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Project Summary

Design Principles for Wetland Treatment Systems

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Published data pertaining to the treatment of wastewater by wetland irrigation have been assembled and analyzed to begin identifying general principles for the successful design of wetland facilities. Sources of operating data have been tabulated. Performance is roughly correlated with overall system features, but cannot be predicted on the current basis. Existing compartmental models require more detailed information than does or will exist; thus a simplified compartment model is presented.

Water quality is controlled by rapid processes related to water movement, mass transport to other compartments, and consumption kinetics. Thus, wetland hydrology is fundamental to the analysis of water quality improvement. The ultimate fate of nutrients and contaminants is determined by sedimentation, biomass production and harvest, soil and microbial processes. Required wetland area depends on effluent quality, ecosystem type and age, and hydraulic regime. These questions can be addressed in terms of a mass transport model for the zone of rapid removal, and a "saturation" model for the expansion of a zone of stabilized activity about the discharge point. Material balances, considering only long-term consumption mechanisms for nutrients and other pollutants, determine the useful life and ultimate performance of a wetland system.

Operational techniques and the use of constructed wetlands are also considered. The economics of wetland treatment are discussed.

This Project Summary was developed by EPA's Robert S. Kerr Environmental Research Laboratory, Ada, OK, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The treatment of wastewater by overland flow through a wetland is a new concept. Only in the last decade has the performance of such systems become a topic of scientific study. Wastewater discharges to wetland areas are not a new practice, for a number of sites have been identified where discharge has been ongoing for more than half a century. New treatment systems are being established at natural wetlands and at wetlands specifically constructed for this purpose. Significant improvements in wastewater quality are generally observed, at a cost which is low when compared to other alternatives.

The purpose of this study is to identify data sources and to present certain design concepts and their application to wetland treatment.

The reliable design of a wetland treatment facility requires the development of performance equations which describe both the response of the ecosystem to wastewater additions and the alteration of water quality. These equations must be developed from the operating data of existing systems and from insight obtained from research studies conducted in the laboratory and at field sites. Since experience is somewhat limited, only the basic features of the wetland treatment process are susceptible to meaningful analysis. These include wetland hydrology and overland flow, removal rates for wastewater components, and the effects of nutrient additions on the continued ability of a wetland to treat wastewater.

When wastewater is discharged to the surface of a wetland it flows away, spreading into a dynamic mound about the discharge. The depth which will result depends upon the hydrological characteristics of the wetland and impounding structures, if any. Each wetland system has a hydraulic capacity, which may change rapidly in response to rain or other hydrological factors. Depth limits will be determined by the tolerance of wetland vegetation and by consideration of operating factors such as residence time. Depth and velocity will also affect the ability of the wetland to remove pollutants from the surface waters. Hydrology of the wetland site is therefore crucial to the understanding of the treatment processes which occur.

The rate at which pollutant removal occurs will determine the relationship between the wastewater inputs and the quality of the wetland effluent. These and other parameters, such as removal efficiency, are interrelated through a material balance about the surface waters. Therefore, the removal rate for each component must be determined. These rates can vary with factors such as water flow rate, depth, season, species composition within the wetland, type of soil substrate, and the age of the treatment facility.

Prediction of removal rates, over time, is a primary task in the analysis of a wetland treatment system design. Two approaches to this problem are possible: the correlation of operating data from existing systems; and the development of a conceptual model for the wetland treatment system.

We have therefore reviewed data from 26 sites, as listed in Table 1. Based on these, a model for the wetland treatment system is proposed and analyzed in terms of contributing processes.

Evaluation of a proposed system design must ultimately turn to economics. The available data on capital requirements and operating expenses were therefore collected and presented.

Table 1. *Site Summary List.*

Site	*Approximate Age, yr.*	*Annual Discharge 10^6 gal.*	*Data Base Size*	*Identifying Number In Figure 1*
Bellaire, MI	*12*	*30*	*Small*	*2*
Bradford, ONT	*1*	*0.5*	*Small*	-
Brillion, WI	*56*	*98*	*Medium*	*4*
Brookhaven, NY	*6*	*3*	*Small*	-
Clermont, FL	*4*	*4*	*Medium*	-
Cootes Paradise, ONT	*62*	-	*Small*	*10*
Drummond, WI	*3*	*15*	*Small*	-
Dulac, LA	*2*	*0.03*	*Small*	-
Gainesville, FL	*7*	*6*	*Large*	-
Great Meadows, MA	*68*	*1600*	*Medium*	*6*
Hamilton, NJ	*2*	*1.7*	*Small*	-
Hay River, NWT	*16*	*11*	*Small*	*1*
Houghton Lake, MI	*4*	*100*	*Large*	*3*
Humboldt, SASK	*2*	*10*	*Small*	-
Jasper, FL	*60*	-	-	-
Kesalahti, Finland	-	-	-	-
Kincheloe, MI	*25*	*150*	*Small*	-
Lake Balaton, Hungary	-	-	*Small*	-
Las Vegas, NV	*60*	*30,000*	*Medium*	-
Listowell, ONT	*2*	*15*	*Medium*	-
Mountain View Sanitary				*9*
District, CA	*7*	*255*	*Small*	-
Seymour, WI	*2*	*0.1*	*Small*	-
Suisun City, CA	*5*	*20*	*Medium*	-
Vermontville, MI	*2*	*25*	*Small*	*8*
Waldo, FL	*46*	*30*	*Small*	*7*
Wildwood, FL	*20*	*55*	*Small*	

Wetland Hydrology

The design or evaluation of wetland wastewater treatment systems requires a sound understanding of the marsh hydrology. Surface water flow rates, soil infiltration, and depth are of primary concern. Water depths and flow rates are usually determined by natural stream flows, overland flow, precipitation, and evapotranspiration. Introduction of wastewater irrigation may result in localized increases in water depths which in turn, combined with increased nutrients, may cause changes in the species composition of the plant and animal communities. Removal of nitrogen, phosphorus, and other pollutants is best accomplished by slow overland flow of surface waters in a thin sheet or by infiltration. Channelized flow, characterized by greater water depths and shorter residence times, tends to reduce the system's effectiveness for pollutant removal.

In order to properly assess the performance of a wetland, a complete water budget must be prepared. All points of influx and efflux must be identified and the flows estimated throughout the year. Similarly, precipitation and evapotranspiration must be quantified. This water budget combined with measurements of nutrient concentrations can provide a complete picture of the wetland treatment system performance.

Correlation of Operating Data

Data from several wetland AWT systems allow calculation of the gross average removal rates of phosphorus and nitrogen. While precise relations cannot be established using these data from diverse systems, a trend of increasing removal rate with increasing nutrient concentration is suggested. Plots of nutrient removal rate versus nutrient loading rates, as shown in Figure 1 for phosphorus, define the operating limits which are observed on existing systems, regardless of hydrology, cover type, or climatic considerations.

A Simplified Compartmental Model

Improved design techniques require consideration of individual phenomena and processes within the wetland. A larger body of reliable data is available on the function of wetland subsystems than on the performance of the wetland as a whole. Relatively simple models of significant ongoing processes make it possible to obtain further insight into the overall interactions between the wetland and applied wastewater. This procedure allows the synthesis of a conceptual model, which when represented in mathematical terms, can be used to evaluate a new design.

To facilitate the use of a model over long periods of time (e.g., 20 to 50 years) a simple, specialized structure is desirable, as described in Figure 2. All transfers between the surface waters and the stationary ecosystem are taken as the annual net accumulation in each compartment. In this way, cycling of nutrients and other materials on seasonal, or even shorter term, basis need not complicate the model.

Removal of dissolved nutrients from surface waters is controlled by a two-step

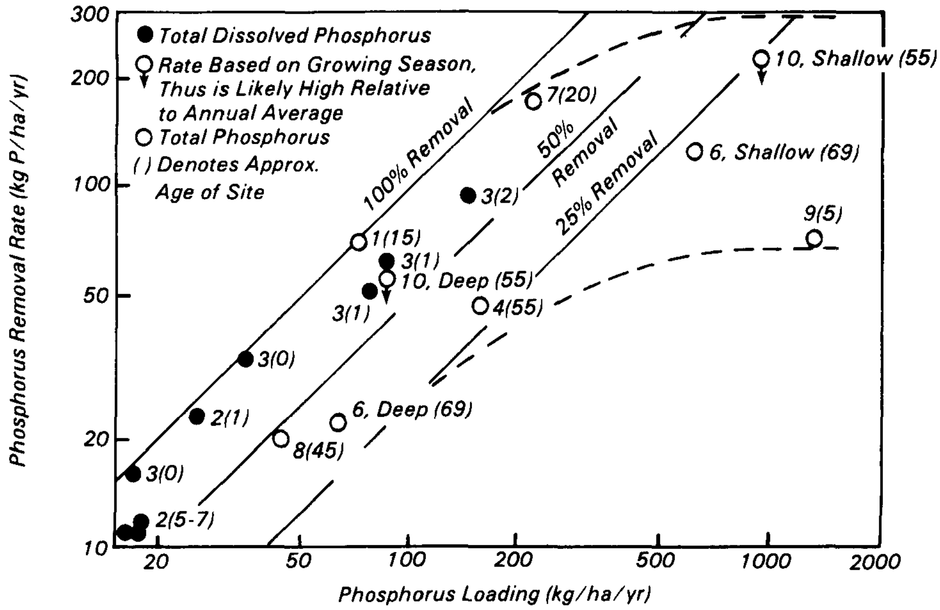

Figure 1. *Effect of phosphorus loading upon removal rate. (See Table 1 for site identification numbers.)*

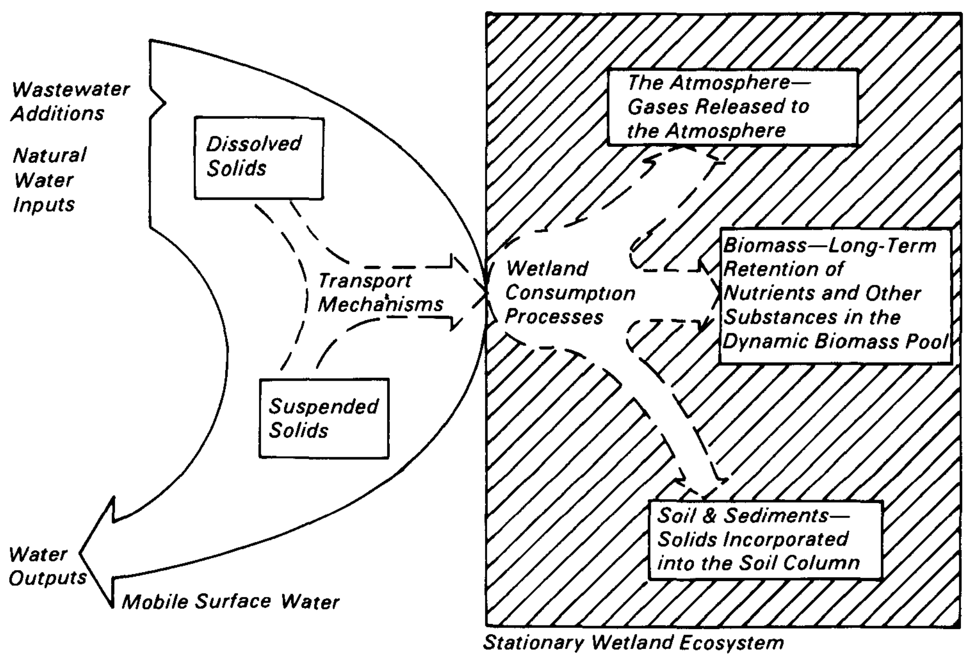

Figure 2. *Simplified compartmental model for use in wetland treatment system design.*

process. The process consists of delivery and consumption. Consumption occurs principally at the surfaces of the soil, litter, plant stems and algal mat. Delivery is accomplished by convective mass transfer within surface waters, overland flow, or by downward flow due to water infiltration. Consumption consists collectively of a number of processes which initially are relatively fast, but of which some slow considerably as wastewater treatment continues. Sorption will reach an equilibrium in the upper soil horizons reducing the average areal uptake rate. Similarly, biomass expansion, which offers a sink for nutrients, will also reach a saturation condition, where the release of nutrients due to litter decay offset any uptake in new growth. Woody biomass production allows longer immobilization of nutrients and constitutes a relatively permanent removal mechanism. Soil production also represents a long-term removal process but is quite slow. While data are extremely sparse, the same basic behavior can be anticipated for heavy metals as well as nutrients.

Two treatment regimes will exist in an older wetland system as shown in Figure 3. In the vicinity of the wastewater discharge a "saturated" region will exist. Here component removal rates will be quite slow, comprised of the uptake rates due to (1) sorption deep in the soil column, (2) incorporation of material into new soil and woody plants, and (3) microbial release of gases to the atmosphere. Outside this "saturated" region, surface water concentrations of wastewater components will drop exponentially with distance. In this latter zone of rapid removal, it is the transport of dissolved components through the surface waters which limits the overall rate. The amount of wetland area needed for this zone of fast removal will be determined by mass transfer considerations and for constant operating conditions (depth, velocity, etc.) will not change. The zone in the "saturated" regime will continue removal at a rate which is slower but insensitive to modest changes in water flow or depth. The expansion of this saturated region continues until the total affected area is sufficient to allow all incoming wastewater components to be removed by water infiltration, incorporation into new soil and woody biomass, or release to the atmosphere. If the actual wetland area is less than that required for total retention of pollutants, breakthrough will occur. In this case, only a portion of the wastewater components fed to the wetland will be retained and collection efficiency will drop sharply.

Harvesting plant biomass is a direct method of preventing saturation of the biomass compartment. Nitrogen, phosphorus and other wastewater components can be removed from the wetland system. Higher removal rates can be maintained indefinitely with limited area, using this technique.

To employ this conceptual model in the evaluation of wetland system designs, it must be cast in mathematical terms.

The Mass Transfer Zone

When wastewater is caused to flow over the surface of a wetland, nutrients and

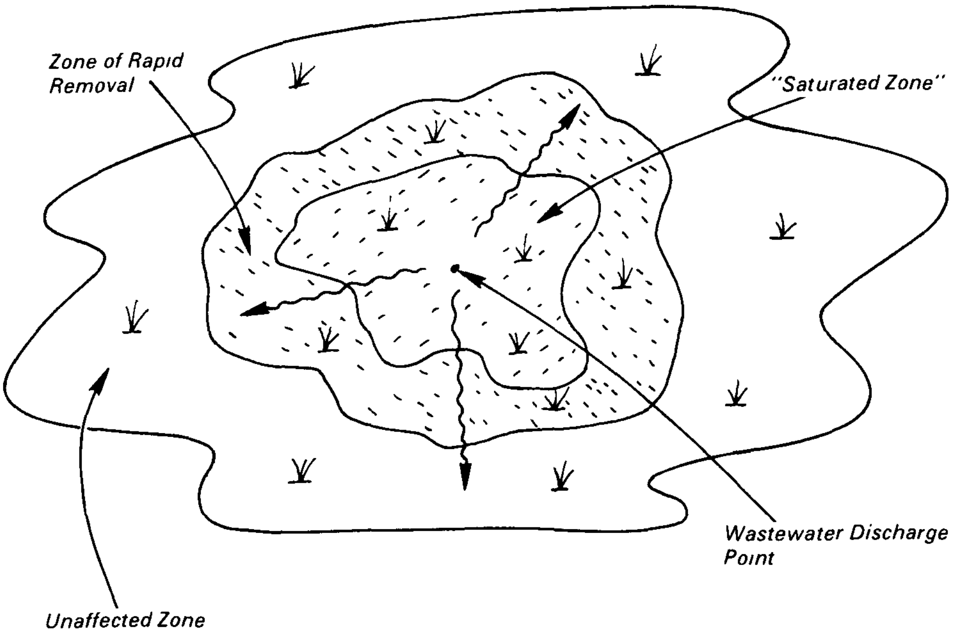

Figure 3. *Schematic of the zone of affected soil and biomass.*

other pollutants are removed, primarily by delivery to and consumption at solid surfaces. At the wetland surfaces, sorption and microbial processes may occur, as well as plant uptake. Algal and duckweed uptake may occur at the upper water surface. These processes require that each contaminant be transported to a bounding channel surface.

A typical relationship to describe this transport is:

$$N = kA\,(C_w - C_s)$$

where:

- N = contaminant transport rate, gm/day
- k = mass transfer coefficient, m/day
- A = area of surface, m^2
- C_w = contaminant concentration in water, gm/m^3
- C_s = contaminant concentration in water at channel surface, gm/m^3.

Such a rate expression must be coupled with mass balances for the contaminant and for the surface water to predict the distance or time for the removal of a dissolved substance.

The contaminant mass balance is, for a linear-flow wetland

$$v\phi_s h \frac{dC_w}{dx} = -k\phi(C_w - C_s) - iC_s + pC_p - eC_e$$

where:

- C_e = the contaminant concentration in evapotranspired water, gm/m^3
- C_p = the contaminant concentration in precipitation, gm/m^3
- ϕ = flow porosity across the wetland surface
- ϕ_s = storage porosity
- h = depth, m
- t = time, days
- x = distance, m
- v = actual velocity, m/d
- p = precipitation, m/d
- e = evapotranspiration, m/d
- i = infiltration, m/d

At some upstream point, x = 0, the concentration will be known. Presumably this is either the discharge point; or, if the area around the discharge is saturated, it will be the outer edge of the slow removal zone. For example, the zone of rapid removal should begin near the discharge line for denitrification (NO_3^- removal), since no saturation can occur. For an "older" facility, this rapid uptake zone for phosphorus would begin at a distance where saturation ends.

This model may be easily solved in a variety of special cases. It works well for those sites where transect data are available with which to validate it. The mass transfer parameter, k, and the depth-velocity relation are site specific.

The Loaded Zone

The addition of nutrients to a natural or newly constructed wetland will cause a zone of increased vegetative growth to appear. This zone will expand with time until either the permanent capacity of the zone equals the loading rate or the loaded zone reaches the boundaries of the wetland. The mathematical description of the advance of such a loaded zone for each substance of interest, such as phosphorus, consists of a mass balance on the zone and the rates at which the substance is taken up by the stationary ecosystem. These uptake rates fall in three general categories. The first of these is a permanent binding of the substance in question, or a gaseous loss to the atmosphere, such as denitrification. In these cases, a component is permanently removed from surface waters. A second general category consists of an increase in the adsorbed quantity of the substance, which is the physical or chemical binding of the substance to the soil substrate within the wetland. Such processes are known to occur for phosphorus and ammonia, for example. The third general category of nutrient consumption is storage in an expanding biomass compartment.

Other uptake/release processes also occur in the wetland ecosystem at rapid rates. An example of this is the uptake of phosphorus and nitrogen by algae. These algae grow during the summer months, die, and contribute a certain amount of algal litter to the sediment layers within the wetland. These algal sediments decompose and re-release the nitrogen and phosphorus that was incorporated in the biomass. This process is fairly rapid in the summer months, and if one considers only year-to-year variations in area, this process is too fast to be noticeable. There is little net effect of such rapid cycling. A second type of rapid cycling of nutrients is the uptake by vascular plants. With their senesence and death, the leaching of nitrogen, phosphorus and carbon from the biomass directly back to the water column occurs yearly. This cycle is also too fast to be considered in a framework that is geared to predicting the change of the affected area from year to year. Thus, in the model development which follows, only those processes which persist for a period greater than one growing season are considered as long-term consumers for nutrients. Put in another way, all quantities are expressed as rates, but these are averages over the period of one year or longer.

To make this model more tractable, it is assumed that sufficient residence time is provided so that all material can reach the plant and soil community. The zone of mass transfer limitation of the removal rate is neglected. This idealization results in a sharp line of demarcation between the loaded and unloaded zones. This is not entirely accurate since according to the principles of mass transfer a zone must be present in which nutrient levels within surface water are decreasing.

In terms of the possible sinks, the mass balance equation in words is:

addition rate = sorption rate + permanent removal rate + temporary binding rate + discharge rate.

A variety of ways of expressing these terms exists; one set of choices leads to the following mass balance for the expanding loaded zone:

$$QC_i = kyC_l \frac{dA}{dt} + (r_sC_s + r_A + r_wX_w + r_HX_H)A + X_L \int_0^t Fe^{-\alpha(t-\tau)} \frac{dA}{d\tau} d\tau$$

where:

- Q = average annual wastewater addition rate, m^3/yr [380,000]
- C_i = mass average concentration of contaminant or nutrient in influent wastewater, gm/m^3 [3.5]
- A = area, m^2
- t, τ = time, yr
- k = sorption equilibrium constant, $(gm/m^3)_s / (gm/m^3)_l$ [2.7]
- C_l = average contaminant concentration in surface water, gm/m^3 [1.8]
- y = average sorption depth, m [0.05]
- r_s = excess average annual soil accretion rate, m/yr [0]
- C_s = contaminant concentration in new soil, gm/m^3
- r_A = excess average annual rate of loss to atmosphere, $gm/m^2/yr$ [2.1]
- r_w = excess average annual woody stem accumulation rate, $gm/m^2/yr$ [0]
- X_w = fraction contaminant in woody stems
- r_H = average annual harvest rate, $gm/m^2/yr$ [0]
- X_H = fraction contaminant in harvested biomass
- F = average annual excess litter fall, $gm/m^2/yr$ [1600]
- α = average annual specific litter decay rate, yr^{-1} [0.15]
- X_L = fraction contaminant in remaining litter. [0.2]

The word excess used above means above background. System parameters were estimated for operation of the Houghton Lake treatment site. Utilizing the mass balance equation, the predicted nitrogen from progression was calculated. The observed system behavior and the prediction, based on the data given above, for the nitrogen front movement are shown in Figure 4. These data are from operational specifications and prior field research.

The expansion of the "saturated" zones about the discharge point have been found to be much as predicted by the material balance, considering only the principal mechanisms. The aging of the Houghton Lake site can so far be described by this model.

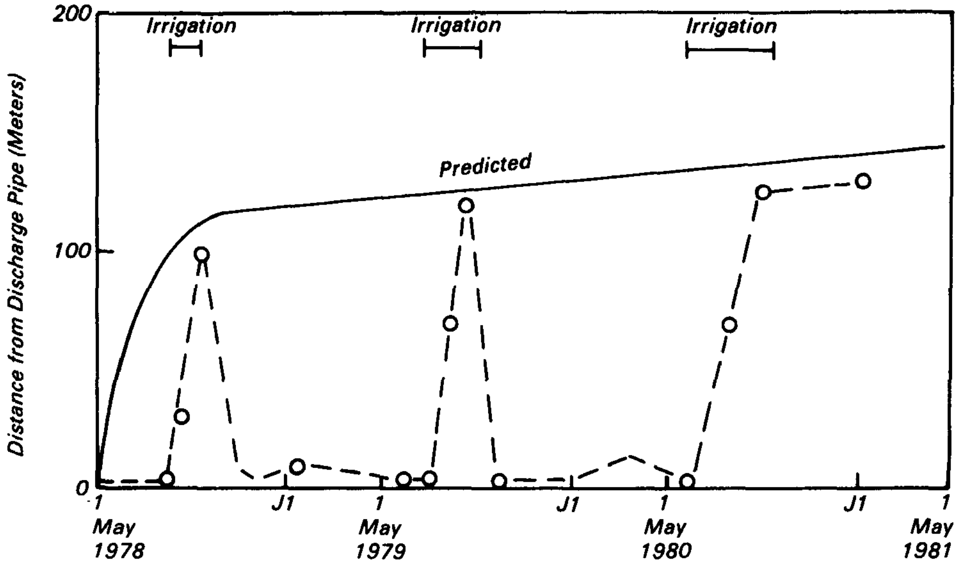

Figure 4. *Movement of nitrogen (NH_4^+-N) concentration fronts in surface waters, C=1 mg/l. Houghton Lake treatment site.*

Wetland System Design: Synthesis

The design process consists of two distinct phases, synthesis and analysis. Synthesis is the development of a plan for a wastewater treatment facility. Analysis is the evaluation of that plan and concludes by acceptance of the proposed design or rejection and another try at synthesis. There are no explicit equations for synthesis. Design parameters are chosen based upon past experience or educated guesses.

If a wetland treatment system is to be built in a natural wetland, the designer may have little freedom in synthesis. This phase may consist largely of site selection. Since one of the principal costs in wetland treatment is a wastewater delivery system (piping, pumps, etc.), proximity of the site is fundamental. Technical questions are not the only ones which the designer must address. Land ownership, political considerations, and public attitudes must be investigated. In the case of a natural wetland site, environmental impacts will be of particular concern. It is extremely important to maintain open channels of communication between the designers and the community, regulatory agencies and any other concerned parties.

With a natural wetland, the only construction needed is often a wastewater delivery line. Since wetlands tend to be at low elevations, delivery can sometimes be accomplished without a transfer pump, by gravity flow. Wastewater can be effectively applied to the wetland by a number of schemes. If flows are small (less than about 100,000 gallons per day) water can be discharged from several nozzles or even at a single point. Larger flows can be better accommodated by a linear discharge. This can be conveniently obtained by using gated irrigation pipe. The choice of material for distribution lines is generally aluminum irrigation pipe or plastic pipe. At northern sites, provision for draining the lines in winter should be included to prevent damage by ice. In some cases, these lines can be run directly on the surface of the wetland soil; however, provision should be made to prevent the pipe from sinking into the peat under its weight when filled. The distribution piping has been successfully supported by logs or an elevated platform, which also serve as a convenient walkway.

Placement of pipe, platforms and other material in the wetland can pose a problem. In northern climes, this is often best accomplished when ice cover has formed. Heavy equipment can be used with minimal residual damage to the vegetation.

The construction of artificial marshes for wastewater treatment theoretically provides a number of technical advantages. Control can easily be maintained over water levels and flow rates. The soil plants and other component parts included in the system can be selected for their ability to treat wastewater. Treatment cells can be shaped like ditches or large basins, which can be lined to assure a bottom seal. The wetland can be built in a configuration which permits easy harvesting of biomass. Cells can be operated in batch-mode, offering reliable control on the quality of effluent. The constructed wetland can be located conveniently.

The political advantages may be even greater than these technical advantages. While objections are sometimes raised to wetland treatment sites utilizing natural marshes, the constructed wetland concept circumvents much of the controversy. In many aspects, the constructed wetland is akin to a piece of processing equipment at the municipal treatment plant.

Operation of a wetland treatment facility generally involves establishment of a discharge schedule and monitoring activities. In certain cases, biomass harvesting may also be considered. The discharge schedule in northern climates is usually seasonal. Wastewater is held in ponds during the winter and discharged only during the warm months, when plants, algae, and microorganisms are most active.

Economics

The economics of wetland treatment are attractive in those situations where a suitable land parcel exists adjacent to the community. This appears to be true whether or not an existing wetland eliminates some construction costs.

The basis for an estimate must contain the following key items:

1. Total acreage to be obtained, for both irrigation and isolation.
2. Flows, both annual average and irrigation season actual.
3. Distance to the wetland from the treatment site.
4. Length of distribution pipe required within the wetland.
5. Pumping requirements, if any, expressed in terms of static, friction and site discharge heads.
6. Disinfection requirements.
7. Harvesting requirements.
8. Grading, ditching and diking requirements.
9. Plant community establishment.
10. Wetland discharge collection system.

The first seven items are common to all systems; the last three pertain only to constructed wetlands.

This type of analysis shows the major contributions to capital costs for an existing wetland to be pumps and piping, land and land access, and disinfection. Site alteration must be added for a constructed wetland. The major contributions to operating and maintenance expense are manpower, pumping energy, and monitoring costs.

Capital costs, estimated and actual, are shown in Figure 5. The estimates are those of Sutherland (1978). The data are lower than these estimates for four cases and higher for two cases.

Operation and maintenance (O & M) costs are shown in Figure 6, with Sutherland's (1978) estimates as a referent. Data are sparse, and difficult to determine accurately, but actual systems are cheap to run by any standard. They require little attention, essentially no chemicals, and have simple equipment.

Capital recovery costs and O & M costs combine to yield a cost for advanced secondary treatment for a gallon of wastewater. Figure 7 gives Fritz and Helle's (1978) estimates for cypress strands for 200,000 gpd facilities. Sutherland's estimates for comparable size facilities are included, using a capital recovery factor of 0.1. Data are in reasonable agreement with their estimates. Thus, from a cost viewpoint, wetland treatment looks attractive for small communities with appropriate land/wetland availability.

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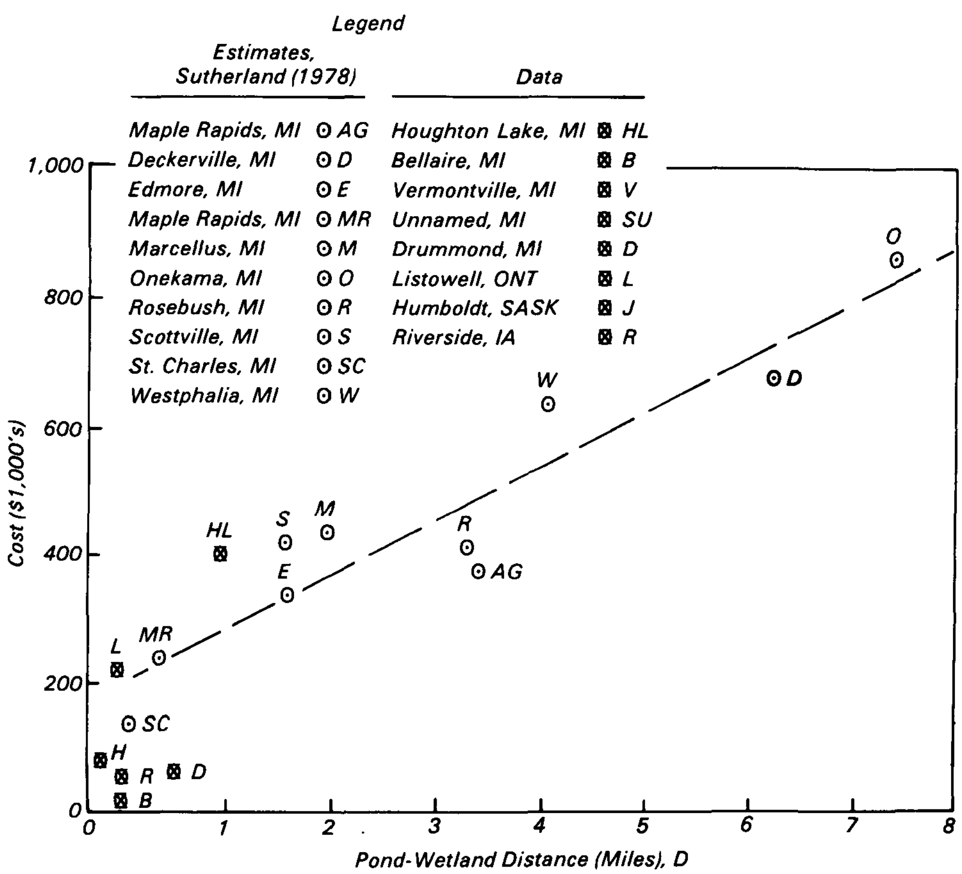

Figure 5. *Wetland capital costs versus wetland distance from pond (adapted from Sutherland, 1978). (See Table 1 for site symbol identification.) Pipeline costs predominate.*

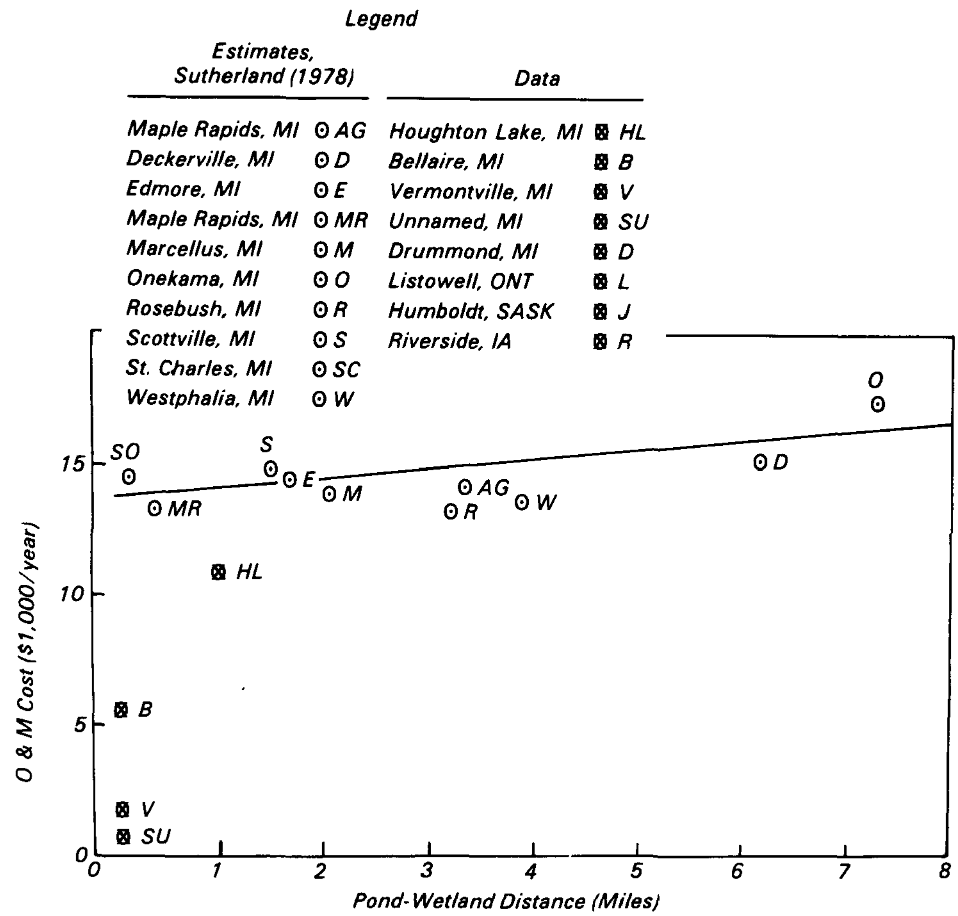

Figure 6. Wetland O & M costs versus wetland distance (adapted from Sutherland, 1978) (See Table 1 for symbol identification.) Line is for Sutherland estimates.

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The complete report, entitled "Design Principles for Wetland Treatment Systems," (Order No. PB 83-188 722; Cost: $22.00, subject to change) will be available only from:

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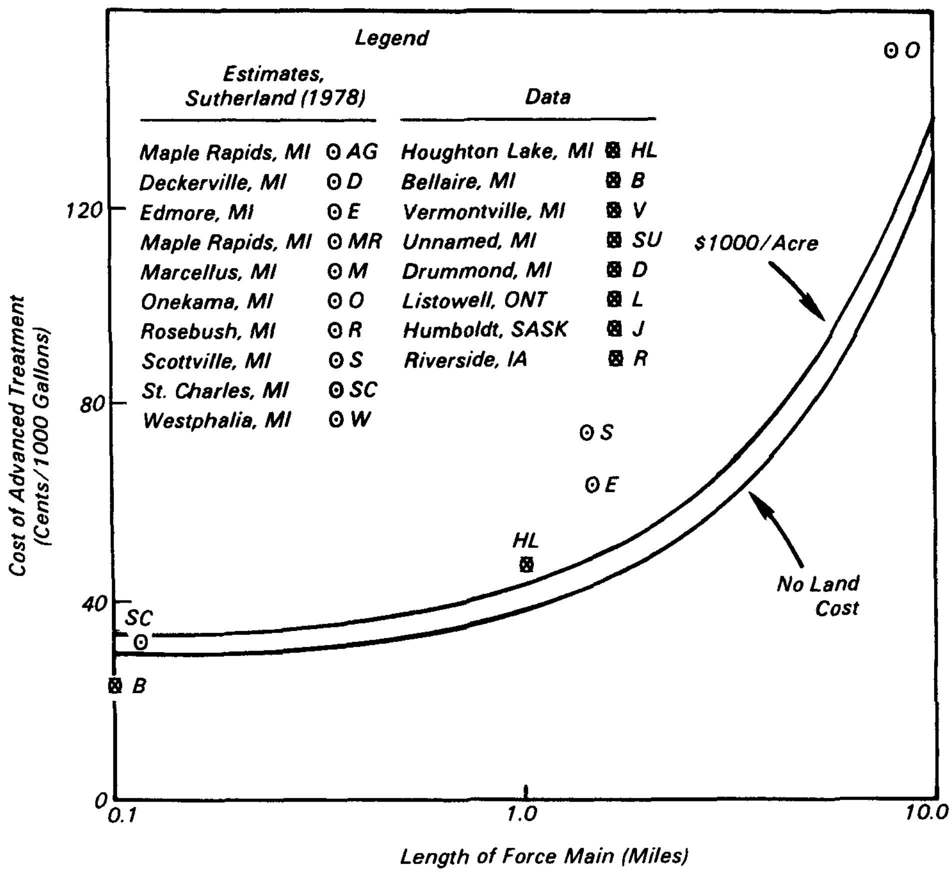

Figure 7. *Incremental cost estimate for advanced secondary wetland treatment (adapted from Fritz & Helle, 1978). Curves based on 0.2 Mgd. No land cost for $1000/acre. (See Table 1 for symbol identification.)*