr (accessed 12 May, 2009).

SEPA and Pond Action. (2000). Ponds, pools and lochans. Guidance on good practice in the management and creation of small waterbodies in Scotland. Stirling, UK, p.69.

Sheoran AS, Sheoran V (2006). Heavy metal removal mechanism of acid mine drainage in wetlands: A critical review. Minerals Eng., 19: 105-16.

Sinicrope TL, Langis R, Gersbery RM, Busnardo MJ, Zedler JB (1992). Metal removal by wetland mesocosms subjected to different hydroperiods. Ecol. Eng., 1: 309-322.

Szczepanska W, Szczepanska A. (1982). Interactions between *Phragmites australis* (Cav.) Trin. Ex. Steud. and *Typha latifolia* L. Ekologia Polska, 30: 1165-86.

USDA, NRCS, EPA (1995a). Handbook of constructed wetlands. A guide to creating wetlands for: agricultural wastewater, domestic wastewater, coal mine drainage, storm water in the Mid-Atlantic Region. Volume 1: general considerations. US EPA, Washington, D.C., USA, p. 55.

USDA, NRCS, US EPA (1995b). Handbook of constructed wetlands. A guide to creating wetlands for: agricultural wastewater, domestic wastewater, coal mine drainage, stormwater in the Mid- Atlantic Region. Volume 3: agricultural wastewater. US EPA, Washington, D.C., USA, p. 35.

US EPA (United States Environment Protection Agency) (2000). Guiding principles for constructed treatment wetlands: providing for water quality and wildlife habitat. Washington DC, USA, p.41.

Van de Weg M, Reay DS, Gouriveau F, Grace J (2008). Pollution-swapping: nitrate interception and nitrous oxide production in a constructed wetland in the Scottish Borders. In: Bosch A, Teira MR, Villar, JM (eds.). Towards a Better Efficiency in N Use. Editorial Milenio, Lleida, Spain.

Verhoeven JTA, Van der Toorn J (1990). Marsh eutrophication and wastewater treatment. In: Patten, B.C. (ed.). Wetlands and Shallow Continental Water Bodies, Vol. 1. SPB Academic Publishing, The Hague, Netherlands, pp. 571-586.

Vymazal J, Kröpfelová L (2008). Wastewater Treatment in Constructed Treatment Wetlands with Horizontal Sub-Surface Flow. Springer Science.

Walker DJ, Hurl S (2002). The reduction of heavy metals in a stormwater wetland. Ecol. Eng., 18: 407-414.

Walski TM (1993) Long-term effects of wetland treatment of mine drainage. J. Environ. Eng., 119: 1004-1005.

Tarutis WJ, Stark LR, Williams FM (1999). Sizing and performance estimation of coal mine drainage wetlands, Ecol. Eng., 12: 353-372.

Woltemade CJ (2000). Ability of restored wetland to reduce nitrogen and phosphorus concentrations in agricultural drainage water. J. Soil Water Cons., 55: 303-309.