Introduction:

Effluent discharges from existing wastewater treatment plants (WWTP) can contain pollutants that are toxic to specific species of plants and animals. One way to manage these pollutants is with the use of constructed wetlands. “Wetlands can effectively remove pollutants from wastewaters and runoff and improve water quality” (Phillips et al., 1993). A literature review was conducted of past studies of the effectiveness of constructed wetlands for reducing ammonia and ammonium concentrations in treated wastewater. The results of the studies are summarized in this report.

Wetland Systems

A wetland system has a hydraulic regime similar to plug flow hydraulics, although the flow volume into the wetland is never the same as the outflow volume. Losses in the flow include evaporation, evapotranspirtation, precipitation, and infiltration (Wallace et al, 2006). Constructed wetlands afford the designer liberties in achieving a specific design performance by controlling substrate conditions, water depth, and plant species. Although start-up costs are lower for natural wetlands than for constructed wetlands, the annual operation and maintenance costs are similar. Larger projects generally benefit from economies of scale, resulting in lower unit costs (Wallace et al, 2006). Nitrogen species in constructed and natural wetlands can be transformed by five possible processes; nitrification, denitrification, volatilization, adsorption, and plant uptake. For ammonia reduction, nitrification is the most effective process. The removal of ammonia in a wetland is dependent upon the configuration of the wetland and the availability of dissolved oxygen (DO) for nitrification (EPA, 2000). Wetland configurations discussed in this review include Free Water Surface (FWS) and Subsurface Flow (SF), and these configurations have other possible variations that include but are not limited to marsh, cell, or aeration. The performance of each wetland reviewed in this report was measured based on its nitrogen removal performance.

Ammonia Removal Mechanisms

Nitrification

During nitrification, ammonium is oxidized to nitrate in a biologically mediated, aerobic reaction. The rate of nitrification is temperature dependant, with the reaction rate increasing as water temperature increases. Nitrification requires 4.3 mg/L O_2 per mg N oxidized (EPA, 2000); therefore increased levels of dissolved oxygen increase the probability of nitrification occurring in a wetland. Oxygen demand from other constituents such as biological oxygen demand (BOD) and eutrophication can often consume the available oxygen and decrease the opportunity for nitrification to occur.

Denitrification

Denitrification, reduction of nitrate to nitrogen gas (N_2) and nitrous oxide (N_2O), takes place under anoxic conditions (EPA, 2000). Denitrification is microbially mediated by heterotrophic bacteria that require availability of a readily degradable carbon source.

Volatilization

Aqueous ammonia volatilizes to ammonia gas at the air/water interface and is released into the atmosphere. Ammonia volatilization occurs predominately at pH values of 9.0 and above.

Adsorption/Plant Uptake

Nitrogen species such as ammonium and nitrate can mineralize or diffuse into soil where they are consumed by plant uptake at the root zone.

Types of Wetlands

Free Water Surface (FWS)

Free water surface wetland systems have a water surface that is exposed to the atmosphere on a year around basis. This generally includes marshes and bogs with emergent vegetation (Figure 1). Water near the bottom of the wetland is in an anoxic state which inhibits nitrification. Near the surface, aerobic water conditions are aided by the emergent plant canopy. Oxygen is available at the water surface and on microsites on the living plant surfaces, root, and rhizome surfaces so aerobic reactions are possible within the system (Crites et al, 2006). Mosquito control can be an issue with this system due to pond type conditions and areas of open water. These conditions also attract a variety of other wildlife including fish, amphibians, reptiles, and birds.

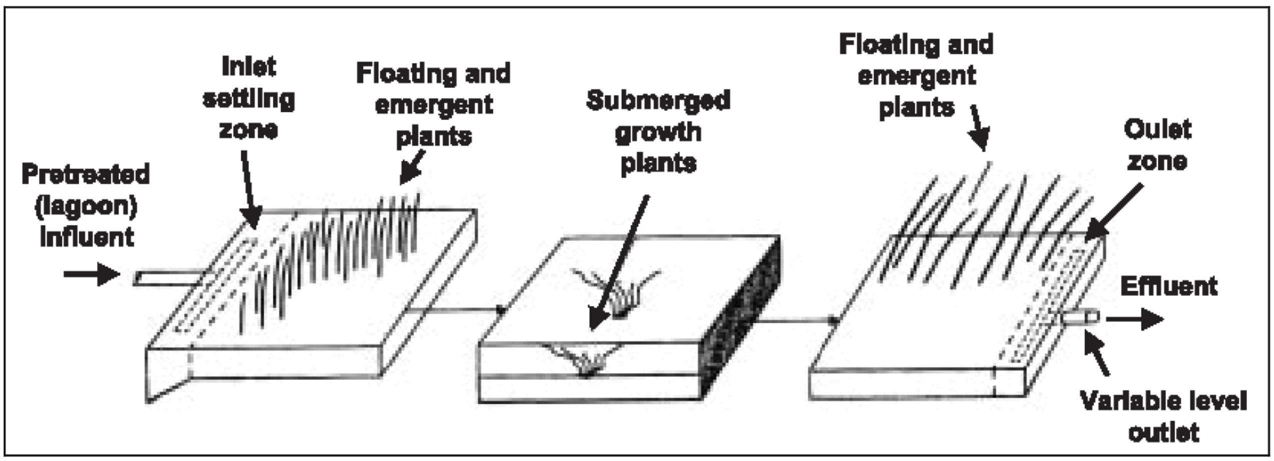

Figure 1: FWS Wetland General Layout
(EPA, Onsite Wastewater Treatment Systems Technology Fact Sheet 7, 2008)

There are many constructed wetlands that existed today that act as a secondary or tertiary treatment to wastewater from smaller communities. The state of Georgia manages at least seventeen of these constructed wetlands, and uses them to polish pretreated municipal effluent via a surface flow (SF) treatment process. Discharge Monitoring Reports (DMRs) present the average influent and effluent concentrations of NH_4^+-N. These effluent concentrations are below the discharge limit thresholds for each site (Table 1). All sites operate under dual seasonal permit limits of 5 mg/L and 10 mg/L NH_4^+-N concentration in the winter and summer seasons respectively. Higher concentration averages were monitored in the winter months for NH_4^+-N, BOD, and total suspended solids (TSS) (Inman, 2001). These flow values and wetland areas are common in scale for existing municipal wetland use.

Table 1: Performance Results of FWS Wetlands in Georgia

Location	Wetland Area (ac)	Design Flow (mgd)	Unit Loading (ac/mgd)	Design Influent Concentration NH4+-N (mg/L)	Average Effluent Concentration NH4+ (mg/L)	Percent Removal NH4+ (%)
Baconton	2.68	0.40	6.7	35	11.9	66
Folkston	8.80	0.26	33.9	9	2.3	74
Gordon	8.00	0.75	10.7	15	4.3	71
Lakeland	10.00	0.65	15.4	<10	0.9	91
Ochlocknee	2.06	0.05	41.2	10	4.2	58
Richmond Hill	100.00	1.50	66.7	5	0.6	88
Sardis	0.05	0.20	0.3	10	3.9	61
Tignall	10.00	0.79	12.7	17	1.3	92

(Inman, 2001)

Crites et al. (2006) investigated and reported ammonia removal performance of several constructed wetlands in the United States (Table 2). Crites reported that DO concentrations needed by nitrifying organisms are often not present in heavily loaded systems (BOD loading > 100 lb/ac·d) or in newly constructed systems with incomplete plant cover, which can limit their ammonia removal performance.

Table 2: Ammonia and Total Nitrogen Removal Averages in Free Water Surface Constructed Wetlands

Location	Type of Wastewater	Hydraulic Loading Rate (in/d)	Design Flow (mgd)	NH_3 Influent (mg/L)	NH_3 Effluent (mg/L)	Percent Removal (%)
Arcata, California	Oxidation Pond	—	2.30	12.8	10	22
Beaumont, Texas	Secondary	0.30		12	2	83
Iselin, Pennsylvania	Oxidation Pond	7.95	—	30	13	57
Jackson Bottoms, Oregon	Secondary	1.86	1.40	9.9	3.1	69
Listowel, Ontario	Primary	4.60	—	8.6	6.1	30
Pembroke, Kentucky	Secondary	0.30	1.00	13.8	3.35	76
Salem, Oregon	Secondary	0.40	—	12.9	4.7	64

(Crites et al, 2006)

Constructed wetlands at the Plant A demonstration project experienced typical seasonal changes seen in FWS wetlands (Table 3). Higher nitrogen removal occurred in the warmer growing seasons, while lower results occurred in colder seasons when biomass was killed and accumulated as detritus (*Redacted*, 1998).

Table 3: Ammonia Removal Seasonal Averages in *Redacted*, CA

Seasonal Values, 1994 to 1998	NH_3 Influent (mg/L)	NH_3 Effluent (mg/L)	Percent Removal (%)
Winter	13.11	8.98	32
Spring	16.33	7.93	51
Summer	14.05	7.08	50
Fall	16.11	12.21	24

(*Redacted*, 1998)

Marsh Wetlands – Free Water Surface

Marsh wetlands utilize nitrification in shallow water and plant uptake of nitrogen in a healthy and well-developed rhizosphere. The development of the rhizosphere, or root system, can be controlled by the substrate. Different substrates have been tested including gravel, sand, and soil; all of which have shown promising results when polishing WWTP effluent from small communities. Each substrate supports aquatic plant life, although they vary greatly in permeability. Higher permeability rates can increase plant uptake in the rhizosphere, where a majority of microbial activity occurs. Aquatic plant species that increase DO concentrations most efficiently also show the highest nitrification rates.

Gersberg et al., (1989) compared the ammonia removal efficiency for three different plant species in a high infiltration rate, gravel marsh wetland and an unplanted wetland cell. Primary effluent, with average concentration of 32 mg/L NH_4^+-N, enter at 1 MGD and passed through unplanted, reed, cattail, and bulrush planted cells 71 x 11.6 x 0.76 m. Differences in percentage removals varied from 11% (unvegetated), 28% (cattails), 78% (reeds), to 94% (bulrushes). With average BOD removal requiring 31 mg/L of DO, the bulrush plant supplied an average of 120 mg/L of O_2 to the system, indicating that the translocation DO by plants can increase nitrification rates.

In a similar study, partially nitrified and unaltered liquid swine manure was passed through two constructed parallel wetlands cells with a loamy sand substrate. One cell contained three different bulrush species, and the other had two cattail species along with one bur-reed. Although NH_4^+-N influent concentrations ranged between 140 mg/L and 260 mg/L, overall removal percentages reached levels higher than 70% (Poach et al, 2003). With these higher concentration levels, greater detention time was required. The bulrush showed the greatest removal efficiency, outperforming other plant species with a 10% - 40% greater ammonia removal.

The City of Mandeville, Louisiana WWTP modified their existing wetland system due to low ammonia removal in the winter months by installing a reticulating gravel trickling filter to the output end of the wetland. Anoxic conditions found during colder months decreased DO concentrations and increased the NH_4^+-N effluent levels beyond the permit standards. The gravel filter produced more than a 60% improvement in the NH_4^+-N effluent level by increasing DO levels.

A wetland area in West Palm County, Florida totaling more than 39 acres in wetted acreage contains wetland cells ranging in size from 2.3 acres to 10.9 acres and contains some pond areas (Bay, 2000). Over a two year period the wetlands observed an average inflow of secondary effluent of 1.40 MGD and removal rate efficiency of total nitrogen (TN) of 82%. Flow rates varied from 0.5 mgd at 0.9 cm/d with a 40 day detention time to 2 mgd at 4.6 cm/d with a 10 day detention time. TSS concentrations increased an average of 115%, and BOD increased an average 1%. These increases were due to lack of emergent marsh vegetation during start up and algae growth and decomposition, or eutrophication. Total nitrogen (TN) influent and effluent concentrations averaged 28.0 mg/L and 8.4 mg/L, respectively, and an overall removal efficiency of 70% was observed for the two year period. TN levels did increase over the winter months consistently with the TSS and BOD levels, indicating a substantial amount of organic nitrogen bound in the algae during colder months.

Subsurface Flow Wetlands (SSF)

SSF wetlands have a similar configuration to FWS wetlands except the water level is completely contained within a porous media, i.e. gravel, sand or soil. Wastewater flow is intended to stay beneath the media surface and flow around the rhizomes of the plants (Kadlec, 2009). With abundant DO concentrations, nitrification occurs on biofilms in these rhizospheres.

Denitrification can dominate nitrogen removal in subsurface flow wetlands if or when nitrate is the dominate nitrogen species present. The startup cost for these systems is higher than for free water surface wetlands due to an increase in media needed, but these systems have advantages in cold weather areas and where mosquito control is a priority. Subsurface flow wetlands generally serve individual septic tank systems or small communities in the United States today with daily flows less than 50,000 gallons per day (Crites, 2006). DO levels in these systems are generally too low to provide adequate nitrification for a large scale operation, so SSF systems that incorporate a reciprocating or recirculation system were the selected focus for this review. These combined process systems have significantly higher operation and maintenance costs due to the addition of mechanical components.

A recirculation subsurface flow system with a gravel base (Sikora, F. J. et al, 1995) produced ammonia removal rates ranging from 0.3 $g/m^2/d$ to 1.1 $g/m^2/d$ when using initial concentrations of 50 mg/L NH_4^+-N. During a series of six trials, 90% ammonia removal was achieved with detention times ranging from eight to 30 days. An increase in required detention time occurred as ambient temperature declined from 26 °C to 14 °C.

A reciprocating flow process was created by two adjoining subsurface flow wetland cells in series with a pump that alternated wastewater between the two cells. As each cell was dewatered, substrate and thin biofilms were rapidly oxygenated to saturation levels (Fanning et al, 2000). When compared to similar gravity flow devices, these test results show a nearly 100% improvement in the nitrification of ammonia. Gravity flow devices produced removal rates of 35% and the reciprocating system removed ammonia at a 64% rate.

Conclusions

Ammonia and ammonium removal in constructed wetlands is most efficient in free water surface and subsurface flow wetlands when nitrification is occurring. The primary limiting agent for nitrification in wetlands is dissolved oxygen concentration, followed by temperature and detention time. Increased BOD levels have been shown to decrease nitrification rates in wetlands due to competition for available dissolved oxygen (Crites et al, 2006). Existing FWS wetlands using bulrush species of plant have shown the greatest nitrification rates of all plant species, with calculations showing translocation of 120 mg/L O2 in the wetland and removal rates up to 98% of TN. The addition of a gravel trickling filter to the outlet of an existing wetland was an effective modification that increased aeration and improved ammonia removal. FWS wetlands organized in cells show great success due to well maintained plant cover and algal control. Subsurface flow wetlands serve well for small scale facilities due to the cost of materials and land size required to achieve the proper detention time. When augmented with pumping systems to increase DO levels, results were promising, but operational and maintenance costs are high. Results reported in this review have been primarily for small scale facilities that manage 1 MGD or less of wastewater. Wastewater Treatment Plants that manage more than 1 MGD and use a wetland facility for a polishing process have done so with the intention of decreasing BOD and usually nitrify the effluent prior to entering the wetland.

The average ammonia removal efficiency for constructed SFW and SF wetlands in North America is 34% and 22%, respectively, with daily loads of 8.84 mg/L and 7.89 mg/L (Kadlec, 2009). Ammonia removal is pH and temperature dependant (Wallace et al, 2006), and seasonal changes, such as lower temperature or plant decay, that decrease the amount of dissolved oxygen, will greatly impact system performance. In free water surface systems, when oxygen demand exceeds the oxygen supply, systems will not exhibit significant nitrification (EPA, 2000). Oxygen sources in vegetated submerged bed systems are negligible (EPA, 2000); therefore nitrification is generally unlikely without the addition of aeration, and this process is more efficient when used for denitrification.

When designing a wetland system, the size, media, plant species, layout, and effluent concentrations determine the success. This report has reviewed a number of wetlands systems that have achieved success in the removal of ammonia and ammonium using a combination of nitrification, plant uptake, adsorption, and ammonia volatilization. The greatest success has been achieved using a combination of linear cell FWS wetlands well planted with bulrush species aquatic plants.

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