WASTEWATER GARDENS INTERNATIONAL INFORMATION
SHEET IS20120105

CONSTRUCTED WETLANDS TO TREAT WASTEWATER

FRAMEWORK AND SCHEMATIC OVERVIEW

Index

PHOTO GALLERY


Municipal Wastewater Treatment plant (6000 m²), Koh Phi Phi Don, Thailand): 400 m3/day: Organic water: 3,000 – 4,000 permanent residents + 1.2 million tourist/year

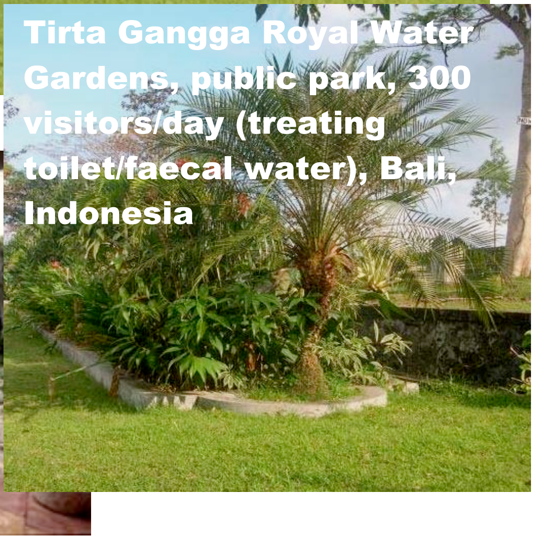

Xu-Park Eco Park, Hotel + Restaurant, 1500 guests + visitors/day


Offices , 45 persons (BAPEDALDA Govt. Agency), CW treating toilet/faecal water only * *Note: unit recently planted*


11,000 m3/day gasoline contaminated water, BP, USA(tbc)


Partial view of municipal STP, Honfleur, France: 3-5,000 m3/day, 26,000 habitants


Private residence, 6 habitants, Bali, Indonesia


Tirta Gangga Royal Water Gardens, public park, 300 visitors/day (treating toilet/faecal water), Bali, Indonesia

CONSTRUCTED WETLAND (CW): DEFINITIONS

➔ *"Constructed treatment wetlands are engineered systems, designed and constructed to utilise the natural functions of wetland vegetation, soils and their microbial populations to treat contaminants in surface water, groundwater or waste streams"* [1] + [2].
Synonymous terms of CWs include: Man-made, engineered, artificial or treatment wetlands.
There are also a number of terms used for subsurface flow CWs, which can be confusing for novices:
· Planted soil filters: Their vegetation is composed of macrophyte plants from natural wetlands and this sets them apart from the unplanted soil filters, also called subsurface biofilters, percolation beds, infiltration beds or intermittent sand filters.
· Reed bed treatment system: A term used principally in the United-Kingdom, Europe, resulting from the fact that the most frequently used plant species is the common reed (*Phragmites australis*).
· Vegetated submerged beds, vegetated gravel-bed and gravel bed hydroponics filters.
. Phytorestoration: a term covering all technologies using plants to restore soils, ecosystems, and/or water integrity.

➔ Constructed wetlands treat the sewage water using highly effective and ecologically sound, design principles that use plants, microbes, sunlight and gravity to transform wastewater into gardens and reusable water. The water treatment mechanisms are biological, chemical and physical, these include physical filtration and sedimentation, biological uptake, transformation of nutrients by bacteria that are anaerobic (bacteria that flourish in the absence of oxygen) and aerobic (oxygen-needing bacteria), plant roots and metabolism, as well as chemical processes (precipitation, absorption and decomposition) that purify and treat the wastewater. While the system does not normally use machinery (except pumps if necessary to get wastewater to the CW unit/s against gravity), nor chemicals, the variety of natural mechanisms that do the water recycling and purification make CW very effective. In the case of WWG, our water treatment level often exceeds local Health Authority treatment requirements. When even higher treatment than normal municipal standards is required for special purposes, an increase in wetland area can provide the equivalent of advanced water treatment. Working with Subsurface Horizontal Flow CW, there is no wastewater is exposed on the surface, there are no odours, no mosquito breeding grounds, nor possibility of accidental contact with sewage; furthermore, since most people will only see a beautiful garden, they can be placed near entrances and gathering places, as well as be used as green belts around communities. They are so designed that they can be integrated into existing gardens if there is limited space on the Site and have been proven to be far more effective, economical and long-lasting than conventional sewage treatment systems. [3]

➔ "… A designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life, and water that simulates natural wetlands for human use and benefits". [4]

➔ Constructed Wetlands are an effective, environmentally friendly means of treating liquid and solid waste. CWs could bring major economic benefits to developing countries through the provision of biomass and aquaculture. Such wetland systems can yield a significant profit for local communities, and might be a powerful tool for breaking the poverty cycle. CWs are effective at reducing loads of BOD/COD, nitrogen, phosphorus and suspended solids by up to 98%. However, despite the suitability of climate in developing countries, the spread of wetlands in such areas has been "depressingly slow". [5]

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[1] ITRC, 2003 - Interstate Technology Regulatory Council Wetlands Team, USA (www.itrcweb.org/guidancedocument.asp?TID=24)
[2] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
[3] Wastewater Gardens International
[4] Hammer, 1989.
[5] (Denny et al., 1997). Fujjita Research, 1998.

CONSTRUCTED WETLAND (CW): DEFINITIONS (CONT. .. / ..)

➔ [6]: (Constructed wetlands) can be considered treatment systems that use natural processes to stabilize, sequester, accumulate, degrade, metabolize, and/or mineralize contaminants. Although constructed wetland applications were limited to treating primarily storm water and municipal wastewaters, they are now being used in new applications and on new contaminants.

. Wetland systems have always served as natural water treatment systems. During the past few decades people have seriously studied and utilized wetland systems for meeting wastewater treatment and water quality objectives in a controlled manner. The role of wetlands as a passive approach to improving water quality is a compelling argument for preserving natural wetlands and, in recent years, constructing wetlands systems for wastewater treatment.

. Constructed wetland treatment systems use rooted wetland plants and shallow, flooded or saturated soil to provide wastewater treatment. Constructed wetlands are designed to take advantage of the chemical and biological processes of natural wetlands to remove contaminants from the wastewater (Skousen 2004).

. The technology is now mature and tested. Increasingly, studies have provided evidence that wetlands systems can effectively improve water quality while providing many benefits, including food and habitat for wildlife.

. Constructed wetlands are proving to be a valid treatment option for acid mine drainage, hazardous waste site wastewaters, petroleum refinery wastes, compost and landfill leachates, agricultural wastes and pre-treated industrial wastewaters, such as those from pulp and paper mills and textile mills (ITRC 2003, USDA 1995*)*.

. Wetlands remove metals using a variety of processes including filtration of solids, sorption onto organic matter, oxidation and hydrolysis, formation of carbonates, formation of insoluble sulphides, binding to iron and manganese oxides, reduction to immobile forms by bacterial activity, and uptake by plants and bacteria. Metal removal rates in both subsurface flow and surface flow wetlands can be high, but can vary greatly depending upon the influent concentrations and the mass-loading rate. Removal rates of greater than 90% for copper, lead and zinc have been demonstrated in operating surface flow and subsurface flow wetlands.

. Wetlands possess a rich microbial population in the sediment to bring about the biochemical transformation of pollutants, are biologically productive, and are self-sustaining. Constructed wetlands also have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems (ITRC 2003). Compared to conventional systems, natural systems can be operated using less electricity and less labor (USEPA 1988).

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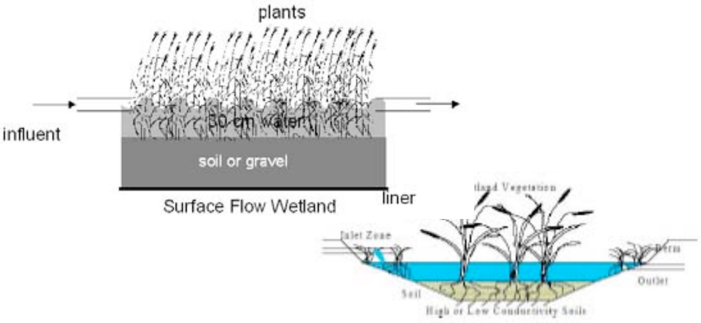
[6] *Review of Constructed Subsurface Flow vs. Surface Flow Wetlands*, Nancy V. Halverson, September 2004, prepared for the U.S. Department of Energy.

TYPES OF CONSTRUCTED WETLANDS

1. Surface Flow Constructed wetlands (SFCW)
Also called Free Water Surface CWs (FWS)

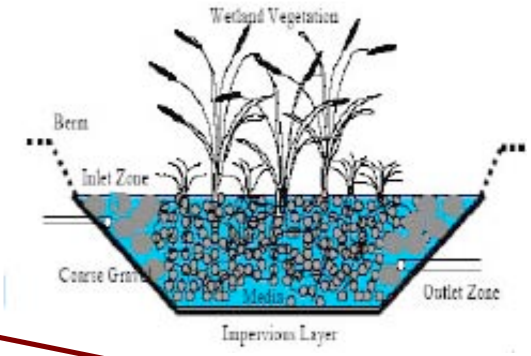
Biological activity takes mainly place in the superior layer of the soil, in the stems of the plants and in the water. Waterproofing is not always used. SFCW are birthing grounds to mosquitoes and require greater protection from public access than Subsurface Flow CWs.

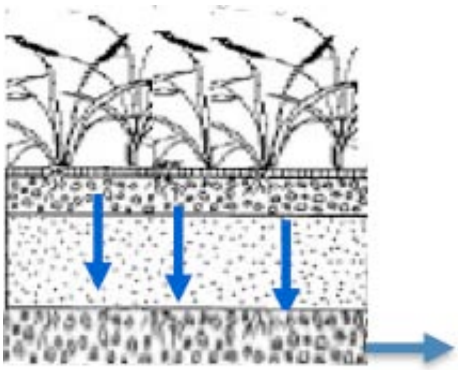
(Drawing in black and white courtesy of "Constructed wetlands" by Rob Van Deun, Katholieke Hogeschool Kempen – Geel Departement Industrieel Ingenieur en Biotechniek - Co-operation programme between Flanders and Central and Eastern Europe).



2. Subsurface Flow Constructed wetlands (SSFCW)
Also abbreviated as SSF

The wetland is filled with gravel/crushed rocks whose level is 5 cm to 10 cm above water level so that there is no exposure of wastewater to the surface. SSFCW need to be waterproofed, either through compacted clay, reinforced concrete or geomembranes of polyethylene type. **SSFCW take 80% +/- less space than a SFCW** because of a longer hydraulic retention time as well as a more intense biological and treatment activity. There are two principal types of designs within SSFCW: Vertical Flow and Horizontal Flow SSFCWs.

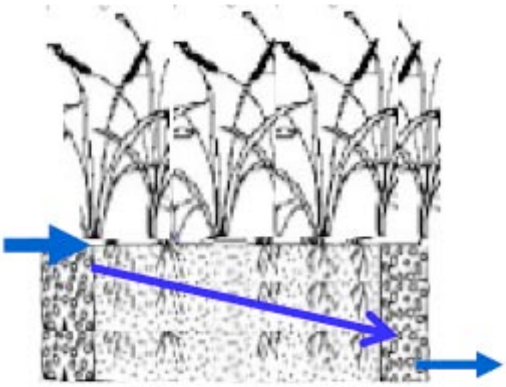




2a - VERTICAL FLOW SSFCW

Sewage water is pumped at regular intervals (every 2 to 6 hours, depending on design and treatment levels sought) through a network of pipes laid on top of a bed filled with gravel-type media of generally 3 different granulometries through which the water percolates. Vertical Flow CWs generally **require 2/3 of the space of an horizontal flow CW** and can raise treatment quality in certain parameters yet they are less passive systems as they rely on a controlled source of energy.

(Drawing below courtesy of "Constructed wetlands" by Rob Van Deun, Katholieke Hogeschool Kempen – Geel Departement Industrieel Ingenieur en Biotechniek - Co-operation programme between Flanders and Central and Eastern Europe).



2b - HORIZONTAL FLOW SSFCW

Sewage effluent fills the space between the gravel and circulates horizontally, naturally, each time water comes into the system. There is no external energy dependency (and therefore no contribution to pollution output).

(Drawing below courtesy of "Constructed wetlands" by Rob Van Deun, Katholieke Hogeschool Kempen – Geel Departement Industrieel Ingenieur en Biotechniek - Co-operation programme between Flanders and Central and Eastern Europe).

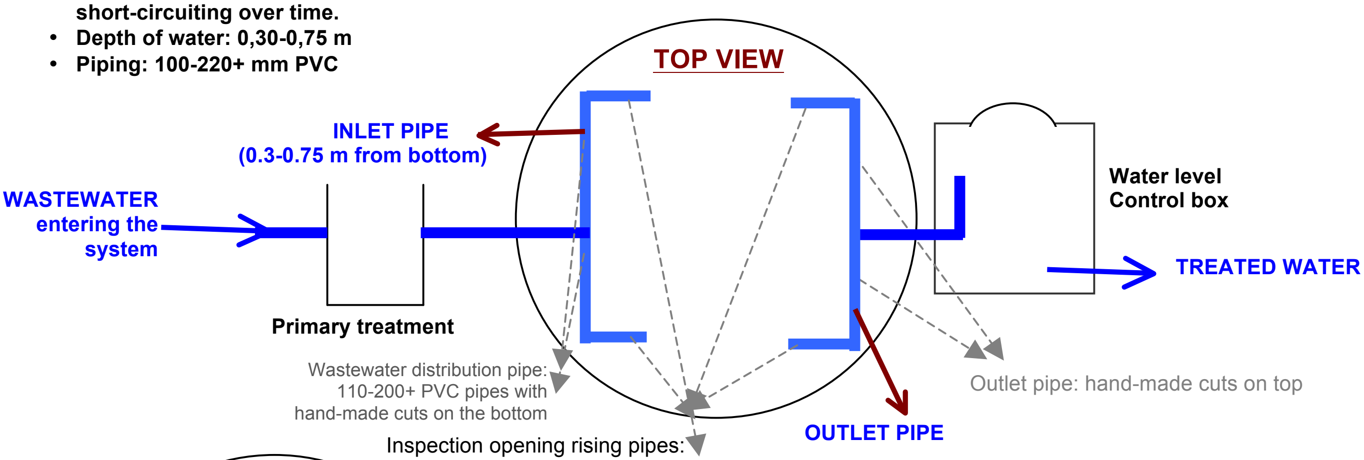
Note: Some constructed wetlands are also being designed to treat raw-wastewater (vertical-flow CWs), and/or act simultaneously as sludge-drying CWs.

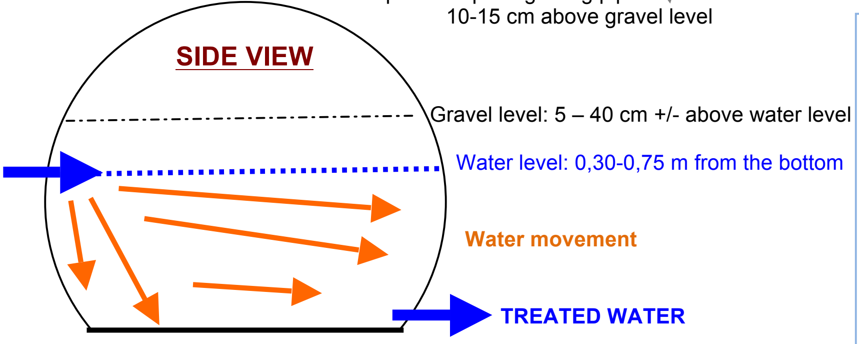
SCHEMATIC PIPING AND BASIC HYDRAULICS IN SUBSURFACE FLOW CONSTRUCTED WETLANDS

(Please note that experienced constructed wetland designers may apply variations)

HORIZONTAL FLOW design:

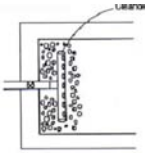
- **Gravel depth: 0,40 m – 0,85 m**
  4-8 mm, clean and screened as main media and 40-80 mm at entrance and exit for 1-2 meters length for large systems to avoid short-circuiting over time.
- **Depth of water: 0,30-0,75 m**
- **Piping: 100-220+ mm PVC**





INLET and OUTLET pipe of the CW

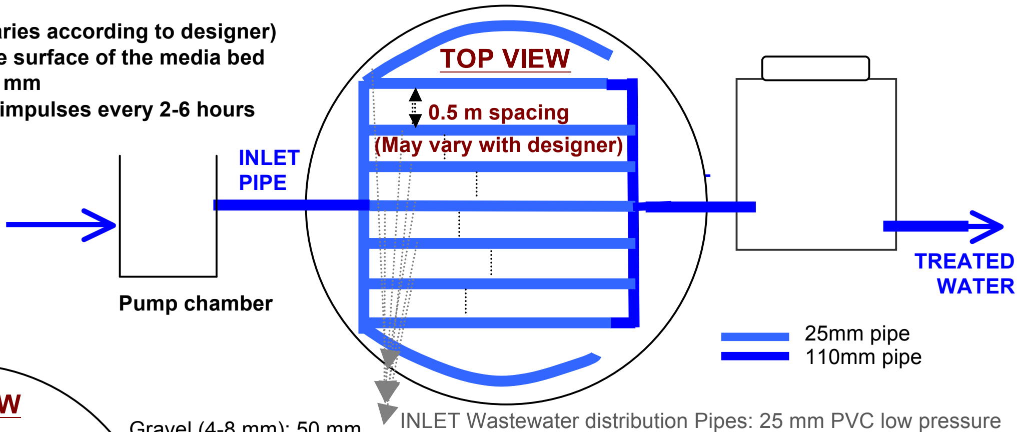
40-80 mm diameter filter media at both the inlet and outlet of the CW over 1-2 meters length and throughout the width of the pipe will provide increased ease of long-term maintenance (minimizing potential clogging).



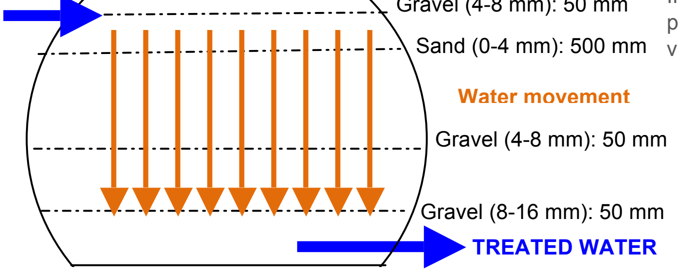
(Reference drawing: Constructed wetlands by Rob Van Deun, Katholieke Hogeschool Kempen – Geel - Departement Industrieel Ingenieur en Biotechniek)

VERTICAL FLOW design:

- **Media depth: 0.65 m (varies according to designer)**
- **Water distributed on the surface of the media bed**
- **Pipes: 110+ mm and 25 mm**
- **Wastewater coming by impulses every 2-6 hours**



INLET Wastewater distribution Pipes: 25 mm PVC low pressure pipes with holes made by hand every 20 cm on the sides (can vary according to designer)

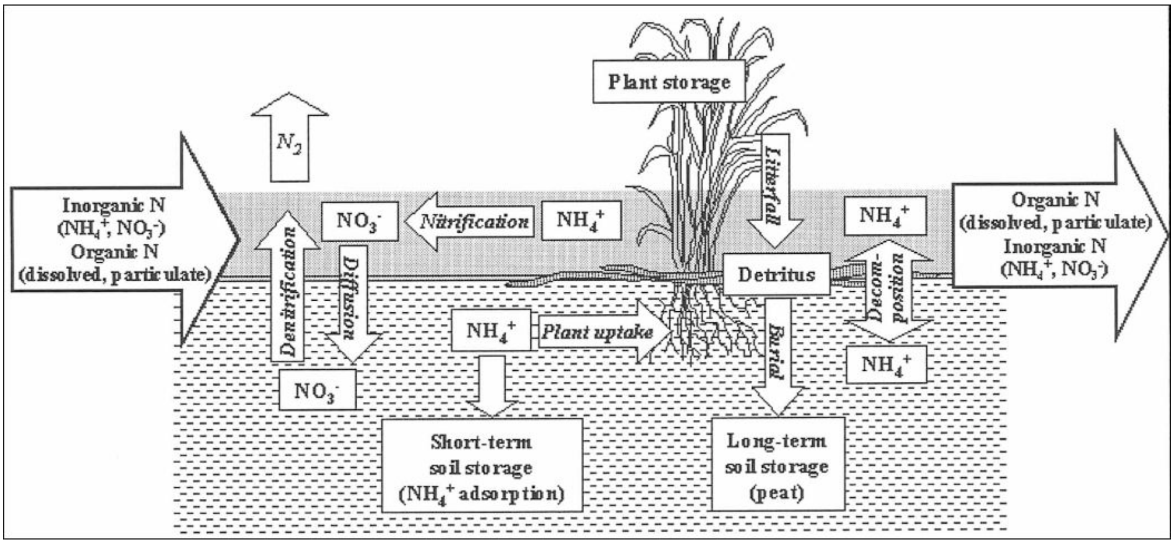


Note: Some designers for a typical depth of 0.7 m apply: 1-mm sand at the top 50 mm, then 5-10mm for the next 350 mm and 30-60 mm rounded stones at the bottom. *D. D. Mara, Good practice in water and environmental management, Natural Wastewater Treatment, published by Aqua Enviro Technolgoy Transfer on behalf of CIWEM*

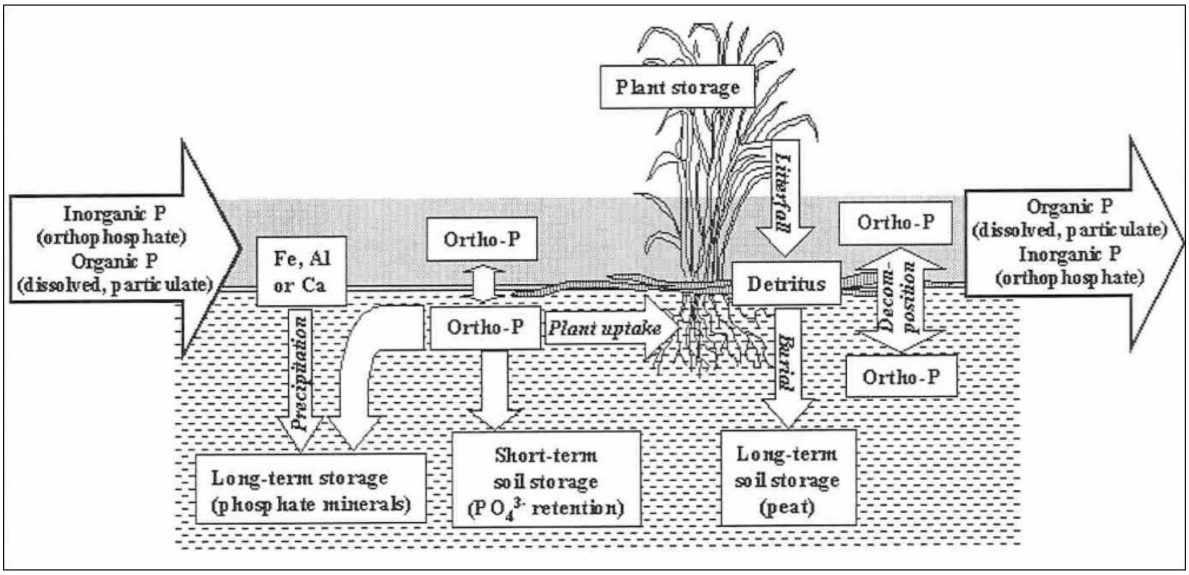
EXAMPLES OF BIOGEOCHEMICAL CYCLES IN A WETLAND

BIOGEOCHEMISTRY OF WETLAND SOILS FOR NITROGEN AND PHOSPHORUS

Nitrogen**:** Nitrogen processes in wetland soils include:
Nitrification (in aerobic zones), denitrification (in aerobic zones) – releasing N2 and N2O gases, plant uptake, sedimentation, decomposition, litterfall, ammonia volatilization and accretion/accumulation of organic N in peat because of redox potential of hydric sediment conditions.
Diagram courtesy of Soil and Water Science Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

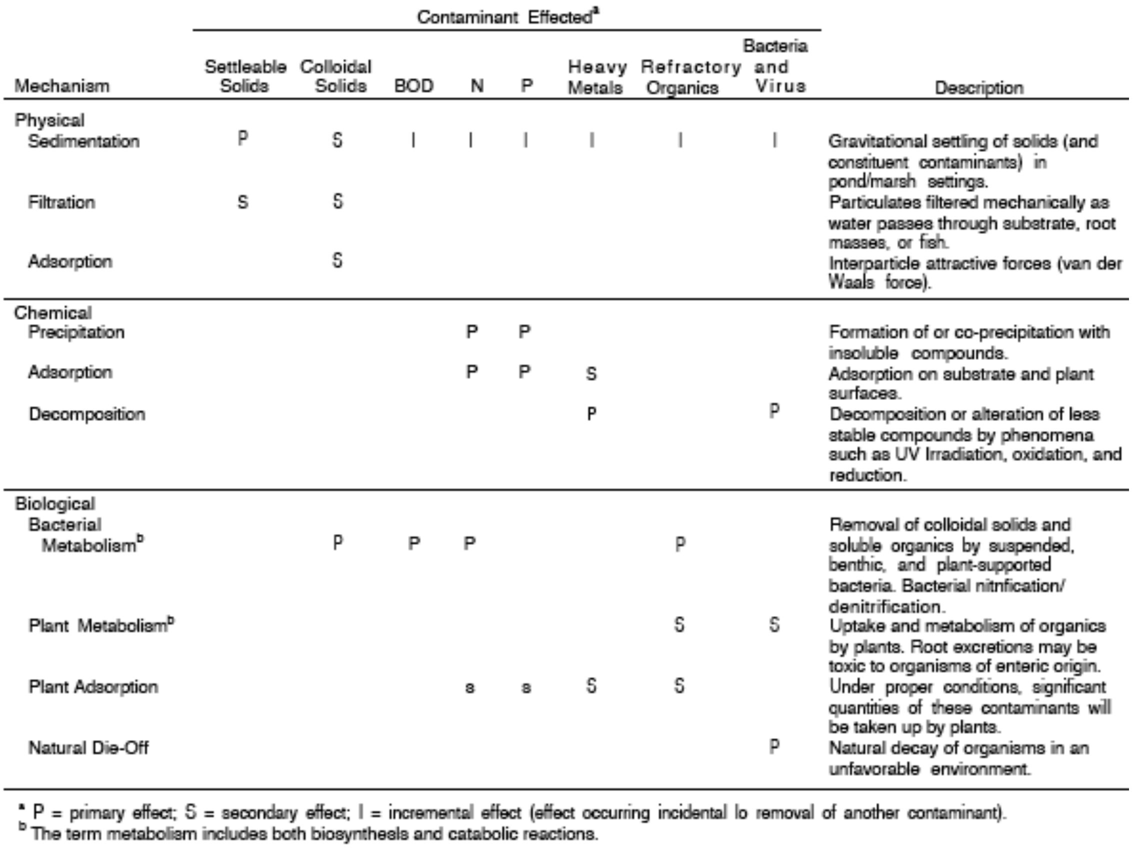


Phosphorus: The fate of phosphorus is quite different in wetland soils, since there is no mechanism comparable to denitrification as P has no gaseous phase. Consequently although the processes of plant uptake, sorption, decomposition and long-term storage occur, P tends to accumulate in wetlands at a higher rate than does N. Precipitation of phosphate minerals can provide a significant sink for P in wetlands with large stores or inputs of iron and aluminium (low-pH wetlands) or calcium (high-pH wetlands). Although wetlands may remove and store substantial quantities of P, they also potentially release a significant amount of P to downstream ecosystems. It's estimated that the long-term elimination rate of the Phosphorus through plants is about 0.05g/m^2/day in a constructed wetland.



Removal mechanisms in Wetlands for the Contaminants in Wastewater

Reference: Design Manual- Constructed Wetlands and Aquatic Plant Systems for Municipal Water Treatment, United States Environmental Protection Agency Office of Research and Development- EPA/625/1-88/022, September 1998.



	Contaminant Effected[a]								
Mechanism	Settleable Solids	Colloidal Solids	BOD	N	P	Heavy Metals	Refractory Organics	Bacteria and Virus	Description
Physical									
Sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and constituent contaminants) in pond/marsh settings.
Filtration	S	S							Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption		S							Interparticle attractive forces (van der Waals force).
Chemical									
Precipitation				P	P				Formation of or co-precipitation with insoluble compounds.
Adsorption				P	P	S			Adsorption on substrate and plant surfaces.
Decomposition						P		P	Decomposition or alteration of less stable compounds by phenomena such as UV Irradiation, oxidation, and reduction.
Biological									
Bacterial Metabolism[b]		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitnfication/ denitrification.
Plant Metabolism[b]							S	S	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant Adsorption				s	s	S	S		Under proper conditions, significant quantities of these contaminants will be taken up by plants.
Natural Die-Off								P	Natural decay of organisms in an unfavorable environment.

[a] P = primary effect; S = secondary effect; I = incremental effect (effect occurring incidental lo removal of another contaminant).

[b] The term metabolism includes both biosynthesis and catabolic reactions.

Processes in Sub-surface Flow Constructed Wetlands (SSFCW)

Reference: Design Manual on Waste Stabilization Ponds and Constructed Wetlands, UNEP-IETC with the Danish International Development Agency (Danida).

Wetland can effectively remove or convert large quantities of pollutants from point sources (municipal, industrial and agricultural wastewater) and non-point sources (mines, agriculture and urban runoff), including organic matter, suspended solids, metals and nutrients. The focus on wastewater treatment by constructed wetlands is to optimise the contact of microbial species with substrate, the final objective being the bioconversion to carbon dioxide, biomass and water. Wetlands are characterized by a range of properties that make them attractive for managing pollutants in water (Bavor and Adcock, 1994). These properties include high plant productivity, large adsorptive capacity of the sediments, high rates of oxidation by microflora associated with plant biomass, and a large buffering capacity for nutrients and pollutants.

1. Biological processes: There are six major biological reactions involved in the performance of constructed wetlands, including photosynthesis, respiration, fermentation, nitrification, denitrification and microbial phosphorus removal (Mitchell, 1996b). Photosynthesis is performed by wetland plants and algae, with the process adding carbon and oxygen to the wetland. Both carbon and oxygen drive the nitrification process. Plants transfer oxygen to their roots, where it passes to the root zones (rhizosphere). Respiration is the oxidation of organic carbon, and is performed by all living organisms, leading to the formation of carbon dioxide and water. The common microorganisms in the CW are bacteria, fungi, algae and protozoa. The maintenance of

optimal conditions in the system is required for the proper functioning of wetland organisms. Fermentation is the decomposition of organic carbon in the absence of oxygen, producing energy-rich compounds (e.g., methane, alcohol, volatile fatty acids). This process is often undertaken by microbial activity. Nitrogen removal by nitrification/denitrification is the process mediated by microorganisms. The physical process of volatilization also is important in nitrogen removal. Plants take up the dissolved nutrients and other pollutants from the water, using them to produce additional plant biomass. The nutrients and pollutants then move through the plant body to underground storage organs when the plants senesce, being deposited in the bottom sediments through litter and peat accretion when the plants die.
Wetland microorganisms, including bacteria and fungi, remove soluble organic matter, coagulate colloidal material, stabilize organic matter, and convert organic matter into various gases and new cell tissue (Mitchell, 1996a). Many of the microorganisms are the same as those occurring in conventional wastewater treatment systems. Different types of organisms, however, have specific tolerances and requirements for dissolved oxygen, temperature ranges and nutrients.

<u>2. Chemical processes</u>: Metals can precipitate from the water column as insoluble compounds. Exposure to light and atmospheric gases can break down organic pesticides, or kill disease-producing organisms (EPA, 1995). The pH of water and soils in wetlands exerts a strong influence on the direction of many reactions and processes, including biological transformation, partitioning of ionized and un-ionised forms of acids and bases, cation exchange, solid and gases solubility.

<u>3. Physical processes</u>: Sedimentation and filtration are the main physical processes leading to the removal of wastewater pollutants. The effectiveness of all processes (biological, chemical, physical) varies with the water residence time (i.e., the length of time the water stays in the wetland). Longer retention times accelerate the remove of more contaminants, although too-long retention times can have detrimental effects.

<u>Wetland nitrogen processes</u>: The most important nitrogen species in wetlands are dissolved ammonia (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). Other forms include nitrous oxide gas (N_2O), nitrogen gas (N_2), urea (organic), amino acids and amine (Kadlec & Knight, 1996). Total nitrogen in any system is referred to as the sum of organic nitrogen, ammonia, nitrate and nitrous gas (Organic-N + NH_4^+ + NO_3^- + N_2O). The various nitrogen forms are continually involved in transformations from inorganic to organic compounds, and vice-versa. Many of these transformations are biotic, being carried out by nitrobacter and nitrosomonas (Kadlec & Knight, 1996). As it undergoes its various transformations, nitrogen is taken up by wetland plants and microflora (preferentially as $NH_{4,}^+$ and NO_3^-), some is leached to the subsoil, some is liberated as gas to the atmosphere, and some flows out of the wetland, normally in a dissolved form. Organic nitrogen comprises a significant fraction of wetland biota, detritus, soils, sediments and dissolved solids (Kadlec and Knight, 1996). It is not readily assimilated by aquatic plants, and must be converted to $NH_{4,}^+$ or NO_3^- through multiple conversions requiring long reaction time (Kadlec & Knight, 1996). The process of biological nitrogen removal follows several sequences:

- Nitrification first takes place, generally in the rhizosphere and in biofilms (aerobic process).
- Denitrification may then follow, occurring in soils and below the oxidized microzone at the soil/water interface, as it is an anaerobic process (Broderick et al., 1989).

- *Nitrification* is a two-step process catalysed by Nitrosomonas and nitrobacter bacteria. In the first step, ammonia is oxidized to nitrite in an aerobic reaction catalyzed by Nitrosomonas bacteria, as shown in Equation 3.1:

  $NH_{4,}^+ + O_2 \overset{\text{+Nitrosomonas}}{} H^+ + NO_2^- + H_2O$ (3.1)

  The nitrite produced is oxidized aerobically by nitrobacter bacteria, forming nitrate (Equation 3.2), as follows:

  $NO_2^- + O_2 \overset{\text{Nitrobacter}}{} NO_3^-$ (3.2)

  The first reaction produces hydroxonium ions (acid pH), which react with natural carbonate to decrease the alkalinity (Mitchell, 1996a). In order to perform nitrification, the nitrosomonas must compete with heterotrophic bacteria for oxygen. The BOD of the water must be less than 20 mg/l before significant nitrification can occur (Reed et al., 1995). Temperatures and water retention times also may affect the rate of nitrification in the wetland.

- *Denitrification* is the process in which nitrate is reduced in anaerobic conditions by the benthos to a gaseous form. The reaction is catalyzed by the denitrifying bacteria Pseudomonas spp. and other bacteria, as follows:

  $NO_3^- + \text{Organic-C} \xrightarrow{\text{Denitrifying Bacteria}} N_2 (NO \& N_2O)_{(G)} + CO_{2(G)} + H_2O$ (3.4)

  Denitrification requires nitrate, anoxic conditions and carbon sources (readily biodegradable). Nitrification must precede denitrification, since nitrate is one of the prerequisites.

- The process of denitrification is slower under acidic condition. At a pH between 5-6, N_20 is produced. For a pH below 5, N_2 is the main nitrogenous product (Nuttall et al., 1995). NH_4^+ is the dominant form of ammonia-nitrogen at a pH of 7, while NH_3 (present as a dissolved gas) predominates at a pH of 12. Nitrogen cycling within, and removal from, the wetlands generally involves both the translocation and transformation of nitrogen in the wetlands, including sedimentation (resuspension), diffusion of the dissolved form, litter fall, adsorption/desorption of soluble nitrogen to soil particles, organism migration, assimilation by wetland biota, seed release, ammonification (mineralisation) (Orga-N – NH_4^+), ammonia volatilization (NH_4^+ – NH_3 (gas)), bacterially-mediated nitrification/denitrification reactions, nitrogen fixation (N_2, N_2O (gases – organic-N)), and nitrogen assimilation by wetland biota (NH_4^+, Nox organic – N, with NO_x usually as NO_3^-). Precipitation is not a significant process due to the high solubility of nitrogen, even in inorganic form. Organic nitrogen comprises a significant fraction of wetland biota, detritus, soils, sediments and dissolved solids (Kadlec and Knight, 1996).

Phosphorus removal: Phosphorus is an essential requirement for biological growth. An excess of phosphorus can have secondary effects by triggering eutrophication within a wetland, and leading to algal blooms and other water quality problems. Phosphorus removal in wetlands is based on the phosphorous cycle, and can involve a number of processes. Primary phosphorus removal mechanisms include adsorption, filtration and sedimentation. Other processes include complexation/precipitation and assimilation/uptake. Particulate phosphorus is removed by sedimentation, along with suspended solids. The configuration of constructed wetlands should provide extensive uptake by Biofilm and plant growth, as well as by sedimentation and filtration of suspended materials. Phosphorus is stored in the sediments, biota, (plants, Biofilm and fauna), detritus and in the water. The interactions between compartments depend on environmental conditions such as redox chemistry, pH and temperature. The redox status of the sediments (related to oxygen content) and litter/peat compartment is a major factor in determining which phosphorus cycling processes will occur. Under low oxygen conditions (low redox potential), phosphorus is liberated from the sediments and soils back into the water column, and can leave the wetland if the anaerobic condition is not reversed (Moss et al., 1986).

Suspended solids: With low wetland water velocities and appropriate composition of influent solids, suspended solids will settle from the water column within the wetland. Sediment resuspension not only releases pollutants from the sediments, it increases the turbidity and reduces light penetration. The physical processes responsible for removing suspended solids include sedimentation, filtration, adsorption onto Biofilm and flocculation/precipitation. Wetland plants increase the area of substrate available for development of the Biofilm. The surface area of the plant stems also traps fine materials within its rough structure.

Pathogen removal: Pathogens are disease-causing organisms (e.g., bacteria, viruses, fungi, protozoa, helminthes). Wetlands are very effective at removing pathogens, typically reducing pathogen number by up to five orders of magnitude from wetland inflows (Reed at al., 1995). The processes that may remove pathogens in wetlands include natural die-off, sedimentation, filtration, ultra-violet light ionization, unfavorable water chemistry, temperature effects, predation by other organisms and pH (Kadlec & knight 1996). Kadlec and Knight (1996) showed that vegetated wetlands seem more effective in pathogen removal, since they allow a variety of microorganisms to grow which may be predators to pathogens.

Heavy metal removal: Heavy metals is a collective name given to all metals above calcium in the Periodic Table of Elements, which can be highly toxic, and which have densities greater that 5g/cm^3 (Skidmore and Firth, 1983). The main heavy metals of concern in freshwater include lead, copper, zinc, chromium, mercury, cadmium and arsenic. There are three main wetland processes that remove heavy metals; namely, binding to soils, sedimentation and particulate matter, precipitation as insoluble salts, and uptake by bacteria, algae and plants (Kadlec & Knight, 1996). These processes are very effective, with removal rates reported up to 99% (Reed et al., 1995). A range of heavy metals, pathogens, inorganic and organic compounds present in wetlands can be toxic to biota. The response of biota depends on the toxin concentration and the tolerance of organisms to a particular toxin. Wetlands have a buffering capacity for toxins, and various processes dilute and break down the toxins to some degree.

Abiotic Factors and their Influence on Wetlands:

- **Oxygen**: Oxygen in wetland systems is important for heterotrophic bacterial oxidation and growth. It is an essential component for many wetland pollutant removal processes, especially nitrification, decomposition of organic matter, and other biological mediated processes. It enters wetlands via water inflows or by diffusion on the water surface when the surface is turbulent. Oxygen also is produced photosynthetically by algae. Plants also release oxygen into the water by root exudation into the root zone of the sediments. Many emergent plants have hollow stems to allow for the passage of oxygen to their root tissues. The oxygen-demand processes in wetlands include sediment-litter oxygen demand (decomposition of detritus), respiration (plants/animals), dissolved carbonaceous BOD, and dissolved nitrogen that utilizes oxygen through nitrification processes (Kadlec & Knight, 1996). The oxygen concentration decreases with depth and distance from the water inflow into the wetland. It is typically high at the surface, grading to very low in the sediment –water interface.
- **pH**: The pH of wetlands is correlated with the calcium content of water (pH 7 = 20 mg Ca/L). Wetland waters usually have a pH of around 6-8 (Kadlec and Knight, 1996). The biota of wetlands especially can be impaired by sudden changes in pH.
- **Temperature**: Temperature is a widely-fluctuating abiotic factor that can vary both diurnally and seasonally. Temperature exerts a strong influence on the rate of chemical and biological processes in wetlands, including BOD decomposition, nitrification and denitrification.

Limitations of wetland processes

Process rates: The chemical and biological processes occur at a rate dependent on environmental factors, including temperature, oxygen and pH. Metabolic activities are decreased by low temperature, reducing the effectiveness of pollutant uptake processes relying on biological activity. Low oxygen concentrations limit the processes involving aerobic respiration within the water column, and may enhance anaerobic processes, which can cause further degradation of water quality. Many metabolic activities are pH-dependent, being less effective if the pH is too high or low.

Hydrological limitations: The capacity of wetlands to treat wastewater is limited, both in terms of the quantity of water, and the total quantity of the pollutants. Hydraulic overloading occurs when the water flow exceeds the design capacity, causing a reduction in water retention time that affects the rate of pollutant removal. Pollutant overloading occurs when the pollutant input exceeds the process removal rates within the wetland (White et al., 1996). Hydraulic overloading may be compensated for by using surcharge mechanisms, or the design may be based on a flush principle, whereby large water flows bypass the wetland when used for storm water treatment (White et al., 1996). Inflow variations are typically less extreme for wetlands treating municipal wastewaters, with incoming pollutant loads also being more defined and uniform.

It is (also) not safe to ignore water exchanges with the atmosphere, mainly because they can significantly contribute to water flows. Rain causes two opposing effects, including (1) dilution of waters, thereby reducing material concentrations, and (2) increased water velocity, decreasing the water retention time within a wetland. The presence of vegetation may retard the evapotranspiration, although wetland evapotranspiration is usually 0.8 times the Class A pan set at an adjacent open site. Preparation of an accurate hydrological budget is needed to properly design a constructed wetland. The water balance to a wetland can be calculated as follows:

$$\frac{dV}{dt} = \mathrm{Qi} + Qe + P - ET$$

Where Q_i is the influent wastewater flow (volume/time), Q_e is the effluent wastewater flow (volume/time), P is the precipitation (volume/time), ET is the evapotranspiration (volume/time), V is the volume, and t is time. The equation does not consider the inflow from, and to, the groundwater, since the SSF wetlands should be lined.

The role of Plants

Plants play the role of aerators although transfer from plants is minimal (about 0.02 g/m2 per day Oxygen)* and their roots support symbiotic bacteria and fungi, resulting in a more diverse microbial environment*. While the Net effect of plants on treatment is minimal, it is important for Nitrogen and Phosophorus removal to some extent (less than 10% of applied nitrogen and less than 5% of applied phosphorus removal) as well as its added biodiversity value.

** Source: "Constructed Wetland Systems: Design Approaches" by Scott D. Wallace, P.E. Vice PresidentNorth American Wetland Engineering P.A., University Curriculum Development for Decentralized Wastewater Management.*

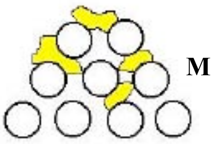
HYDRAULIC CONDUCTIVITY ACCORDING TO THE TIME OF MEDIA[1]

- Coarse gravel, high permeability: of the order of 10-2 m/s
- Gravel, good permeability: of the order of 10-4 m/s
- Fine to medium sand, poor permeability: of the order of 10-5 m/s
- Loamy sand, permeable with difficulty: of the order of 10-6 m/s
- Fine-particulate clay, very poor permeability: of the order of 10-8 m/s

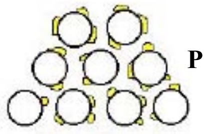
Depending on the kind of plants used, hydraulic conductivity increases with time as old rhizome channels remain open after the rhizomes decayed thereby creating a series of pores through the bed. They can develop in any significant quantity after three to five years.

GRAVEL ROCKS AND CRUSHED STONES

The media used in subsurface flow constructed wetlands (SSFCW) is fundamental; it is crucial that the gravel or sand be clean, washed and without impurities. When available, volcanic rock is the best medium but other materials such as limestone, river rocks, recycled concrete and recycled crushed glass to desired diameter are also being used. The gravel is the growth medium for microorganisms, works as a sieve and determines hydraulic residence time.



Mechanical Straining



Physical adsorption

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[1] *Constructed wetlands*, Rob Van Deun, Katholieke Hogeschool Kempen – Geel - Departement Industrieel Ingenieur en Biotechniek - Co-operation programme between Flanders and Central and Eastern Europe.

ESSENTIAL CONSIDERATIONS

Climate, geological and regional applicability:

Since Constructed wetlands rely on green plants and microbes, they perform better in warm, sunny conditions, the approach being thus ideal for a range of climates, from tropical to oceanic or Mediterranean-type climates. In these conditions of higher temperatures and increased sunlight, system effectiveness is high year-round. Applications for either desert type climates or colder regions for example, can however also be very effective, as has been shown in numerous systems installed in northern and Eastern Europe and the United-States. Constructed wetlands are especially recommended for use in on-site systems, for buildings in areas with groundwater close to the surface (such as often occurs during the wet season), for sites with rocky or impermeable clay soils that prevent standard leachfields from operating and near sensitive areas like rivers, lakes and coastal waters.

Space requirement:

For Subsurface Horizontal Flow Constructed wetlands treating domestic wastewater to the average standard given for secondary treatment, the assumed size is between 3 to 5 square meter per 150 Liter of water for a temperate to warm climate, depending on the nature of the water to be treated (treating black/faecal water only, grey water only or both type of waters together). In cold climates, these numbers may be twice or three times as large, depending on the level of treatment required during the cold periods of the year when plants may be dormant and bacterial activity slower because of low temperatures.

Subsurface Vertical Flow Constructed wetlands generally require half the size from a horizontal flow SSCW. Design can however vary greatly according to the type of activities generating the wastewater, its concentration of polluting factors, desired quality of treated effluent and intended disposal or reuse of treated water.

Principal Maintenance . / .. :

Simple and regular maintenance of Constructed Wetlands guarantee a life cycle of several decades (minimum 25 years, renewable). Proper functioning of the systems is dependent on several simple but important maintenance steps:

- PRIMARY TREATMENT: at the beginning of a CW, proper separation between solids and liquids is fundamental. In most cases a filter will be installed which will need regular checking and washing/rinsing if necessary. If a septic tank is installed for decentralised domestic sewage primary treatment, it should be pumped out when solids fill more than half its depth (a standard requirement for septic tank maintenance). In some cases CW can also be designed to deal directly with raw influent.
- GRAVEL: if porosity of the original gravel declines (which can occur over a period of 5 years to 15 years later, depending on the nature of the wastewater), new gravel can be substituted or the original gravel removed and cleaned. The plants can then be transplanted back in and the system can continue effective treatment.
- WATER LEVEL*:* Water levels in the wetland cells need to be checked periodically via their control box, especially during periods of lower water flow when evapotranspiration may exceed input into the treatment wetland. Until plants become well established it is important that water levels not be allowed to drop below their root zone.
- PLANTS . / .. *:* Plants should have considerable biomass and stem densities. Other than the aesthetics of the wastewater treatment plant, *the root system increases the surface available to bacterial colonization and transfers oxygen to provide an aerobic/oxidized environment, providing substrate to the microorganisms. Plants are responsible for providing* and *maintaining hydraulic pathways in the substrate as well as uptaking nutrients such as Nitrogen or Phosphorus (although to a limited extent).* Some wetland plant species can enhance root-zone oxidation and oxygen-dependent processes (f.e. BOD-removal) such as *Carex sp.* and *Scirpus sp. (Hook, Stein, Allen, Biederman, 2003)*. In cold climates, *accumulated litter serves as thermal insulation and* plant species selection may be more important than in warmer climates. Some species provide a good cover and insulation during winter (f.e. *Carex sp.*). (*Reference: Constructed wetlands by Rob Van Deun, Katholieke Hogeschool Kempen – Geel - Departement Industrieel Ingenieur en Biotechniek - Co-operation programme between Flanders and Central and Eastern Europe).*

ESSENTIAL CONSIDERATIONS (CONT .. / ..):

Principal Maintenance (cont.) ../.. :

- PLANTS (CONT.) .. / .. : Wetland plants need normal garden care – pruning for appearance and encouragement of new flowers. In some cases regular pruning is important as it increases (although modestly) Nitrogen intake. Leaf litter can be allowed to remain in the system providing mulch if it is above the gravel, and encouraging an aerobic microbial community in the layer above the saturated gravel. But heavy prunings of plants should be removed from the CW to prevent reduction of gravel porosity when that material decays. The prunings can be used for mulch outside the system or added to compost piles.
- WATER DRAINAGE: it is important to ensure that drainage is adequate around a CW so that runoff rainwater and soil do not wash into the system. Systems should be built with a protective beam higher than surrounding ground level and one must check occasionally to make sure soil has not built up around the system, which will allow rain runoff to enter.

Key design factors:

- Proper assessment of water quantity to be treated.
- Treatment objectives: standard, for reuse in agriculture and/or on the contrary for disposal of treated water in sensitive ecosystems.
- Ensuring proper primary treatment.
- Integration or not of a productive vegetation: fast-growing timber, medicinal plant and/or weaving plants, fodder for animals.
- Integration or not of a "closed" primary treatment cycle: creation of soil through vermicomposting or composting.

Construction:

- Good general ratios are considered to be 1:3 or 1:4 (1 m width for 3 or 4 meter length). Note that when this spatial arrangement is not possible internal deviation walls can also be used.
- Middle walls on long or round systems to ensure sufficient water residence time.
- Location: No shade, no rain-gathering areas.
- Construction: Fine and precise (levels).
- Materials used: gravel or broken recycled concrete (washed and screened)

Advantages:

- **Long life and robustness:** Renewable cycles of 15 years minimum renewable; If water nature changes, clean gravel and replace plants, but basic structure not in danger. Efficiency increases with time and ecosystem matures.

- **Lower Cost:** Compared to so-called conventional wastewater treatment plants (WTP): Construction: 1/3 depending on scale and country - Maintenance: minimum 1/4 +/- of so-called conventional WTP.

- **Adaptability & Flexibility of treatment:** Sizing depends of final use. All kinds of water, no limits of quantity, treatment units can be added as population grows, shape adaptable to site.
- **Simplicity and auto-organization:** CW rely on biological complexity instead of forced mechanical or synthetic processes highly dependent on external energy sources.

- **Aesthetics**: Great public spaces without additional cost.

- **Highly productive system and Water saving:** Important added ecological value (ecosystem creation with CO2 absorption and O2 production + Wildlife habitat) as a new green zone is created at no extra water consumption.

- **No additional pollution nor chemical products:** No harmful products are used in the disinfection process nor contributing pollution.

- **Protection of vital ecosystems** such as rivers, lakes, oceans, groundwater sources and soils,as sizing is done according to required levels of water purification before release into the environment.

- **Potential economical tool:** plant selection according to their value to the site of implementation: - - Wildlife attractor and habitat
  - Fast growing timber
  - Flowers
  - Weaving material
  - Animal fodder
  - Collection services of septic tanks owners and vermicomposting from primary treatment

- **High efficiency in Total Suspended Solids removal** *(courtesy: "Constructed Wetland Systems: Design Approaches" by Scott D. Wallace, P.E. Vice PresidentNorth American Wetland Engineering P.A., University Curriculum Development for Decentralized Wastewater Management).*

- From*: Review of Constructed Subsurface Flow vs. Surface Flow Wetlands, Prepared for the U.S. Department of Energy by Nancy V. Halverson September 2004:*

  . Constructed wetlands have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems.

  . Additionally, constructed wetlands:
    . Tolerate fluctuations in flow and pollutant concentrations,
    . Provide flood protection,
    . Be built to fit into the landscape,
    . Provide habitats for plants and wildlife,
    . Enhance aesthetics of open spaces,
    . Provide recreational and educational opportunities, and are an environmentally sensitive approach viewed favorably by the general public and regulatory agencies (ITRC 2003).

Inconvenients / Challenges

➔ **Space**: for household sewage treatment (+/-) 1 to 4 m^2 per person in warm weather, depending on type of water treatment (black/faecal water only, grey water only, or mixed water). Double size (+/-) in cold climates.

➔ **Lack of Professionalism / Experience**: behind the apparent simplicity of Constructed Wetlands lay a complex ecosystem with numerous parameters to take into account in the design phase, requiring tested experience to ensure proper design and implementation.

➔ **Local terrain not always adapted / possible**: lack of space, excessive shade.

➔ **Ignorance by public health officials and engineers:** although the situation has been evolving rapidly, constructed wetlands are still too unknown and not being considered on equal terms with so-called conventional wastewater treatment plant. Not understood by numerous engineers who misinterpret apparent simplicity with lack of effectiveness and reliability. Politicians and public officials need to understand better the field of wastewater, what is at stake and treatment options.

➔ **Significantly longer design phase**: must take into account and be adapted to site / topography / local climatic conditions (rain / winds / sun …), / evolution of quantity and nature of water flow, etc.

➔ **Construction «Finesse»:** While apparent simplicity, implementation must be very careful and attentive, in particular for small scale treatment plants where construction quality control can be overlooked or is too expensive to be included in implementation (not a problem if the constructor is professional).

➔ **Inter-sectorial collaboration:** in particular on large-scale systems successful design needs to take into account and collaborate with fields of competency not usual in the wastewater treatment world where the majority are hydraulic and civil engineers. Depending on the context and scale of the treatment plant, exchange and collaboration will be occurring with architects, landscapers, agronomists, in addition to hydraulic and civil engineers.

➔ **Maintenance**: simpler than other technologies but essential, can be overlooked in small-scale applications. Involves also gardening and/or agronomical knowledge in addition to standard plumbing maintenance.

➔ *From Review of Constructed Subsurface Flow vs. Surface Flow Wetlands, Prepared for the U.S. Department of Energy by Nancy V. Halverson September 2004:*

. They generally require larger land areas than conventional wastewater treatment systems, so adequate land must be available.

. They may be relatively slow to provide treatment compared to more conventional treatment technologies. (WWG note: plants need to develop good root systems and the new ecosystem to stabilize before optimal treatment takes place; in some cases a larger area of CW will compensate for this initial lower quality of treatment or a final temporary polishing stage will be included after the CW).

. Performance may be less consistent than in conventional treatment (in cold climates); constructed wetlands depend on climate and, thus, may have reduced efficiencies during colder seasons (note WWG: this reduce efficiency is compensated by larger CW surface or complementary polishing stage).

. Surges in flow or pollutants may temporarily reduce treatment effectiveness.

. They require a base flow of water; they can tolerate temporary water level drawdowns, but not complete drying.

. Contaminant accumulation must be monitored to maintain ecological health of the system (USDA 1995, ITRC 2003).

CASE STUDY

Example of a wastewater treatment plant via constructed wetlands for 8,000 residents

3 options are presented

(Ref.: WWG/IE Fuvahmulah municipal treatment, Maldives for Male' Water & Sewerage Company Pvt. Ltd (MWSC))

Population served: 8,000 persons - 1752 homes, small businesses and 27 mosques.
No industrial activity.

Daily amount to treat		BLACK WATER	GREY WATER	MIXED WATER
		192 m³	**640 m³.**	**832 m³**
OPTION 1 **Decentralized treatment: each house has its own treatment servicing households of 8 to 15 residents**	Primary Treatment	1 septic tank with 2 chambers of 1100 Liters minimum inside clean volume	1 simple filter (gravel, husks, …)	
	Secondary Treatment	1 horizontal subsurface flow constructed wetland of 10 m²		
	Drainage of treated water	1 gravel bed of 1m³ (1 m² surface x 1 m depth +/-) or reuse for fruit trees	Reuse in the garden or direct return to the water table	
OPTIONS 2 **Centralized treatment of black water and decentralized treatment for greywater**	Primary Treatment	1 screener followed by a 4-chamber sedimentation tank for a total interior clean volume of 108 m³.	1 simple filter (gravel, husks, …)	
	Secondary Treatment	Total wetland area: 4080 m²: 2 WWG units of vertical flow of 880 m² surface each - or 8 WWG units of vertical flow of 220 m² each (1760 m² total) + 8 WWG units of horizontal flow of 290 m² surface each (2320 m² total).		
	Drainage of treated water	Reuse for agriculture (principally fruit trees) with partial return to the water table after final sand filter	Reuse in the garden or direct return to the water table	
OPTION 3 **Centralized treatment of all wastewater (grey + black/faecal) – 832 m 3/day**	Primary Treatment	1 screener followed by a 3-4 chamber sedimentation tank for a total interior clean volume of 400 m³.		
	Secondary Treatment	Total wetland area: 8560 m²: 8 WWG units of vertical flow of 630 m² surface each (5040 m² total) + 4 WWG units of horizontal flow of 880 m² surface each (3520 m² total).		
	Drainage of treated water	Reuse for agriculture (principally fruit trees) with partial return to the water table after final sand filter		

Treatment levels aimed

BLACK / FAECAL WASTEWATER				ALL WASTEWATER (BLACK WATER + GREY WATER)			
Parameters of analysis	**Entrance WWG unit/s**	**Exit WWG unit/s**		Parameters of analysis	**Entrance WWG unit/s**	**Exit WWG unit/s**	
COD	1200	120	mg/L	**COD**	500	120	mg/L
BOD5	500	25	mg/L	**BOD5**	308	25	mg/L
NH4 / Amonium N	62.5	10	mg/L	**NH4 / Amonium N**	20	10	mg/L
NO3-N / Nitrate N	125	10	mg/L	**NO3-N / Nitrate N**	68	10	mg/L
NT	187.5	20	mg/L	**NT**	88	20	mg/L
PO4 / Phosphate	18.75	5	mg/L	**PO4 / Phosphate**	23.4	2	mg/L
TSS (Total Susp. Solids)	230	30	mg/L	**TSS (Total Susp. Solids)**	228	30	mg/L
Coliforms bacteria	1800000	99	% + elimination	**Coliforms bacteria**	1800000	99	% + elimination

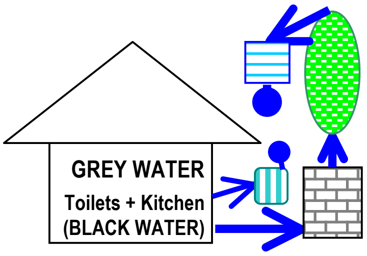
Case study (Cont .. / ...):

Schematic drawings of 3 options of wastewater treatment plant (WTP) constructed wetlands for 8,000 residents

(Ref.: WWG/IE Fuvahmulah municipal treatment, Maldives for Male' Water & Sewerage Company Pvt. Ltd (MWSC))

Schematic of WTP according to options

OPTION 1: Decentralized treatment



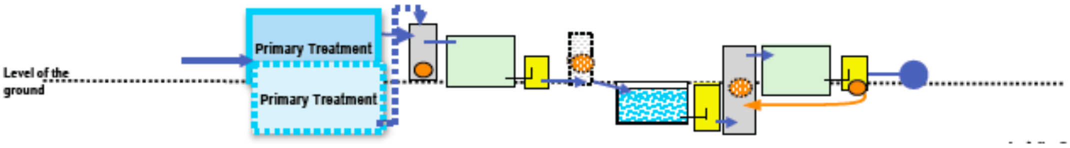
- Subsurface horizontal -flow constructed wetland
- Gravel bed
- 2-chambers septic tank + Filter
- Sedimentation tank
- ● Exit of treated water

OPTION 2: Centralized treatment of black water and decentralized treatment for greywater

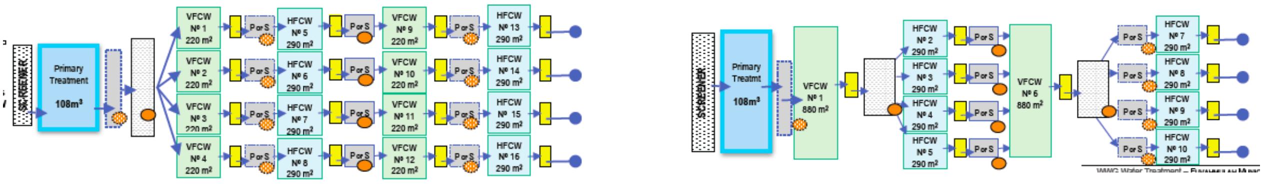
LEGEND

- **Primary Treatment**
- **HFCW: Horizontal Flow CW**
- **VFCW: Vertical Flow CW**
- → Wastewater pipes and direction of flow
- ● Exit of treated wastewater
- Pumps or siphons
- **Chamber for a pump or syphon for "water raising"**
- Distribution chamber
- Water level control boxes

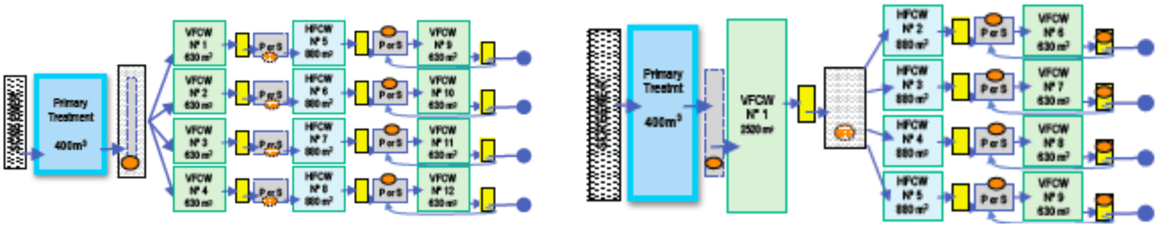
SIDE VIEW



Layout options (seen from the top):



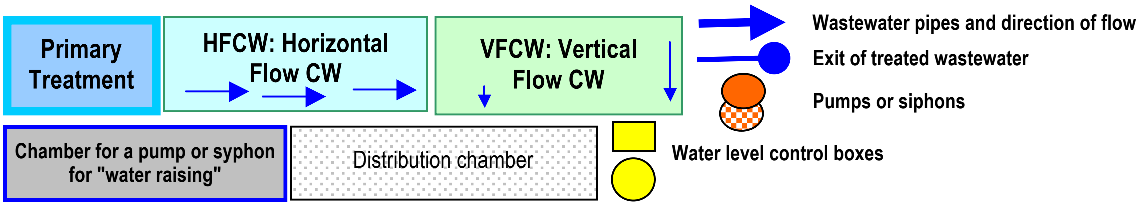
OPTION 3: Centralized treatment of all wastewater (Black/faecal water + Grey water)



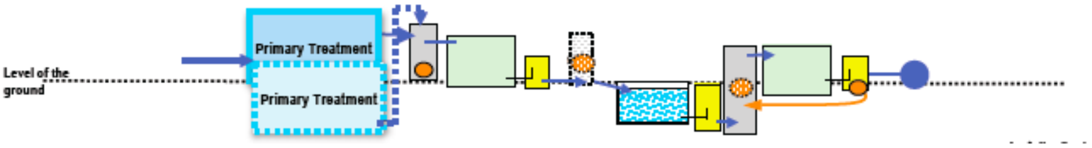
Case study (Cont ... / ...):

Layout options for Option 2 or 3:

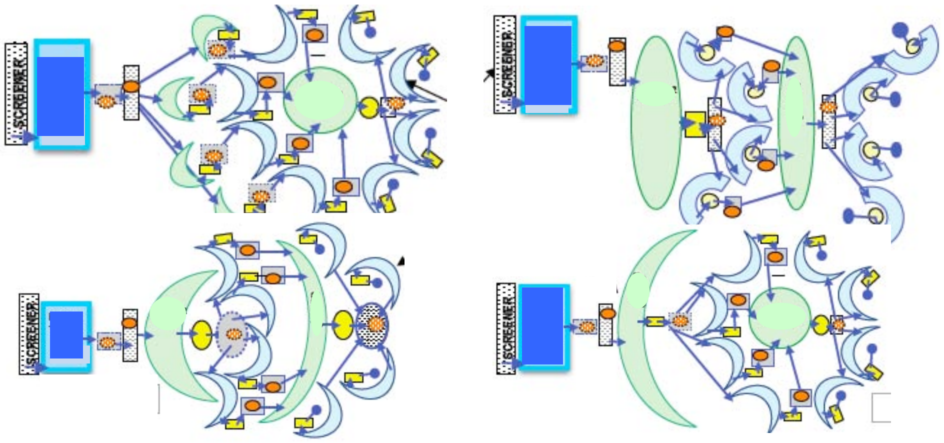
REMINDER LEGENDS



Side view



Example of 4 options of space allocation (seen from the top)



Example of a municipal treatment plant by constructed wetlands using surface-flow CW + Horizontal-flow and Vertical-flow Constructed Wetlands (Ref: Hans Brix) built in 2006-2007

Photo here taken immediately after plantation (vegetation not grown yet – See photo page 3 with growing vegetation)

Population: 3,000 – 4,000 residents + 1.2 million tourists/year (island Koh Phi Phi Don, Thailand)
Amount of wastewater treated: 400 m^3 day
Treatment plant surface: 6,000 m^2

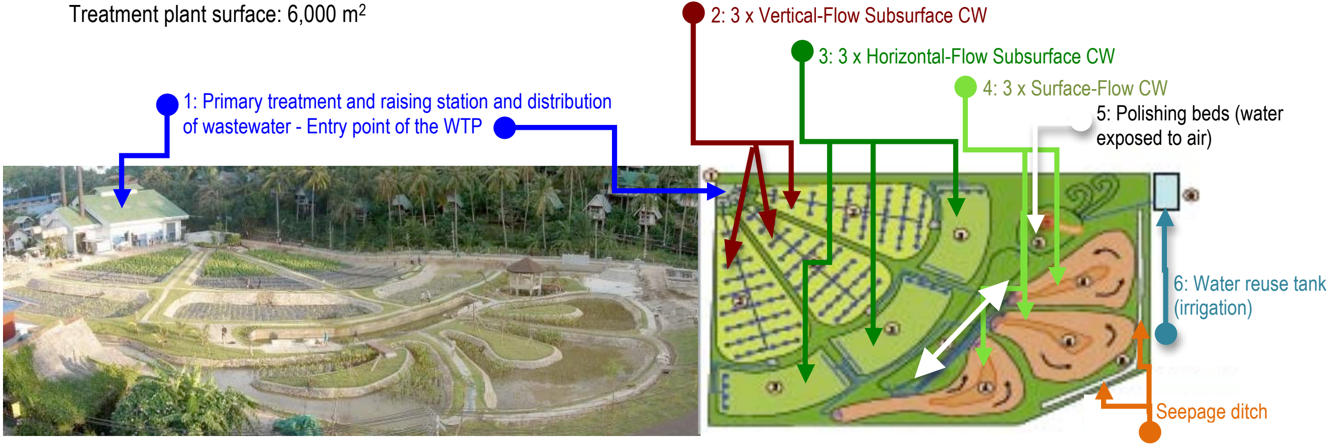


PHOTO GALLERY OF PRINCIPAL CONSTRUCTION STEPS (SMALL UNITS)

Overview of the principal construction steps (here only Horizontal Subsurface-Flow constructed wetlands are featured and not the primary treatment nor drainage of treated water): we will have ensured that the sewage effluent coming from primary treatment is properly filtered so that no solids enter the WWG unit/s and that manholes are regularly installed on the plumbing network and on connection points in order to facilitate long-term ease and agreeable of maintenance.

Marking/staking location of elements and taking levels by choosing as point O the inside bottom of the entry pipe into the constructed wetland/WWG unit:

Marking the principal elements:

Excavation and compacting of soil (by hand or machine)

Note: in some cases CW can also be made elevated above ground level

Installation process (Cont .. / …..):

Excavation of the pipe network and areas of drainage (if subsurface drainage trenches are installed by hand or machine, with regular levels checking:

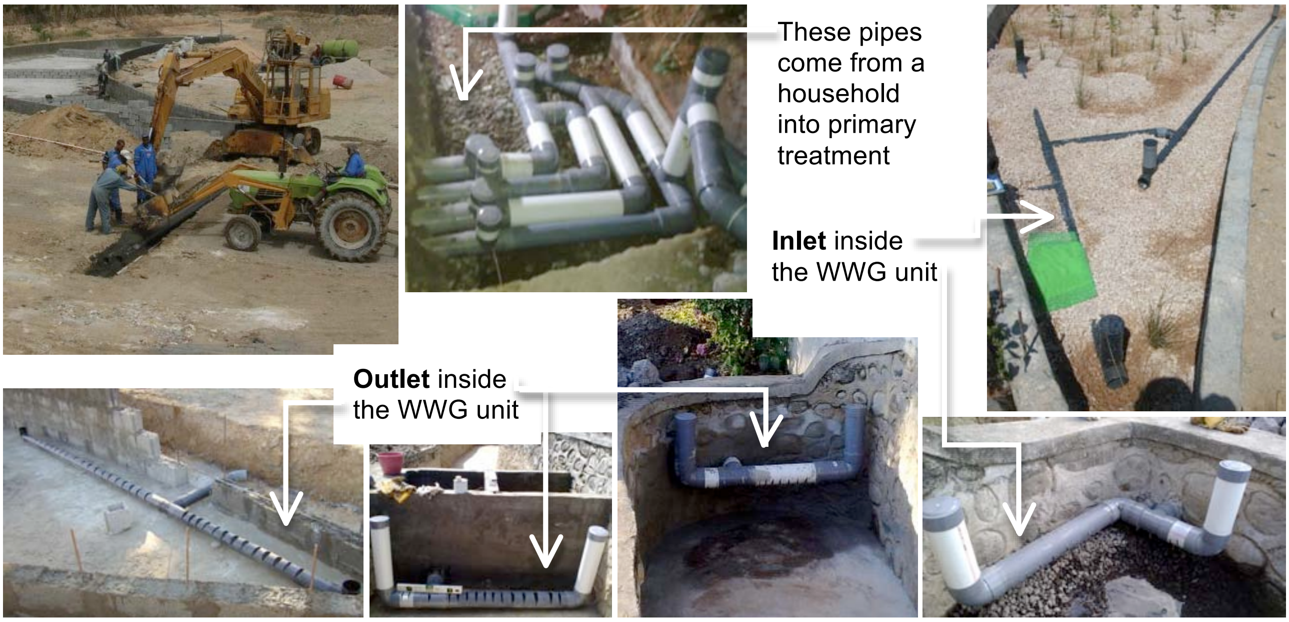
Pipe preparation with pipe riser at each beginning and ending of each line:

Waterproofing of the constructed wetland (clay, concrete with final waterproofing mortar or geomembrane)
+ CW Water level Control Box:

Installation process (Cont ... / …..):

Water level Control Box/es with airtight covers as light and practical of access as possible (fiberglass, cast iron, concrete – not too heavy – and/or wood, with practical handles) ensuring **airtightness** while being easy to open for ease and agreeable long-term maintenance (here for small-scale systems); they can also be made aesthetical by painting or engraving on their top:

Plumbing, preparation and placement of pipes inside the WWG unit/s:



These pipes come from a household into primary treatment

Inlet inside the WWG unit

Outlet inside the WWG unit

Installation process (Cont …. / …..):

Waterproofing test during 24 to 72 hours (depending on size of project) to ensure no leaking is taking place:

After the water test, filling up the CW with gravel (Subsurface Horizontal-Flow CW on photos):

Installation process (Cont ….. / …..):

Once the gravel is well levelled, the constructed wetland is ready to be planted:

Plantation (2 to 3 plants per square meter

The borders of the constructed wetland / WWG unit are covered with gravel, stones or made in masonry, according to the desired aesthetics. They protect the CW from any dirt, loose soil and rainwater entering into the treatment area; depending on the climate, the elevation will be between 5 to 30 cm on top of the surrounding soil level with, in some cases, a small drainage channel around the CW.