Centre for Development Innovation

Constructed wetland and aquatic treatment systems for fish farms in Egypt

Desk study report

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Constructed wetland and aquatic treatment systems for fish farms in Egypt
Literature study report

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This report summarises the information found in scientific literature regarding the mechanisms and processes that enable constructed wetlands to remove heavy metals and pesticides from waste water. It examines what factors have an influence on the effectiveness of constructed wetlands to treat waste water containing such pollutants and shows the impact on the design and operation of constructed wetlands. It focuses on free surface flow wetlands and aquatic treatment systems because these types are found to be most able to treat the large volumes of water that are required to fill and maintain water levels of fish ponds as operated in Egypt. This literature study is part of the project 'Investigating the suitability of constructed wetlands for the treatment of water for fish farms' (BO-27.02-001-007), which aims to test the effectiveness of a pilot constructed wetland at a private fish farm in Kafr El Sheikh Governorate, Egypt.

Photos
Photo on front page: Nile tilapia being caught at a fish farm in Kafr El Sheikh Governorate, Egypt.
Photo by Peter G.M. van der Heijden

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List of abbreviations and acronyms

BOD_5	Biological Oxygen Demand (determined over 5 days)
CDI	Centre for Development Innovation, Wageningen UR
COD	Chemical Oxygen Demand
CWs	Constructed wetlands
DOM	Dissolved Organic Matter
FPEA	Fish Producers and Exporters Association
HRT	Hydraulic Retention Time
PBCPs	Personal Body Care Products
SF	Surface-Flow
SSF	Sub-surface Flow
SS	Suspended Solids
TN	Total Nitrogen content
TOC	Total Organic Carbon
VHL	Van Hall Larenstein
Wageningen UR	Wageningen University & Research centre

1 Introduction to constructed wetland systems for fish farms in Egypt

Constructed wetlands and natural water treatment systems aim to control and optimize the ability of a wetland to remove or transform wastewater pollutants. In many cases an attractive environment for the development of wildlife and social objectives is obtained.

The constructed wetland can either mimic natural systems in the sense that the water flows over the bed surface and is filtered through the dense stand of aquatic plants. The system can also promote subsurface flow through the shallow, permeable substratum in which the plants are established (2).

Fish farms in Egypt produce over 900,000 tons of fish annually and contribute over 60% of the fish consumed by the Egyptian population (1). Egyptian laws prohibit the use of (relatively clean) irrigation water by fish farms, causing the majority of the farms to rely on water from drainage canals to fill the ponds. The use of such water includes the risk of contamination of the produced fish with pollutants (agrochemicals and heavy metals). Constructed wetlands (CWs), that are in principle sand filters planted with reeds and other swamp plants, may be able to filter (part of) the hazardous chemicals from the water. They can also play a role in treating the waste water that is drained from the ponds and make it suitable for re-use on the fish farm.

The project 'Investigating the suitability of constructed wetlands for the treatment of water for fish farms (BO-27.02-001-007)' is financially supported by the Netherlands Ministry of Economic Affairs, coordinated by the Centre for Development Innovation, Wageningen UR (CDI) and executed in collaboration with the ECOFYT and the Fish Producers and Exporters Association (FPEA). The project investigates the suitability of Constructed Wetlands to remove hazardous compounds from the drainage canal water and will analyse if the fish produced in water treated by the pilot CW is of better quality (i.e. has lower levels of hazardous chemicals). After selection of the type of Constructed Wetland deemed to be most suitable for Egyptian fish farm conditions (free surface flow), a pilot CW has been constructed on a private fish farm. The effectiveness of the pilot CW will be assessed by comparing the levels of various hazardous compounds accumulated in fish raised in ponds filled with treated water with the levels in fish raised in ponds filled with untreated drainage canal water.

This report is the result of an assignment executed by Van Hall Larenstein for the Centre for Development Innovation, Wageningen UR, as part of the above mentioned project. It serves as theoretical basis for the practical work undertaken in Egypt. The report summarises the information found in scientific literature regarding the mechanisms and processes that enable constructed wetlands to remove heavy metals and pesticides from waste water. It examines the factors that have an influence on the effectiveness of CWs to treat waste water containing such pollutants and shows the impact of these factors on the design and operation of constructed wetlands. The focus of the report is on free surface flow wetlands and aquatic treatment systems because these types are found to be best able to treat the large volumes of water that are required to fill and maintain water levels of fish ponds as operated in Egypt.

2 Advantages of natural treatment systems

Constructed wetlands are relatively cheap to build where land is available. They can be easily operated and maintained. Aesthetically, a CW looks more like a natural wetland landscape when compared to the conventional wastewater treatment plants. This system promotes sustainable use of local resources, which is an environment friendly biological wastewater treatment system.

Besides from lower construction costs than other treatment options, constructed wetlands can operate with low-technology methods where no new or complex technological tools are needed. The system relies on renewable energy sources such as solar and kinetic energy; wetland plants and micro-organisms are the active agents in the treatment processes (5).

The system can tolerate both great and small volumes of water and varying contaminant levels. These include municipal and domestic wastewater, urban storm runoff, agricultural wastewater, industrial effluents and polluted surface waters in rivers and lakes. The system could be promoted to various potential users for water quality improvement and pollutant removal. These potential users include the tourism industry, governmental departments, private entrepreneurs, private residences, aquaculture industries and agro-industries.

Utilisation of local products and labour helps to reduce the operation and maintenance costs of the applied industries. Less energy and raw materials are needed, with periodic on-site labour, rather than continuous full time attention.

The constructed wetland system also could be used to clean polluted rivers and other water bodies. This derived technology can eventually be used to rehabilitate grossly polluted rivers in the country. The constructed wetland treatment system is widely applied for various functions. These functions include primary settled and secondary treated sewage treatment, tertiary effluent polishing and disinfection, urban and rural runoff management, toxicant management, landfill and mining leachate treatment, sludge management, industrial effluent treatment, enhancement of in-stream nutrient assimilation, nutrient removal via biomass production and export, and groundwater recharge.

The primary purpose of constructed wetland treatment systems is to treat various kinds of wastewater (municipal, industrial, agricultural and storm-water). However the system usually serves other purposes as well. A wetland can serve as a wildlife sanctuary and provide a habitat for wetland animals. The wetland system can also be aesthetically pleasing and can serve as an attractive destination for tourists and local urban dwellers. It can also serve as a public attraction sanctuary for visitors to explore its environmental and educational possibilities. It appeals to different groups varying from engineers to those involved in wastewater facilities as well as environmentalists and people concerned with recreation. This constructed wetland treatment system also provides a research and training ground for young scientists in this new research and education arena (2).

3 Types of natural treatment systems

Constructed wetlands used for the treatment of (municipal) waste water can be divided into three systems according to the life form of the dominant macrophyte (= higher plant) (3):

- Free floating system;
- Rooted emergent system;
- Submergent system.

While on other continents all these systems are in use, the vast majority of European systems are based on rooted emergent macrophytes. Within this group different designs are used (4):

1. Surface flow systems;
2. Subsurface flow systems with either soil or gravel as a substrate and a horizontal or vertical flow regime;
3. Aquatic Treatment Systems.

The elimination principles are the same for all systems. Raw or pre-treated wastewater is piped into the facility and flows through the substrate. The elimination processes take place during this passage; organic matter is biodegraded either aerobically or anaerobically and nutrients are eliminated in various ways.

3.1 Surface flow or free-water surface systems

The majority of constructed wetland treatment systems are Surface-Flow (SF) or Free-Water surface systems (Figure 1). These types utilise influent waters that flow across a basin or a channel that supports a variety of vegetation; water is visible at a relatively shallow depth above the surface of the substrate materials. Substrates are generally native soils and clay or impervious geotechnical materials that prevent seepage (5). Inlet devices are installed to maximise sheet flow of wastewater through the wetland, to the outflow channel. Typically, bed depth is about 0.4 m. (5)

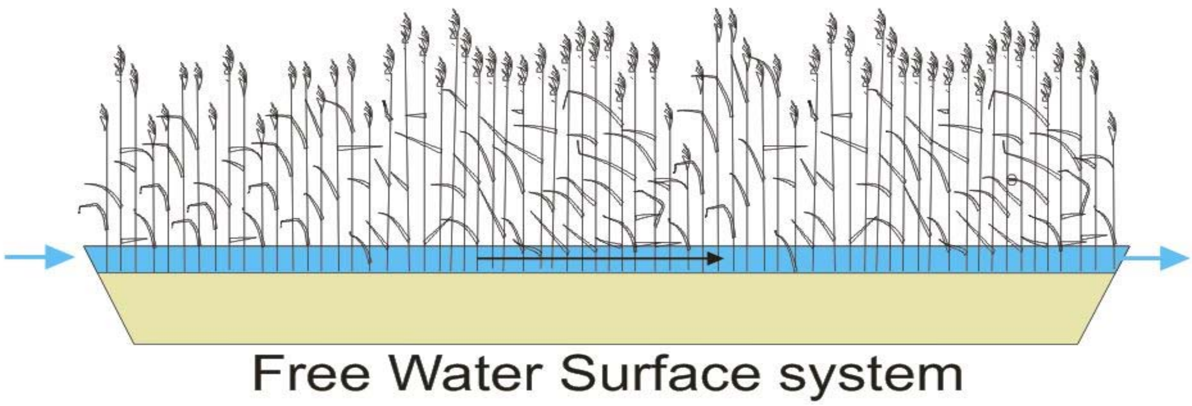

Figure 1: Typical configuration of a surface flow wetland system (source: © ECOFYT.com)

3.2 Sub-surface flow systems

In a vegetated Sub-surface Flow (SSF) system, water flows from one end to the other end through permeable substrates which is made of mixture of soil and gravel or crusher rock. The substrate will support the growth of rooted emergent vegetation. It is also called “Root-Zone Method” or “Rock-Reed-Filter” or “Emergent Vegetation Bed System”. The media depth is about 0.6 m and the bottom is a clay layer to prevent seepage. Media size for most gravel substrate ranged from 5 to 230 mm with 13 to 76 mm being typical. The bottom of the bed is sloped to minimise water that flows overland. Wastewater flows by gravity horizontally through the root zone of the vegetation about 100-150 mm below the gravel surface. Many macro and micro-organisms inhabit the substrates. Free water is not visible. The inlet zone has a buried perforated pipe to distribute maximum flow horizontally through the treatment zone. Treated water is collected at outlets at the base of the media, typically 0.3 to 0.6 m below bed surface (6).

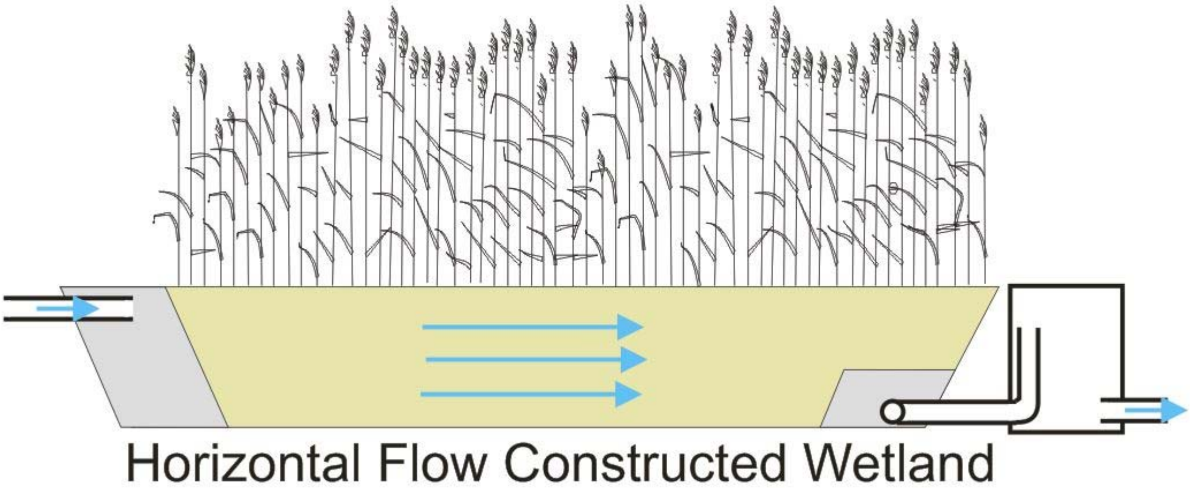

Figure 2. Typical configuration of a horizontal-flow wetland system (source: © ECOFYT.com)

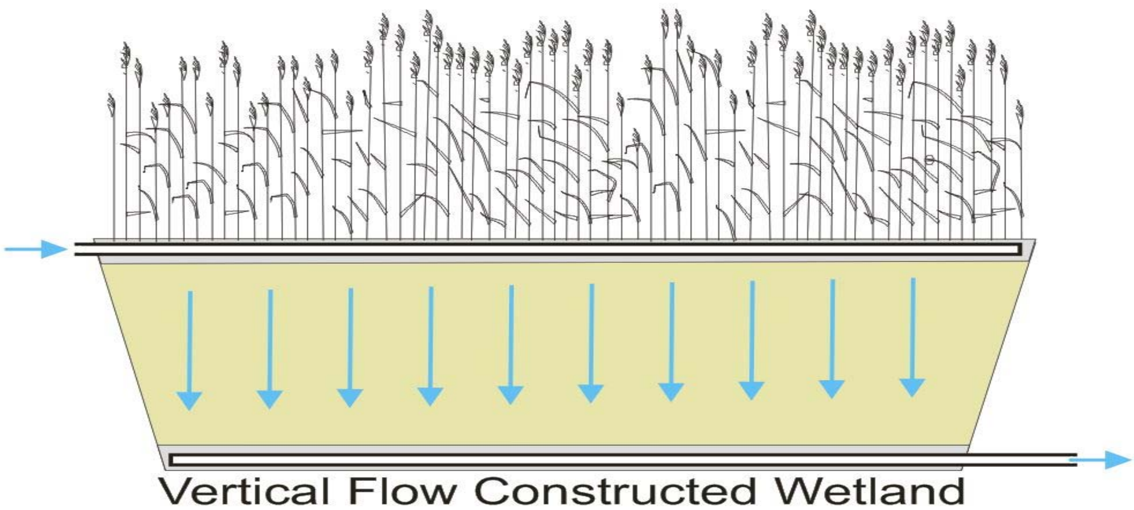

Figure 3. Typical configuration of a vertical flow wetland system (source: © ECOFYT.com)

3.3 Aquatic Treatment Systems

Aquatic plant systems are engineered and constructed systems that use submerged or floating aquatic plants in the treatment of industrial or domestic wastewater. They are designed to achieve a specific wastewater treatment goal. Aquatic plant systems can be divided into two categories (5):

- Systems with floating aquatic plants such as water hyacinth, duckweed, pennywort; and
- Systems with submerged aquatic plants such as waterweed, water milfoil, and watercress

Aquatic treatment systems consist of one or more shallow ponds in which one or more species of water tolerant vascular plants such as water hyacinths or duckweed are grown (7). The shallower depths and the presence of aquatic macrophytes in place of algae are the major differences between aquatic treatment systems and stabilization ponds. The presence of plants is of great significance in wastewater treatment practices because the effluent from aquatic systems is of higher quality than the effluent from stabilization pond systems for equivalent or shorter detention times.

4 Roles of plants in wastewater treatment

In general, the most significant functions of wetland plants (emergent) in relation to water purification are the physical effects brought by the presence of the plants. The plants provide a huge surface area for attachment and growth of microbes. The physical components of the plants stabilise the surface of the beds, slow down the water flow thus assisting in the sediment settling and trapping process and finally increasing water transparency.

Wetland plants play a vital role in the removal and retention of nutrients and help in preventing the eutrophication of wetlands. A range of wetland plants has shown their ability to assist in the breakdown of wastewater. The common reed (*Phragmites spp.*) and cattail (*Typha spp.*) are good examples of marsh species that can effectively take up nutrients. These plants have a large biomass both above (leaves) and below (underground stem and roots) the surface of the substrate. The sub-surface plant tissues grow horizontally and vertically, and create an extensive matrix, which binds the soil particles and creates a large surface area for the uptake of nutrients and ions.

Hollow vessels in the plant tissues enable oxygen to be transported from the leaves to the root zone and to the surrounding soil (17). This enables the active microbial aerobic decomposition process and the uptake of pollutants from the water system to take place.

The roles of wetland plants in constructed wetland systems can be divided into 6 categories:

1) Physical - Macrophytes stabilise the surface of plant beds, provide good conditions for physical filtration and provide a huge surface area for attached microbial growth. Growth of macrophytes reduces current velocity, allowing for sedimentation and increase in contact time between effluent and plant surface area.

2) Soil hydraulic conductivity - Soil hydraulic conductivity is improved in an emergent plant bed system. Decay of root mass creates macropores in a constructed wetland soil system allowing for greater percolation of water, thus increasing effluent/plant interactions.

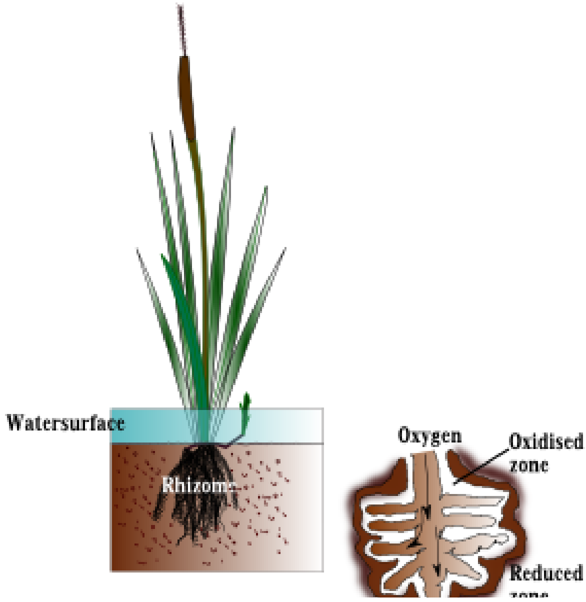

Figure 4: The extensive root system of marsh plants

3) Organic compound release - Plants have been shown to release a wide variety of organic compounds through their root systems, at rates up to 25% of the total amount of carbon fixed by means of photosynthesis. This carbon release may act as a source of food for denitrifying microbes (18). Decomposing plant biomass also provides a durable, readily available carbon source for the microbial populations.

4) Microbial growth - Macrophytes have biomass above and below ground to provide a large surface area for the growth of microbial biofilms. These biofilms are responsible for a majority of the microbial processes in a constructed wetland system, including Nitrogen reduction (18).

Plants create and maintain the litter/humus layer that may be likened to a thin layer of bacteria. As plants grow and die, leaves and stems falling to the surface of the substrate create multiple layers of organic debris (the litter/humus component). This accumulation of partially decomposed biomass creates highly porous substrate layers that provide a substantial amount of attachment surface for microbial organisms. The water quality improvement function in constructed and natural wetlands is related to and dependent upon the high conductivity of this litter/humus layer and the large surface area for microbial attachment.

5) Creation of aerobic soils - Macrophytes mediate transfer of oxygen through the hollow plant tissue and leakage from root systems to the rhizosphere where aerobic degradation of organic matter and nitrification will take place. Wetland plants have adaptations with lignified layers in the hypodermis and outer cortex to minimise the rate of oxygen leakage.

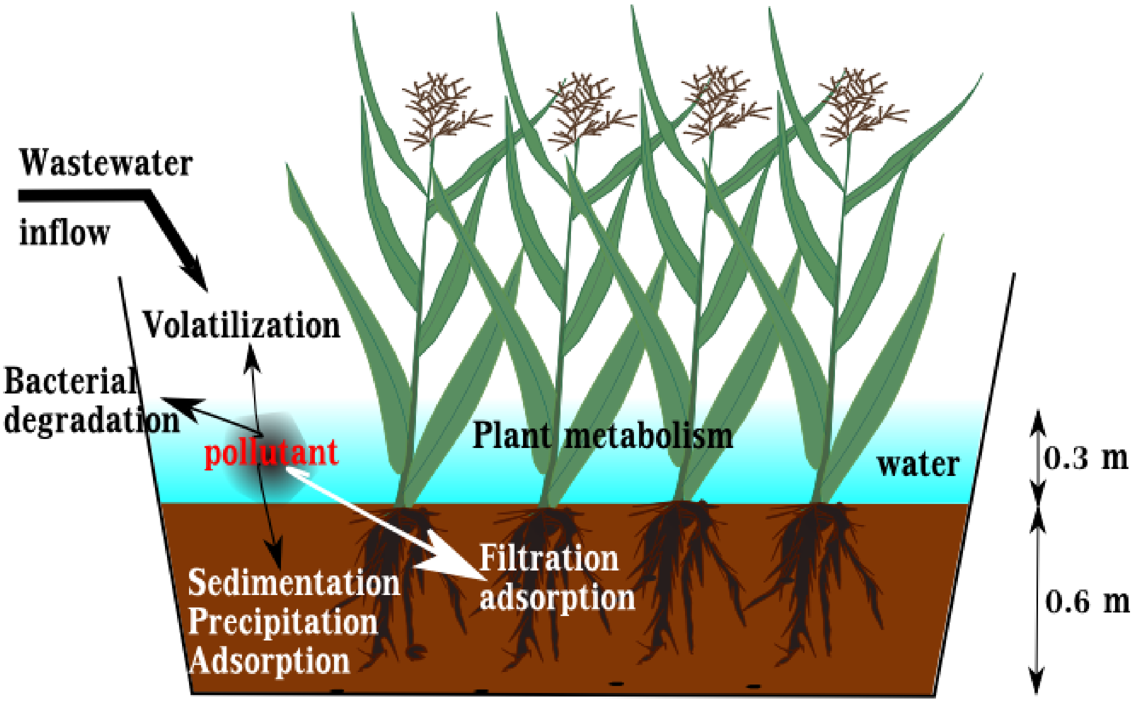

Figure 5. The various processes leading to pollutant removal in Constructed Wetlands

6) Aesthetic values - The macrophytes have additional site-specific values by providing habitat for wildlife and making wastewater treatment systems aesthetically pleasing.

4.1 Aquatic Treatment Systems

Aquatic plants have the same basic nutritional requirements as plants growing on land and are influenced by many of the same environmental factors. The treatment responses in an aquatic plant system are due to the presence of the plants in the water system altering the physical environment of the systems.

Floating plants have their photosynthetic parts at or just above the water surface with roots extending down into the water column. In photosynthesis, floating aquatic plants use atmospheric oxygen and carbon dioxide. Nutrients are taken up from the water column through the roots. These roots are an excellent medium for the filtration/adsorption of suspended solids and growth of bacteria. Root development is a function of nutrient availability in the water and nutrient demand (i.e., growth rate) of the plant. Thus, in practice, the density and depth of treatment medium (i.e., plants roots) will be affected by wastewater quality/pre-treatment and factors affecting plant growth rate such as temperature and harvesting.

With floating plants, the penetration of sunlight into water is reduced and the transfer of gas between water and atmosphere is restricted. As a consequence, floating plants tend to keep the wastewater nearly free of algae and anaerobic or nearly so, depending on design parameters such as BOD_5 loading rate, detention time, and the species and coverage density of floating plants selected for use (7). An observation of interest is that some molecular oxygen produced by photosynthetic tissue is transferred to the roots and may keep root zone-microorganisms metabolizing aerobically, though the surrounding water is anaerobic/anoxic (5).

In aquatic systems, wastewater is treated principally by bacterial metabolism and physical sedimentation, as is the case in conventional trickling filter systems. The aquatic plants themselves bring about very little actual treatment of the wastewater (7). Their function is to provide components of the aquatic environment that improve the wastewater treatment capability and/or reliability of that environment (12).

Floating aquatic plants have been used for wastewater treatment in a variety of processes, including the upgrading of facultative lagoon effluent, thereby achieving various degrees of advanced wastewater treatment depending on loading and management. The floating plants that have most been studied and used are water hyacinths and duckweed.

4.1.1 Water hyacinth

Water hyacinth systems are an emerging technology being developed in large scale pilot systems. The primary characteristics of water hyacinth that make them an attractive biological support medium for bacteria are their extensive root systems and rapid growth rate (see figure 6)

Water hyacinth (*Eichhornia crassipes*) is a perennial, freshwater aquatic vascular plant with rounded, upright, shiny green leaves and spikes of lavender flowers (13). The petioles of the plant are spongy with many air spaces and contribute to the buoyancy of the hyacinth plant. When grown in wastewater, individual plants range from 0.5 to 1.2 m from the top of the flower to the root tips (13). The plants spread laterally until the water surface is covered and then the vertical growth increases. Hyacinths are very productive photosynthetic plants. Their rapid growth is a serious nuisance problem in many slow flowing southern waterways. These same attributes become an advantage when used in a wastewater treatment system.

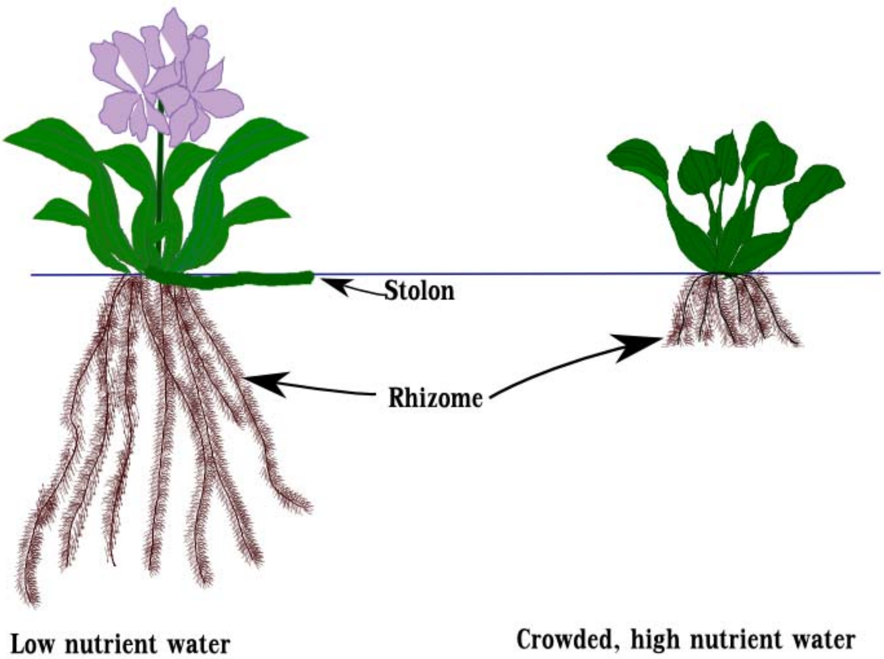

Figure 6. The extensive root system of the water hyacinth

Water hyacinth is a rapid growing aquatic macrophyte and is ranked eighth among the world's top 10 weeds in growth rate (14). It reproduces primarily by vegetative propagation, but seeds may be a major source of re-infestation once the parent plants have been removed. Water hyacinth also develops a large canopy, which may provide a good competitive edge over other floating aquatic plants growing in the same system. Growth of water hyacinth is influenced by:

- efficiency of the plant to use solar energy;
- nutrient composition of the water;
- cultural methods; and
- environmental factors (14).

Plant growth is described in two ways. The first is to report the percentage of pond surface covered over a period. The second more useful method is to report the plant density in units of wet plant mass per unit of surface area. Under normal conditions, loosely packed water hyacinth can cover the water surface at relatively low plant densities (10 kg/m^2 wet weight). It can reach a maximum density of 50 kg/m^2 wet weight (14), before growth ceases. As in other biological processes, growth rates in water hyacinth systems depend on temperature. Both air and water temperature are important in assessing plant vitality. Water hyacinths are reported to survive 24 hour exposure at temperatures of 0.5 to -5°C but die at temperatures of -6 to -7°C and cannot become established in regions where winter temperatures average 1°C (15). Growth is rapid at 20 - 30°C and nearly stops at 8 - 15°C (15).

4.1.2 Duckweed

Duckweeds are small, green freshwater plants with leaf-like frond from one to a few millimetres in width. Lemna and Spirodela have a short root usually between 10 mm and 20 mm in length (Figure 7). Duckweed such as *Lemna spp.*, *Spirodela spp.*, and *Wolffia spp.*, have all been tested for pollutant removal or used in wastewater treatment systems (13).

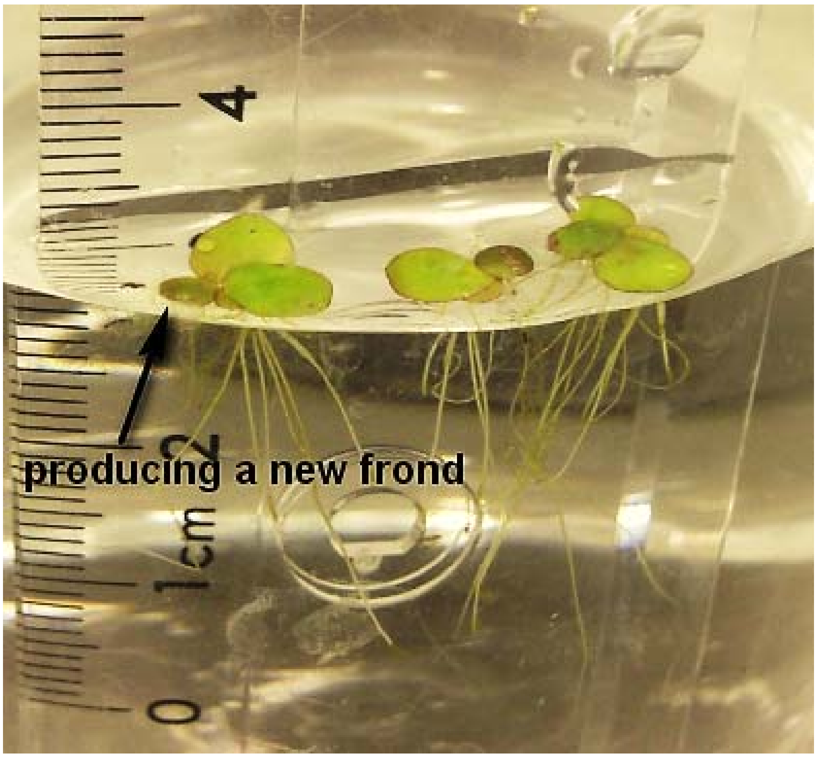

Figure 7. Duckweed (*Spirodela polyrhiza*) has a short root usually 10 mm till 20 mm in length (Photo: G. Truijen)

Duckweeds are the smallest and the simplest of the flowering plants and have one of the fastest reproduction rates. A small cell in the frond divides and produces a new frond (photo 1) ; each frond is capable of producing at least 10-20 more during its life cycle (16). *Lemna sp.* grown in wastewater effluent (at 27°C) doubles in frond numbers, and therefore in area covered, every four days. It is believed that duckweed can grow 30 % faster than water hyacinths. The plant is essentially all metabolically active cells with very little structural fibre (13).

Duckweed systems are developed by following the conventional design procedures for facultative lagoons. Effluent from a duckweed covered system should exceed performance of conventional facultative lagoons for BOD_5, SS and nitrogen removal (13). The effluent from a duckweed system is likely to be anaerobic and post aeration may be necessary. The advantage of duckweed systems over a similar additional facultative lagoon cell is lower algae concentrations in the effluent. This is due to extensive shading of the water by the layer of duckweed. Duckweed, like hyacinths, contains about 95 % water. It contains at least twice as much protein, fat, nitrogen, and phosphorus as water hyacinth.

Small floating plants, particularly duckweed, are sensitive to wind and may be blown in drifts to the leeward side of the pond. Redistribution of the plants requires manual labour. If drifts are not redistributed, decreased treatment efficiency may result due to incomplete coverage of the pond surface. Also piles of decomposing plants can result in the production of odours.

Duckweed (family Lemnaceae) systems have been studied alone and together with water hyacinths in polyculture systems. The primary disadvantage of duckweed are its shallow root systems and sensitivity to movement by winds. Experience has shown that loading rates ranging from 140 to as high as 700 m^3/ha.d can reduce BOD by as much as 80%.

Both water hyacinth and duckweed need to be harvested regularly.

5 Metal removal

Wetlands have the capability to remove metals from (waste)water (19). Different unique characteristics contribute to this capability.

Plants in treatment wetlands show elevated metal concentrations (20). The accumulated metal, however, generally accounts for less than 5% of total amount removed. There are no “metal-accumulators” in wetlands, like those found in terrestrial environments. Nonetheless, aquatic macrophytes play an essential role in creating an environment that promotes the removal of metals. Metal removal in wetlands stems from a variety of biogeochemical processes, including aerobic and anaerobic processes in the water column, on the surface of living and decaying plants and in sediments. A number of articles have reviewed these processes (21).

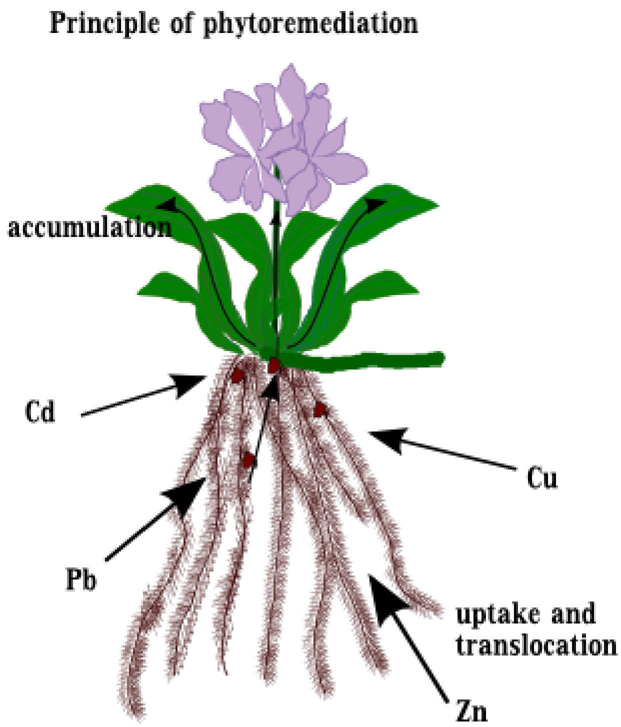

Figure 8. Metal accumulation process in plants

The most significant mechanisms include:

- Sorption and/or exchange onto organic matter (detritus);
- Filtration of solids and colloids;
- Formation of carbonates;
- Association with iron and manganese oxides;
- Metal hydrolysis (catalyzed by bacteria under acidic conditions);
- Reduction to non-mobile forms (also catalyzed by bacteria);
- Formation of insoluble metal sulfides;
- Biological methylation, followed by volatilization.

5.1 Sorption Onto Organic Matter

The affinity of metals for organic matter and their sorption onto it are well documented (22). These interactions are mainly mediated by the carboxyl and phenolic hydroxyl residues of molecules (e.g., humic acids) produced or exposed during the decomposition of plant matter (23). These molecules may contain different concentrations of ligands that bind complex metals through weak or strong interactions (24). Continued degradation may expose additional sites, and metals ultimately may form stable strong chelate complexes. Metals may also interact with organic matter associated with iron and manganese oxyhydroxides (23). Organic matter is abundant in the detritus layer of natural wetlands and clearly plays an important role in metal retention. Constructed wetlands can be designed to contain an organic substrate (e.g., spent mushroom compost), which partly mimics the detritus layer of a mature wetland.

Metals are adsorbed to particles by either ion exchange depending upon factors such as the type of element and the presence of other elements competing for adsorption sites (25) or chemisorption. Retention of Pb, Cu, and Cr by adsorption is greater than Zn, Ni, and Cd (26).

5.2 Filtration of Solids and Colloids

The filtration of colloid-associated metals may also play a role in metal removal.

5.3 Metal Oxidation and Hydrolysis

Aluminum, iron, and manganese can form insoluble compounds in treatment wetlands through oxidation and/or hydrolysis reactions:

$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$
$2Fe^{2+} + ½O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O$
$Fe^{3+} + 2H_2O \rightarrow FeOOH + 3H^+$
$2Mn^{2+} + ½ O_2 + 3H_2O \rightarrow 2MnOOH + 4H^+$

5.4 Formation of Carbonates

If ambient concentrations of bicarbonate are high, metals in water flowing into a treatment wetland may form carbonates. There are very few known cases of wetlands that retain significant amounts of metals as carbonates.

5.5 Reduction To Non-Mobile Forms

Chromium, copper, selenium, and uranium can all be reduced (biologically or chemically) in wetland sediments into non-mobile forms. A variety of processes accounts for this.

Eh-pH stability diagrams predict that copper will be transformed into the metallic form in slightly acidic, reduced wetland sediments. Sulfide concentrations must be relatively low, otherwise sulfide minerals will form. This prediction is corroborated by several reports of native copper accumulating in slightly acidic wetlands, but not in neutral or alkaline ones (27,28). Copper salts in mineralized water are probably reduced chemically in wetland sediments by organic matter or minerals such as iron oxides, thereby accumulating as native copper.

5.6 Sorption Onto Metal Oxides or Hydroxides

Surface water flowing into a wetland, groundwater recharging it, or pore water in wetland sediments may all contain elevated iron and manganese concentrations. These metals will precipitate as oxides, oxyhydroxides, or hydroxides when exposed to the oxidizing environment of the wetland surface.

5.7 Formation of Metal Sulfides

Bacterial sulfate reduction is generally an important process in the treatment of wetlands. Hydrogen sulfide (one end-product of bacterial sulfate reduction) can react with transition metals to form highly insoluble compounds (29). The overall reaction for precipitation of divalent metal ions with hydrogen sulfide is

$M^{2+} + HS^{-} \rightarrow MS + H^{+}$

Clearly, certain metals, including silver, cadmium, copper, mercury, lead, and zinc, form highly insoluble sulfide compounds. Conversely, even small concentrations of hydrogen sulfide are sufficient to precipitate these metals.

5.8 Summary metal removal

Metals introduced into the constructed wetland system are removed by processes which include sedimentation, filtration, adsorption, complex formation, precipitation, cation exchange, plant uptake and microbiologically-mediated reactions (31). The bulk of the metals are immobilized through sorption, most probably by the biofilms developed on the media and vegetation roots. Thus, the sorption capacity of the media will impose a limit on the amount of metal that can ultimately be removed in the wetland system. Plant uptake was found to be generally small compared to other removal pathways (32).

Water hyacinths (*Eichhornia crassipes*) are well known for their use in wastewater treatment but have also been found to be effective in accumulating heavy metals and in the uptake of residues of pesticides such as PCB, DDE, DDD, and DDT (33,34). Duckweed (*Lemna minor*) and water velvet (*Azolla pinnata*) were both found to effectively remove iron and copper (35,36) and cadmium (34) at low concentrations in laboratory experiments.

A literature review shows the occurrence of more than 500 organic and metallic pollutants in wetlands. The removal of heavy metals is reported typically in the order of 30 to 60%, but can reach 80 to 90%. An effective removal of hydrocarbons requires aerobic conditions. Typical removal of hydrophobic organic compounds is 50 to 100%.

6 Pesticides removal

Constructed wetlands (CWs) have proven an effective and practical option for removing certain pesticides from runoff water (46). Environmental conditions within CWs often enhance organic contaminant removal through both non-destructive (sedimentation, plant uptake) and destructive (microbial degradation, phyto-degradation) processes (47). Although studies have demonstrated various degrees of effectiveness for CWs to remove pesticides, comparatively little is known about the mechanisms of contaminant removal. For instance, while it is accepted that partitioning to the wetland bed sediment contributes to the retention of hydrophobic pesticides in CWs, few actual measurements have been made under field conditions to verify this assumption. Partitioning of chemicals between water and a solid phase is typically determined either in the laboratory using freshly spiked samples (48), or theoretically utilizing a chemicals water solubility and octanol–water partition properties (49). However, under field conditions, environmental parameters such as pH, temperature, dissolved organic matter (DOM), and contact time (i.e. aging) can all affect a chemical's actual phase distribution (50). Knowledge of the field-relevant contaminant distribution among different compartments within a wetland can be used to guide the design and management of CWs for maximizing contaminant removal. Constructed wetlands and other similar management practices operate on the principle of removing contaminants from the passing flow, by sedimentation or vegetative filtration. Once retained in a CW, pesticides in the system may accumulate to levels that are detrimental to wildlife that utilize the wetland as habitat. Further, a subsequent event (e.g., a heavy rain storm) may mobilize the accumulated pesticides, causing a delayed discharge of the retained contaminants. However, so far essentially no studies have considered the long-term fate of retained contaminants in CWs.

Retention of suspended solids within a CW would lead to accumulation of pesticide-loaded sediment on the wetland floor. Once removed from the passing flow via sedimentation or vegetative filtration, the retained pesticides may undergo biotic and abiotic transformations.

The following conclusions are drawn (45):

1. In the runoff flow, pyrethroids were overwhelmingly associated with suspended solids, and sedimentation or trapping of these particles was the main mechanism for the wetlands to attain the high pesticide removal efficiency;
2. Pesticide loading in a wetland cannot be estimated based on sedimentation rates alone, the sorption of particles in organic carbon, including clays and lighter partially decomposed plant materials;
3. Pyrethroids and chlorpyrifos showed moderate persistence in the wetland sediments under anaerobic conditions, but the retained pesticides displayed significant persistence under dry, aerobic conditions, suggesting a potential for pesticide accumulation over time;
4. The long-term environmental impact of constructed wetlands should be considered along with their short-term benefits for mitigating water-borne pollutants.

Pesticide removal is typically in the order of 40 to 99%, but some compounds show much less removal. The removal of personal body care products (PBCPs) seems to be good in wetlands. The performance of wetland systems with regard to removing pharmaceuticals and PBCPs are similar to that obtained in conventional activated sludge wastewater treatment facilities.

7 Design of Constructed Wetlands

The process of designing and predicting performance of wetlands is improving rapidly, as more experience is gained with the operation of these systems. Designing constructed wetlands entails:

- Sizing for a particular wastewater flow rate, pollutant loading, and desired removal of a given pollutant;
- Inlet and outlet structures for water level control, recycling, flow splitting and distribution;
- Flow path configuration for cells in parallel and/or series;
- Depth variation within and between cells for habitat diversity (if and when required), better flow distribution, and pollutant removal;
- Planting details, including species selection, planting density, range of species; and
- An operation and maintenance plan.

Different sets of guidelines for design of constructed wetlands have been developed. Kadlec and Knight (37) pointed to the exponential growth of new information in the field of constructed wetlands and warn against the blanket use of simplistic design guidelines for all situations. The approaches currently used to design constructed wetlands are not significantly different from the approaches used in conventional biological treatment systems. Constructed wetlands are commonly designed as attached growth biological reactors. In attached growth processes, sufficient contact with biofilms on such substrates as gravel, plant stems, roots, and sediment layers is important, because much of the pollutant removal is mediated by microbial activity. To maximize pollutant removal by this process, wetland design aims to optimize the theoretical hydraulic retention time (HRT), and then ensure that the actual HRT is as close as practicable to the theoretical HRT.

The process and formula to compute the dimensions of a certain constructed wetlands are described in Appendix 2.

The principal design factors for free surface flow constructed wetlands are detention time, organic loading rate, water depth, aspect ratio and shape. Typical ranges of design criteria are presented in Table 1.

Table 1 Ranges of design criteria from literature

Factor	**Literature suggested ranges**
Detention time (for soluble pollutants removal) (d)	5 to 14
Detention time (for suspended pollutants removal) (d)	0.5 to 3
Maximum BOD_5-loading rate (kg/ha.d)	80 to 112
Hydraulic loading rate (m^3/m^2.d)	0.01 to 0.05
Aspect ratio	2:1 to 10:1
Water depth - average condition (m)	0.1 to 0.5
Bottom slope (%)	1 to 0.5

Source: (13, 31, 37, 40, 43, 44) >>

In Appendix 1 details of studies concerning type of constructed wetland and retention time are given.

7.1 Design considerations Water Hyacinth Systems and Duckweed Systems

Shallow, rectangular basins with a high length-to-width ratio are usually designed for aquatic treatment systems to reduce the potential for short-circuiting and to simplify harvesting operations. Small basins or surface baffles are needed to minimize distribution of plants by wind action. The use of baffles and influent distribution manifolds helps to maximize the detention time. Influent manifolds and multiple inlet/step feed systems also can be used effectively for recycling treated effluent to reduce the influent concentrations of wastewater constituents.

Design parameters used to size aquatic systems include organic loading rate, hydraulic loading rate, water depth, retention time and harvesting/ vegetation management. Design parameters based on the required level of treatment have been summarized in Table 1. Design criteria for effluent polishing using duckweed in facultative ponds are summarized in Table 2.

7.1.1 Organic loading rates

Organic loading rates is a key parameter in the design and operation of water hyacinth systems, which represent the majority of aquatic plant treatment systems.

The hydraulic loading rates applied to water hyacinth facilities vary widely and usually are governed by the organic loading rate. The hydraulic loading rate is typically between 200 and 600 m^3/ha-d.

Table 2 Design criteria for Water Hyacinth systems and Duckweed systems

	Water hyacinth system	**Duckweed system**
Factor	**Aerobic non-aerated**	**Facultative pond effluent**
Influent wastewater	screened or settled	
Influent BOD (mg/l)	130-180	
Expected effluent		
BOD, (mg/l)	>30	>10
SS, (mg/l)	>30	>10
TN, (mg/l)	>15	>5
BOD loading (kg/ha.d)	40-80	22-28
Hydraulic loading, (m^3/ha.d)	200-600	>50
Water depth, (m)	0.5-0.8	1.5-2
Detention time, (days)	10-36	15-25

Source: 10

7.1.2 Water depth

The range of depths for water hyacinth ponds is 0.5 – 1.4 m with most application at depths of 0.6 – 1 m. The critical concern is to provide adequate depth for the root systems to penetrate through most of the liquid flowing through the hyacinth pond. A greater depth is sometimes desirable for the final cell in a series of hyacinth ponds, since the hyacinth roots will be longer when fewer nutrients are present in the water.

7.1.3 Vegetation management

Vegetation management encompasses the harvesting of aquatic plants and depends on water quality objectives for the system, the growth rates of the plants, and the effects of predators, such as weevils. Harvesting of aquatic plants is needed to maintain a crop with high metabolic uptake of nutrients.

Plant growth may be described as a percentage of pond surface covered over a period or by plant density, expressed in units of wet plant mass per unit of surface area. Loosely packed water hyacinth can cover the water surface at low plant densities, 10 – 15 kg/m^2, and avoid problems associated with algae production. Higher densities of up to 50 kg/m^2 may occur before growth is completely inhibited and the hyacinth foliage dies and adds to the pond loading. Thus harvesting should begin before reaching the higher densities and should continue until densities approach 15 – 25 kg/m^2.

7.1.4 Nutrient removal

Nitrogen removal by plant uptake can only be accomplished if the plants are harvested. Nitrate, produced through nitrification, is removed by denitrification and plant uptake, as is organic nitrogen. Typical nitrogen loading rates are 450 – 900 kg/ha-d.

Phosphorus removal from aquatic macrophyte systems results from plant uptake, microbial immobilization into detritus plant tissue, retention by the underlying sediments, and precipitation in the water column. Since phosphorus is retained by the system, the ultimate removal from the system is achieved by harvesting the plant and dredging the sediment. Typical loading rates may range up to 115 – 230 kg/ha-d.

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Appendix 1 – Selected details of studies of different types of constructed wetland and retention time

Details of selected studies.

Study	Authors	Metal selected	Location	Type of CW[a]	Size[b]	Retention time (hours)	Number	Unit replication[c,e]	Statistical tests	Control[d]
1	Kamal et al., 2004	Fe, Zn, Cu, Hg	N. Amer	SF	Meso	504	3	1	N	N
2	Samecka-Cymerman et al., 2004	Al, Ba, Mn, Ni, Sr, V, Zn, Cd, Cu, Pb, P, N, Cl,Ca,Mg, Fe, K	Europe	HSSF (and SF)	Large	?	3	1	ANOVA (pseudoreplication)	N
3	Peng et al., 2008	Cd, Pb, Mn, Zn, Cu	Asia	BR	Micro	2	2	3	ANOVA+Tukey post hoc test	Y
4	Zhang et al., 2007	Cr, Pb, Cu, Cd, Mn, Fe	Asia	BR	Micro	360	6	4	ANOVA + LSD test	Y
5	Nelson et al., 2006	Hg, Cu, Pb, Zn	N.Amer	SF	Large	48	1	4	N	N
6	Ha et al., 2009	Cb, As, Cu, Zn	Asia	BR	Micro	24	1	3	N	N
7	Lim et al., 2003	Zn, Pb, Cd	Asia	HSSF	Meso	?	1	1	N	N
8	Crites et al., 1997	Sr, As, Cd, Cr, Cu, Pb, Hg, Ni, Ag, Zn	N.Amer	SF	Large	~120	2	10 (?)	N	Y
9	Maine et al., 2009	Cr, Ni, Fe,(Zn)	S. Amer	SF	Large	168–288	3	1	ANOVA + Duncan's test (pseudoreplication)	N
10	Rai et al., 1995	Cu, Cr, Fe, Mn, Cd, Pb	Asia	BR	Micro	48–360	8	3	N	Y
11	Nyquist and Greger, 2009	Fe, Zn, Cu, Cd	Europe	SF	Large	?	3 (mixed stand)	1	ANOVA + Tukey post hoc test (pseudoreplication)	Y
12	Mishra and Tripathi, 2009	Zn, Cr	Asia	BR	Micro	264	1	3	Regression	Y
13	Megatelli et al., 2009	Cu, Cd, Zn	North-Africa	BR	Micro	240	1	3	*T*-test	Y
14	Mishra and Tripathi, 2008	Fe, Zn, Cu, Cr, Cd	Asia	BR	Micro	360	3	1	Linear regression (+ANOVA, pseudoreplication)	Y (but data not shown)
15	Hadad et al., 2006	Cr, Zn, Ni	S. Amer	SF	Large	168	11 (mixed stand)	1	*T*-test (pseudoreplication)	N
16	Mantovi et al., 2003	Cu, Ni, Pb, Zn	Europe	HSSF	Large	240	1	1	N	N
17	Maine et al., 2007a	Cr, Ni, Fe	S.Amer	SF	Large	168–288	2 (mixed stand)	1	ANOVA (pseudoreplication)	N
18	Chagué-Goff, 2005	Fe, Cu, Pb, Zn	Oceany	SF	Large	2400	7 (mixed stand)	4	N	N
19	Khan et al., 2009	Cd, cr, Fe, Pb, Cu, Ni	Asia	SF	Large	40	11 (mixed stand)	1	ANOVA (pseudoreplication)	N
20	Dorman et al., 2009	Zn, Hg, Cr, As, Se	N. Amer	SF	Meso	120	2 (dissociated mixed stand)	2	N	N
21	Cheng et al., 2002	Cd, Cu, Mn, Zn, Al, Pb	Europe	VF	Meso	?	2 (dissociated mixed stand)	1	N	N

[a] Type of CW. VSSF: vertical subsurface flow; HSSF: horizontal subsurface flow; SF: free water, surface flow; BR: Batch reactor.
[b] Size of experimental units (surface area): Micro: microcosms (columns, buckets) < 0.5 m^2; Meso: mesocosms, from 0.51 to 5 m^2, Large: pilot scale and full-size CW > 5 m^2 (from Brisson and Chazarenc, 2009).
[c] Number of units per species treatment. One means no replication.
[d] Control: presence of unplanted control (yes/no).
[e] Datas concern exclusively removal experiments (and no others experiments when there are others. e.g. Phytoaccumulation) N.Amer.: North America, S.Amer.: South America.

Efficiency removal (%) in constructed wetlands with plants grown in monocultures.

Species name	Common name	Code	Study	Removal rate (%)		
				Fe	Zn	Cu
Mentha aquatica	Aquatic mint	Men	1	92.9	34.7	30.9
Ludwigia palustris	Creeping primrose	Lud	1	63.6	32.6	44.9
Myriophyllum aquaticum	Parrot feather	Myr	1	75.6	34.4	42.5
Phragmites communis/australis	Reed	Phr	2, 16	W: 86 S: 79, –	W: 59 S: 68, 85.7	W: 43 S: 56, 79.4
Salix viminalis	Common osier	Sav	2	W: 97 S: 82	W: 84 S: 92	W: 16 S: 36
Populus canadensis	Carolina poplar	Poc	2	W: 90 S: 91	W: 38 S: 73	W: 49 S: 60
Potamogeton pectinus	Sago pondweed	Pop	3	–	66	74
Potamogeton malaianus	–	Pom	3	–	67	65
Acorus gramineus	Dwarf sedge	Acg	4	99.7	–	98.5
Acorus orientale	?	Aco	4	98.7	–	98.4
Acorus calamus	Sweet flag	Acc	4	98.7	–	98.2
Lythrum salicaria	Purple loosestrife	Lsa	4	99.1	–	98.7
Iris pseudacorus	Paleyellow iris	Irp	4	99.6	–	99.1
R. carnea	?	Rca	4	98.5	–	97.9
Control	–	C	4	97.7	–	97.6
Shoenoplectus californicus	Giant bulrush	Sca	5	–	47	80
Eleocharis acicularis[a]	Needle spikerush	Nsp	6	–	50	52
Typha latifolia	Cattail	Tla	7	–	84–99	–
Shoenoplectus acutus	Bulrush	Sac	8	–	81.09	55.06
Eichhornia crassipes	Water hyacinth	Ecr	9, 12, 14, 17	72, –, 78.6–90.1, 79	–, 88–94, 85–95, –	–, –, 86–95, –
Typha domingensis	Southern cattail	Tdo	9, 17	73, 80	–	–
Hydrodictyon reticulatum	Water net alga	Hre	10	95	–	55
Spirodela polyrrhiza	Giant duck weed	Spo	10, 14	65, 77.5–83.5	–, 82–90	90, 76–91
Chara corallina	Water horsetail	Cco	10	60	–	37
Ceratophyllum demersum	Horn tail	Cde	10	95	–	90
Vallisneria spiralis	Channel grass	Vsp	10	38	–	55
Bacopa monnieri	Water hyssop	Bmo	10	50	–	82
Alternanthera sessilis	Alligator weed	Ase	10	40	–	37
Hygrorhyzza aristata	Wild rice	Har	10	40	–	10
Lemna gibba	Gibbous duckweed	Lgi	13	–	100	77
Control	–	C	13	–	10	22–36
Pistia stratiotes	Water lettuce	Pst	14	87–95	82–92	88–96

Species name	Common name	Code	Study	Removal rate (%)				
				Sr	Ni	Mn	Ba	Cr
Mentha aquatica	Aquatic mint	Men	1	–	–	–	–	–
Ludwigia palustris	Creeping primrose	Lud	1	–	–	–	–	–
Myriophyllum aquaticum	Parrot feather	Myr	1	–	–	–	–	–
Phragmites communis/australis	Reed	Phr	2, 16	W: 24 S: 51, –	W: 33 S: 55, 58.6	W: 99 S: 99, –	W: 70 S: 95, –	51.6
Salix viminalis	Common osier	Sav	2	W: 13 S: 43	W: 30 S: 46	W: 98 S: 99	W: 13 S: 44	
Populus canadensis	Carolina poplar	Poc	2	W: 17 S: 23	W: 55 S: 67	W: 99.6 S: 99.5	W: 59 S: 62	–
Potamogeton pectinus	Sago pondweed	Pop	3	–	–	89	–	–
Potamogeton malaianus	–	Pom	3	–	–	83	–	–
Acorus gramineus	Dwarf sedge	Acg	4	–	–	99.3	–	91.8[a]
Acorus orientale	?	Aco	4	–	–	99	–	78.1
Acorus calamus	Sweet flag	Acc	4	–	–	99.3	–	93.3[a]
Lythrum salicaria	Purple loosestrife	Lsa	4	–	–	99.6	–	81.3
Iris pseudacorus	Paleyellow iris	Irp	4	–	–	99.6	–	95.8
R. carnea	?	Rca	4	–	–	98.7	–	79.9
Control	–	C	4	–	–	99.1	–	76.9
Shoenoplectus californicus	Giant bulrush	Sca	5	–	–	–	–	–
Eleocharis acicularis[a]	Needle spikerush	Nsp	6	–	–	–	–	–
Typha latifolia	Cattail	Tla	7	–	–	–	–	–
Shoenoplectus acutus	Bulrush	Sac	8	–	14.6	–	–	70.6
Eichhornia crassipes	Water hyacinth	Ecr	9, 12, 14, 17	–	48, –, –, 48	–	–	66, 63–84, 81–89, 62
Typha domingensis	Southern cattail	Tdo	9, 17,15	–	52, 48, –	–	–	65, 58, –
Hydrodictyon reticulatum	Water net alga	Hre	10	–	–	82	–	90
Spirodela polyrrhiza	Giant duck weed	Spo	10,14	–	–	62, –	–	80, 62–83
Chara corallina	Water horsetail	Cco	10	–	–	55	–	50
Ceratophyllum demersum	Horn tail	Cde	10	–	–	90	–	90
Vallisneria spiralis	Channel grass	Vsp	10	–	–	20	–	40
Bacopa monnieri	Water hyssop	Bmo	10	–	–	60	–	50
Alternanthera sessilis	Alligator weed	Ase	10	–	–	82	–	25
Hygrorhyzza aristata	Wild rice	Har	10	–	–	60	–	25
Lemna gibba	Gibbous duckweed	Lgi	13	–	–	–	–	–
Control	–	C	13	–	–	–	–	–
Pistia stratiotes	Water lettuce	Pst	14	–	–	–	–	70–81

Species name	Common name	Code	Study	Removal rate (%)					
				Al	Hg	Cd	Pb	As	Sb
Mentha aquatica	Aquatic mint	Men	1	–	99.9	–	–	–	–
Ludwigia palustris	Creeping primrose	Lud	1	–	99.7	–	–	–	–
Myriophyllum aquaticum	Parrot feather	Myr	1	–	99.9	–	–	–	–
Phragmites communis/australis	Reed	Phr	2, 16	W: 81 S: 97, –	–	W: 17 S: 56, 23.7	W: 64 S: 81, 69.6	–	–
Salix viminalis	Common osier	Sav	2	W: 51 S: 64	–	W: 58 S: 71	W: 44 S: 72	–	–
Populus canadensis	Carolina poplar	Poc	2	W: 33 S: 47	–	W: 66 S: 55	W: 52 S: 69	–	–
Potamogeton pectinus	Sago pondweed	Pop	3	–	–	96	79	–	–
Potamogeton malaianus	–	Pom	3	–	–	88	78	–	–
Acorus gramineus	Dwarf sedge	Acg	4	–	–	95.2[a]	91[a]	–	–
Acorus orientale	?	Aco	4	–	–	92.9	84.1	–	–
Acorus calamus	Sweet flag	Acc	4	–	–	90.5	89.1	–	–
Lythrum salicaria	Purple loosestrife	Lsa	4	–	–	92.2	87	–	–
Iris pseudacorus	Paleyellow iris	Irp	4	–	–	96.1[a]	93.4[a]	–	–
R. carnea	?	Rca	4	–	–	95.2[a]	82	–	–
Control	–	C	4	–	–	83.3	77	–	–
Shoenoplectus californicus	Giant bulrush	Sca	5	–	80	–	70	–	–
Eleocharis acicularis[a]	Needle spikerush	Nsp	6	–	–	–	–	5	0.7
Typha latifolia	Cattail	Tla	7	–	–	99–96	99–89	–	–
Shoenoplectus acutus	Bulrush	Sac	8	–	55.61	54.55	87.26	1.1	66.1
Eichhornia crassipes	Water hyacinth	Ecr	9, 12, 14, 17	–	–	–, –, 77–85, –	–	–	–
Typha domingensis	Southern cattail	Tdo	9, 17	–	–	–	–	–	–
Hydrodictyon reticulatum	Water net alga	Hre	10	–	–	80	75	–	–
Spirodela polyrrhiza	Giant duck weed	Spo	10,14	–	–	80, 63–71	50	–	–
Chara corallina	Water horsetail	Cco	10	–	–	58	50	–	–
Ceratophyllum demersum	Horn tail	Cde	10	–	–	60	80	–	–
Vallisneria spiralis	Channel grass	Vsp	10	–	–	60	45	–	–
Bacopa monnieri	Water hyssop	Bmo	10	–	–	90	17	–	–
Alternanthera sessilis	Alligator weed	Ase	10	–	–	60	20	–	–
Hygrorhyzza aristata	Wild rice	Har	10	–	–	90	80	–	–
Lemna gibba	Gibbous duckweed	Lgi	13	–	–	90	–	–	–
Control	–	C	13	–	–	5	–	–	–
Pistia stratiotes	Water lettuce	Pst	14	–	–	70–82	–	–	–

W: Winter, S :Summer, Control: presence of unplanted control.
[a] Our own calculation.

Appendix 2 – Computing the dimensions of a constructed wetland

Organic degradation (BOD, COD, TOC), nitrification, adsorption, disinfection (pathogen removal) in biologically driven processes generally follow first-order kinetics (38). Accordingly, performance of attached-growth biological reactors is described as first-order kinetic reactions model assuming that plug flow and steady state conditions prevail in the reactor. First-order reactions are said to occur when the rate of reaction is directly proportional to first power of the concentration of the reactants (in case of treatment systems, the pollutants). Thus, pollutant removal in treatment wetland can be expressed as follows:

$$\frac{C_e}{C_0} = e^{-\mathrm{kTt}} \qquad (1)$$

where,

Co	= average influent concentration, $mg.L^{-1}$,
Ce	= average design effluent, $mg.L^{-1}$,
kT	= temperature dependent first-order reaction rate constant, day^{-1},
t	= hydraulic retention time, day.

Hydraulic retention time t is expressed as:

$$t = \frac{LWD\eta}{Q} \qquad (2)$$

where

L	= length of wetland, meter,
W	= width of the wetland, meter,
D	= depth of water column, meter,
η	= porosity of the substrate medium (percentage expressed as fraction),
Q	= average flow rate, $m^3.day^{-1}$.

Substituting the value expression for 't' from Equation 2 in Equation 1, and converting into linear format, the following expression is obtained.

$$(\ln C_e - \ln C_0) = -k_T \frac{LWD\eta}{Q} \qquad (3)$$

Rearranging the terms to obtain the area (m^2) of **subsurface** flow wetland required,

$$A_S = LW = \frac{Q(\ln C_0 - \ln C_e)}{k_T D\eta} \qquad (4)$$

The value of the rate constant kT is estimated using the following equation:

$$k_T = k_{20}.\theta_{20}^{(T-20)} \quad (5)$$

where θ_{20} is the temperature coefficient for rate constant. The values of θ_{20} and k_{20} depend on the type of pollutants encountered in surface and subsurface flow systems. Values for common pollutants are presented in Table 3 (see below). Assuming that laminar flow prevails and that Darcy's law applies, the flow rate in a constructed wetland can be determined as:

$$Q = A_c.k_s.S \quad (6)$$

where Ac = cross-sectional area of flow, m^2,
ks = hydraulic conductivity of the substrate medium, $m.day^{-1}$,
S = hydraulic gradient (dimensionless).

In turn, the width of the wetland is then determined as:

$$W = \frac{A_c}{D} = \frac{Q}{k_s.S.D} \quad (7)$$

Once the width is determined, the length of the constructed wetland can be obtained from the surface of the wetland obtained from Equation 4.

Table 3. Temperature Coefficients and Rate Constants. (39)

Pollutant	Surface flow system	
	θ_{20}	k_{20}
BOD	1.060	0.678
Nitrification	1.048	0.2187
Denitrification	1.150	1.000
Pathogen removal	1.190	2.600

Based on the kinetic and hydraulic model outlined in the previous section, the currently recommended design procedure is:

- Selection of plant species and determination of bed depth.
  In all the SSF systems with BOD loading rate higher than 0.2 $kg.m^2.day$ surface flow was reported (40). For design, the depth of total water column both in and above the substrate (instead of only the depth of bed), is to be considered for the term 'D' in the model. That is, D = Db + Df , where Db is the depth of substrate media and Df is the depth of surface flow.

- Selection of the bed slope and defining hydraulic gradient will be the next step. A review by Conely et al. (41) indicates that slope varied from 0 to 10%, with most designs occurring within the 0 to 3% range.
  According Cooper it should not exceed 1% (42).
- Selection of substrate media, in case of subsurface flow wetlands, and defining hydraulic conductivity (ks) and porosity (η).
- Determination of cross sectional area of flow (Ac) using Equation 6.
- Determination of bed width (W), using Equation 7.
- Calculation of seasonal kT (for both winter and summer conditions, in regions where the fluctuation is very high) according to Equation 5.
- Determination of required surface area (As) (for summer and winter loading, where required), using Equation 4.
- Determination of bed length (L) from the area requirement.

This report summarises the information found in scientific literature regarding the mechanisms and processes that enable constructed wetlands to remove heavy metals and pesticides from waste water. It examines what factors have an influence on the effectiveness of constructed wetlands to treat waste water containing such pollutants and shows the impact on the design and operation of constructed wetlands. The report focuses on free surface flow wetlands and aquatic treatment systems because these types are found to be most able to treat the large volumes of water that are required to fill and maintain water levels of fish ponds as operated in Egypt. This study is the scientific basis for the project 'Investigating the suitability of constructed wetlands for the treatment of water for fish farms, Egypt' (BO-27.02-001-007).

More information: www.wageningenUR.nl/cdi

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