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USING FRESHWATER WETLANDS FOR WASTEWATER MANAGEMENT IN NORTH AMERICA

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ABSTRACT

The potential for using freshwater wetlands for wastewater management has received much attention in North America during recent years. Experimental studies have been conducted in several types of wetlands, mostly in the central and eastern United States. Several types of natural and artificial wetlands can be used for short-term treatment of wastewater, but the long-term effects are unknown for most types of wetlands. Only peat-based systems appear to be capable of long-term efficient processing of domestic wastewater, although the use of artificial pond-wetland systems appears to have the most potential and should be considered as an alternative to using natural wetlands. Other types of freshwater wetlands have limited ability to remove nutrients from wastewater. Because there is much variation between wetlands that have been studied, it appears that each situation is unique and must be considered individually with pilot studies being conducted before any wetland is used for wastewater processing.

INTRODUCTION

Since publication of the proceedings from a conference on biological control of water pollution (Tourbier and Pierson 1976), there have been several meetings during which the topic of using freshwater wetlands for treating wastewater, primarily domestic sewage, has been considered (Tilton *et al.* 1976, Am. Soc. Civil Eng. 1978). As a result, there are several review papers (Sloey *et al.* 1978, Kadlec 1980, Whigham and Bayley 1980, van der Valk *et al.* 1980) as well as several papers that have reported results of experiments on the ability of specific artificial and natural freshwater wetlands to assimilate wastewater (Tilton and Kadlec 1979, Whigham *et al.* 1980, Ewel and Odum 1978, Fetter *et al.* 1978, Boyt *et al.* 1977). Large-scale experimental wastewater projects have been conducted in Florida (Odum and Ewel 1978) and Michigan (Kadlec 1975, Tilton *et al.* 1976). While other projects, more modest in scale, have been conducted in Florida (Zoltek *et al.* 1979), New Jersey (Whigham *et al.* 1980), Minnesota (Stanlick 1976), Wisconsin (Spangler *et al.* 1976), and New York (Small 1976, Woodwell 1977, Woodwell *et al.* 1974). Several other freshwater wetlands have been used to treat wastewater even though they were not initially designed as part of experimental studies (Kadlec 1980, Boyt *et al.* 1977, Grant and Patrick 1970). One question that needs to be asked at this point is whether or not any general conclusions have been reached from these studies. The purpose of this paper is not to provide a review of each of the sudies that have been conducted but to present a framework by which past experiences can be used to evaluate some general questions about whether or not natural or artificial wetlands can be used as design components in systems that are used for secondary and tertiary treatment of wastewater.

PREVIOUS STUDIES

Studies of wastewater additions to natural peat-based wetlands in Michigan (Tilton and Kadlec 1979, Kadlec 1980) and Florida (Zoltek *et al.* 1979) as well as Cypress wetlands in Florida (Odum and Ewel 1978, Nessel 1978) have shown that those types of of ecosystems can efficiently process wastewater. Artificial wetlands in Wisconsin (Spangler *et al.* 1976), peat-based systems in Minnesota (Stanlick 1976), combined marsh-pond systems in California (Jokela and Jokela 1978) and New York (Small 1976, Woodwell 1977, Wolverton *et al.* 1976), and wetlands developed on dredge spoil material (Lee *et al.* 1975 and 1976) have been studied. All of these systems, with the exception of the gravel-based wetlands, appear to be able to process wastewater and the marsh-pond systems constructed in New York were shown to be particularly efficient at removing nutrients from wastewater.

Many of the artificial systems were based on earlier work of Seidel and coworkers in Europe (Czerwanda and Seidel 1965, Seidel 1976) which has resulted in the use of man-made wetlands to treat wastes in Holland, Hungary, Poland, and Yugoslavia. A commercial version of the systems used by Seidel was patented in the United States (Wagner 1974).

FACTORS DETERMINING USE OF WETLANDS

The most important primary factors that determine whether wetlands can be used as part of large-scale operations (e.g., more than a million gallons of wastewater per day), as part of small-scale operations (less than 1 million gallons per day), or not used at all, are:

a. hydrologic characteristics, especially the turnover rate of water (*i.e.*, the contact time)
b. type of substrate and ability of macrophytes to utilize nutrients applied in wastewater, and
c. seasonality.

Hydrologic characteristics are poorly understood for most types of wetlands (Greeson *et al.* 1980) yet are undoubtedly very important. In situations where water moves quickly through the wetland, one can expect minimal uptake of nutrients (Tilton and Kadlec 1979, Whigham *et al.* 1980) compared to situations where water would have a long residence time (Zoltek *et al.* 1979, Ewel and Odum 1978). As has been noted by van der Valk *et al.* (1980) and Tilton and Kadlec (1979), there are well-defined channels in many types of wetlands and the water is carried through the wetland with very little contact with the wetland surface. This situation would be particularly common in palustrine systems. On the other hand, peat-based systems seem to be quite appropriate because water usually has a long residence time in the substrate which increases the chances for sorption or assimilation (Tilton and Kadlec 1979, Zoltek *et al.* 1979). Even if the emergent plants did not efficiently remove nutrients, their presence would cause a decline in water velocity and would enhance the possibilities for sediment flocculation, and sorption in the litter and substrate (Boto and Patrick 1980). In all instances where efficient nutrient removal has occurred, influent water had a long residence time in the system.

One advantage of man-made wetlands would be the potential to control hydrologic characteristics. For example, in temperate latitudes where there is a strong pulse of nutrient uptake during the growing season and release usually associated with decomposition in the fall (Simpson *et al.* 1978) or losses during the spring thaw (Sloey *et al.* 1978), water could be processed during the assimilation period and the wetland could be treated as an open system while during the release period water could be retained or released at a much slower rate (Sloey *et al.* 1978).

Substrate conditions appear to be important in determining the capability of specific wetlands to efficiently treat wastewater (Whigham and Bayley 1980) although much more information is needed. Almost all types of wetlands appear to be able to process nutrients for some part of the year (van der Valk *et al.* 1980). For nitrogen, denitrification appears to be very important and may account for the notion that many wetlands may have an infinite capacity to process nitrogen (Patrick and Reddy 1976). For phosphorus, the patterns are not as clear. Tilton and Kadlec (1979), Zoltek *et al.* (1979), and Ewel and Odum (1978) found efficient phosphorus removal in the peat-based systems that they studied. Some of the phosphorus was accounted for by increased phosphorus uptake in the vegetation (Ewel and Odum 1978), with the remainder having been sorbed or otherwise immobilized in the substrate. It has been analytically very difficult to account for all phosphorus that was added and several authors did not find significant increases in substrate phosphorus. In nonpeat-based wetlands (Spangler *et al.* 1976, Fetter *et al.* 1978, Simpson *et al.* 1978), phosphorus may be retained seasonally, but there appears to be little long-term substrate storage and most display strong seasonal release patterns.

In nonpeat-based wetlands, immobilization appears to occur primarily in the litter zone (Whigham *et al.* 1980), although several authors (Klopatek 1978, Prentki *et al.* 1978, Kitchens *et al.* 1975) have suggested that macrophytes are very important. Consequently, it has been suggested that harvesting of macrophytes would increase the nutrient assimilation capacity of wetlands. It appears, however, that only a small amount of N and P could be removed by harvesting emergent (Spangler *et al.* 1976, Zoltek *et al.* 1979) or submerged (McNabb 1976) vegetation. The best possibilities for using wetland plants for nutrient removal appear to occur in situations where the nutrients are stored in woody plants (Ewel and Odum 1978).

Seasonal patterns of nutrient immobilization in wetlands must be considered. Wetlands in subtropical areas may be capable of processing wastewater throughout the year (Zoltek *et al.* 1979, Boyt *et al.* 1977, Odum and Ewel 1978). In areas where the wetland surface freezes, it is only possible to use wetlands during the summer months (Spangler *et al.* 1976). It should be noted, however, that eutrophication problems are not as bad during the winter months, and Kadlec (1980) listed one Michigan site as being operational for the entire year even though winters are severe in that part of the country.

DESIRABILITY OF TREATMENT BY WETLANDS

Other scientists have recommended against the widespread use of freshwater wetlands for wastewater management. Some wetlands may be capable of wastewater polishing but cannot be used for cost-effective treatment of large quantities of wastewater. These recommendations have been based on results of experimentation with wastewater addition to freshwater tidal wetlands in New Jersey (Whigham *et al.* 1980) and gravel-based artificial systems in Wisconsin (Spangler *et al.* 1978). Studies of nutrient dynamics in various types of wetlands (e.g., Correll *et al.* 1975), or a concern about the expanded use of wetlands for those purposes when much more information is needed about functional processes in wetlands has also led some authors to suggest that wetlands should not be used for wastewater management (van der Valk *et al.* 1980, Greeson *et al.* 1980).

LONG-TERM CONSEQUENCES OF WASTEWATER ADDITIONS

Most of the research projects that have been cited, were conducted for relatively short periods of time. We still do not know how long particular wetlands can be used to process wastewater before their efficiency declines. Table 1 lists data reported in

TABLE 1. *Typical results of wetland tertiary treatment in freshwater wetlands* (Age, geography, and physical characteristics are all variable; percentage removals are based on concentration.) [from Kadlec 1980, except for the last 3 entries]

Site	Loading People/ Acre	Age Year	BOD	Nitrogen NO_3^-	NH_4^+	TN	Phosphorus Total	Suspended Solids	Coliforms Fecal	Total
Houghton Lake, Michigan	3	1	..	40	99	..	97**	..	..	..
Bellaire, Michigan	11	2				91*	97**			
Mt. View, California	1600	4	—19	54	39	..	3	—250	..	..
Hay River, N.W.T.	40	5	98	..	96	..	98	97	..	99
Wildwood, Florida	5	20	..	99	99	90	98	..	99	..
Kincheloe, Michigan	15	20	..	99	98	..	..	..	..	..
Brillion, Wisconsin	7	55	80	51	..	..	13	29	..	86
Dundas, Ontario	..	59	80	83	96	88	87,98**	—47	66	—14
Great Meadows, Massachusetts	..	69	89	33	98	..	89	12	66	—1285
Gainesville, Florida Ewel and Odum (1978)	..	..	..	..	..	..	88	..	..	..
Clermont, Florida Zoltek *et al.* (1979)	..	..	..	98.5	88	43***	..	..	..	..
Oshkash, Wisconsin Spangler *et al.* (1978)	..	..	91—97	..	..	..	75	..	..	..

* Total dissolved nitrogen
** Total dissolved phosphorus
*** Includes organic matter

Kadlec 1980, Zoltek *et al.* 1979, and Ewel and Odum 1978. The data clearly show that some areas have been able to process wastewater for long periods. It should be noted, however, that in only one instance (Mt. View, California), was the loading rate very high and the efficiency of that system for removal of BOD, NO_3^-, NH_4^+, P and suspended solids was very low or nonexistent. It is not known whether the loading rate is simply too large or whether the wetland capacity has already been exceeded.

Other long-term issues must be considered. Tilton and Kadlec (1979) suggested that long-term application of wastewater to peat wetlands would likely result in the replacement of bog species by other plants, especially cattail, that are more common in nutrient rich environments. There are, however, few data to support this hypothesis. Whigham *et al.* (1980) found that the freshwater tidal wetlands that they were studying, underwent dramatic species shifts during the first year of application of chlorinated secondarily treated wastewater. Those effects might be alleviated by varying the contact time, but it is also interesting to note how vegetation can respond to stress situations.

Figure 1 shows seasonal trends of biomass, nitrogen (Total N), and phosphorus (Total P) for one site for two years of their study. Site 2 received wastewater for two daily

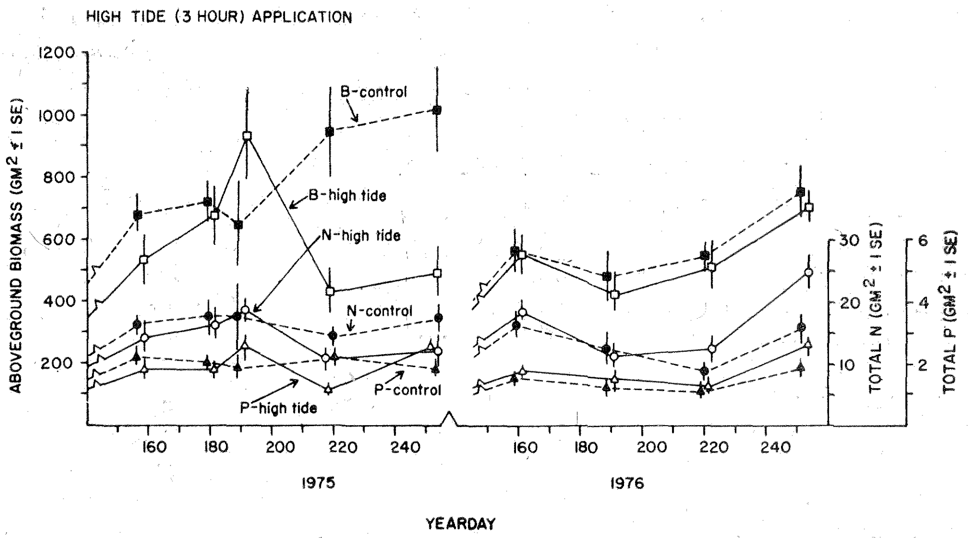

FIG. 1. Seasonal patterns of standing crop biomass, Total N, and Total P for Site 2 which received 12.5 cm of wastewater daily during two 3-hour spray periods (Whigham *et al.* 1980). Data for control Site 8 are shown for comparison. All values are means ± 1 standard error of the mean.

periods of three hours of application at a rate of approximately 12.5 cm per day. There was a sharp decline in all three variables by the fourth sampling date. This response was due to elimination of almost all annuals (Whigham *et al.* 1980) which are very highly productive (Whigham *et al.* 1978). Biomass and Total N remained low throughout the first growing season. In 1976, the dramatic early season decline in the three variables did not occur. Although the annuals were still absent or uncommon, biomass and standing stocks of N and P remained high because the perennials did not experience the mid-summer die-back that normally occurs in those wetlands (Whigham *el al.* 1978). There were distinct species shifts during their study, yet the entire system responded to ameliorate those shifts. This leads to the question of whether or not shifts in species composition affect any important functional processes.

Zoltek *et al.* (1979) also found short-term changes in vegetation in the Florida wetland that they studied. Shrub species, *Hibiscus*, had very high growth rates during a dry year while floating species (e.g., *Lemna*) were abundant during wet years. They suggested that the changes may, in fact, be beneficial because it permits the wetland to respond to variations in hydrologic as well as nutrient loading rates. Odum and Ewel (1978) found floristic changes in Cypress stands following wastewater addition, but the long-term effects are unknown.

Few data exist on the fate of heavy metals, toxic chemicals, and pathogenic organisms in freshwater wetlands (Kadlec 1980), although (Valiela *et al.* (1974, 1976), and Banus *et al.* (1935) have performed extensive experimentation in salt marshes and have found very few negative effects as a result of long-term addition of sludge.

What kind of changes occur in wetland substrates after long-term application of wastewater? Odum and Ewel (1978) found significant differences in substrate composition in Florida Cypress domes while other wetlands (Kadlec 1980) appear to be able to assimilate wastewater for long periods of time without any significant changes in the substrate. Kadlec reported, however, one instance where the substrate have changed and resembled sewage sludge. Whigham and Simpson (unpublished data) found similar results in the freshwater tidal wetland that they studied. Zoltek *et al.* (1979) have suggested that substrate, as well as other ecosystem components, changes can be minimized by using rest periods between wastewater additions.

COST-BENEFIT ANALYSIS

The most detailed cost-benefit analyses have been performed by Odum and his his colleagues at the University of Florida (Ewel and Odum 1978). As an example, they calculated that 1,000 gallons of wastewater can be treated for $0.42 compared to $1.07 for advanced wastewater treatment and $0.63 for upland spray irrigation (1978 dollars). Their work has resulted in consideration being given to widespread use of Florida wetlands in situations where the amount of wastewater to be treated is not excessive. Similar planning is being considered in Michigan where peat-based wetlands may be used to treat wastewater from small municipalities. It does not appear that wetlands can be used to process wastewater from large cities, although wastewater polishing may be possible (Whigham *et al.* 1980). It may also be possible to use wetlands to treat non-human wastes. Turner *et al.* (1976) have, for example, shown that it would be economically feasible to use wetlands to polish wastes from menhaden processing plants in Louisiana.

REFERENCES

American Society of Civil Engineers. 1978. *Coastal Zone* 78. Symposium on Technical, Environmental, Socioeconomic, and Regulatory Aspects of Coastal Zone Management. Vols. I-IV. New York. 3091 p.

Banus, M., I. Valiela, and J. M. Teal. 1975. Lead, zinc, and cadmium budgets in experimentally enriched ecosystems. *Est. Coastal Mar. Sci.* **3** : 421-430.

Boto, K. G., and W. H. Patrick, Jr. 1980. Role of wtelands in the removal of suspended sediments. p. 479-489, *In* : P. E. Greeson, J. R. Clark and J. E. Clark (Eds.). *Wetlands Functions and Values. The State of Our Understanding.* American Water Resources Assoc., Minneapolis, Minn.

Boyt, F. L., S. E. Bayley, and J. Zoltek, Jr. 1977. Removal of nutrients from treated municipal wastewater by wetland vegetation. *J. Water Pollut. Control Fed.* **49** : 789-799.

Correll, D. L., M. A. Faust, and D. J. Severn. 1975. Phosphorus flux and cycling in estuaries. p. 108-136, *In* : L. E. Cronin (Ed.). *Estuarine Research*, Vol. 1, Academic Press, New York.

Czerwanda, W., and K. Seidel. 1965. New methods of groundwater enrichment in Krefeld. *Das Gas un Wasserfach.* **106** : 828-833.

Ewel, K. C., and H. T. Odum. 1978. Cypress swamps for nutrient removal and wastewater recycling. *In* : W. P. Wanielista and W. W. Eckenfelder (Eds.). *Advances in Waste and Wastewater Treatment* : *Biological Nutrient Removal.* Ann Arbor Science Publishers, Inc., Ann. Arbor.

Fetter, W. C., Jr., W. E. Sloey, and F. L. Spangler. 1978. Biogeochemical studies of a polluted Wisconsin marsh. *J. Water Pollut. Control Fed.* **50** : 290-307.

Grant, R. R., and R. Patrick. 1970. Tinicum Marsh as a water purifier. p. 105-131, *In* : J. McCormick, R. R. Grant, Jr., and R. Patrick (Eds.). *Two studies of Tinicum Marsh, Delaware and Philadelphia Counties, Pa.* The Conservation Foundation, Washington.

Greeson, P. E., J. R. Clark, and J. E. Clark. 1979. *Wetland Functions and Values* : *The State of Our Understanding.* Proceedings of the National Symposium on Wetlands. American Water Resources Association. Minneapolis. 674 p.

Jokela, A. T., and A. W. Jokela. 1978. Water reclamation, aquaculture, and wetland management. p. 2176-2188, *In* : *Coastal Zone* 78. Vol. III. American Society of Civil Engineers. New York.

Kadlec, J. A. 1975. The effects of sewage effluent on wetland ecosystems. Report No. 4. Wetlands Ecosystem Research Group. University of Michigan. Ann Arbor.

Kadlec, R. H. 1980. Wetlands for tertiary treatment. p. 490-504, *In* : P. E. Greeson, J. R. Clark and J. E. Clark (Eds.,) *Wetland Functions and Values. The State of Our Understanding.* American Water Resources Association, Minneapolis.

KITCHENS, W. M., JR., J. M. DEAN, L. H. STEVENSON, AND J. M. COOPER. 1975. The Santee Swamp as a nutrient sink. p. 349-366, *In* : F. G. HOWELL, J. B. GENTRY, AND M. H. SMITH (Eds.). *Mineral Cycling in Southeastern Ecosystems.* ERDA Symposiums Series CONF. 740513.

KLOPATEK, J. M. 1978. Nutrient dynamics of freshwater riverine marshes and the role of emergency macrophytes. p. 195-216, *In* : R. E. GOOD, D. F. WHIGHAM AND R. L. SIMPSON (Eds.). *Freshwater Wetlands : Ecological Processes and Management Potential.* Academic Press, New York.

LEE, G. F., E. BENTLEY, AND R. AMUNDSON. 1975. Effects of marshes on water quality. p. 105-127, *In* : A. D. HASLER (Ed.). *Coupling of Land and Water Systems.* Springer-Verlag, New York.

LEE, C. R., R. E. HOEPPEL, R. G. JUNT, AND C. A. CARLSON. 1976. Feasibility of the functional use of vegetation to filter, dewater, and remove contaminants from dredged material. Environmental Effects Laboratory. U. S. Army Engineer Waterways Experiment Stations, Vicksburg. Technical Report. D-76-4.

MCNABL, C. D., JR. 1976. The potential of submersed vascular plants for reclamation of wastewater in temperate zone ponds. p. 123-132, *In* : J. TOURBIER AND R. PIERSON, JR. (Eds.). *Biological Control of Water Pollution.* University of Pennsulvania Press, Philadelphia.

NESSEL, J. 1978. Phosphorus cycling, productivity, and community structure in the Wado Cypress stand. p. 750-801, *In* : H. T. ODUM AND K. C. EWEL (Eds.). *Cypress Wetlands for Water Management, Recycling, and Conservation.* Fourth Annual Report. Center for Wetlands, University of Florida, Gainesville.

ODUM, H. T., AND K. C. EWEL (Editors). 1978. *Cypress Wetlands for Water Management, Recycling, and Conservation.* Fourth Annual Report. Center for Wetlands, University of Florida, Bainesville.

PATRICK, W. H., JR, AND K. R. REDDY. 1976. Nitrification-denitrification reactions in flooded soils and water bottoms : Dependence on oxygen supply and ammonium diffusion. *J. Environm. Qual.* **5** : 469-472.

PRENTKI, R. T., T. D. GUSTAFSON, AND M. S. ADAMS. 1978. Nutrient movement in lakeshore marshes. p. 169-194, *In* : R. E. GOOD, D. F. WHIGHAM, AND R. L. SIMPSON (Eds.). *Freshwater Wetlands : Ecological Processes and Management Potential.* Academic Press, New York.

SEIDEL, K. 1976. Macrophytes and water purification. p. 109-122, *In* : J. TOURBIER AND R. R. PIERSON, JR. (Eds.). *Biological Control of Water Pollution.* University of Pennsylvania Press, Philadelphia.

SIMPSON, R. L., D. F. WHIGHAM, AND R. WALKER. 1978. Nutrient movement in freshwater tidal wetlands. p. 243-257, *In* : R. E. GOOD, D. F. WHIGHAM AND R. L. SIMPSON (Eds.). *Freshwater Wetlands: Ecological Processes and Management Potential.* Academic Press, New York.

SLOEY, W. E., F. L. SPANGLER, AND C. W. FETTER. 1978. Management of freshwater wetlands for nutrient assimilation. p. 321-340, *In* : R. E. GOOD, D. F. WHIGHAM AND R. L. SIMPSON (Eds.). *Freshwater Wetlands : Ecological Processes and Management Potential.* Academic Press, New York.

SMALL, M. H. 1976. Marsh/pond sewage treatment plants. p. 197-214, *In* : D. L. TILTON, R. H. KADLEC AND C. J. RICHARDSON (Eds.). *Freshwater Wetlands and Sewage Effluent Disposal.* University of Michigan, Ann Arbor.

SPANGLER, F. L., W. E. SLOEY, AND C. W. FETTER, JR. 1976. Experimental use of emergent vegetation for the biological treatment of municipal wastewater in Wisconsin. p. 161-171, *In* : J. TOURBIER AND R. PIERSON, JR. (Eds.). *Biological Control of Water Pollution.* University of Pennsylvania Press, Philadelphia.

STANLICK, H. T. 1976. Treatment of secondary effluent using a peat bed. p. 257-268, *In* : D. L. TILTON, R. H. KADLEC, AND C. J. RICHARDSON (Eds.). *Freshwater Wetlands and Sewage Effluent Disposal.* University of Michigan, Ann Arbor.

TALLING, J. F. 1958. The longitudinal succession of water characteristics in the White Nile. *Hydrobiologia* **11** : 73-89.

TILTON, D. L., R. H. KADLEC, AND C. J. RICHARDSON (Editors). 1976. *Freshwater Weltands and Sewage Effluent Disposal.* University of Michigan, Ann Arbor. 343 p.

TILTON, D. L., AND R. H. KADLEC. 1979. The utilization of a fresh-water wetland for nutrient removal from secondarily treated wastewater effluent. *J. Environ. Qual.* **8** : 328-334.

TOURBIER, J., AND R. R. PIERSON, JR. (Editors). *Biological Control of Water Pollution.* University of Pennsylvania Press, Philadelphia. 340 p.

TURNER, R. E., J. W. DAY, JR., M. MEO, P. M. PAYONK, J. H. STONE, T. B. FORD, AND W. G. SMITH. 1976. Aspects of land-treated waste applications in Louisiana wetlands. p. 147-167, *In* : D. L. TILTON, R. H. KADLEC, AND C. J. RICHARDSON (Eds.). *Freshwater Wetlands and Sewage Effluent Disposal.* University of Michigan, Ann Arbor.

VALIELA, I., M. BANUS, AND J. M. TEAL. 1974. Metal retention by salt marsh sediments and the response of marsh bivalves to enrichment with metal-containing fertilizers. *Environ. Poll.* **7** : 149-157.

VALIELA, L., S. VINCE, AND J. M. TEAL. 1976. Assimilation of sewage in wetlands. p. 234-253, *In* : M. WILEY (Ed.). *Estuarine Processes,* Vol. 1. *Uses, Stresses, and Adaptation to the Estuary.* Academic Press, New York.

VAN DER VALK, A. G., C. B. DAVIS, J. L. BAKER, AND C. E. BEER. 1980. Natural freshwater wetlands as nitrogen and phosphorus traps for land runoff. p. 457-467, *In* : P. E. GREESON, J. R. CLARK, AND J. E. CLARK (Eds.). *Wetland Functions and Values : The State of Our Understanding.* American Water Resources Assoc., Minneapolis.

WHIGHAM, D. F., AND S. E. BAYLEY. 1980. Nutrient dunamics in freshwater wetlands p. 468-478, *In* : P. E. GREESON, J. R. CLARK AND J. E. CLARK (Eds.). *Wetland Functions and Values : The State of Our Understanding.* American Water Resources Assoc., Minneapolis.

WHIGHAM, D. F., J. MCCORMICK, R. E. GOOD, AND R. L. SIMPSON. 1978. Biomass and primary production in freshwater tidal wetlands of the middle Atlantic coast. p. 1-23, *In* : R. E. GOOD, D. F. WHIGHAM, AND R. L. SIMPSON (Eds.). *Freshwater Wetlands : Ecological Processes and Management Potential.* Academic Press, New York.

WHIGHAM, D. F., R. L. SIMPSON, AND K. LEE. 1980. The effect of sewage effluent on the structure and function of a freshwater tidal marsh ecosystem. Water Resources Research Institute. Rutgers University, New Brunswick. 160 p.

WOLVERTON, B. C., R. M. BARLOW, AND R. C. MCDONALD. 1976. Application of vascular aquatic plants for pollution removal, energy, and food production in a biological system. p. 141-149, *In* : J. TOURBIER AND R. R. PIERSON, JR. (Eds.). *Biological Control of Water Pollution.* Philadelphia.

WOODWELL, G. M. 1977. Recycling sewage through plant communities. *Am. Sci.* **65** : 556-562.

WOODWELL, G. M., J. BALLARD, M. SMALL, E. V. PECAN, J. CLINTON, R. WETZLER, F. GERMON, AND J. HINNESSY. 1974. Experimental eutrophication of terrestrial and aquatic ecosystems. First annual report of the upland recharge project. BNL 50420. Brookhaven National Laboratory, Upton, 28 pp.

ZOLTEK, J., JR., S. E. BAYLEY, A. J. HERMANN, L. R. TORTORA, T. J. DOLAN, D. A. GRAETZ, AND N. L. ERICKSON. 1979. Removal of nutrients from treated municipal wastewater by freshwater marshes. Final Report to City of Clermont, Florida. Center for Wetlands, University of Florida, Florida. 325 p.