Journal of Environmental Protection, 2015, 6, 710-718
Published Online July 2015 in SciRes. http://www.scirp.org/journal/jep
http://dx.doi.org/10.4236/jep.2015.67064

A Review on Constructed Wetlands Components and Heavy Metal Removal from Wastewater

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Received 28 May 2015; accepted 21 July 2015; published 27 July 2015

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Abstract

Constructed wetlands are man-made complex of substrates, emergent/submergent vegetation, and water. Constructed wetlands have been known as an efficient and low-cost treatment process. Constructed wetland is a natural treatment system that physical, chemical, and biological processes occur when water, soil, plants, and microorganisms interact. They are considered as natural treatment ecosystems that are designed to take advantages of the natural processes to provide wastewater treatment. Constructed wetlands treat different types of wastewaters such as municipal, industrial, agricultural, and storm water. The removal of heavy metals within wetlands is performed generally by plant uptake and by adsorption onto sediments. Heavy metal treatment examples and some specifications and regulations are finally discussed.

Keywords

Constructed Wetlands, Wastewater, Heavy Metals

1. Introduction

Constructed wetlands have been known as an efficient and low-cost treatment process. They are considered as natural treatment ecosystems that are designed to take advantages of the natural processes to provide wastewater treatment [1]. The removal of metals within wetlands is performed generally by plant uptake or by adsorption onto sediments in the system [2]. Heavy metals are harmful components associated with many agricultural and industrial wastewaters. Heavy metals may undergo a variety of physical and chemical transformations, subsequently, various heavy metals can be found in soils, water, air, and in living species. The hazards of heavy met-

How to cite this paper: Qasaimeh, A., AlSharie, H. and Masoud, T. (2015) A Review on Constructed Wetlands Components and Heavy Metal Removalfrom Wastewater. *Journal of Environmental Protection*, **6**, 710-718.
http://dx.doi.org/10.4236/jep.2015.67064

als are associated with their toxicity, carcinogenety, and their impairment to the environmental systems.

Constructed wetlands have been used for the treatment of municipal, industrial, acidic, and agricultural wastewater. The natural treatment system is the one that physical, chemical, and biological processes occur when water, soil, plants, and microorganisms interact. Natural treatment systems are utilized to take advantage of these processes to provide wastewater treatment [1]. Constructed wetlands are man-made complex of saturated substrates, emergent and submergent vegetation, and water, which simulate natural wetlands for human benefits [3]. They consist of inundated land areas with water depth typically less than 0.6 m that support the growth of emergent plants such as Cattail, Reeds, and Water Hyacinth. Both natural and constructed wetlands have been used for the treatment of wastewater, although the use of wetlands is generally limited to the polishing or further treatment of secondary or advanced treated effluent [1]. Constructed wetlands can be designed as free water surface system (FWS) or subsurface flow system (SFS). FWS typically consists of basin with relatively impermeable bottom soil, emergent vegetation, and shallow water depths of 0.1 to 0.6 m. SFS consists of basin that is filled with permeable soil or gravel media where plant is growing, and the wastewater is flowing through the permeable media from the inlet toward the outlet with impermeable bed of 1% slope [1].

2. Wetland Components Description

2.1. Wetland Influent Water

The influent wastewater entering the constructed wetlands can be municipal, industrial, agricultural, or storm water.

2.1.1. Municipal Wastewater

In many countries, wetlands are being used as a post-treatment facility for domestic wastewater [4]. The main components that should be removed from municipal wastewater are organic and inorganic materials, nutrients, pathogens, and suspended solids. Biodegradable components can be removed by bacterial metabolism, whereas some inorganics like phosphorus should be removed by chemical coprecipitation with iron, aluminum, and calcium compounds in the soil [3]. The recommended biological oxygen demand (BOD) loading rate is in the value of 60 kg/ha·d. It must be limited such that the oxygen demand of the applied wastewater does not exceed the oxygen-transfer capacity of wetland vegetation. The oxygen-transfer rate for emergent plants is in the range 5 to 45 g/m^2·d with average value of 20 g/m^2·d, which is considered to be typical. Increased oxygen transfer on a system wide basis can likely be achieved by using alternating vegetated and open-water cells [1]. In Canada, municipal wastewater is being treated by constructed wetlands, including primary and secondary effluent from activated sludge and lagoon systems, landfill leachate, and septic tank effluent [5]. The municipality of Stoke (Quebec) completed a constructed wetland in the fall of 1993 to treat the effluent from an existing septic system after carrying out preliminary feasibility study for the wetland system [6]. In July 1980, the Ontario Ministry of Environment (MOE) initiated the Listowel Marsh project in Southern Ontario. The community of Cobalt was selected to check the suitability of wetlands for wastewater treatment in Northern Ontario. The results of this project showed that the BOD_5 concentrations were reduced by 80% [7]. Another example showed by authors in reference [8] as they conducted experiment for utilizing constructed wetlands to treat municipal wastewater including sewage and landfill leachate. The experimental units of wetlands with macrophytes were used successfully for the post-treatment of effluent from a UASB (upflow anaerobic sludge blanket) reactor treating domestic sewage.

New York began in the spring of 1988 an investigation of the feasibility of constructed wetlands for landfill leachate treatment [9]. Sewage treatment with emergent aquatic macrophytes was introduced in Denmark in 1983, the results showed the reduction of BOD_5 by 70% - 90%, total nitrogen by 25% - 50% and total phosphorus by 20% - 40% [10].

2.1.2. Industrial Wastewater

The wastewater discarded from industry can be correlated with several activities: the acid mine drainage, oil refining, pulp and paper industry, industrial thermal discharge, and manufacturing processes. Reference [5] reported that constructed wetlands in Canada were applied for treating industrial wastewaters released from dairy industry; meat processing, rendering plants, and refinery processes. The wetlands are able to achieve variety of treatments such as, 1) metals removal; 2) pH adjustment; 3) ammonia removal; 4) BOD removal.

Industrial wastewater treatment requires that the wetland discharge effluent temperature does not exceed 32.2˚C and pH to be in the range from 6.0 to 8.5 [11]. The importance of microorganisms as catalysts of inorganic chemical reactions has been recognized in commercial metal recovery. These reactions are presented with their relevance to generation, prevention, and abatement of acidic drainage in mining processes. Wetlands are enrolling previously mentioned reactions through solubilization and reprecipitation to remove metals such as Fe, Cu, Zn, Mn, and Al [12]. The Acid mine drainage is commonly related to coal and metal mining. Several hundred of wetlands have been constructed in the coal bearing states of Maryland, West Virginia, Pennsylvania, and Ohio to reduce the impacts from acid mine drainage [13]. In Canada, constructed wetlands are being used to treat fish hatchery wastewater at Rosewall United Fish Farms in Coal Creek (British Columbia) [6].

Primary treatment of wastewater from the refinery process unit is accomplished by separating and recovering oil from other contaminants, and then the water is discharged to the wetland for secondary series of treatment [14]. Amoco Oil Company used constructed wetlands for wastewater treatment at its refinery in Mandan, North Dakota, before to discharge the effluents to the Missouri River [14].

Natural and artificial wetland systems have been used for treatment of pulp mill effluents. About 60% - 90% of phenol and m-cresol could be removed by artificial marshes containing Cattail or Reed at a retention time of 24 hours [15]. Allender in reference [16] tested the effectiveness of a variety of aquatic plants native to Australia to treat pulp and paper mills effluents. These experiments were conducted under static conditions over a period of few weeks. The aquatic plants proved effectiveness in removing several pollutants such as: ligosulfates, foaming propensity, color, BOD, and total suspended solids (TSS).

2.1.3. Agricultural Wastewater

In USA by 1984, officials from 49 states reported that 29% of lakes and reservoirs were moderately to severely affected by nonpoint source of pollution, mainly from agricultural activities [17].

In Canada, CMHC-SCHL in reference [5] stated that the agricultural wastewater was a resultant from farm feedlot runoff, milkhouse wash-water discharge, and runoff subsequent to fertilizers application. In Stratford (Ontario), constructed wetlands are used to treat contaminated barnyard runoff resulted from farms in Fullerton Township-Stratford [6].

Wetlands are used as treatment system in dairy farms; Lough Gara Farms Limited established in Ireland had an intensive dairy farm to produce milk for direct retail sale in 1961. The treatment system in Lough Gara Farms uses natural wetland formed as a result of successive drainage schemes carried out in a lake and its tributaries, and rivers [18]. In Maryland the creation of wetlands for the improvement of water quality led to have a proposal for incorporation the public lands through joint use of highway-right of way. The proposal identifies a potential highway site for joint use as a constructed wetland to control urban non-point source pollution from highly developed and established urban areas and provides preliminary analysis of the site's control effectiveness and life cost [19].

2.1.4. Storm Water Runoff

Wetlands are the default recipients of storm water runoff, due to their position in the landscape. Various wetland types can act as sinks or transformers of nutrients, organic and inorganic materials, and suspended solids of storm water runoff [20]. Rainfall could affect the component of wetland system by either diluting the pollutant concentration or decreasing the retention time and thus affecting the quality of final effluent [21]. Runoff from parking lots and roadways in residential areas contains high concentrations of suspended solids, nutrients, trace metals, oil, grease, and deicing salts [22]. Runoff at airports may contain leakage from aircraft fueling and defueling. In cold weather areas deicing chemicals are also important pollutant [23]. Wetlands enhance water quality through a variety of physical, chemical, and biological processes that trap and degrade pollutants. The physical processes of sedimentation, adsorption to soils, filtration, and uptake by plant are keys in capturing pollutants. Pollutants may be degraded biologically by microorganisms and flora, stored, or removed by dredging [24]. Carleton in reference [25] suggested the constructed wetland approach for the treatment of storm water runoff from residential town-home complex in northern Virginia. This approach was to convert dry detention pond facility to be storm water wetland for the treatment of town runoff. Applying such approach may have a promise for providing a low-cost retrofit to improve water quality at older detention facilities, where water quality improvement was not a primary design issue.

2.2. Wetland Vegetation

Wetlands have individual and group characteristics related to plant species and to their adaptations to specific hydrological, nutrient, and substrate conditions. Plants utilized in wetlands are either terrestrial or aquatic habitats. Aquatic plants are divided into free floating and rooted forms. The rooted class is subdivided into emergent, floating, and submerged classes. The adaptation of certain plant depends on the design criteria of wetland, morphological, and physiological features of plant. The growth of plant in relation to the water surface should be taken in consideration, as well as the plant foliage, inflorescence, phytosociologic criteria, life growth, and growth form [26].

Vegetation play an integral role in wetland treatment system by transferring oxygen through their roots to the bottom of treatment basins, and by providing a medium beneath the water surface for the attachment of microorganisms that perform the biological treatment. The plants used frequently in constructed wetlands include Cattails, Reeds, Water Hyacinth, Rushes, and Duckweed [1]. Water Hyacinth (*Eichhornia crassipes*) is an aquatic plant that grows very vigorously and uses highly the nutrients in the environment. The growth rate of Water Hyacinth is affected by the water quality, nutrient content, harvesting interval, and solar radiation. The growth rate of Water Hyacinth is higher in the period from May to June than in other seasons [27]. Reeds (*Phragmites communis*) grow along the shoreline and in water up to 1.5 m but are poor competitors in shallow waters; they are selected for SFS systems because the depth of rhizome penetration allows for the use of deeper basins [1]. Aquatic plants have ability to uptake trace metals; this phenomenon has brought wetlands to new scale of treatment.

2.3. Wetland Soil

Mineral composition of the bottom of the wetland has an important impact on the dynamics of pollutant cycle within the wetland. Clay is the most common component of wetland bottom sediments due its low permeability. Clay mineral particles are colloids having high specific surface area that influences soil adsorption properties [28]. The presence of organics as opposed to mineral soil constituents has an important impact on soil chemical characteristics. The chemical and physical differences between mineral and organic soils play a large role in determining the suitability of particular soil for a specific wastewater treatment [29]. The development of biofilms on contaminated bed sediments can reduce erosion and contaminant transport from the bottom [30]. Wetlands should have low-permeable soil surfaces (Permeability < 1.41×10^{-6} m/s), because the objective is to treat the wastewater in water layer in wetland; therefore, percolation losses through the soil profile are minimized [1]. The physical and chemical properties of soil affect the design and the term of treatment. These properties can be summarized as the following: soil matrices of minerals, organic matter, particle size, pore spaces, hydraulic conductivity, specific surface area, ionic charge, cation exchange capacity, pH, and temperature [29].

The most common sorption models are Langmuir and Freundlich isotherms. The diffuse double layer model (DDL) and Triple-layer model (TLM) describe the sorption process of the charged species into soil particles from the solution. These models can describe the process through which wetland bottom sediments attract the ionic forms of contaminants from wastewaters.

The Freundlich isotherm is a general empirical adsorption isotherm. It has been characterized by sorption that continues as the concentration of sorbate increases in the aqueous phase. It is expressed in the following form:

$$W_s = \alpha C_w^{1/n} \tag{1}$$

where W_s is the weight of contaminant adsorbed on the soil solid; C_w is the concentration of contaminant in the solution; α and n are constants to be determined from experimental data.

The Langmuir isotherm is based on the assumption that a single monolayer of sorbate accumulates at the solid surfaces, it can be derived by assuming that a finite number of sorption sites in the solid phase exist and that the rate of sorption is proportional to the sites remaining. The Langmuir isotherm has the general form:

$$W_s = \alpha_1 \frac{c_w}{1 + \alpha_2 c_w} \tag{2}$$

where α_1 and α_2 are empirical constants to be determined from experimental data [31].

In the diffuse double layer (DDL) model, the cations in the wastewater such as heavy metals come to interaction with the negatively charged soil particle surface, which generate an arrangement of negative and positive charges at the interface. The separation distance between positive and negative charges, and the distribution of positive charges are important items considered in the development of what is generally identified as diffuse double layer model (DDL model) [28].

The electrical potential drops off exponentially with distance from the particle and reaches a uniform value in the solvent outside the DDL. The zeta potential is the voltage difference between plane a short distance from the particle surface and the bulk liquid beyond the double layer [32].

The thickness of this electric double layer (ion cloud) around colloidal particles determines how close two particles can get to each other before they start experiencing repulsive forces. The thickness depends on some factors such as:

1) The magnitude of the surface charge which depends on the solution concentration of the adsorbing ion;

2) The concentration of electrolyte in solution.

Triple-layer model is generally more complex. By the implementation of the triple-layers model, only protonation and deprotonation of surface sites are assigned to what so called the 0-plane with the charge σ_0 and potential ψ_0 in that zone. Other specifically adsorbed ions are assigned to the β-plane and determine the charge σ_β and potential ψ_β in that zone. Non-specifically adsorbed ions are envisioned as residing in the diffuse layer (d) and are influenced by ψ_d potentials (**Figure 1**). The capacitance between the o-plane and the β-plane is denoted C_{cap1} and between the β-plane and d-plane is denoted C_{cap2}. The potential gradients in the inner and outer zones are linear, but potentials decay exponentially in the diffuse layer zone [33].

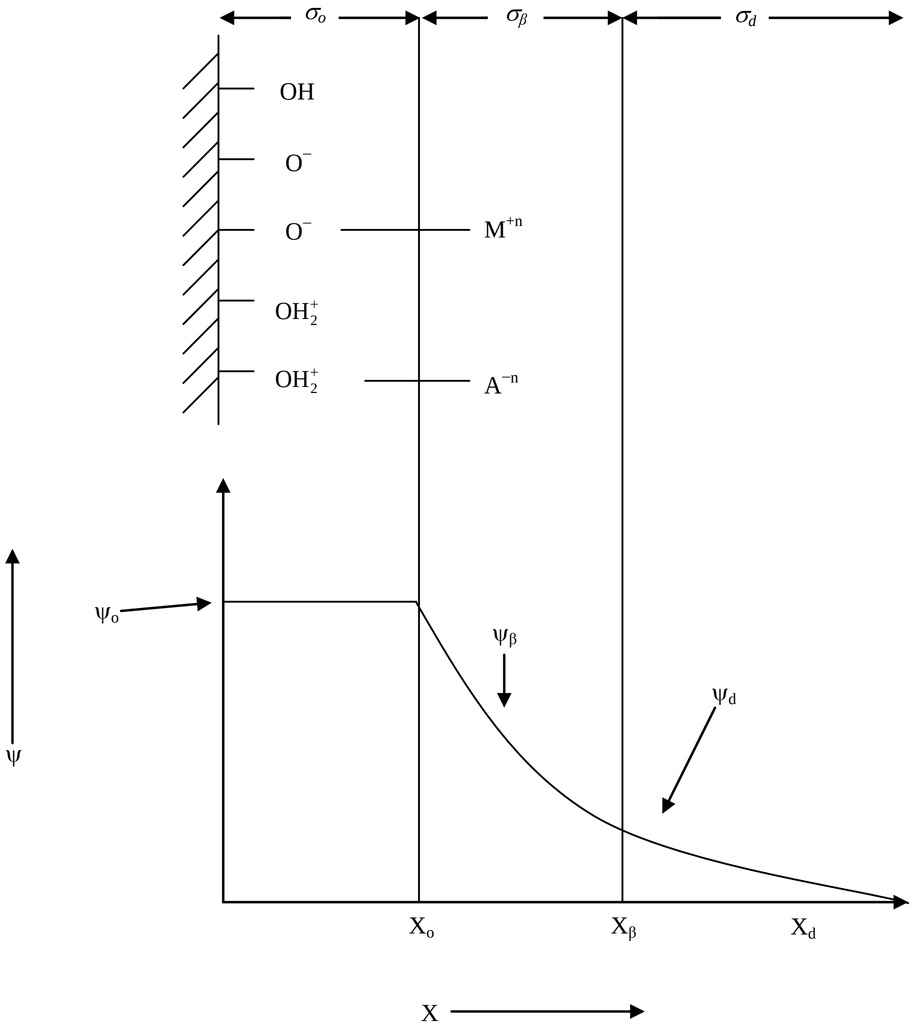

Figure 1. Schematic diagram of the triple layer model.

3. Heavy Metals Removal

Aitchison in reference [34] obtained results suggested that phytoremediation was a viable alternative to remove dioxane from contaminated soils and should be considered for other hydrophilic contaminants. This is an example for the role of plants to uptake industrial heavy pollutants in constructed wetlands.

All pollutants found in airport runoff, including heavy metals and glycols, were treated and removed to low levels in well-designed constructed wetland systems [25].

Authors in reference [25] suggested the constructed wetland approached for the treatment of storm water runoff from residential town-home complex in northern Virginia. The constituents of the runoff for both townhouse and forested subwater sheds were sinks for metals such as Al, Cu, Pb, and Zn. Most constituents were lower in the outlet of the wetland than that in the inlet.

Constructed wetlands are enrolling solubilization and reprecipitation processes to remove metals such as Fe, Cu, Zn, Mn, and Al from wastewaters [12].

Author in reference [2] showed that Water Hyacinth in constructed wetlands were able to remove up to 95% of bioavailable mercury discharged within the wetland system during a period of 3 days. The bioavailablility of mercury was influenced mainly by initial mercury concentration, chloride concentration, and pH value. These conditions influence the mercury speciation in the solution. Plants are able to uptake the bioavailable ionic form of mercury $\left(Hg_2^{2+}\right)$ from wastewater.

There is a general tendency for mercury to accumulate in the roots of the plants [35]. For initial mercury concentration in solution of 50 ppb, the average mercury content in the roots of Water Hyacinths was 3.5 times greater than those in Reeds. After the first three hours, the Water Hyacinth roots accumulate 110.55 μg/g compared to only 28.9 μg/g accumulated in Reeds roots [2]. In reference [36], the authors showed that mercury concentration in alfalfa roots was 133 times higher than its concentration in alfalfa foliage. Authors in reference [37] used artificial intelligence approach and concluded that the highest bioavailable mercury concentration for Water Hyacinth uptake achieved by maintaining the following conditions: the initial total mercury concentration between 1×10^{-4} and 1×10^{-3} moles/l; the chloride concentration between 1×10^{-8} and 1×10^{-6} moles/l; and pH values between 5.36 and 6.5. Considering the above-mentioned conditions, it is expected to achieve the concentration of bioavailable mercury as 6.7×10^{-6} moles/l. These conditions are recognized as the best removal parameters, as they provide higher bioavailable mercury to be uptaken by plants [38] [39].

4. Constructed Wetlands Specifications and Regulations

With the increased use of constructed wetlands, government agencies are concerned with devising appropriate design criteria, specifications, and regulations. According to the North American Wetlands Conservation Council (Canada), the wetland design requires careful consideration of the wetland system, the configuration, the size, the detention time, the water source, the bottom sediments, and the type of vegetation. In SFS, a maximum hydraulic loading rate of 0.025 to 0.05 m/d, and a minimum size of 3 - 4 ha for 1000 m^3/d have been recommended by the Water Pollution Control Federation-1990 [6]. The wetland configuration is specified to have (length: width) ratio of at least 2:1, gradual wetland slope on the order of 0.05%, and deep zones oriented perpendicular to the wetland flow to provide even distribution of the wetland flow. The maximum water depth for surface flow wetland is confined to 0.5 m. Minimum hydraulic retention time for surface flow and subsurface flow wetlands can be in the range of 5 - 10 days. Maximum BOD_5 loading rates of 100 - 110 kg/ha/d are recommended for surface flow wetlands, and 80 - 120 kg/ha/d for subsurface flow wetlands as regulated by Water Pollution Control Federation-1990 [6]. USEPA's Environmental Technology Initiative Program is supporting a team of regulators and affected parties to identify, describe, and provide recommendations to resolve constructed wetlands policy and permitting issues at the federal level [40].

Good construction practices and specifications should be followed during the construction of wetland. Examples include properly evaluating the site, limiting damage to the local landscape by minimizing excavation and surface runoff during construction, and maximizing flexibility of the system to adapt to extreme conditions. Construction specifications and drawings should be utilized that clearly convey the procedures to be used in construction criteria. USEPA stated that general construction storm water CWA Section 402 (NPDES) permit must be obtained for any project 5 acres in size or greater. This permit requires development and implementation of a Stormwater Pollution Prevention Plan including best management practices to minimize pollutant loading during construction. In wetland soils; it is recommended to avoid soil sources that contain a seed bank of unwanted species. The soil's permeability and the implications for ground water protection should be considered. Vegetation selection criterion is that the species should be chosen for water quality and treatment conducted in the project. The use of weedy, invasive, or non-native species should be avoided. Also designer should consider the plants' abilities to adapt to various water depths, soils, and light conditions at the constructed wetland site [41].

5. Conclusion

Constructed wetlands have proved their efficiency and low-cost wastewater treatment processes. In the literature reviewed, the constructed wetlands are natural water, soil, plants, and microorganisms' integral systems, they provide physical, chemical, and biological processes for wastewater treatment. They treat different types of wastewaters such as municipal, industrial, agricultural, and storm water. The removal of heavy metals within wetlands is performed generally by plant uptake and by adsorption onto sediments. With the increased use of constructed wetlands, design criteria, specifications, and regulations are concerned.

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