174
67

THE USE OF WETLANDS AS A WASTEWATER TREATMENT TECHNIQUE - A LITERATURE REVIEW

by

Gary Boyd Fillmore

Major paper submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Environmental Engineering and Science

APPROVED:

Thomas Grizzard, Chairman

A. N. Godrej

H. E. Post

April, 1991

Blacksburg, Virginia

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

I. INTRODUCTION

Starting in the mid 1970's, it was recognized from work performed by the National Aeronautic and Space Agency that one of the most urgent environmental needs in the world today could be addressed through the use of biotechnology. Through the manipulation of natural biological processes, involving the symbiotic relationships between certain plants and microorganisms found in wetlands, a simple, low cost means of wastewater treatment and water reuse could be achieved. The use of constructed wetlands (also called artificial, created, or engineered wetlands) began around 1975 in the United States and Canada. From that point on, as evidenced by the literature, the interest/research in this technology has blossomed [126, 149].

Interest in wetlands for wastewater treatment can be attributed to four basic factors:

1. Public demands for more stringent wastewater effluent standards, including removal of nutrients and trace contaminants as well as organic and suspended solids matter;

2. Rapidly escalating costs and operation associated with conventional treatment facilities;

3. Recognition of the natural treatment functions of wetlands, particularly as nutrient sinks and buffering zones;

4. Emerging or renewed appreciation of aesthetic, wildlife and other incidental environmental benefits associated with the preservation and enhancement of wetlands [55].

The 1987 Amendments to the Clean Water Act (CWA) have changed direction since the amendments made in 1972. Under this new legislation, there has been a shift from a federally focused and funded water program to one funded by the states. The federal grants program for municipal wastewater treatment works was phased out in 1990 and a State Revolving Loan Program funded in its place. Concern over increasingly smaller amounts of conventional pollutants, such as biochemical oxygen demand (BOD_5) and total suspended solids (SS), along with the restrictions for nutrients phosphorous and nitrogen places additional treatment burdens on wastewater treatment facilities. In light of the new financial responsibility, the magnitude of the problem of providing cost effective wastewater treatment becomes apparent. The following further highlights the dilemma that is faced by many publicly owned treatment works:

1. Treatment costs to small communities become prohibitive with estimates nationwide believed to amount to between $10 and $15 billion dollars.

2. In at least 24 states, agricultural nonpoint pollution is causing serious water quality problems.

3. Nonpoint pollution from agriculture and urbanized areas has taken its toll on one-third of existing lakes and reservoirs.

4. Treatment of acid mine drainage continues to pose severe problems to many miles of streams of Appalachia.

5. Solid waste leachate from both municipal and industrial sources affects water quality.

6. Toxic waste treatment and disposal has become a major water quality concern [117].

The need for an innovative approach to this problem is apparent; but the estimated savings of $3 billion nationwide that constructed wetlands might provide should not influence scientific objectivity [126]. The U.S. Environmental Protection Agency (EPA) points out the potential limitations on this technology:

1. Wastewater Characteristics - High concentrations of pesticides, refractory chemicals, or heavy metals may make this form of treatment unsuitable.

2. Climate - In northern climates, treatment may be limited by dormant vegetation and frozen conditions. Consequently holding ponds might be necessary in certain areas.

3. Site Availability - A major cost of this technique is the acquisition of suitably sized and located land [130].

Natural wetlands are protected under section 404 of the Clean Water Act, which prohibits the discharge of dredge and fill material into wetlands without a permit issued by the U.S. Army Corps of Engineers [117]. Critics of the program say that permit decisions tend to be based on local, not regional, considerations, with the result that wetlands often become casualties. Doubt exists as to the long term performance of constructed wetlands when compared to that of natural wetlands. Consequently there is great concern over continued protection of natural wetlands and a need for a more thorough understanding about the capabilities and limitations surrounding constructed wetlands in the rush to put this technology to use [97].

The term wetlands itself is a fairly recent term that encompasses what in the past has been referred to as marshes, swamps and bogs. All wetland types are believed to have four basic functions that make them feasible for wastewater treatment. Upon entering a wetland, water is subjected to dispersion through intricate channelization of flow. Physical entrapment of pollutants through sorption in the surface soils and organic litter takes place. Nutrients in the water will be taken up by the plants and metabolized. Microorganisms will likewise take in and transform many of the elements present [55].

Ecological considerations are a major concern where natural wetlands are involved in wastewater treatment or disposal of treated effluents, or where wastewater is involved in the enhancement or restoration of wetlands. For example, the pH and the volume of the water added to a wetlands can have greater impact than the nutrient load typical of municipal wastewater. Obviously, the long term impact of elevated nutrient concentrations will have direct effects on productivity [105].

Ecological aspects are less of a concern for constructed wetlands than for natural wetlands treatment systems. The constructed wetlands system is designed to addresses nutrient loading. In a natural wetlands, a balance must be achieved between the optimization of wastewater treatment and species diversity present. The aesthetic nature of the wetland is enhanced by a high degree of diversity along with its stability as a biological system.

It is the purpose of this paper to present the literature that has become available concerning the new technology of wetlands treatment. The abundance of research on many aspects of constructed wetlands technology is impressive while concern over the fate of natural wetlands continues. The promise of this technology along with its general acceptance as an environmentally appropriate undertaking has driven the wheels of investigation. The available literature is very wide in scope reflecting the multidimensional nature of this technology.

II. REVIEW OF LITERATURE

Wetlands Ecology

The ecology of natural wetlands is very complex in light of the multitude of interactions that exist between the biotic and abiotic factors present. This complexity is an asset in that it imparts stability to the system but at the same time does not lend itself to easy manipulation. Each wetland system is unique and requires an in depth study of the biotic and abiotic factors that have evolved through time. The structure and composition of a wetland is hydrologically controlled, that is to say that flow rate, flood frequency, and water quality determine the unique nature of a wetland. It follows, as a result of the species diversity and the hydrologic and climatic regimes, that wetland systems may differ in many ways, each showing a discrete response to chronic effluent discharges. One way to better understand the relationship between wetland structure, function and effluent discharge is to construct artificial systems and model these interactions on natural systems. Such systems can be more easily manipulated with different variables isolated and monitored [51].

The modeling of a wetland to determine its value as a mechanism of water conservation and its economic implications illustrates the inherent value of these systems. It might be said that the hydrologic cycle is the

ATP of the biosphere because of its role in organizing and driving ecosystems. The treatment performed by a wetland through the use of the hydrologic cycle should be evaluated on a case by case basis. With the addition of nutrients in the water supplied to wetlands, the rate of photosynthesis and transpiration will generally increase. The economic impact on an upland wetlands system, for example, can be complex. The value of the harvestable crop could be increased at the expense of water lost by means of transpiration. In general, the question that needs to be addressed is "What do wetlands do with water and how is this role related to energy and regional value?" Because of their role in converging the embodied energy of water with a rich biota they make a higher contribution to economic dollar circulation than those of many other ecosystems [99].

Finn [36] has proposed an analytical technique of flow analysis as a method for predicting the consequences of wetland modification. The technique utilizes the flow of carbon and energy, and provides a mathematical approach for the transference of carbon and energy from the various trophic levels found in wetland systems. In the wetland models examined it sometimes takes years for material/energy to flow through a system. This takes on special significance when considering the fate of toxins in wastewater administered to a wetlands systems and the suitability of a system for a particular purpose [36].

The impact of freshwater to coastal wetlands is of concern in regions where coastal wetlands have been on the decline. To maintain native salt marsh communities it is important to avoid major changes in the hydrologic regime that the importation of recycled water could bring about. The threat to coastal ecosystems, such as in Southern California, could be reduced if the location, amounts and timing of discharge were properly controlled. In fact, for certain coastal-wetland restoration areas, it could be advantageous in reestablishing marsh vegetation, brackish and freshwater marshes while increasing habitat diversity. The long term solution to combining wetlands treatment and marsh restoration is creative management at the watershed level [151].

Wetlands Dynamics

Wetlands, by their very nature, are constantly undergoing change. In the geological sense, they are ephemeral entities. Wetlands are not static. In fact, their very existence is dependent upon this changing nature. Given sufficient time, a New England bog or prairie marsh will gradually fill in, ultimately becoming forest or a prairie. All wetlands are dependent upon disturbance or cyclic fluctuations in local hydrology. In fact, stable water levels are responsible for lowering productivity almost as much as the lack of water during drought years [54]. Mathematical models for the hydrodynamics of wetlands have been developed which take into account the role of flow resistance, evaporation and transpiration, atmospheric augmentation and their relevance to water quality [60, 76].

The physical and chemical nature of freshwater wetland soils dictate the following in order to enhance the removal of specific contaminants:

-For nitrogen (N) removal, enhancement of denitrification by alternating oxidizing and reducing conditions will maximize nitrification during aerobic periods, thereby supplying nitrates for denitrification during anaerobic (reducing) conditions [11,33].

-Phosphorous (P) is removed by soil sorption processes with a finite P capacity, an entirely different mechanism than N removal. Maintaining contact with soils high in calcium or oxalate-extractable (amorphous) iron and aluminum is preeminent for wastewater P removal. Alternating oxidizing and reducing conditions can recharge sorption sites, allowing greater P removal than under permanently reducing conditions. In this case, operational procedures for N and P are compatible. Increased peat accretion can also result in higher P storage [33,98].

-Sulfate removal from most effluents requires permanent reducing conditions for $(SO_4)^{-2}$ reduction and incorporation into sediment storage. Alternating with an oxidation cycle would oxidize reduced sulfur compounds to $(SO_4)^{-2}$, which is mobile and easily flushed from the system. Therefore, optimization of sulfur removal is not compatible with maximum N or P removal.

-The database for iron and manganese removal from acid mine drainage is insufficient to develop guidelines for maximizing removal/retention in constructed wetlands. Current methods of enhancing geochemical and biological oxidation mimic the success of traditional chemical techniques; however, the exact mechanisms and long-term viability of these systems are unclear despite their reported effectiveness. Reduction processes with permanent sediment storage may be the preferred long-term solution, but successful implementation of these mechanisms has not yet been achieved [33].

From studies of the Mississippi River delta by Gosselink and Gosselink [47], it was possible to observe the long-term effect of high nutrient-loading rates on a natural wetland system. Due to the depositional nature of the delta, it was possible to take a historical view of the treatment that had been naturally taking place. As a result of this examination, the following observations have been made and might have applicability in municipal overland flow treatment systems:

-the key to permanent, long term retention of nutrients other than carbon, nitrogen, and sulfur is accretion;

-the quantity of nutrients retained is related both to inorganic sediment input and to the contact time of the flooding water with the marsh surface;

-it would be advantageous to plan municipal overland flow systems in duplicate so that one field could be used to cleanse water while the other has its water level reduced to oxidize accumulated organics or farmed to remove the trapped nutrients;

-in areas of subsidence, or those areas in need of building up, the deposition of sediments can have a positive impact.

Bayley [9] concluded from her work on the effect of natural hydroperiod fluctuations that both N and P were removed from a marsh during wet and dry years. In fact, only at the highest level of effluent application (9.6 centimeters per week (cm/wk)) could any differences in vegetation or soil chemistry be detected. Plots receiving 1.5 cm/wk and 3.7 cm/wk of effluent could not be distinguished from the control plot. While the species composition changed with the addition of effluent, it also changed as a result of marsh-water levels. Vegetative growth rates, standing crop, and P tissue content were influenced as much by the presence of standing water as they were by the application of 9.6 cm/wk of treated effluent. Nitrogen concentrations in tissue were found to be more related to the effluent application than the presence of standing water.

Taking a larger view of the wetlands ecosystem, Kelly and Harwell [78] examined ecosystem responses to anthropogenic stresses based upon a view of the ecological landscape. It is their contention that, although many studies have included some aspect of nutrient cycling, only a few studies comprehensively detail exchanges with other ecosystems or consider the internal dynamics in relation to external inputs. Kelly and Harwell concluded that more information was needed to assess the effect of nutrient cycling in wetlands.

Metal-budget and metal-flux data for wetland ecosystems show that the percentage of metal removed by passage through the ecosystem varies widely between metals and among wetlands. While some metals, such as lead, may be well retained by wetlands under conditions of low loading rates, the majority of metals, such as zinc and cadmium, may pass through the ecosystem. Although in a geochemical sense, wetlands are "sinks" for some metals, these studies indicate that they may not function as efficient "traps" for all metals. By better understanding the biogeochemical processes that alter metal retention, it may be possible to manipulate wastewater release to maximize metal removal in natural and artificial wetlands [43].

Wetland vegetation plays several roles in the ability of wetland systems to treat wastewater. Rooted vegetation provides for the filtration of particulate matter as the wastewater moves through the system. Additionally, the vegetation also provides a substrate for microbial activity. One of the most important functions that wetland vegetation provides is the release of oxygen to the water and root-zone where it is available for bacterial uptake in the nitrification and to increase the hydraulic conductivity of the soil. Consequently, internal gas spaces (arenchyma) are found in the plant tissue of some wetland plants. The function of these parts is to supply oxygen to the submerged plant parts, but oxygen leaks out from the roots and rhizomes into the sediments creating pockets of oxygen. These pockets produce an oxygenated environment that is favorable to the aerobic and facultative bacteria. The pockets also increase the porosity of the sediments which promotes hydraulic conductivity [14].

In general, only a few taxa of wetland plants have been used in wastewater treatment studies. Emergent and floating leafed species have been preferentially used in pilot studies of constructed wetlands where they act as temporary storage pools. Most useful emergent species include many members of the cattail reed, rush, sedge, and grass families. Submerged aquatic plants do not appear to have the attributes that would be useful in wastewater treatment. Because different treatment facilities have varying objectives it isn't possible to devise a listing of plants that would be useful across the board [52,31].

Microorganisms in association with soil, water or other biota play a critical role in the processing of materials entering a wetland. Inherent in their genetic constitution is the ability to transform various substances. It is, in large part, this ability that is sought to be utilized in wetlands treatment. Microorganisms have a substantial role in transforming of free nitrogen molecules in the air for use by plants. The environmental fate of man-made compounds, i.e. pesticides, polycyclic aromatic hydrocarbons and domestic wastes, is an important issue. One aspect of microbial life, that relates well to the fluctuating wetland conditions, is the ability to become dormant and wait for more favorable conditions to occur. According to Portier, microbial life possesses a genetic plasticity that needs to be exploited. As such, they may be considered living catalysts [102].

As a last consideration in this section on the dynamics of wetland systems, is the role of wildlife. Wetlands constructed for the single purpose of wastewater treatment can yield benefits beyond simply discharging water that meets local, state and federal water quality standards. A number of important questions that must be addressed in this respect are:

-What might be the impact, if any, of constructed wetlands for wastewater treatment on the short and long-term viability of wildlife attracted to those areas?

-What might be the lethal and sublethal impacts of contaminants in water, vegetation and soils on wildlife?

-Who has legal responsibility for potential impacts, especially in the case of migratory or threatened and endangered species?

Will constructed wetlands be managed in such a way to replicate natural wetlands without impairing their function and utility for treating wastewater effectively?

If these above questions can be addressed successfully, constructed wetlands could have the effect of enhancing habitat richness in areas lacking wetlands [34,73].

Community Changes

The research on wetlands that receive wastewater has addressed the impact primarily on hydrology, changes in plant life, nutrient uptake and retention by soils, sediments and plants and changes in plant life forms and communities. Insufficient information is available on the animal communities in areas that have received effluent discharges. An assessment of the changes that take place is made difficult by the fact that animals are: mobile; capable of adjusting their behavior as conditions change; and migratory. Responses of terrestrial vertebrates to a change from xeric, mesic to near hydric conditions is also poorly studied. Disease vectors, i.e. ticks, mosquitoes and the transmission of arboviruses within and adjacent to treatment sites needs to be addressed. There is insufficient information on the impact of pests in agricultural areas, such as the redwing blackbird, skunks and raccoons. While the organisms of interest to the process have been studied, the species that will be attracted need to be better understood. This is particularly important if the idea of enrichment and enhancement of degraded environments is to have merit and a point of interest to the public [12,70].

Whigham addressed the impact that wastewaters may bring about on the seed bank of a wetland through the use of a model that was proposed by van der Valk [142]. The model is based upon three life attributes of wetland vegetation. They are: life span; propagule longevity; and propagule establishment. The model can be used to predict vegetation changes associated with water-level manipulations. Although no data are available for wetlands that have received wastewater for extended periods of time, the model is capable of providing insights into management strategies to be used to minimize impacts due to wastewater irrigation [142].

Environmental Health

Central to the impact of wastewater on the public health are microorganisms. It is important to bear in mind the potential risks that exist in relation to improperly prepared wastewater to a wetland environment. Valiela [132] has summarized the present understanding of microbiological health implications for wetland treatment systems:

-Organisms of major concern to human health are *Salmonella* spp., *Shigella* spp., *Campylobacter fetus*, and *Leptospira* spp. Bacteria respond to conventional wastewater treatment.

-Viruses of major concern to public health are hepatitis A virus, rotavirus, and enteroviruses. A better understanding of the fate of viruses in the aquatic environment is needed. They tend to be persistent.

-Detoxification of pollutants by microorganisms in aquatic systems is not well understood.

-The transformation of nontoxic compounds to toxic forms is not understood and requires further study.

Stengel and Schultz-Hock [121] identified indirect problems, such as the production of hazardous metabolic waste, i.e. nitrite, that may occur as a result of wetlands treatment. The bioaccumulation of toxins was observed to be a function of the microbial mass.

Wildlife health concerns associated with disposal of sewage effluent in wetlands are of three primary types: (1) introduction of pathogens, (2) introduction of pollutants that adversely impact on host body defense mechanisms, and (3) changes in the physical and chemical properties of wetlands that favor the development and maintenance of disease problems. Of these three concerns the third one is believed to pose the greatest danger with the fear that marshes could become disease incubators and death traps for wildlife [37].

Microbiological studies of municipal waste release to aquatic environments have found that many of the more sensitive pathogens die, or become undetectable. However, both pathogens and fecal indicator bacteria are capable of surviving in water for long periods of time, although in a nonculturable state (i.e. *Vibrio cholerae, Escherichia coli*). In addition to this, it has become increasingly apparent that many bacteria are capable of surviving, and even growing in the sediment. The concern here should also be the possibility of resuspension by a number of mechanisms. Wetlands are lentic habitats and consequently only have periodic flushing by spring snowmelt and floods. Accordingly, introduction of improperly treated wastes could have serious deleterious impact on the health status of such wetlands [48].

Hodson, et al. [64], have proposed a model that can be used to make both in vitro determinations of pollutant loading capacity and intermittent monitoring of microbial processes in situ for both artificial and natural wetland systems. From this model they have come to the conclusion that in order to avoid overburdening the system with organic loading, and to maintain viability of the microbial processes, it is necessary to deal directly with the increased production of the macrophyte biomass or to promote its degradation. It was felt that the most cost effective management approach would be to promote in situ degradation with the added advantage of potentially producing and harvesting commercially marketable animals that feed directly or indirectly on the microbial biomass resulting from plant degradation.

Case, Field and Laboratory Studies

Perhaps the most impressive aspect of the potential applicability of this technology is the numerous conditions in which it has been employed. The case studies involve the application of wetlands treatment under full-scale operations. The case studies are summarized in Table 1 and cover a multitude of wastewaters, i.e. raw sewage, acid mine drainage, ash pile run-off, non-coal mining effluents, municipal secondary effluents, petroleum refinery effluent, septic tank sewage, etc. Field studies are those conducted on a smaller scale to evaluate specific objectives. The following section presents information obtained from these studies on wetland treatment.

1. Municipal Wastewater Treatment

The largest portion of the field and case studies on wetlands treatment have been for treating municipal wastewaters. Most of the case studies have been conducted in very small municipalities that were attracted to constructed wetlands because of its cost effectiveness and simple maintenance requirements. Some of the constructed wetland systems are an alternate technology to provide secondary treatment, however, most of the case study sites

TABLE 1. Summary of Case Study Findings on Wetlands Treatment

Location	Wastewater Type	Design	Principal Plant Species	Loading Rates	Removal Efficiencies	Comments
Arcata, California (2,4,39)	Municipal	primary- oxidation pond- marsh cells- sedimentation pond- chlor-dechlorination- freshwater marsh	Bulrush (Scirpus) Cattail (Typha)	0.02-.24 m3/m2/day	BOD5 - 55% SS - 54%	Full scale plant data 6% pH drop 8.5 days detention time
Iselin, Pennsylvania (22,135)	Municipal	primary- aeration cell- lateral flow marsh (sand base)- facultative pond- meadow- concrete trough collection- chlorination- contactor tank- stream discharge	Reed Canary grass (Phragmites australis)	46-75 m3/ha/day	BOD5 -97% SS - 89% Fecal Coliform - 99% Nitrogen - 77%(W) - 93%(S) Phosphorus - 68%(W) - 90%(S)	Must trap muskrats
Cannon Beach, Oregon (134)	Municipal	aeration basin- lagoons (3)- chlorine contact- secondary effluent polishing in forrested wetland	Spruce/elderberry Alder/spruce Sedge/alder Sedge/twinberry	61,000 gal/acre/day	BOD5 - 67.2% SS - 78.4%	Twinberry, alder and spruce expected to die off - Sedges and emergent species increasing
Santee, California (42)	Municipal	primary- gravel marsh	Scirpus sp.	5 cm/day (7.5-8 ha/ 3,785 m3/day)	BOD5 - 90% SS - 90% Nitrogen - >95% Fecal Coliform - 97%	

TABLE 1. Summary of Case Study Findings on Wetlands Treatment (continued)

Location	Wastewater Type	Design	Principal Plant Species	Loading Rates	Removal Efficiencies	Comments
Gravesend, United Kingdom (63)	Municipal	reed bed system- receiving: crude sewage settled sewage sludge liquor	Phragmites australis	100 m3/1225m2 /day	BOD5 - 67% SS - 60% NH3-N - 16% O-PO4-P - 82%	Maturity of plants not yet established - Improved effluent with time believed to be associated with plant maturation
Holtby, United Kingdom (63)	Municipal	reed bed system- receiving: screened crude sewage	Phragmites australis	30 m3/day 612 m2	BOD5 - 79% SS - 85% NH3-N - 6% O-PO4-P - 12%	Several weed problems not corrected by flooding
Marnehule, United Kingdom (63)	Municipal	reed bed system- receiving: screened crude sewage settled sewage	Phragmites australis	85 m3/day 735 m2	BOD5 - 83% SS - 71% NH3-N - 6%	Major weed problems
Middleton, United Kingdom (63)	Municipal	reed bed system- humus tank effluent	Phragmites australis	40 m3/day 450 m2	BOD5 - 73% SS - 73% NH3-N - 46% Oxidized Nitrogen - 27% O-PO4-P - 30%	
Valley Field, United Kingdom (63)	Municipal	reed bed system- screened crude sewage	Phragmites australis	17 m3/day 45 m2	BOD5 - 79% SS - 87% NH3-N - 70% O-PO4-P - 78%	Removals are average of four effluents
Little Stretton, United Kingdom (63)	Municipal	reed bed system- septic tank effluent	Phragmites australis	10 m3/day 20 m2	BOD5 - 77% SS - 84% NH3-N - increased by 4% O-PO4-P - NA	

TABLE 1. Summary of Case Study Findings on Wetlands Treatment (continued)

Location	Wastewater Type	Design	Principal Plant Species	Loading Rates	Removal Efficiencies	Comments
Castleroe, United Kingdom (63)	Municipal	reed bed system- settled sewage	Phragmites australis	5 m3/day 28 m2	BOD5 - 61% SS - 6% NH3-N - 17% O-PO4-P - 12%	New beds
Picayune, Mississippi (148)	Domestic	septic tank- rock/plant/marsh- leachfield	Elephant ears (Colocasia esculenta)	Single home - (2-3 people) 36.6 m2	BOD5 - 90% NH3-N - 75% Fecal Coliform - 97%	Cold tolerant plants (bulrush and cattails) can be used in cold climates
Sandhill Crane National Wildlife Refuge, Mississippi (56)	Municipal	primary treatment- land treatment- percolate into collection system	Coastal bermuda grass (Cynodon dactylon) Annual Rye grass (Lolium temulentum)	76 cm/hr/ 150 ha	NA	Cooperative effort Mississippi Gulf Coast Regional Wastewater Auth. and U.S. Fish and Wildlife Service - Major structural erosion problems
Eddington, Maine (20)	Domestic	septic tank- distribution over peat beds in ground or in mounds	Sphagnum	30-60% moisture in peat bed	BOD5 - 5-20 mg/l NH3-N - 0-17 mg/l Organic-N - 0-7 mg/l NO3-N - <5 mg/l TSS - 5-15 mg/l DO - 3-13.3 mg/l Fecal Coliform - 99%	Fungi in association with peat may be source of removal- High cation exchange
Muscle Shoals, Alabama (88)	Livestock Waste	swine waste lagoon- algae and filter feeding fish- fish waste irrigation to water chestnut wetland	Chinese Water Chestnut (Eleocharis dulcis)	103 l/m2/day	BOD5 - 75% COD - 69% SS - 82% Fecal Coliform - 74% TKN - 66% TP - 66%	Wastewater treatment to secondary standards obtainable during winter

TABLE 1. Summary of Case Study Findings on Wetlands Treatment (continued)

Location	Wastewater Type	Design	Principal Plant Species	Loading Rates	Removal Efficiencies	Comments
Flat Rock, Alabama (18)	Acid mine drainage	drainage from seep area-series wetland impoundments-stream discharge	Cattails (Typha latifolia) Wool grass (Scirpus cyperinus)	hydraulic: 0.7 l/m2/min chemical: iron - 1.1 m2/mg/min manganese - 2.8 m2/mg/min	Iron - 94% Manganese - 77% TSS - 71%	Receiving water macroinvertebrate and vegetative taxa increased ten fold- Muskrats caused dike failure
Jackson County, Alabama (17)	Ash pond seepage and coal yard runoff	wetland cells (3)	Cattails (Typha latifolia) Rush (Juncus effusus) Bull rush (Scirpus cyperinus) Iris versicolor Eleocharis quadrangulata	iron - 0.2 m2/mg/min	Iron - 97% Manganese - 9% pH change - 2.1 s.u.	Nutra Nugget applied at 6.75 mt/ha- Armyworms treated with Lorsban
Roane County, Tennesse (17)	Ash pond and acid seepage		Cattails Bullrush	NA	Iron - 85% Manganese - negligible pH change - 3 s.u.	Limestone and fertilizer added
Colbert County, Alabama (17)	Ash pond and acid seepage		Cattails Bullrush	manganese - 1.3 m2/mg/min	Manganese - 84%	
Big Five Tunnel Idaho Springs, Colorado (145)	Mineral mine drainage	effluent to 3 cells- 1) mushroom compost- 2) peat/manure/ decomposed wood 3) limestone under peat/manure/ decomposed wood	NA	NA	Aluminum - 0-38% Copper - 9-96% Iron - 39-61% Manganese - 0% Sulfates - 3-4.3%	

TABLE 1. Summary of Case Study Findings on Wetlands Treatment (continued)

Location	Wastewater Type	Design	Principal Plant Species	Loading Rates	Removal Efficiencies	Comments
Mandan, North Dakota (84)	Refinery process wastewater	secondary treatment- followed by cascade pond system	Reeds Bullrushes	NA	BOD5 - 84% COD - 71% NH3-N - 85% Phenols - 95% Oil & Grease - 95% Hexavalent Chromium - 100% Total Chromium - 75% TSS - 89%	Removals given due to pond system only- Sharp increase in wildlife species- System has received numerous awards
National Space Technology Lab, Mississippi (127)	Pulp mill wastewater bleached kraft process	secondary treatment- eight artificial marshes with marl substrate for polishing step	Cattail (Typha latifolia) Reed (Phragmites australis) Cordgrass (Spartina cynosuroides)	3.2 - 0.8 m3/ 4.32 m2/day	TSS - 46-55% BOD5 - 27-35% NH3-N - 42-80% Organic Nitrogen - 32-35% Phosphorus - 14-21%	Little color removal- Filtration and anaerobic breakdown major mechanisms except P removal due to plants
Southern Louisiana (29)	Agricultural runoff	natural levees of Mississippi River and Bayou LaFourche bring runoff to swamp forest	Bald cypress (Taxodium distichium) Water tupelo (Nyssa aquatica)	Nitrogen - 15.54 g/m2/yr Phosphorus - 4.2 g/m2/yr	Nitrogen - 26% Phosphorus - 41%	Swamp acts as buffer in time and composition- DO in water column governs sediment-water exchange of PO4- Swamp subsidence buries PO4 precipitate in sediments

utilized wetlands treatment for its nutrient removal potential.

The case study conducted in Iselin, Pennsylvania [135], is typical of many of the municipal applications of wetlands treatment. Iselin is a small community of approximately 300 residents. The Pennsylvania Department of Environmental Resources established a Rural Wastewater Research and Demonstration Program in Iselin which utilized artificial and natural wetlands for the treatment of wastewater.

The Iselin wetlands treatment system consisted of a Marsh-Pond-Meadow system. A schematic of this system is presented in Figure 1. Wastewater from the collection system first enters an aeration cell. The aeration cell was designed to achieve a 50 percent BOD_5 reduction with a 2.9 day retention time. After aeration, the wastewater is split between two marsh cells. *Typha* sp. was established in the marsh. In this phase of treatment, denitrification occurs, and N and P are removed by plant growth. Additional BOD_5 and SS removal also occured in the marsh cells.

Upon leaving the marsh, effluent enters a 7059 square foot pond with a detention time of 15 days. From the pond, the effluent travels through a meadow with a detention time of one day. The meadow has a two percent slope and is covered with Reed Canary grass. After the meadow, effluent is chlorinated and discharged into Harpers Run. Summer

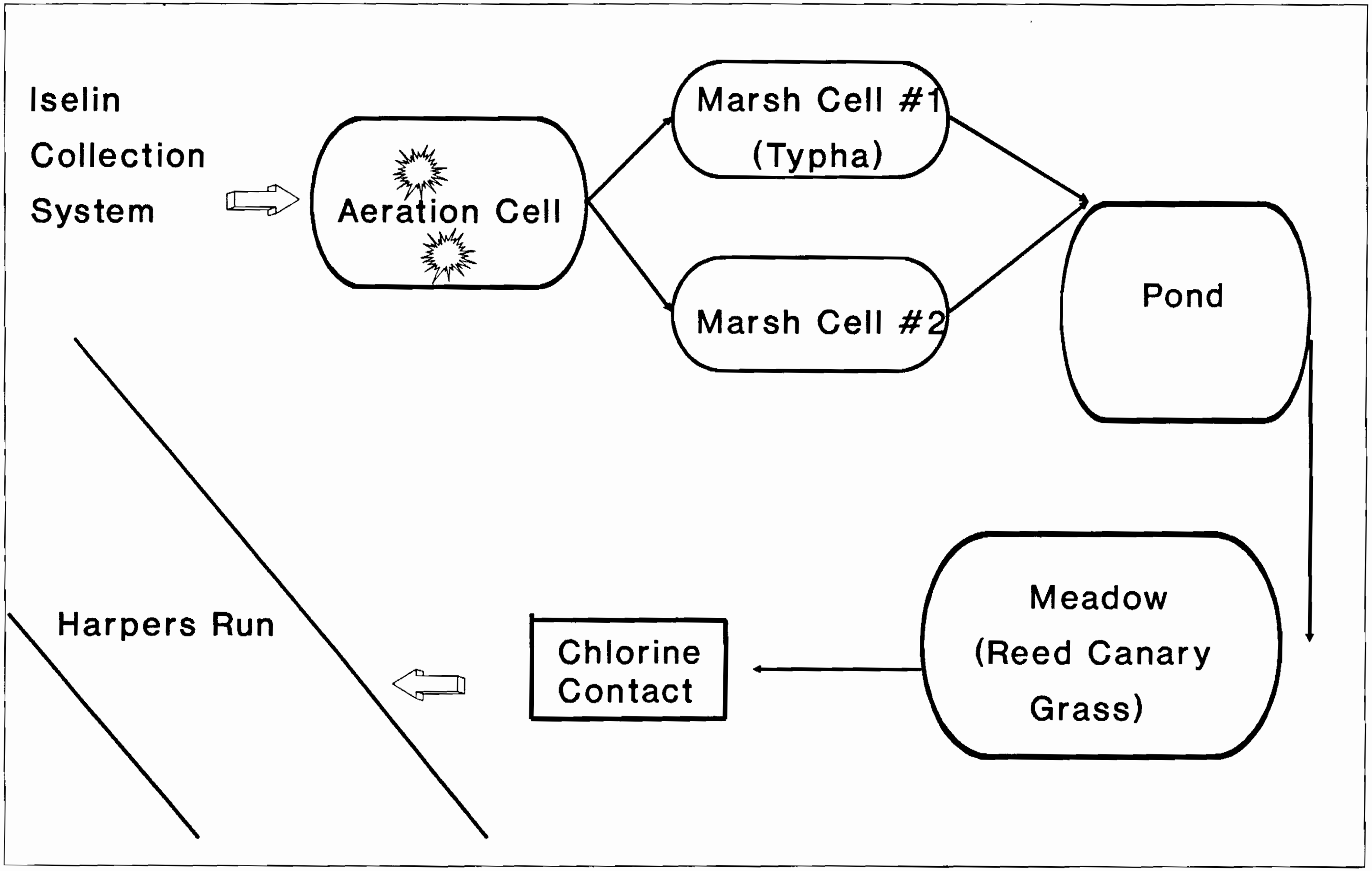

Figure 1. Schematic of the Iselin, Pennsylvania, Marsh-Pond-Meadow Treatment Facility for Municipal Wastewater [135].

effluent characteristics vary between 1-2 mg/l BOD_5, 7-8 mg/l SS and 0.01-3.25 mg/l ammonia. Winter effluent characteristics are similar except for ammonia concentrations which fall between 2-6 mg/l.

Brix and Schierup [15] reviewed the literature and the progress concerning constructed reed beds utilized to treat domestic wastewater in Denmark. The findings from the literature are listed below:

-BOD_5 removal has been typically 70-90% yielding an effluent of less than 20 mg/l.

-TN and TP reductions were 25-50% and 20-40% respectively. Surface runoff and insufficient oxygen in the root zone have been a problem.

-Hydraulic loading rates must be less than 2 cm/day in order to get N and P reductions of over 50%.

-Hydraulic permeability of the soil is slow to develop.

Brix and Schierup concluded that future construction of macrophyte based treatment systems should utilize different process types including different macrophytes, different substrates, different flow patterns and some degree of water recirculation.

Jackson [69] reviewed the performance of two Florida wetland systems in Lakeland and Orlando. Time has demonstrated that both systems can achieve permitted effluent requirements with loadings at less than design conditions. More of the systems are expected to be used as flows are increased but permitted effluents are anticipated. With increased loadings, continued monitoring, and study additional insights will be forthcoming.

Wood and Hensman [150] discussed the current research that is underway in developing the engineering data needed for the implementation of constructed wetlands in Southern Africa. It was felt that the concept had considerable merit for the treatment of raw wastewaters being discharged from rural communities, for upgrading oxidation pond and secondary effluents to general and special discharge standards, and for treatment of industrial effluent.

Whalen, et. al. [141] recommended that the following factors be considered in the design of a community wetland treatment facility for nitrogen removal:

-process/conceptual- includes target removal, carbon source, carbon/nitrogen ratio;

-basin design- includes liner, baffles, length/width ratio, media, vegetation, storm impact;

-process control- includes adjustment of carbon/ nitrogen ratios, variable loadings, adjustable hydraulic loadings, odor control.

Other comments for guidance were: construction should be modular to facilitate future needs; hydraulic loadings should insure maintenance of wetland vegetation; and costs (1989 inflated) were $\$530/m^3$/day of treated wastewater capacity.

Haberl and Perfler [53] presented new results from the full-size experimental wetlands treatment plant in Mannersdorf of Lower Austria. The facility has had ongoing research into sewage technology, hydraulics, microbiology, plant physiology, and soil science regarding the root-zone system employed there. Results of the research plant indicate that the root-zone systems may be applicable to wastewater treatment in areas of 100 to 500 population equivalents (1.0 mm/day). It also appeared necessary to have mechanical pretreatment before the wetland process.

Mingee and Crites [95] reviewed the history, pilot-study effort, construction problems, construction costs, and initial performance data for a constructed wetlands treatment system in Gustine, California. They concluded that constructed wetlands can provide a low cost wastewater treatment to achieve secondary treatment for small to medium sized communities.

Miller [94] discussed the use of artificial cattail (*Typha* sp.) in Northern Ontario, Canada. Although the need existed for secondary sewage treatment, the costs associated with conventional technologies made this prohibitive. As a result of this financial reality, a marsh system was designed. Effluent from the marsh averaged the following: BOD, 4.1 mg/l; SS, 10.9 mg/l; and TP, 0.66 mg/l. Fecal coliform counts varied but at all times the marsh was capable of discharging an effluent that met swimming and bathing water quality objectives. He concluded that marsh treatment technology can be transferred successfully to northern climates. Despite the 3 to 5 fold loading increase over the intended rate, the results compared favorably to secondary sewage treatment standards.

The creation of wetlands using municipal wastewater in northern Arizona illustrates the value of this technology in not only producing tertiary level of treatment but also as it benefits wildlife. Wilhem et. al. [146] observed an increase in the number of duck nests counted in the area of the created wetland from 3 in 1979 to 380 in 1982. This has resulted in an increase in the number of ducklings observed from 9 in 1979 to 2819 in 1982. Costs associated with this treatment have been calculated to be 32% less than lowest non-marsh alternative and annual operating costs were 47% less with the marsh. With an expected five-fold population increase, in the particular communities of Arizona studied, plans are underway for the expansion of waste water facilities employing wetlands technology.

James and Bogaert [71] reported on the Mt. View Sanitary District's combined use of a wetlands marsh forest system for wastewater treatment, wildlife habitat and recreational use. From fifteen years of experience it has been possible to provide a rich wildlife habitat, both for terrestrial and aquatic biota, at the same time meeting the needs for water treatment in the area.

Schwartz and Knight [111] examined some ancillary benefits of a natural land treatment system developed by the Grand Strand Water and Sewer Authority in Horry County, South Carolina. Besides the obvious treatment benefit the following assets were identified:

-an increased opportunity for public access and education about riverine wetlands;

-the development of a data base and communication among agencies on objectives of natural land treatment projects;

-and, the stimulus for the development of goals and objectives for a wetlands policy.

2. Application to Industrial Wastewater and Leachate

Ailstock [1] reported on the creation of a wetlands plant nursery to handle the thermal discharge of Nevamar Corporation in Odenton, Maryland. As a result of their manufacturing process 32,000 l/hr of water at a temperature of 43.3 degrees C and a pH of 6.6-6.8 was released into Picture Spring Branch, a small tributary of the Severn River. As a part of the NPDES permit, the discharge to the river was upgraded to not exceed 32.2 degrees C and a pH of 6.0-8.5. In association with Anne Arundel Community College, a wetlands plant nursery was established to handle the thermal wastewater. As a result of the project the following was accomplished: a reduction of Nevamar Corporation's effluent temperature; plant production for constructing wetlands to meet local environmental objectives; and the development of a self-supporting employment program for a local organization for the mentally handicapped.

Kaczynski [72] performed a generic research study that investigated the feasibility of disposing spent industrial geothermal fluids by wetlands treatment. The study focused around two areas: the presentation of two sets of ecological criteria for effluent application in wetlands in order to discuss their appropriateness; and the presentation of general design and ecological factors associated with selecting sites and designing wetlands for effluent treatment.

Guida and Kugelman [50] investigated salt marsh "polishing" of clam processing waste to meet New Jersey state regulations for BOD_5 and TSS and anticipated standards for N and P. With salt-tolerant microbiota, plants, and animals, salt marshes would be expected to be ideal for treating saline clam processing water. Complex tidal hydrology makes quantitative assessment of treatment for aqueous wastes efficacy difficult. The results indicated: short residence time (6 hr) did not preclude effective treatment and marsh behavior under pristine conditions is not a good indicator of the marsh's ability to polish wastewater. Removal efficiencies of selected pollutants between January 22 and August 23 were as follows: BOD_5, 29-100%; TSS, 58-108%; total N, 69-98%; and total P, 30-73%.

Staubitz, et. al. [119], discussed the potential use of constructed wetlands to treat landfill leachate. Although leachate quality may vary from relatively harmless to extremely hazardous waste, it does have some consistent characteristics. Leachate is generally anoxic and has a high BOD_5 and high concentrations of organic carbon, nitrogen, chloride, iron, manganese, and phenols, but little or no phosphorus. It was believed that wetlands treatment due to the various mechanisms at work might hold promise for dealing with this waste effluent.

Dornbush [30] reviewed the natural renovation of leachate-degraded groundwater in excavated ponds at the Brookings, South Dakota refuse landfill. Groundwater degradation began with the inception of the landfill in 1960 and was monitored to some degree from that point on. A large measure of the successful monitoring history at the landfill site must be afforded the groundwater wetlands. The landfill illustrates the potential for construction of similarly constructed trenches and ponds to intercept leachate-degraded plumes in shallow groundwater at abandoned or poorly located solid waste sites.

Trautmann, et. al., [129] have designed a wetlands system to deal with the leachate released by the municipal solid waste landfill for the Town of Fenton, Broome County, N.Y. In this system, leachate will be pretreated using overland flow followed by horizontal flow through the root zone in a bed of wetland plants. In the absence of previous experience in treating landfill leachate with this technique, its efficacy is not known. Overland flow theoretically will remove much of the dissolved iron and manganese, readily oxidizable organic matter, ammonia nitrogen, and volatile organics such as benzene. Additional removal of nitrogen and organic matter, as well as removal of phosphorous and metal ions, will occur in the root-zone bed. This process should produce an effluent that can be directly discharged to surface waters. Through a combination of laboratory studies and evaluation of the prototype system performance, the feasibility of this approach will be evaluated.

3. Treatment of Nonpoint Source Pollution from Urban Runoff and Agricultural Wastes

The use of wetlands for stormwater management has received a great amount of interest in recent years but should not be considered a panacea. According to Livingston [85], it should be viewed as just one of many BMPs included in any stormwater management program. In both Maryland and Florida, the legislatures have become involved in this pressing issue. This involvement has led to to the promulgation of design criteria for wetland systems. Unfortunately, at that present time more information is need to ascertain the possible effects on wetlands and their fauna from the addition of untreated stormwater. Little is known about the potential for bioaccumulation of heavy metals or other toxics typical of stormwater. Monitoring of wetland stormwater systems is also essential to determine relations between design variables and pollutant removal efficiency.

Silverman [114] discussed the development of urban runoff treatment wetlands in Fremont, California where stormwater runoff is a significant pollution source to the San Francisco Bay. Both the chemical and hydrological nature of urban runoff is so markedly different from that of municipal wastewater that it presents new technical problems. Urban runoff is extremely variable in both quality and quantity which affects the institutional and design considerations of wetland systems.

Meiorin [91] discussed the technical aspects of treatment in a fresh/brackish water marsh in Fremont, California. Of the three systems developed at Fremont, positive treatment performance was observed in the most mature marsh system. This system, with its heavy vegetation and extensive inundation during high waters was able to bring about the greatest reduction in incremental BOD_5, organic P, and all metals except manganese. However, all three systems were effective in reducing SS, inorganic nitrogen, phosphorus and lead. Because of the degree and significance of bioaccumulation of pollutants in the food chain, the authors felt that urban runoff treatment should not be imposed on natural systems.

Daukas, et. al. [27], discussed design considerations for a constructed wetland receiving stormwater from a regional shopping mall in Massachusetts. The following were considered design mitigation measures for this project:

- -wet detention ponds
- -constructed wetlands basins
- -catch basins with oil and grease traps
- -parking lot sweeping
- -sodium-free deicing salts
- -restricted use of herbicides, pesticides, and fertilizers

Table 2 presents the preformance of this wetland system for selected pollutants. It was concluded, based upon the performance of the system, that the receiving river could continue being used as a water supply.

Linker [83] discussed a proposal for the joint-use of a highway right of way and the creation of wetlands for the

TABLE 2. Removal Efficiencies Observed in a Constructed Wetland Receiving Stormwater [27].

Pollutant	Removal Efficiency (percent)
Suspended Solids	80-95
Total Phosphorus	60-85
Total Nitrogen	40-70
BOD_5	50-80
Sodium	0
Cadmimum	50-90
Chromium	50-90
Copper	50-90
Lead	80-95
Mercury	50-90
Zinc	50-90

improvement of water quality entering the Chesapeake Bay. In an effort to meet the goal of the 1987 Chesapeake Bay Agreement, the concept of using highway right of ways for more than just public transportation was offered. The Chesapeake Bay Agreement goal is a 40% reduction in nitrogen and phosphorus entering the main stem of the Bay by the year 2000. Simply put, placing constructed wetlands in close proximity to surfaces generating highway runoff is expected to provide the following removal efficiencies: sediment, 75-90%; total phosphorus, 55-65%; total nitrogen, approximately 40%; BOD_5, approximately 40%; metals, 0-80%. Taking cost and effectiveness into account, it was felt that this represented the most cost effective urban best management practice (BMP).

Meyer [92] reviewed the detention basin/artificial wetland treatment system (DBAWTS) that was designed to counter stormwater runoff from urban, highway, industrial, residential, and commercial areas. The system employs a detention basin with an underdrain filter coupled to an artificial wetland consisting of a shallow marsh planted with cattail (*Typha* spp.) for nutrient removal. Phosphorus, heavy metals, hydrocarbons and toxic refractory organic substances are removed through sedimentation and absorption within the wetland. This system was felt to be capable of providing effective, low-cost, low maintenance treatment of stormwater from urban, highway, and industrial areas.

Goldstein [46] discussed the utilization of wetlands as a BMP for the reduction of nitrogen and phosphorus in agricultural runoff from south Florida watersheds. Five sites were studied to determine the efficiency and efficacy of both natural and constructed wetlands to remove nutrients. The land uses ranged from native range to highly improved pasture supporting cattle densities of .05-1.5 per acre. Results indicate variable removal efficiencies. Dissolved inorganic forms of nitrogen and phosphorus were actively taken up while particulate-bound forms (mostly organics) were exported in amounts comparable to those measured in the inflows.

Costello [24] discussed the use of wetlands for the treatment of dairy animal waste in Drumlin, Ireland. Using a system that was initiated in 1816 as a treatment technique, the wetlands continues to produce high quality effluent. Dairy farm waste is anaerobically digested and then filtered prior to wetlands application. Data collected along a receiving stream demonstrated the reduction of BOD_5 by 99% and SS by 97%. Dissolved oxygen increased to 7.2 mg/l in the stretch of the stream monitored.

Lowe, et. al. [87], discussed the potential role that marsh creation could have on restoring a hypertrophic lake.

Lake Apopka, located in central Florida, has the highest trophic index value of any large lake and receives agricultural runoff from farmland. The proposal is to recirculate, by pumping, water from the highly eutrophic lake for repeated processing through the surrounding marshes. It is anticipated that the marsh will be able to remove 50% or more of the phosphorous because 80% of it is in particulate form. Based on the performance of the surrounding wetlands, 26-55% of the suspended phosphorus is expected to be removed. At an areal loading rate of 3.1 g $P/m^2/yr$, 50 metric tons would be removed. Economic constraints will determine the feasibility of the project since water must be moved against its concentration gradient to achieve the necessary gravity feed through the marsh.

Barten [5] studied Clear Lake, located in south central Minnesota, that had become eutrophic from the inflow of nutrient rich runoff from the nearby city of Waseca. In 1981, 50% of the hydraulic load and 55% of the phosphorus load to the lake were diverted into a 21.4 ha marsh. The phosphorus load to the lake was reduced by 44% (1,073 kg). A second marsh system project, completed in 1986, is expected to filter 20% of the phosphorus concentration from urban and agricultural sources. In total, the phosphorus load has been reduced by 32% from 147 ug/l to 100 ug/l, since 1981. The total nitrogen to phosphorus (TN:TP) ratio increased from 10:1 to 22:1 since the diversion began.

Harper and Wanielista [58] investigated the removal efficiencies for residential stormwater runoff in a hardwood forest located adjacent to Hidden Lake north of Orlando, Florida. They found that with 150 meters of flow through the wetland, 50-80% of particulate metal species was removed, less of dissolved species. Metal species settled very quickly after entering the wetland, forming relatively stable metal-sediment associations with the majority of the metals retained near the surface layers. From column studies it was found that removal efficiencies for nitrogen, phosphorus, and heavy metals were substantially greater during infiltration than during a flow-through situation. Because this type of wetland was more effective at removing metals than nutrients it was felt to be more suited for treating highway runoff than municipal wastewater.

Weidenbacher and Willenbring [139] investigated the ability of a natural wetland to reduce nutrient loading by urban stormwater to Lake Josephine in Minnesota. It was found that by diverting 37% of the flow that normally enters the lake to a nearby wetland, nutrient reductions could be realized and lessen human impact on the lake. The removal efficiencies were: 62%, total phosphorus; 69%, ortho-phosphorus; 48%, TKN; and 79%, SS. Over a three year period all data indicated that the wetland has lowered the overall amount of nutrients and suspended solids entering the lake.

Berry and Martens [10] studied the degradation of three herbicides in wetland soil. These herbicides, found in agricultural runoff, may either accumulate or degrade. Soil samples were collected from sites near the Virginia Towns of Holland and Tappahannock. The results after 123 days indicated that atrazine and cyanazine, in the Holland soil microcosm, had 100 and 95% disappearance, respectively. Alachor was not degraded in the Holland soil microcosm at all. The Tappahannock wetland soil produced no significant degradation in any of the three herbicides.

McKallip, et. al. [90], studied the impact that development would have on a proposed lake/wetland area. A nonpoint source loading model, a phosphorus model and a dilution model were used to predict the impact that might be expected. Results indicated that with ultimate development, phosphorus levels would increase 11%, nitrogen by 6%, lead by 8%, zinc by 7%, and sediment by 17%. It was recommended that monitoring of the proposed lake take place and that several BMPs be employed. These included: dredging the lake in a timely manner; an aeration system within the lake; infiltration trenches; porous pavement; and street sweeping.

4. Control of Acid Mine Drainage Including Coal Pile and Ash Pond Seepage.

Silver [113] reviewed the present understanding of the biology and chemistry of generation, prevention and abatement of acid mine drainage. The biology and chemistry took into account: oxidation of iron sulfide minerals; oxidation of nonsulfide minerals; anaerobic oxidation of elemental sulfur and sulfur compounds; and, jarosite formation by ferric iron hydrolysis. It was felt that only those abatement options that contained a substantial biological component offered freedom from perpetual maintenance. Permanence was found to depend on self-regenerative properties of biological systems. The underlying objectives of acid mine drainage treatment are the decrease in acidity through neutralization or sulfate removal, and precipitation of metallic pollutants.

Howard, et. al. [66], discussed the design and construction of a research site for passive mine drainage treatment in Idaho Springs, Colorado. The mine drainage treatment structures were 3.05 by 18.3 meters. Drains within the structures delivered the overflow water to the existing pond. Passage of mine drainage over organic substrate at the inlets provided maximum cross sectional contact. Sampling wells at various heights and locations were throughout. The substrates tested were mushroom compost, peat, aged steer manure, and decomposed wood shavings and sawdust. The plants tested were cattails (*Typha latifolia*), sedges (*Carex utriculata, C. aquatilis*) and rushes (*Juncus arcticus*). Results were compiled for acid mine drainage output water, DTPA extracts, substrates and plants samples.

Stevens, et. al. [122] studied manganese and iron encrustations on green algae living in acid mine drainage (AMD). Utilizing energy dispersive spectroscopy (EDS) with the scanning electron microscopy (SEM), it was possible to determine the metallic components of algal encrustations. If a particular metal is found to be significantly accumulated by an algae then it may play a role in treatment of AMD. It was found that *Oedogonium, Mougeotia*, and *Microspora* to be the most commonly encrusted genera of algae growing in AMD. The mechanism used by metal-encrusting algae in metal removal is unclear.

Howard, et. al. [67] investigated the feasibility of using forest products or on-site materials in the treatment of AMD in Colorado. It was found that ponderosa and aspen had better ion exchange capacities than lodgepole and spruce-fir litter and humus. It was believed that the cation exchange capacity (CEC) did not adequately estimate the cumulative percent removal capacities for litter and humus due to sodium saturation. Overall trends in the efficiency are consistent and decrease markedly as 60-90% of CEC is reached. All four forest materials tested removed metal ions from mine drainage, but spruce-fir and acid decomposition materials had higher cumulative removal efficiencies in laboratory studies and it was felt that they should be tested in pilot studies. Reduction of metal ion concentrations on abandoned mine drainages with on-site forest litter and humus appeared promising.

Fennessy and Mitsch [35] evaluated a 0.22-ha constructed wetland for its ability to treat approximately 340 liters per minute of coal mine drainage. The wetland contained a 15 cm layer of crushed limestone followed by a 45 cm layer of organic rich mushroom compost. Into this substrate cattails (*Typha*) were planted. Hydraulic loading rates ranged from 15 to 35 cm/d. Figure 2 presents a schematic of this wetland system.

The removal efficiency for iron was found to be 50-60%, with slightly higher decreases during the growing season. Effluent improvement was observed for the following parameters: conductivity - 11.6 percent; iron - 53.2 percent; sulfate - 3.3 percent; alkalinity - 60.0 percent; and acidity - 44.3 percent. The study suggested that longer retention times (5 cm/d) and lower iron loading rates (40 g iron/m^2/d) would increase efficiency. As such, the

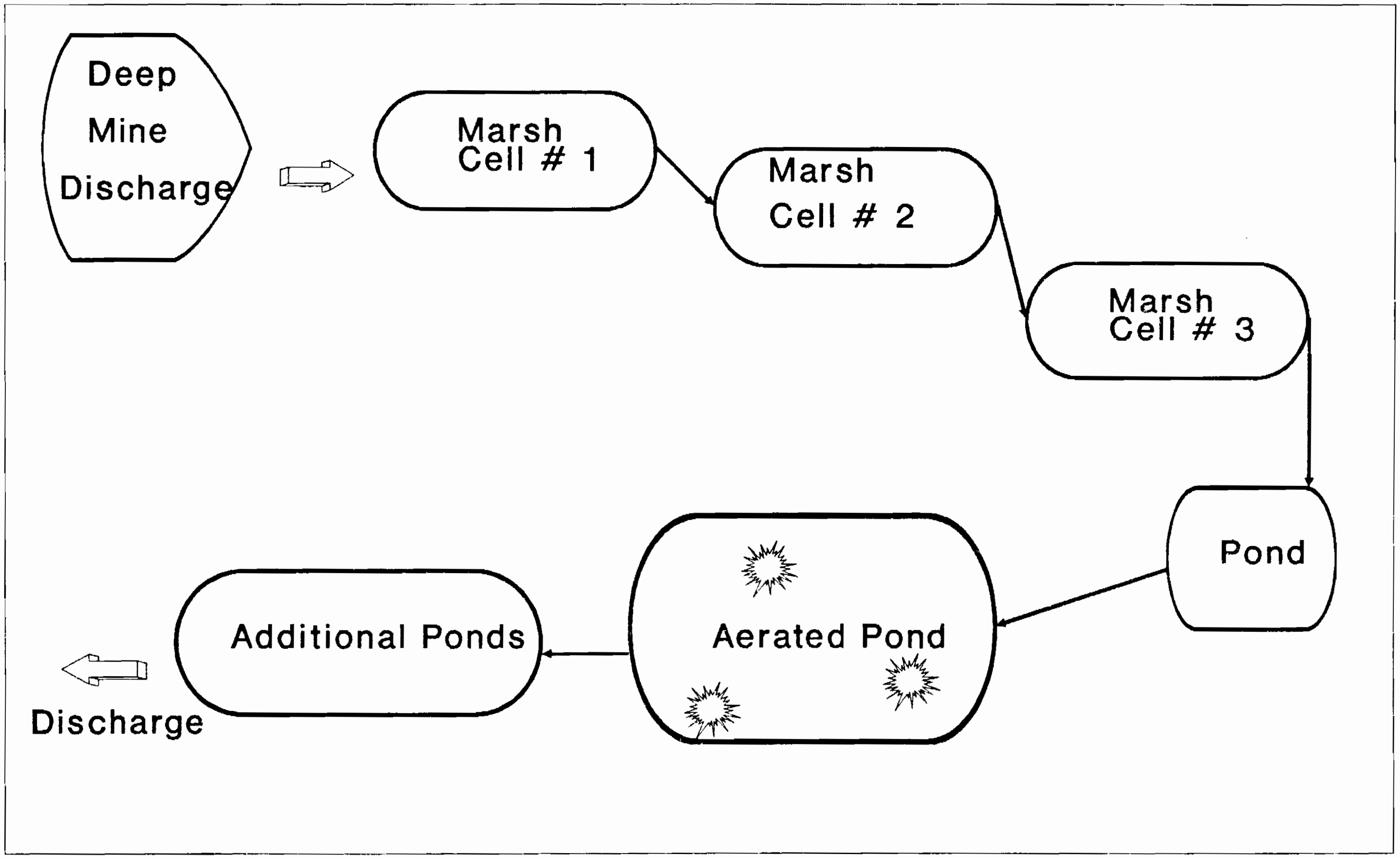

Figure 2. Schematic of the Coshocton County, Ohio, Constructed Marsh Mine Drainage Treatment System [35].

constructed wetland exhibited some success in abating acid mine drainage pollutants.

Hedin, et. al.[59], discussed the factors which affect sulfide formation in aquatic systems and evaluate the theoretical potential of the process in wetlands constructed to treat acid mine drainage (AMD). Dissimilatory sulfate reduction and iron sulfide formation are biogeochemical processes that could significantly affect mine drainage chemistry. If the potential of sulfide formation processes is to be realized, wetland designs for treating acid mine drainage must be modified to increase the movement of water through anoxic sediments. One design currently being evaluated inputs water through a perforated pipe beneath a limestone bed within a constructed wetland. This arrangement permits a partial neutralization as water diffuses upward through the organic substrate and is followed by oxidizing processes at the wetland surface.

Eger and Lapakko [32] reported on a cooperative effort between the LTV Steel Mining Company and the Minnesota Department of Natural Resources to use wetlands for the removal of nickel and copper from mineralized mining stockpiles. Drainage from these stockpiles have elevated the metal concentrations of nickel, copper, cobalt, and zinc 400 times over background levels in receiving waters. Preliminary studies were done to determine the retentive capacities of the specific types of peat present in the available wetlands. Results indicate that a nickel removal efficiency of 10,000 mg/kg dry peat would be valid design parameter. Based upon the strength of the drainage, the estimated volume and the calculated removal efficiencies, estimates of required size and longevity of the system could be determined. It was felt that wetland treatment appeared to be a useful mitigation method. Four wetland cells were established with peat, cattails (*Typha*), sedges (*Carex* sp.), and grasses (*Calamograstis*). In addition to inflow and outflow samples, ground and surface water were monitored. Cells became operational in 1989.

Kolbash and Romanoski [80] reported on efforts by the Windsor Coal Company to minimize the impact of a refuse pile from their coal operations through wetlands treatment. The wetlands treatment components employed were: .5-cm limestone; sterile mushroom compost; and cattail (*Typha*). Because of the physical location restraints and the slope it was necessary to use a Hypalon liner to protect against slope saturation. Results indicate that even with less than one year of operation, the wetland has been effective in removing 50% of the incoming iron. The Hypalon liner appears to be enhancing algal growth with the consequent loss of interaction between soil and plants.

Henrot, et. al. [61] presented results on a laboratory pilot study in which replicate model wetland systems were subjected to inputs of water at uniform flow rates but differing iron concentrations. The models were filled with *Sphagnum* and received iron concentrations of 0, 50, or 100 mg/l at a pH of 4.0. After eight days of treatment, it was found that effluent iron concentrations were approximately equal to influent iron concentrations. It was felt that microbially mediated iron oxidation was probably inhibited in this pilot study by high greenhouse temperatures. Prior to the completion of the eight day study, iron removal was indicated in the peat analysis where it was found that (1) iron retention was more pronounced at the inflow end, and (2) accumulated iron was mainly present as organically bound iron (63.8% of total iron) and iron oxides (29.1%), with little accumulation as exchangeable iron.

Wenrick, et. al. [140] discussed studies performed to ascertain the tolerance of three wetland plant species to AMD. The plant species utilized were cattail (*Typha latifolia*), turf-moss (*Pohlia nutans*), and peat moss (*Sphagnum recurvum*) which were subjected to tap water, and diluted and undiluted mine drainage. To assess the impact of mine water on plant health, initial and final samples were taken to measure chlorophyll concentration. A record of the growth for the cattails was maintained. In conclusion, the results indicated that *Typha* was the most generally tolerant of the three species. It was noted that there was a change in the chlorophyll a/b ratio for *Sphagnum* and *Pohlia* but the physiological significance of this was unknown.

Snoddy, et. al [118] discussed control measures for the armyworm (*Simyra henrici*) on cattail plantings in an AMD wetland. At the Widows Creek Fossil Fuel Plant an infestation of armyworm was observed in mid-August 1986 with the wetlands treatment system only being online for four months. Although rush (*Juncus effusus*) and cattail were present the latter suffered the greatest vegetative destruction. Over 95% control of the pest was obtained through the application of Lorsban, an insecticide. It was felt that due to the recency of the development of the wetland area the complex population regulating mechanisms hadn't had time to develop, i.e. parasites and predators. It was advised that routine inspection of plantings for insect pests should be incorporated into a management plan for constructed wetlands. It was also suggested that an edge effect planting could be a means of keeping pests away from the main vegetative body of a wetland.

5. Dynamics of Oxygen Transfer

Grosse [49] explores the principle of thermoosmosis (thermal flow of molecules) as it relates to oxygen and wetlands plants. It is this phenomenon (thermoosmotic gas transport) by which oxygen is brought to the root zone of plants where it plays an oxidative role. This information would be of value in selecting plants for wetlands treatment processes.

Michaud and Richardson [93] studied five wetlands plant species to determine their relative radial oxygen loss (ROL) or the loss of oxygen through the root system. Theoretically, plants with the largest oxygenated rhizosphere and largest population of metal-oxidizing microbes would maximize the wetland's potential to remove toxic metals from the water column by oxidation. Results of their experiments indicated that dissolved oxygen concentration in the soil-water matrix can vary with plant species. The following trend was noted with the loss of oxygen to the rhizosphere: cattail (*Typhus latifolia*); rush (*Juncus effusus*); burreed (*Sparganium americanum*); spike-rush (*Eleocharis quadrangulata*); woolgrass (*Scirpus cyperinus*). Individual growth characteristics, such as stand density, need to be considered when comparing rhizome oxygen level.

6. Nitrification and Denitrification in Wetland Systems

Davido [28] has found that nitrification and denitrification in the Iselin Marsh-Pond-Meadow treatment system accomplished a TKN removal efficiency of 95 percent. The most effective nitrification component is the marsh. Nitrification occurs throughout the water column in the marsh but most effectively at the surface. Nitrification also takes place in the upper zones of the pond and at all depths in the meadow. Denitrification occurs in the aeration basin within the anaerobic layers of the sludge floc, in the anaerobic microsites throughout the marsh and may occur in the pond sediments. Denitrification appears to be minimal in the upper pond strata and in the meadow.

Stengel and Schultz-Hock [121] concluded from their studies on denitrification in artificial wetlands the following:

-Nitrate elimination in artificial wetlands is possible throughout the whole year, when specific conditions are fulfilled (low oxygen concentration in water, availability of organic carbon).

-Even at low temperatures, high denitrification rates have been verified.

-In summer, denitrification occurs in the whole plant bed, when oxygen concentration in the inflowing water is low.

-Oxygen was not added in the root zone through flowing water.

-Further study is needed regarding "controlled aeration" through the root zone of macrophytes.

Hsieh and Coultas [68] demonstrated that nitrification-denitrification coupling existed in the acidic freshwater wetlands under study. Altering pH values through liming caused a decrease in the nitrification rate in most cases after seven day preincubation, suggesting that other unidentified factors might control nitrification in these soils. At the same time, ammonium levels were found to rise rapidly during seven day preincubation rather than two-day incubations. It was felt that liming might cause reduction of the soil microbial population. The C/N ratio correlated with both nitrification and denitrification rates. "Nitrification rate is essentially the limiting factor for nitrogen removal through denitrification in wetlands."

Broderick, et. al., [19] examined the potential of a natural wetland receiving secondary wastewater for its ability to remove nitrogen. This was accomplished by observing the denitrification rates and the activity in soils containing decaying plant material. By lowering the E_h of soils the effluent flow favors denitrification. Effluent inflow increased the concentration of inorganic nitrogen in the soil, thereby encouraging higher rates of denitrification. It was found that the highest denitrification rates occurred downstream of the effluent inflow with maximum rates in soils between 0-60 cm in depth and in decaying plant material. Denitrification activity and nitrite plus nitrate concentrations were found to decline rapidly below 6 cm in upstream and downstream soil samples. It was concluded that denitrification rates in natural wetlands are increased by the addition of secondary treated effluent and are responsible for the continued removal of nitrogen from wastewater.

Lindau, et. al. [82], researched the fate of nitrate and ammonium-nitrogen added to a Louisiana gulf coast forest. This was accomplished by adding labeled inorganic nitrogen, 15_N, to observe the significance of nitrification-denitrification in flooded swamp soil on removing nitrogen. Labeled $(NH_2)_2SO_4$ and KNO_3 were added to six plexiglass chambers placed in the swamp forest substrate receiving agricultural runoff. It was found that applied nitrate rapidly underwent denitrification and produced nitrous oxide and nitrogen gas that escaped to the atmosphere. Ammonium was nitrified to nitrous oxide and nitrogen gas. Ratios of evolved N_2 to N_2O varied over the length of the study. The ratios could be used to estimate future swamp forest denitrification fluxes. It was concluded that nitrification-denitrification reactions are important removal mechanisms in the coastal Louisiana wetlands.

7. Efficiencies of Substrates, Vegetation, Water Levels and Microbial Populations

DeBusk, et. al. [28], examined BOD_5 and SS removal rates from primary effluent using floating emergent macrophytes. The study took place in central Florida using raceways at a hydraulic loading rate of 10 cm/day. Gravel beds were used for swordgrass (*Scirpus americanus*) and arrowhead (*Sagittaria latifolia*) while the floating macrophyte pennywort (*Hydrocotyle umbellata*) was in an open water system. Results, over the six months of the study, indicated that pennywort was most effective in BOD_5 and SS removal followed by arrowhead, swordgrass and the control. After the six months of study, it was found that the arrowhead system rivaled the pennywort system. It was felt that several months were required for the establishment of full treatment capacity. This was believed to be related to the bacterial colonization of the gravel bed system.

Suzuki, et. al. [125], explored the role of harvest time of *Phragmites australis* with their ability to remove total dry matter, nitrogen and phosphorous. It was found that harvesting *Phragmites* twice during the growing season increased their total amount of biomass, and thereby N and P removal from the plot. The authors concluded that the first harvest should occur when maximum nutrient content is reached followed by a second.

Hobson [63] presented hydraulic considerations and design parameters for reed bed treatment systems. His recommendations included:

-The upper green parts of *Phragmites* must be removed at the end of the growing season.

-Although gravel beds are easier to design, soil beds give superior treatment if surface flow is avoided.

Portier [102] presented cost-effective approaches for in situ analysis of related soil/sediment microenvironments that were used to evaluate wastewater impact and effect in constructed wetlands. By employing a modified extraction procedure, microbial ATP can be analyzed along a salinity gradient reflecting microenvironments of considerable diversity and biomass.

Kadlec [77] developed a method for quantifying the rates of key biomass processes and the amounts of nutrients and biomass involved in wetlands receiving municipal wastewater. The method accounted for growth, litterfall, litter decomposition, leaching and mineralization processes. These determinations lead him to the conclusion that constructed wetlands will probably require 5-10 years for these processes to become established and fully operative.

Bavor, et. al. [8], examined the performance of solid-matrix wetland systems viewed as fixed-film bioreactors. Removal of SS, BOD5, N, P, and fecal coliforms was investigated with respect to loading, detention time, and temperature parameters to allow predictive modeling of system performance (assuming first-order kinetics and treating the units as fixed-film bioreactors). First order kinetics, he cautioned, may not adequately describe the removal performance for a number of effluent constituents. Through the examination of removal data from discrete compartments in the systems and/or analysis using removal kinetics of increased complexity, improved models were being developed.

8. Disease Vectors and Other Pests in Wetlands Treatment

Scheurman, et. al. [110], studied the fate of microbial indicators in a forested wetland. The results indicate that initial removal of microbial indicators, such as *E. coli*, is rapid. Part of the microbial population was found to be capable of long-term survival. Because fecal steptococci were found to accumulate in sediments, it was felt that this organism may be a more conservative indicator for fecal pollution than *E. coli*. Bacteriophages were removed at a slower rate than bacterial indicators and enteroviruses.

Dill [26] cautioned that early input by mosquito professionals is extremely important in the use of wetlands as a treatment technology. Good preventive design coupled with water management and vegetation control will normally be enough to minimize mosquito problems. Diseases of particular concern that are passed by mosquitos (*Culex tarsalis*) are western equine encephalitis (WEE), and St. Louis encephalomyelitis (SLE). Although mosquito fish are extremely effective in controlling this problem, mishaps at the treatment plant or unusually hot weather can kill off these fish populations. Mosquito control must be a basic element of the preproject planning as well as in the operation and management of wetlands treatment.

Design, Construction and Operation/Management

1. Design

In setting out to design a constructed wetland it is of paramount importance that, in addition to all of the engineering considerations, the human element be held in regard. If properly designed, placed and managed, this treatment technology can bring greater value than its technological capabilities alone. It is the aesthetic element that will attract people to the wetlands based upon the presence of clean water, plant life, animal life and in general the seemingly natural nature of the landscape. Future use of the area should not be preempted by its present use [143, 144].

Sather [109] discussed the ancillary benefits that are possible if in the design process for constructed wetlands the basic principle of treatment through complexity is kept in mind. It is one of those rare instances where the process design can dovetail nicely with ecological relationships. Engineering design, therefore, should be sensitive to the hydrologic regimes and soil characteristics required to produce the interspersion of plant life and the subsequent wildlife niches. In nature, monocultures are inherently unstable and constructed wetlands are no different in this regard.

The view from Ducks Unlimited is that the utilization of wastewater treatment for the creation and enhancement of wetlands has significant potential. The obvious benefit of creating habitat for waterfowl must be balanced against the possibility of a negative impact from this technology [65].

Once the need and suitability of constructed wetlands has been established, the first order of business is proper selection and evaluation of a site. Aside from the availability, the site must be evaluated regarding its relationship to performance, construction, and long-term operation. In general, the site evaluation must include land use, hydrology, geology, and environmental, regulatory, geotechnical, and characteristics of the site. All of these factors will be relative to the wastewater treatment needs [16].

Reed and Kubiak [104] argued that little in the way of formalized criteria has been put forth to address the suitability of a natural wetland for receiving wastewater. It was their contention that this criteria needs to be developed in order to provide guidance to those responsible for planning and reviewing wastewater projects. They believed that the wetlands wastewater issue has been trapped in a "deflection of goals".

At the present time, a sufficient engineering database has been developed to address the performance and loading rates for constructed wetlands. The first aspect of design will be whether the system will be surface or subsurface flow. This, in large part, will be answered by what is expected of the process and numerous other variables. Secondly, what is the primary objective of treatment or what does the waste stream contain - AMD, municipal waste, etc. Thirdly, to determine the area necessary for treatment, or what will be the hydraulic loading rate. Unfortunately, there is a limited information available on the kinetics of removal for pollutants other than BOD and the change that can be expected with time which undermines the design process in this last regard [137, 131].

Watson and Hobson [137] have reviewed various control structures that are suitable for use in constructed wetlands treatment in designing for hydraulic considerations. The structures include: flow splitters; inlet and outlet devices; and dikes. Areas for hydraulic consideration affecting residence time in cell design are: length and width; porosity; and depth of submergence, flow, and bed slope.

Steiner and Freeman [120] presented design considerations for configuration and substrate in constructed wetlands. The configurations can be of various types depending upon many other parameters. One design is where preliminary/primary treatment, i.e. stabilization ponds, comminuter, Imhoff tank, septic tanks, is followed by the constructed wetland. Flow patterns within the constructed wetland can be by plug, step, recirculation, or "jelly-roll" in cells operated as one unit, in parallel or in series. Factors that determine the substrate selection include- vegetation, cost, treatment requirements, and pollutant removal. If groundwater contamination is a possibility then an impermeable liner could be added either of synthetic or natural material. Table 3 presents design criteria developed by EPA for two common types of constructed wetlands used for domestic wastewater treatment.

Concern over mosquito production is often an issue that is raised that can be addressed in the design process. The maintenance of aerobic conditions is a prerequisite to the presence of mosquito predators (i.e., mosquito fish, dragonfly, damsel fly nymphs and a variety of water beetles). To avoid the negative impact of mosquitos, pretreatment and adequate distribution must be part of the design. The avoidance of hydraulically static areas

TABLE 3. Design Criteria for Two Common Types of Constructed Wetlands for Wastewater Treatment [131].

Systems:	Water Hyacinth			
Factor	Non-aerated	Non-aerated	Aerated	Duck Weed
Treatment Level	Secondary	Advanced	Secondary	Advanced
Influent BOD_5 (mg/l)	130-180	30	130-180	30-40
Effluent (mg/l)				
BOD_5	<30	<10	<15	no data
SS	<30	<10	<15	no data
TN	<15	<5	<15	no data
Water Depth, M	0.5-0.8	0.6-0.9	0.9-1.4	1.5-2.0
Detention Time, days	10-36	6-18	4-8	15-25
Hydraulic Loading m^3/ha-d	>200	<800	550-1,000	<50
Harvest Schedule	Annually	Twice per Month	Monthly	Monthly

through the removal of thick vegetation and the removal of nonbiodegradables (grit, plastics and grease) that might form plugs in the distribution system would help to maintain the desired oxygen levels. If the design does not effectively address the mosquito potential then abatement measures would be necessary, i.e. parasitic and pathogenic organisms, hormonal substances, oil, and pesticides [123].

As part of the design process Kadlec [74] offered a methods for modeling the interaction of wastewater and wetlands. The prediction of performance of a wetland treatment facility requires equations that describe both the response of the ecosystem to the wastewater additions and the alteration of the water quality. Features that were considered in this model were wetland hydrology and overland flow, removal rates for wastewater components, and the effects of nutrient addition on the continued ability of a wetland to treat wastewater.

2. Construction

In constructing a wastewater treatment wetland, Tomljanovich and Perez [128] outlined the various phases of the process. In general, they consist of: construction plans; preconstruction site activities; cost estimate preparation; construction; inspection, testing, and startup. Upon completion, frequent inspection and monitoring the wetlands is critical to ensure successful operation.

3. Operations/Management

Girts and Knight [45] examined the need for management and operating flexibility in constructed wetland water treatment systems. Because the mechanisms at work in a constructed wetland are, in a sense, "natural", it has been found that flexibility in operations is essential to treatment efficiency and longevity in a well designed system. In so doing, a greater latitude of responses to disturbances that are both predictable and unpredictable is afforded. Predictable disturbances would include the establishment of faunal and floral relationships during the startup phase and with seasonal fluctuations while unpredictable disturbances would be events such as fire and disease outbreaks. Five case studies were examined to illustrate the point that with appropriate monitoring and the ability to make operations adjustments, a constructed wetland can meet the inherent changes that will occur throughout its lifetime.

Gersberg, et. al. [41] examined the ability of constructed wetlands to remove pathogens from wastewater.

In both Arcata and Santee, California, it was found that removal efficiencies of 90-99% could be achieved for bacterial and viral indicators of pollution. Total coliform levels in secondary wastewaters could be reduced to 1000/100 ml. Raw sewage would require chlorination to achieve this level of purification. By allowing a hydraulic residence time of 3-6 days constructed wetlands were more capable of achieving acceptable levels of treatment for pollution indicators than conventional treatment plants.

The need for an ongoing monitoring program in a constructed wetland was discussed by Hicks and Stober [62]. The monitoring plan for the wetland would include information on compliance, performance /treatment efficiency, and viability/ health. From an administrative perspective it should include clearly stated objectives, technical and management responsibilities, quality assurance procedures, resources and schedules. The presumption is that with the implementation of such a plan problem areas will be recognized before they become unmanageable so that the necessary adjustments can be made.

In a constructed wetlands pilot plant in San Diego, California, [89] after 10 years of operation and one million dollars for research, it was concluded that water hyacinth could be used successfully to treat wastewater but questions concerning mosquito production still remained. Nine pilot plants, using aquatic macrophytes, have been built in California since 1974 but due to mosquito problems five no longer operate. From studies since that time it was found that mosquito problems have been alleviated by a number of different operational measures, they are:

-modifications in oxygen loading;
-better water hyacinth management;
-replacement of cattail and bulrush with lower growing forms;
-and bacterial insecticides.

Despite the problems encountered, Martin and Eldridge [89] felt that mosquitos could be controlled with careful planning and management. Mosquito breeding management must be included in the earliest planning stages and must be included in operating procedures after plants have come on line.

Allen, et. al. [2] described the considerations and techniques for vegetation establishment learned from experience in constructing wetlands. Factors influencing wetland plant establishment are: hydrologic regime; substrate; and vegetation. The hydrologic parameters that come to bear on a plant are numerous, they include: water depth and frequency of flooding; water clarity; pH; salt concentration; and dissolved oxygen. The substrate conditions that influence the health and viability of the plant that need to be considered are: texture; organic content; calcium content; and nutrient conditions. The following are offered as general guidelines in selecting plants:

-they should be active vegetative colonizers with spreading rhizomes;

-they should have considerable biomass or stem densities to achieve maximum translocation of water and assimilation of nutrients;

-they should have a maximum surface area for microbial populations;

-they should have efficient oxygen transport into the anaerobic zone to facilitate oxidation of reduced toxic metal compounds and support a large rhizosphere;

-they should be a combination of species that will provide the coverage over the broadest spread of water depths envisioned for the terrain conditions.

Not all plants can be planted successfully in the same manner so it is therefore necessary to plant according to the species at hand. Optimum water level following planting and subsequent growth will not be the same for all species and must therefore be managed appropriately.

Bastian, et. al. [6] and Rusincovitch [108] reviewed the use of wetlands for the treatment of municipal sewage from a regulatory and federal policy perspective. EPA recognizes the value and need for this technology and is aware of the ever expanding database of information. Use of natural wetland treatment systems is limited to providing further treatment of secondary effluent to meet downstream water quality standards. Constructed wetland treatment systems can be established almost anywhere, especially where wastewater treatment is the only function sought. All municipal wastewater treatment systems, except for certain ocean discharges and aquaculture systems, must achieve the degree of effluent reduction attainable through application of secondary treatment prior to discharge to waters of the United States. Permits and grants relevant to this technology were discussed.

Slayden and Schwartz [115] discussed activities, attitudes and policies relevant to constructed wetlands and wastewater treatment based upon a survey of the states.

From the 12 states presented it is apparent that this technology is accepted to varying degrees from state to state. In those states that have had experience with constructed wetlands it is recognized that this is an area that is not yet perfectly understood and must therefore be approached with a degree of skepticism. The economic and treatment benefits are also anticipated with the increasing acceptance of constructed wetlands.

Watson, et. al. [138] discussed how in a Kentucky wetlands project there was a real benefit to be derived from a cooperative effort of a number of agencies and organizations. In this particular project EPA Region IV, the Kentucky Division of Water, and the National Small Flows Clearinghouse teamed up with the Tennessee Valley Authority to finance the world's most extensive field test monitoring program of constructed wetlands for municipal wastewater treatment.

Willenbring [147] examined why some wetland treatment systems work better than others. From studies that he has done on routing stormwater through five wetland treatment systems he has found that there is a relationship between loading rates, detention times and removal of various pollutants. Through the manipulation of these operational parameters removal can be enhanced or diminished. There appears to be an optimal loading rate on a site by site basis. Generally, the longer the detention time the better the removal. During the summer months, in one particular wetland, it was observed that when stormwater storage was increased there would be a corresponding reduction in the nutrient loading downstream. It was also noticed that increasing nutrient concentrations prompted a shift toward physical absorption and sedimentation mechanisms while at lower concentrations, the slower chemical adsorption and microbial and biological utilization mechanisms predominated.

The issue of using natural wetlands as a tool for wastewater management was addressed by Richardson and Nichols [107] from an ecological perspective. The following suggestions were made for a study in analyzing the appropriateness of this treatment process:

-value of wastewater as a resource;
-all wetlands values
-suitability of wastewater discharge;
-wastewater treatment objectives;
-capacity of wetland to accomplish desired treatment on the basis of hydraulic loading, nutrient loading, and wetland area needed;
-comparison with other treatment options by degree of treatment accomplished, cost, and energy requirements;

-environmental impacts (insect problems, disease vectors, odors, species loss community change, etc.);

-legal aspects of wetland utilization.

Sutherland [124] examined the economics of using wetlands for wastewater treatment in two communities in Michigan. For both Vermontville and Houghton Lake the annual wetland operating and maintenance cost was about $160/MG (1981). Of this amount $50/MG and $93/MG was for environmental monitoring in Vermontville and Houghton Lake respectfully. The annual costs per family were $15 for Vermontville and $6 for Houghton Lake.

In Anne Arundel County, Maryland, the Mayo Water Reclamation Subdistrict [86] will manage, finance and operate individual septic systems as part of an overall wastewater management plan. The plan was based upon the specific site requirements and success/failure of the present system. The plan integrates on-site septic systems, cluster soil absorption systems, and a communal treatment system. The communal treatment system treats the effluent from a septic tank/effluent collection system. In general this system has five components: sand filters; freshwater emergent wetland (constructed wetland-cattail and bulrush); ultraviolet disinfection; peat wetland (constructed wetland for phosphorus and nitrogen removal);

and an offshore wetland (sago pondweed, redhead grass, and widgeon grass for additional N and P removal). The Mayo Peninsula Wastewater Management Plan has provided an institutional framework that can effectively manage on-site wastewater systems, in combination with cluster and communal treatment systems. The plan received a 1986 National Honor Award from the American Consulting Engineers Council.

III. CONCLUSIONS

As the database of information for constructed wetlands grows, the benefits and limitations of this alternate wastewater treatment technology will be better understood. Based upon the results for numerous field and case studies, wetlands treatment can be highly successful at a relatively low cost. This technology appears to hold considerable promise for its technological capabilities plus it is widely applicable. Wetlands treatment has been successfully used to treat domestic wastewater, industrial wastewater, leachate, acid mine drainage and stormwater.

Aesthetic and habitat development possibilities are a secondary attribute of constructed wetlands treatment units. Although constructed wetlands yield positive benefits, natural wetlands are best left untouched. As with any issue relevant to the environment, caution must be exercised in releasing wastewaters into any wetlands to avoid degradation of natural wetland systems.

The design of constructed wetlands needs to include a wide variety of factors. Some of the most import factors that must be considered include: substrate type, hydraulic loading, pollutant loading, and vegetative species utilized. In sum, the literature on wetlands treatment contains much information on this new technology that should assist in the application of to a variety of wastewaters.

LITERATURE CITED

1. Ailstock, M.S. "Utilization and Treatment of Thermal Discharge by the Establishment of a Wetlands Nursery", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

2. Allen, H.H., G.J. Pierce, and R. Van Wormer, "Considerations and Techniques for Vegetation Establishment in Constructed Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

3. Allen, G.H., R.A. Gearheart and M. Higley, "Renewable Natural Resources Values Enhanced by Use of Treated Wastewaters within Arcata Treatment and Disposal System", unpublished, 1989.

4. Arnold, C.J., "The Arcata Marshes: A Case Study in Wetland Restoration", State Coastal Conservancy, 1330 Broadway, Suite 1100, Oakland, CA, 94612.

5. Barten, J.. "Stormwater Runoff Treatment in a Wetland Filter: Effects on the Water Quality of Clear Lake", Sixth Annual International Symposium, Lake and Reservoir Management: Influences on Nonpoint Source Pollutants and Acid Precipitation, November 5-8, Portland, Oregon, 1986.

6. Bastian, R.K., P.E. Shanaghan and B.P. Thompson, "Use of Wetlands for Municipal Wastewater Treatment and Disposal-Regulatory Issues and EPA Policies", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

7. Batal, W., L.S. Laudon, T.R. Wildeman and N. Mohdnoordin, "Bacteriological Tests from the Constructed Wetland of the Big Five Tunnel, Idaho Springs, Colorado", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

8. Bavor, H.J., D.J. Roser, P.J. Fisher and I.C. Smalls, "Performance of Solid-Matrix Wetland Systems, Viewed as Fixed-Film Bioreactors", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

9. Bayley, S., "The Effect of Natural Hydroperiod Fluctuations on Freshwater Wetlands Receiving Added Nutrients", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

10. Berry, D.F. and D.C. Martens, "Herbicide Degradation in Wetland Soils", Crop and Soil/Environmental Sciences Department, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, presented at the 1990 Virginia Water Resources Conference.

11. Bowmer, K.H., "Nutrient Removal from Effluents by an Artificial Wetland: Influence of Rhizosphere Aeration and Preferential Flow Studied Using Bromide and Dye Tracers", Water Resources, Vol. 21, No. 5.

12. Brennan, K.M., "Effects of Wastewater on Wetland Animal Communities", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

13. Brinson, M.M., "Management Potential for Nutrient Removal in Forested Wetlands", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

14. Brix, H., "Treatment of Wastewater in the Rhizosphere of Wetland Plants - The Root Zone Method", Water Science and Technology, Vol. 19, p. 179.

15. Brix, H., and Schierup, H.H., "Danish Experience with Sewage Treatment in Constructed Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

16. Brodie, G.A., "Selection and Evaluation of Sites for Constructed Wastewater Treatment Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

17. Brodie, G.A., "Constructed Wetlands for Ash Pond Seepage", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

18. Brodie, G.A., D.A. Hammer and D.A. Tomlijanovich, "Treatment of Acid Drainage with a Constructed Wetland at Tennessee Valley Authority 950 Coal Mine", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

19. Brodrick, S.J., P. Cullen and W. Maher, "Denitrification in Natural Wetland Receiving Secondary Treated Effluent", Water Resources, Vol. 22, No. 4, pp. 431-439, 1988, printed in Great Britain.

20. Brooks, J., "Sphagnum Peat Offers Solution to Maine's Challenging Soils", Small Flows, West Virginia University, Morgantown, WV, June 1989.

21. Burgoon, P.S., K.R. Reddy and T.A. DeBusk, "Domestic Wastewater Treatment Using Emergent Plants Cultured in Gravel and Plastic Substrates", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

22. Conway, T.E. and J.M. Murtha, "The Iselin Marsh Pond Meadow", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

23. Cooper, P.F., and J.A. Hobson, "Sewage Treatment by Reed Bed Systems: The Present Situation in the United Kingdom", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

24. Costello, C.J., "Wetlands Treatment of Dairy Animal Wastes in Irish Drumlin Landscape", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

25. Daukas, P., D. Lowry and W.W. Walker, Jr., "Design of Wet Detention Basins and Constructed Wetlands for Treatment of Stormwater Runoff from a Regional Shopping Mall in Massachusetts", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

26. Davido, R.L. and T.E. Conway, "Nitrification and Denitrification at the Iselin Marsh/Pond/Meadow", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

27. Day, J.W. and G.P. Kemp, "Long-term Impacts of Agricultural Runoff in a Louisiana Swamp Forest", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

28. Debusk, T.A., P.S. Burgoon, K.R. Reddy, "Secondary Treatment of Domestic Wastewater Using Floating and Emergent Macrophytes", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

29. Dill, C.H., "Wastewater Wetlands: User Friendly Mosquito Habitats", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

30. Dornbush, J.N., "Natural Renovation of Leachate-Degraded Groundwater in Excavated Ponds at a Refuse Landfill", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

31. Ewel, K.C., "Responses of Wetlands and Neighboring Ecosystems to Wastewater", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

32. Eger, P. and K. Lapakko, "Use of Wetlands to Remove Nickel and Copper from Mine Drainage", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

33. Faulkner, S.P. and C.J. Richardson, "Physical and Chemical Characteristics of Freshwater Wetland Soils", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

34. Feierabend, J.S., "Wetlands: The Lifeblood of Wildlife", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

35. Fennessy, S.M. and W.J. Mitsch, "Treating Coal Mine Drainage with an Artificial Wetland", Research Journal-Water Pollution Control Federation, Vol. 61, 11/12, Nov./Dec., 1989.

36. Finn, J.T., "Energy Flow in Wetlands", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

37. Friend, M., "Wildlife Health Implications of Sewage Disposal in Wetlands", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

38. Gearheart, R.A., et. al., "The Use of Wetland Treatment Processes in Water Reuse", Future of Water Reuse, Vol. 2, American Water Work Association Research Foundation, August, 1984.

39. Gearheart, R.A., F. Klopp and G. Allen, "Constructed Free Surface Wetlands to Treat and Receive Wastewater: Pilot Project to Full Scale", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

40. Gersberg, R.M., B.V. Elkins, S.R. Lyon and C.R. Goldman, "Role of Aquatic Plants in Wastewater Treatment by Artificial Wetlands", Water Research, Vol. 20, No. 3, P. 363.

41. Gersberg, R.M., R.A. Gearheart and M. Ives, "Pathogen Removal in Constructed Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

42. Gersberg, R.M., S.R. Lyon, R. Brennan and B.V. Elkins, "Integrated Wastewater Treatment Using Artificial Wetlands: A Gravel Marsh Case Study", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

43. Giblin, A.E., "Comparisons of the Processing of Elements by Ecosysytems, II: Metals", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985

44. Giggey, M.D., R.W. Crites and Karl A. Brantner, "Spray Irrigation of Treated Septage on Reed Canarygrass", Journal of the Water Pollution Control Federation, Vol. 61, No.3, p.333, 1989.

45. Girts, M.A. and R.L. Knight, "Operations Optimization", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

46. Goldstein, A.L., "Utilization of Wetlands as BMPs for the Reduction of Nitrogen and Phosphorous in Agricultural Runoff from South Florida Watersheds", Lake and Reservoir Management, Vol. II. Proceedings of the Fifth Annual Conference and International Symposium on Applied Lake & Watershed Management, Northern Lake Management Society, 1986, p. 345.

47. Gosselink, J.D. and L. Gosselink, "The Mississippi River Delta: A Natural Wastewater Treatment System", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

48. Grimes, D.J., "Microbiological Studies of Municipal Waste Release to Aquatic Environments", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

49. Grosse, W., "Thermoosmotic Air Transport in Aquatic Plants Affecting Growth Activities and Oxygen Diffusion to Wetland Soils", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

50. Guida, V.G. and I.J. Kugelman, "Experiments in Wastewater Polishing in Constructed Tidal Marshes: Does It Work? Are the Results Predictable?", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

51. Guntenspergen, G.R. and F. Stearns, "Ecological Perspectives on Wetland Systems", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

52. Guntenspergen, G.R., F. Stearns and J.A. Kadlec, "Wetland Vegetation", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

53. Haberl, R. and R. Perfler, "Root-Zone System: Mannersdorf--New Results", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

54. Hammer, D.A. and R.K. Bastian, "Wetlands Ecosystems: Natural Water Purifiers?", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

55. Hantzsche, N.N., "Wetland Systems for Wastewater Treatment: Engineering Applications", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

56. Hardy, J.W., "Land Treatment of Municipal Wastewater on Mississippi Sandhill Crane National Wildlife Refuge for Wetlands/Crane Habitat Enhancement: A Status Report", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

57. Harper, H.H. and M.P. Wanielista, "Design Considerations for Stormwater Treatment in a Hardwood Wetland", Sixth Annual International Symposium, Lake and Reservoir Management: Influences of Nonpoint Source Pollutants and Acid Precipitation, Nov. 5-8, 1986, Portland, Oregon, 1986.

58. Harper, H.H., M.P. Wanielista, D.M. Baker and B.M. Fries, "Treatment Efficiencies for Residential Stormwater Runoff in a Hardwood Wetland", Lake and Reservoir Management, Vol. II, Proceedings of the Fifth Annual Conference and International Symposium on Applied Lake & Watershed Management, North American Lake Management Society, 1986, p. 351.

59. Hedin, R.S., R. Hammack and D. Hyman, "Potential Importance of Sulfate Reduction Processes in Wetlands Constructed to Treat Mine Drainage", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

60. Hemond, H. and W. Nuttle, "Significance of Hydrology to Wetland Nutrient Processing", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

61. Henrot, J., R.K. Wieder, K.P. Heston and M.P. Nardi, "Wetland Treatment of Coal Mine Drainage: Controlled Studies of Iron Retention in Model Wetland Systems", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

62. Hicks, D.B. and Q.J. Stober, "Monitoring of Constructed Wetlands for Wastewater", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

63. Hobson, J.A., "Hydraulic Considerations and the Design of Reed Bed Treatment Systems", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

64. Hodson, R.E., A.E. Maccubbin, R. Benner and R.E. Murray, "Microbial Transformations of Detrital Carbon in Wetland Ecosystems: Effects of Environmental Stress", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

65. Hoffman, R.D., "Overview from Ducks Unlimited, Inc.", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

66. Howard, E.A., J.C. Emerick and T.R. Wildeman, "Design and Construction of a Research Site for Passive Mine Drainage Treatment in Idaho Springs, Colorado", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

67. Howard, E.A., M.C. Hestmark and T.D. Margulies, "Determining Feasibility of Using Forest Products or On-Site Materials in the Treatment of Acid Mine Drainage in Colorado", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

68. Hsieh, Y.P. and C.L. Coultas, "Nitrogen Removal from Freshwater Wetlands: Nitrification-Denitrification Coupling Potential", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

69. Jackson, J., "Man-Made Wetlands for Wastewater Treatment: Two Case Studies", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

70. Jackson, W.B., "Terrestrial Communities: from Mesic to Hydric", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

71. James, B.B. and R. Bogaert, "Wastewater Treatment/Disposal in a Combined Marsh and Forest System Provides for Wildlife Habitat and Recreational Use", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

72. Kaczynski, V.W. "Considerations for Wetland Treatment of Spent Geothermal Fluids", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

73. Kadlec, J.A., "Wetlands, Wastewater, and Wildlife", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

74. Kadlec, R.H., "Aging Phenomena in Wastewater Wetlands", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

75. Kadlec, R.H., "Decomposition in Wastewater Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

76. Kadlec, R.H. "Hydrologic Factors in Wetland Water Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

77. Kadlec, R.H., and D.E. Hammer, "Modifying Nutrient Behavior in Wetlands", Ecological Modeling, Vol. 40 pg. 37-66, Elsevier Science Publishers, Amsterdam, Netherlands. 1988.

78. Kelly, J.P. and M.A. Harwell, "Comparisons of the Processing of Elements by Ecosystems, I: Nutrients", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

79. Kingsley, J.B., J.J. Maddox and P.M. Giordano, "Aquatic Plant Culture for Waste Treatment and Resource Recovery", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

80. Kolbash, R.L. and T.L. Romanoski, "Windsor Coal Company Wetland: An Overview", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

81. Kumar, P. and R.J. Garde, "Potentials of Water Hyacinth for Sewage Treatment", Research Journal of the Water Pollution Control Federation, Vol. 6, No. 11/12, November/December 1989.

82. Lindau, C.W., R.D. DeLaune and G.L. Jones, "Fate of Added Nitrate and Ammonium Nitrogen Entering a Louisiana Gulf Coast Swamp Forest", Journal of the Water Pollution Control Federation, Vol. 60, No. 3, March 1988.

83. Linker, L.C., "Creation of Wetlands for the Improvement of Water Quality: A Proposal for the Joint Use of Highway Right-of-Way", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

84. Litchfield, D.K. and D.D. Schatz, "Constructed Wetlands for Wastewater Treatment at Amoco Oil Company's Mandan, North Dakota Refinery", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

85. Livingston, E.H., "Use of Wetlands for Urban Stormwater Management", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

86. Lombardo, P. and T. Neel, "'Natural' Processes and On-site Treatment Combined in Innovative Wastewater Plan", Public Works, p. 50, October 1986.

87. Lowe, E.F., D.L. Stites and L.E. Battoe, "Potential Role of Marsh Creation in Restoration of Hypertrophic Lakes", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

88. Maddox, J.J. and J.B. Kingsley, "Waste Treatment for Confined Swine with an Integrated Artificial Wetland and Aquaculture System", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

89. Martin, C.V. and B.F. Eldridge, "California's Experience with Mosquitoes in Aquatic Wastewater Treatment Systems", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

90. McKallip, C., J.S. Krolak and R.T. Kilgore, "Forecasting Pollutant Reduction of Combined Wet Pond and Non-Tidal Wetland", GKY and Associates, Inc. 5411-E Backlick Rd, Springfield, VA 22151; presented at the 1990 Virginia Water Resources Conference.

91. Meiorin, E.C., "Urban Runoff Treatment in a Fresh/Brackish Water Marsh in Fremont, California", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

92. Meyer, J.L., "A Detention Basin/Artificial Wetland Treatment System to Renovate Stormwater Runoff from Urban, Highway, and Industrial Areas", Wetlands, Vol. 5, pp 135-146, 1985.

93. Michaud, S.C. and C.J. Richardson, "Relative Radial Oxygen Loss in Five Wetland Plants", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

94. Miller, G., "Use of Artificial Cattail Marshes to Treat Sewage in Northern Ontario, Canada", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

95. Mingee, T.J. and R.W. Crites, "Constructed Wetlands for Secondary Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

96. Moorhead, K.K., K.R. Reddy and D.A. Gretz, "Nitrogen Transformations in a Water Hyacinth-based Water Treatment System", Journal of Environmental Quality, Vol. 17, No. 1, 1988.

97. Nichols, A.B., "A Vital Role for Wetlands", Journal of the Water Pollution Control Federation, Vol. 60, No. 7, p. 1215, 1988.

98. Nichols, D.S., "Capacity of Natural Wetlands to Remove Nutrients from Wastewater", Journal of the Water Pollution Control Federation, Vol. 55, No. 5, p. 495, 1983.

99. Odum, H.T. "Water Conservation and Wetland Values", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

100. Oron, G., A. de-Vegt and D. Porath, "Nitrogen Removal and Conversion by Duckweed Grown on Wastewater", Water Research, Vol. 22, No. 2, pp. 179-184, 1988.

101. Orth, H.M. and D.P. Sapkota, "Upgrading a Facultative Pond by Implanting Water Hyacinth", Water Research, Vol. 22, No. 12, pp 153-154, 1983.

102. Portier, R.J., "Evaluation of Specific Microbial Assays for Constructed Wetlands Wastewater Treatment Management", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

103. Portier, R.J. and S.J. Palmer, "Wetlands Microbiology: Form, Function, Processes", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

104. Reed, D.M. and T.J. Kubiak, "An Ecological Evaluation Procedure for Determining Wetland Suitability for Wastewater Treatment and Discharges", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

105. Reed, S.C. and R.K. Bastian, "Wetlands for Wastewater Treatment: An Engineering Perspective", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

106. Richardson, C.J., "Mechanisms Controlling Phosphorus Retention Capacity in Freshwater Wetlands", Science, Vol. 228, p. 1424, 1985.

107. Richardson, C.J. and D.S. Nichols, "Ecological Analysis of Wastewater Management Criteria in Wetland Ecosystems", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

108. Rusincovitch, F., "Use of Wetlands for Wastewater Treatment and Effluent Disposal: Institutional Constraints", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

109. Sather, J.H., "Ancillary Benefits of Wetlands Constructed Primarily for Wastewater Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

110. Scheuerman, G. Britton, and S.R. Farrah, "Fate of Microbial Indicators and Viruses in a Forested Wetland", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

111. Schwartz, A.L. and R.L. Knight, "Some Ancillary Benefits of a Natural Land Treatment System", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

112. Shiaris, M.P., "Public Health Implications of Sewage Applications on Wetlands: Microbial Aspects", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

113. Silver, M., "Biology and Chemistry of Generation, Prevention and Abatement of Acid Mine Drainage", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

114. Silverman, G.S., "Development of an Urban Runoff Treatment Wetlands in Fremont, California", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

115. Slayden, R.L., Jr. and L.N. Schwartz, "States' Activities, Attitudes and Policies Concerning Constructed Wetlands for Wastewater Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

116. Smardon, R.C., "Human Perception of Utilization of Wetlands for Waste Assimilation, or How Do You Make a Silk Purse Out of a Sow's Ear?", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

117. Smith, A.J., "Wastewaters: A Perspective", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

118. Snoddy, E.L., et.al., "Control of the Armyworm, *Simyra henrici* (Lepidoptera: Noctuidae), on Cattail Plantings in Acid Drainage Treatment Wetlands at Widows Creek Steam-Electric Plant", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

119. Staubitz, W.W. et.al., "Potential Use of Constructed Wetlands to Treat Landfill Leachate", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

120. Steiner, G.R. and R.J. Freeman, Jr., "Configuration and Substrate Design Considerations for Constructed Wetlands Wastewater Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

121. Stengel, E. and R. Schultz-Hock, "Denitrification in Artificial Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

122. Stevens, S.E., Jr., K. Dionis and L.R. Stark, "Manganese and Iron Encrustation on Green Algae Living in Acid Mine Drainage", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

123. Stowell, R. et.al., "Mosquito Considerations in the Design of Wetland Systems for the Treatment of Wastewater", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

124. Sutherland, J.C., "Wetland-Wastewater Economics", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

125. Suzuki, T., W.G.A. Nissanka and Y. Kurihara, "Amplification of Total Dry Matter, Nitrogen and Phosphorus Removal from Stands of *Phragmites australis* by Harveting and Reharvesting Regenerated Shoots", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

126. Tennessee Valley Authority, Wastewater Treatment by Constructed Wetlands, Water Quality Branch, Chattanooga, TN

127. Thut, R.N., "Utilization of Artificial Marshes for Treatment of Pulp Mill Effluents", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

128. Tomljanovich, D.A. and O. Perez, "Constructing the Wastewater Treatment Wetland - Some Factors to Consider", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

129. Trautmann, N.M., J.H. Martin, Jr., K.S. Porter and K.C. Hawk, Jr., "Use of Artificial Wetlands for Treatment of Municipal Solid Waste Landfill Leachate", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

130. U. S. Environmental Protection Agency, An Emerging Technology: Wetlands Treatment, September 1983.

131. U.S. Environmental Protection Agency, Office of Research and Development, Design Manual - Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment, EPA/625/1-88/022, 1988.

132. Valiela, I., et.al., "Some Long-term Consequences of Sewage Contamination in Salt-Marsh Ecosystems", Ecological Considerations In Wetlands Treatment of Municipal Wastewater, edited by P. J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

133. Vymazal, J., "Use of Periphyton for Nutrient Removal from Waters", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers Inc., Chelsea, Michigan, 48118, 1989.

134. Walters, D.H., "Cannon Beach, Oregon, Wetlands/Marsh", Case Study Series, EPA National Small Flows Clearinghouse, West Virginia University, Morgantown, WV, 1986.

135. Walters, D.H., "Iselin, Pennsylvania Marsh-Pond-Meadow Treatment Facility", Case Study Series, EPA National Small Flows Clearinghouse, West Virginia University, Morgantown, WV, 1986.

136. Watson, J.T., et.al., "Performance Expectations and Loading Rates for Constructed Wetlands", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

137. Watson J.T. and J.A. Hobson, "Hydraulic Design Considerations and Control Structures for Constructed Wetlands for Wastewater Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

138. Watson, J.T. G. Steiner and D. Hammer, "Kentucky Wetlands Project Benefits from Team Approach", Small Flows, West Virginia University, Morgantown, WV, June 1988.

139. Weidenbacher, W.D. and P.R. Willenbring, "Limiting Nutrient Flux into an Urban Lake by Natural Treatment and Diversion", Lake and Reservoir Management, U.S. EPA, 440/5/84-001, p. 525, 1984.

140. Wenerick, W.R., et.al., "Tolerance of Three Wetland Plant Species to Acid Mine Drainage: A Greenhouse Study", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

141. Whalen, J., "Constructed Wetlands: Design, Construction and Costs", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

142. Whigham, D.F., "Vegetation in Wetlands Receiving Sewage Effluent: The Importance of the Seed Bank", Ecological Considerations In Wetlands Treatment of Municipal Wastewaters, edited by Paul J. Godfrey, Edward R. Kaynor, Sheila Pelczarski and Jay Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

143. Wile, I., G. Miller and S. Black, "Design and Use of Artificial Wetlands", Ecological Considerations In Wetlands Treatment of Municipal Wastewaters, edited by Paul J. Godfrey, Edward R. Kaynor, Sheila Pelczarski and Jay Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

144. Wieder, R.K., G. Tchobanoglous and R.W. Tuttle, "Preliminary Considerations Regarding Constructed Wetlands for Wastewater Treatment", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

145. Wildeman and L.S. Laudon, "Use of Wetlands for Treatment of Environmental Problems in Mining: Non-Coal-Mining Applications", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

146. Wilhem, S.R. Lawry and D.D. Hardy, "Creation and Management of Wetlands Using Municipal Wastewater in Northern Arizona: A Status Report", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

147. Willenbring, P.R., "Wetland Treatment Systems - Why do Some Work Better than Others?", Lake and Reservoir Management - Practical Applications, Proceedings of the Fourth Annual Conference and International Symposium on Applied Lake and Watershed Management, North American Lake Management Society, p. 234, 1985.

148. Wolverton, B.C., "Aquatic Plant/Microbial Filters for Treating Septic Tank Effluent", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

149. Wolverton, B.C., "Artificial Marshes for Wastewater Treatment", reprint from: First Annual Environmental Health Symposium, Mobile, Ala, 1986.

150. Wood, A., and L.C. Hensman, "Research to Develop Engineering Guidelines for Implementation of Constructed Wetlands for Wastewater Treatment in Southern Africa", Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural, edited by Donald A. Hammer, Lewis Publishers, Inc. Chelsea, Michigan, 48118, 1989.

151. Zedler, J., "Wastewater Input to Coastal Wetlands: Management Concerns", Ecological Considerations In Wetlands Treatment of Municipal Wastewaters, edited by Paul J. Godfrey, Edward R. Kaynor, Sheila Pelczarski and Jay Benforado, Van Nostrand-Rheinhold Company, Inc., N.Y., N.Y., 10020, 1985.

152. Zirschky, J. and S.C. Reed, "The Use of Duckweed for Wastewater Treatment", Journal of the Water Pollution Control Federation, Vol. 60, No. 7, July 1988.

VITA

Gary Boyd Fillmore was born on 17 October, 1950 in Red Bank, New Jersey. He attended public elementary and high schools in Middletown, New Jersey. He completed an A.B. degree in Zoology from Rutgers University, New Brunswick, New Jersey in 1973.

After completing his undergraduate work at Rutgers, he earned a Certificate in Secondary Science Education at Keane College, Union, New Jersey in 1975. Since that time he has taken additional graduate studies at the University of Maine, Farmington Campus, Montclair University, Montclair, New Jersey and Rutgers University, New Brunswick, New Jersey.

In 1984, Mr Fillmore began course work for fulfilling the requirements for a Masters of Science in Environmental Engineering and Science at Virginia Polytechnic Institute and State University, Telstar Campus in Northern Virginia. He completed the degree requirements in March 1991.