

II. INTRODUCTION, WETLAND HISTORY, DESIGN, AND TREATMENT

Introduction

Sewage treatment plant (STP) construction in metropolitan areas typically consists of mechanical systems that can have high construction, energy and labor costs. More advanced mechanical treatment systems require higher operator grades. One of the major concerns for communities that operate such systems is the annual energy and labor cost. These costs are a more significant portion of the budgets for small communities. Treatment systems that require more land and have lower energy and labor costs are more attractive economically to small communities. One land-based alternative to typical treatment systems is the use of constructed wetlands for municipal wastewater treatment.

Constructed wetlands are land-based wastewater treatment systems that consist of shallow ponds, beds, or trenches that contain floating or emergent-rooted wetland vegetation. They rely on biological, chemical, and physical processes in a natural environment to treat wastewater. Some systems are installed in indigenous soils and discharge to surface and/or groundwater. Others are lined with clay soils, bentonite, or a synthetic liner and discharge to surface water or groundwater. Constructed wetlands differ from natural wetlands in that operators have greater control over natural processes in the constructed wetlands because flows are more stable. Whereas, natural wetlands are subject to the variabilities of precipitation. Constructed wetlands have higher solids and biochemical oxygen demand (BOD) concentrations than natural wetlands.

History

Wetlands have been used for at least 90 years for the disposal of wastewater; most discharges were to natural wetlands (U.S. EPA, 1999). Studies on the use of constructed wetlands for wastewater treatment began in the 1950's at the Max Planck Institute in Germany (Seidel, 1976). Research efforts in the U.S. were developing in the 1970's and 1980's. Some systems were installed in the 1970's with an increasing number in the 1980's. The 1990's saw a major increase in the number of these systems as the application expanded for use not only to treat municipal wastewater, but also stormwater, industrial and mining wastes, and agricultural wastes.

System Design and Function

Constructed wetlands are typically used after some sort of primary treatment system that is typically lagoons, ponds, or septic tanks. Design characteristics are well documented in U.S. EPA's Manual for Constructed Wetlands Treatment of Municipal Wastewaters (2000) and Kadlec and Knight's (1996) Treatment Wetlands and IWA's Constructed Wetlands for Pollution Control. There are two types of systems that are characterized by their hydraulic water levels. Surface flow (SF) constructed wetlands are similar to natural wetlands with emergent vegetation, open water areas, and varying water depths and surface features such as dikes. Figure 1 (Pg. 5) provides a diagram of a SF system.

They typically are contained in a bermed area near their primary treatment source. An inlet structure typically regulates wastewater flow to the wetlands and an outlet structure regulates water levels in the wetland. Open water areas and emergent or surface vegetation areas occupy most of the surface of wetlands. There usually may be more than one wetland unit or cell with wastewater distribution often to several cells. Cell sizes and shapes vary depending on site conditions and the designer and installers of these systems. Vegetation is usually dependent on site conditions and availability from local plant sources.

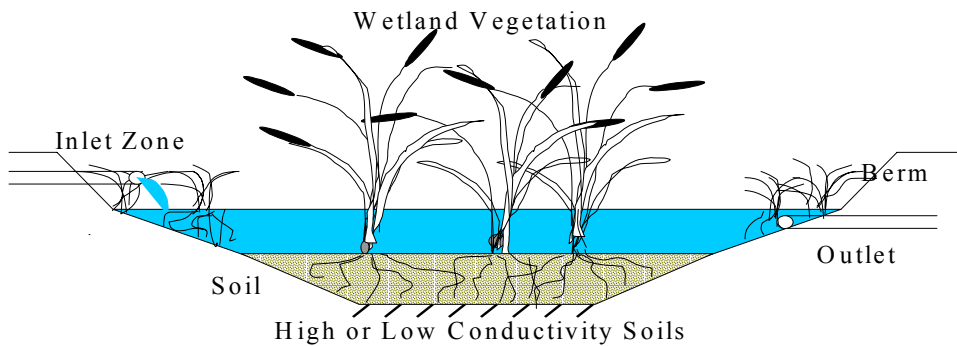


Figure 1. Surface flow (SF) constructed wetland.

Subsurface flow (SSF) wetlands are contained in bermed areas near their source of wastewater and consist of a gravel bed with wetland vegetation as shown in Figure 2 (Pg. 6). Primary-treated wastewater is discharged subsurface to this system so that all that is visible is the media and vegetation. Subsurface wetlands can be designed as horizontal or vertical flow. They also have inlet and outlet structures to manipulate hydraulic levels in the wetland. Sizes and shapes of wetland cells vary along with media (gravel) type and vegetation.

Wetlands are used for solids and BOD (biochemical oxygen demand) removal and on a limited basis for nitrogen removal. Most recent design developments in subsurface wetlands include aerated beds, reciprocating beds, and vertical flow. These wetlands provide excellent ammonia removal. However, they require electrical energy for pumps. Wetlands are not considered effective in removing phosphorus on a long-term basis.

Wetlands, when compared to mechanical treatment systems, require more land area and yet provide more diverse microenvironments using less mechanical and human labor. However microbes including algae, fungi, protozoa, and bacteria accomplish the majority of treatment in both systems.

Treatment in wetlands is accomplished by a complex combination of physical, chemical and biological mechanisms and relies upon vegetation, water depth, substrates and microbial populations according to (U.S. EPA, 1999; Hammer, 1989; Hammer 1993;

Kadlec and Knight, 1996). The water surface area in wetlands allows for the exchange of gases, especially oxygen that promotes decomposition of organic material and oxidation

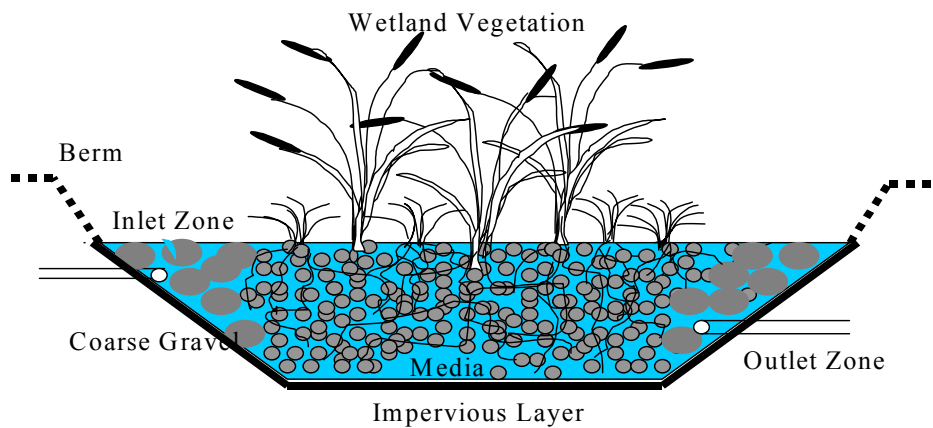


Figure 2. Subsurface flow (SSF) constructed wetland.

of metallic substances. Wetland vegetation not only slows flow and enhances sedimentation of solids but its main function is to provide a substrate or attachment area for microbes which are involved in the transformations of wastewater pollutants. Rooted wetland plants have structures in their leaves, stems, and roots that help move oxygen to their roots. These features allow them to thrive under saturated conditions. The outer cover on plant root hairs has a porous seal that allows oxygen to diffuse past this cover to create a thin film oxygenated region or rhizosphere around each root hair. The greater area surrounding this thin film aerobic region is anaerobic, and it is this combination of oxygenated and anoxic conditions that enables the transformation many wastewater pollutants.

Plants also provide a mulch/litter layer that is a porous substrate for attachment of microbes that treat wastewater. Decomposing plant matter is also a rich carbon source for microbial communities. Treatment efficiencies in wetlands are dependent on the large surface area of the plant mulch layer for attachment of microbes. Pullin and Hammer (1989) have suggested that the most important role for plants in a constructed wetland for wastewater treatment are to grow and die, which is why treatment efficiencies between plant species are somewhat similar on a broad ecological basis.

Emergent and floating-leaved plants are used most commonly in wetlands in the Midwest. Leaves, stems, and roots of these plants are adapted for growth in water or saturated soils. The more commonly used emergents include *Scirpus* (bulrush), *Phragmites* (giant reed), *Typha* (cattail), *Carex* (sedges), and *Iris* (iris). *Lemna* (duckweed) is the most commonly found floating plant.

Treatment and Concerns

Some of the apprehension in considering constructed wetlands for wastewater treatment is related to the perceptions and misperceptions of these systems and their performance in treating certain contaminants. It is important to understand the treatment processes that occur in wetlands.

Biochemical Oxygen Demand (BOD)

Numerous studies have shown that wetlands are effective, after some sort of pretreatment, in removing CBOD to achieve effluent quality discharge limits (U.S. EPA, 1999; Hammer, 1989; Hammer, 1993; Kadlec and Knight, 1996). Biochemical oxygen demand (BOD) is a measure of the amount of oxygen consumed by microorganisms in the oxidation of organic matter, it includes nitrogenous and carbonaceous oxidation. Carbonaceous biochemical oxygen demand (CBOD) is a measure of the amount of chemically oxidizable materials, mostly carbon compounds, in water. Most wastewater treatment facilities monitor CBOD. The effectiveness of wetlands at removing BOD occurs only if the incoming BOD is greater than the natural background level. A notable wetland issue is that they have a background BOD that results from the partial digestion of previously settled influent solids, plant decomposition, and additional byproducts from anaerobic digestion; concentrations can be as high as 10 mg/L. Loadings of BOD from anaerobic digestion begin in spring and continue until materials that have accumulated over the winter are consumed. BOD uptake varies between fully vegetated and open water SF wetlands, and between SF and SSF wetlands. SSF wetlands have a faster uptake of BOD compared to SF by a factor of five (Kadlec and Knight (1996). BOD is relatively unaffected by temperature. When wetlands are designed they are typically over designed for removal of BOD.

Total Suspended Solids (TSS)

Total suspended solids are produced and removed in wetlands through natural processes. Removal of solids is enhanced at the wetland inlet. Physical mechanisms responsible for solids removal include flocculation, sedimentation, and interception. According to Kadlec and Knight (1996) along with others (Reed, et al, 1995), influent solids from lagoons are typically removed in the first 2-3 days of retention time in vegetated zones near the influent discharge point. Removal is by settling and flocculation and depends on the terminal settling velocity of influent and flocculated solids.

Within SF wetlands, trapping and resuspension of solids occurs as water moves through a wetland as well as the generation of suspended solids above and below the water surface. Generation may be caused by a number of factors such as the formation of bacterial, algal, plant, and invertebrate debris and vertebrate activity. Plant debris can include pollen, seeds, and leaf and stem litter. These solids, along with other resuspended solids caused by turbulence or gas lift, will occur at one area in a wetland and settle out further downstream in the wetland. Interception or filtration of solids occurs as solids are trapped in the litter layer formed by wetland plants. Concentrations of TSS in effluent tend to increase during the summer months and decrease during the winter (Kadlec and Knight, 1996). This is due to solids generation processes in the summer. Temperature

does not seem to affect settling and resuspension processes. Kadlec and Knight (1996), in a summary table of research studies, show SF wetland removal efficiencies for wetlands range from a median percent reduction of 66 to 72 percent.

The solids processes within SSF wetlands differ from SF systems. Plant and invertebrate debris accumulates on the media surface of the bed and does not interact with subsurface flow. Wind turbulence and vertebrate activities do not cause resuspension. Solids removal occurs through what has been called granular medium filtration (Kadlec and Knight, 1996). Solids settle in small stagnant spaces between the gravel or are strained by the tortuous flow that creates constrictions. Solids may also stick to media surface due to adhesive forces. Removal and resuspension processes within SSF wetlands have not been studied due to the difficulties in studying a subsurface system. Generation of particulates from plant and animal matter occur through the same processes that occur in SF wetlands. The hydraulic conductivity of a bed, especially near the inlet, can decrease over time and cause clogging due to solids accumulation and root growth that reduces pore space. Kadlec and Knight (1996) in a summary table show suspended solids removal efficiencies based on median percent reductions from research studies of 75-92 percent.

Nitrogen

Nitrogen compounds in wastewater are important because of the impacts they have on receiving surface water and groundwater supplies. Excessive amounts of nitrogen in surface waters can create an ecological environment with an overabundance of plants, such as macrophytes and algae, and animals that degrade water quality, causing eutrophication. They also impact the amount of oxygen in a receiving stream and can be toxic to fish. They do provide some benefit in plant growth.

The nitrogen cycle is very complex with many chemical transformations. Kadlec and Knight (1996) and IWA (2000) provide a simplified diagram of the nitrogen cycle within wetlands. The most important inorganic forms are ammonia, nitrite, nitrate, nitrous oxide, and dinitrogen gas. Ammonia in wetlands may be found as ammonia or more often as ammonium depending on temperature and pH. Organic forms of nitrogen in wetlands include urea, amino acids, amines, purines, and pyrimidines. Septic tank and primary effluent would mostly contain reduced forms of nitrogen, organic nitrogen and ammonia. Lagoons may contain reduced or oxidized forms of nitrogen depending on loading and season (U.S. EPA, 1999).

According to U.S. EPA nearly half of municipal wastewater nitrogen received at a treatment system is organic nitrogen. The remaining portion is converted to ammonium in the sewer (U.S. EPA, 1999). Ammonification is the biological transformation of organic nitrogen to ammonium during degradation of organic matter. Plants can absorb ammonium or it can be held in sediments, remain in soluble form in water, be volatilized as ammonia, and under oxygenated (aerobic) conditions it can be nitrified. Nitrification, which occurs in the presence of oxygen and microbes in water or on biofilms, may transform the ammonium to nitrite and then to nitrate nitrogen. Nitrate may remain in the

water or in sediment pore water, be absorbed by plants or microbes, or be denitrified. Denitrification occurs when nitrate is reduced by microorganisms in the presence of carbon under anaerobic or low oxygen conditions and is converted to nitrogen gas and nitrous oxide gas. This process occurs mostly in anaerobic sediments.

Two other nitrogen processes may occur in wetlands. Nitrogen fixation occurs when nitrogen gas is converted to organic nitrogen by certain organisms. This source of nitrogen is not important in wastewater wetlands. Plant assimilation of nitrogen plays a role in wetlands in that plants use inorganic forms of nitrogen. Nitrogen uptake occurs during the growing season by plants, microbes, and algae. The concern is that plant senescence results in the re-release of nitrogen back to the water in the fall and early spring.

In SF wetlands, ammonium is released from organic nitrogen in sediments and is available to plants. The same processes mentioned for TSS removal may remove organic nitrogen in suspended solids. Ammonium is often released into the water in fall and early spring. Some ion exchange of ammonium will occur by the clay minerals in wetland soils, but this diminishes when a build up of plant litter occurs on the soil surface. Some may be nitrified under aerobic conditions in open areas where there is more oxygen, in areas away from the intake where more carbonaceous organics are removed. Some nitrification may occur near plant rhizomes but this environment near the sediments is usually anaerobic. Nitrate may be taken up by microbes or may be taken up by plants. Under anaerobic conditions when organic material is present, nitrate may be denitrified to nitrogen gas. In moving through a wetland, total nitrogen concentration drops near the initial settling zone near the intake. This will be followed by ammonia release, nitrification, and denitrification. Nitrification and denitrification rates can decrease in winter months. Ammonia volatilization can occur in open water areas when pH and temperatures are elevated and is enhanced by wind turbulence.

Seasonal changes and variability in influent quality will impact nitrogen removal and transformations. Most reliable ammonia removal will be through nitrification, which will occur when a wetland has designated open water and vegetated areas. Nitrification of course will decrease during colder months. Wetlands that receive influent that has undergone some form of primary treatment to nitrify much of the nitrogen, may remove considerable amounts of nitrogen through denitrification.

Anaerobic conditions predominate in SSF wetlands with horizontal flow. Ammonification in the bed will convert organic nitrogen to ammonia, some of which may be taken up by plants. Due to the low oxygen conditions nitrification is minimal and may occur from the intake further downstream in small regions near the rhizomes in the root zone or the surface of the wetland. Nitrification can occur in systems that have low wastewater loadings. This type of wetland would provide an ideal environment for denitrification of wastewater that has undergone nitrification. Plant debris would supply the necessary carbon source for this process. This process decreases with decreasing temperatures. Recently developed aerated wetland beds, reciprocating beds, and vertical

flow wetland designs provide enhanced ammonia removal. They do require pumps that use electrical energy.

Thus, nitrogen removal does occur in conventional wetlands but to a limited extent especially during the winter months. Wetlands are not a reliable system for ammonia removal. However, ammonia removal will increase with increased detention time and adequate oxygen concentrations. Increased detention times can be achieved by increasing the size of the wetlands. Subsurface flow systems that receive nitrified wastes may remove nitrogen. Some SSF in the U.S. that are preceded by a sand filter have achieved considerable nitrogen removal. Recently developed wetlands that include some form of aeration provide enhanced ammonia removal.

Phosphorus

Phosphorus in freshwater systems can be one of the most limiting nutrients because it will settle with sediments and becomes unavailable in the natural system. It occurs in natural waters and wastewater streams as phosphate. Forms of phosphate include orthophosphate, condensed phosphates, and organically bound phosphates. Mitch and Gosselink (2000) provide diagrams of the phosphorus cycle in the environment. Organic phosphates in wastewater are formed by biological processes and derived from food and body wastes, and in treated wastewater as algae or bacteria (U.S.EPA, 1999). Inorganic forms in wastewater are mostly from detergents and fertilizers. In treatment wetlands the main removal process is the accumulation of mineral phosphates and biomass (plant and microorganism debris) in the sediment.

Phosphorus in wetlands systems undergoes physical and chemical separations along with biological transformations. Soluble phosphate can adsorb onto biofilms or sediments. Particulate phosphate can settle onto the sediment, adsorb onto biofilms, or be (assimilated) taken up and stored by wetland vegetation. There are many diffusion, sorption/desorption processes that occur depending on the characteristics of the wetland environment. Soluble inorganic phosphate is the form most available to plants. Uptake is by microorganisms and plants. Plant uptake occurs during the growth phase and release of phosphate occurs during plant senescence and death in fall.

Removal of phosphate in SF wetlands follows a seasonal pattern and is dependent on the form, loading rate, climate, type and number of plants and microorganisms. Phosphate removal in SSF wetlands is similar. Loading to these wetlands is high compared to plant uptake. Some additional temporary removal may occur through sorption, precipitation, and exchange processes associated with the mineral components of some media. When considering the large land/area requirements for adequate phosphate removal, wetlands are not very efficient.

Pathogens

Bacteria, viruses, protozoa, helminths, and fungi are waterborne pathogens found in wastewater. These organisms depend on their host for survival. The wastewater

environment for pathogens is very hostile and survival of these organisms is reduced by natural factors, such as temperature, ultraviolet radiation, unfavorable water chemistry especially anoxic conditions, sedimentation, predation, and natural die-off (Kadlec and Knight, 1995). Studies have shown that facultative lagoons are effective in reducing pathogen populations and many of the processes that reduce pathogens in these systems also apply to constructed wetlands for wastewater treatment. Indicator organisms, such as coliform, fecal coliform, and *Escherichia coli*, are used as indicators of waterborne pathogen contamination to avoid the expense and technical expertise involved in analyzing for pathogens directly.

Coliform bacteria would be naturally occurring in wetland systems open to wildlife. Due to these natural sources of coliforms and other indicator organisms, effluent concentrations would never be near zero unless post-disinfection is used. According to Kadlec and Knight (1995) bacteria removal efficiency is related to inflow concentrations. Removal efficiencies are high when inflow concentrations are high; removal efficiencies are nearly always greater than 90 percent for coliforms. When inflow concentrations are less than background levels, removal efficiencies are low. Removal of indicator bacteria in wetlands may be correlated with solids removal and hydraulic residence times (Gearheart et al., 1999; Gersberg et al., 1989.)

Metals and Organic Contaminants

Currently there is no long-term data on full-scale constructed wetlands for wastewater treatment to determine the effectiveness in removing metals and organic contaminants. The organics would include agricultural and industrial pollutants. Studies have shown that removal of these contaminants does occur in wetlands (U.S. EPA, 2000). Metals may be sequestered by wetland soils and biota. Organics may be taken up by plants but then returned to the system during decomposition. Some may be completely biodegraded or adsorbed in wetland soils.

Specific Design Parameters

Wetland designs are based on hydraulics and pollutant removal. Wastewater treatment wetlands are sized for steady flow as compared to storm water wetlands that are designed for intermittent rainfall events. Wetland design in terms of pollutant removal is based on BOD and solids removal. The equations used for sizing a system are provided in IWA (2000), Kadlec and Knight (1996) and U.S.EPA (2000). These equations take into consideration pollutant influent concentration, background concentration, temperature, and evapotranspiration. Removal rates to determine hydraulic loading or detention times are included in these equations and provide a required concentration of pollutant at the outlet and set the area of the wetland.

Hydraulic Size

The hydraulic size or length and width of wetlands are determined by the hydraulic profile. According to IWA (2000), surface flow wetland hydraulic profiles are

determined by **flow rate, outlet weir setting, aspect ratio, bottom slope, and vegetation resistance**. Subsurface flow wetlands profiles are determined similarly to surface flow except they include **media resistance** as opposed to vegetation resistance.

Wetland Size

Wetland layout is dependent on the existing topography and soil and geologic features that will influence the cost of the system. Costs increase dramatically if excessive earthmoving is necessary due to steep slopes or bedrock features. The boundaries of the wetland may be limited in certain directions by roads, neighboring properties, and surface water bodies.

Number of Cells

It is recommended that wetlands have at least two cells that can be operated in parallel. The extra cell is useful when there are system failures such as vegetation die-off, berm or other structure damage or pretreatment system failure. They can also be used for replanting or managing vegetation, rodent control, and liner repair. The number of wetland cells selected depends on the costs of additional berming, and inlet and outlet structure costs and site limitations.

Ponded Zones

Pond zones can be an additional feature in SF wetlands. They are unvegetated and provide flow stabilization or constant head across the wetland. They extend detention times and also provide a change in habitat within the wetland.

Liners

Some states like Iowa require that all constructed wetlands be lined to prevent interaction with groundwater. However, some of the earlier constructed wetlands in Iowa were unlined and located near surface water outlets to simulate more natural wetland discharge areas. Soils that are on-site can be used for a liner if they can be compacted to have a certain hydraulic conductivity to provide an adequate seal. Bentonite is commonly used as a clay liner material. Synthetic liners can also be used and must be thick enough to prevent root penetration and rodent damage. Bentonite if it is not available on-site and synthetic liners can add to the cost of the wetland.

Soils and Media

It is recommended for SF wetlands that the liner be covered with six to twelve inches of soil to provide bedding material for the plants and prevent the roots from penetrating the liner. The soil used for bedding should not have high clay content. Plants prefer loamy textured soils that have a neat neutral pH. Soils can be tested to determine if concentrations of nutrients are adequate to support the plants selected for the wetland.

Gravels are used most commonly as the media in SSF wetlands. They should be washed to remove the fine materials that can block pore spaces. Vertical flow beds can have layers of sand, pea gravel, and small followed by medium-sized round washed gravel respectively.

Inlet and Outlet Structures

Inlet and outlet structures for many wetlands should be adjustable. Inlets for SF wetlands usually consist of an open-ended pipe, channel, perforated pipe, or gated pipe that diverts pretreated wastewater to the wetland. Subsurface flow systems may use perforated pipe, open trenches, or weir boxes. Flow splitters are used when wetland cells are designed in parallel. Wetland outlets are used to adjust the water level and SF systems use a weir, spillway, or adjustable riser pipe. Subsurface manifolds, weir boxes, or similar devices are used for SSF wetlands.

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