Stanley, L. D., and Hoffman, G. R. (1974). The natural and experimental establishment of vegetation along the shorelines of Lake Oahe and Lake Sakakawea, Mainstem Missouri River Reservoir. Annual report submitted to the Omaha District Corps of Engineers, Omaha, Nebraska.

Stanley, L. D., and Hoffman, G. R. (1975). Further studies on the natural and experimental establishment of vegetation along the shorelines of Lake Oahe and Lake Sakakawea, lakes of Mainstem Missouri River. Annual report submitted to the Omaha District Corps of Engineers, Omaha, Nebraska.

Woodhouse, W. W., Jr., Seneca, E. D., and Broome, S. W. (1974). Propagation of *Spartina alterniflora* for substrate stabilization and salt marsh development. TM-46, U.S. Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, Virginia.

Woodhouse, W. W., Jr., Seneca, E. D., and Broome, S. W. (1976). Propagation and use of *Spartina alterniflora* for shoreline erosion abatement. TR76-2. U.S. Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, Virginia.

EFFECTS OF CANALS ON FRESHWATER MARSHES IN COASTAL LOUISIANA AND IMPLICATIONS FOR MANAGEMENT

James H. Stone, Leonard M. Bahr, Jr., and John W. Day, Jr.

Department of Marine Sciences
Center for Wetland Resources
Louisiana State University
Baton Rouge, Louisiana 70803

Abstract Water flow and quality determine and control species composition and function in the freshwater marshes of coastal Louisiana. Man's activities alter this when he disrupts or removes the marsh. For example, man-made canals can change the hydrologic regime, depending on its alignment and local elevations, from −1% to −35% of normal flow. This in turn likely accelerates land loss from increased wave action. It is estimated that perhaps 172 hectares per year of freshwater marsh in coastal Louisiana is being lost due to man's activities. Canals also tend to divert runoff water away from the marsh (where it would be purged of pollutants) to open water bodies, thereby probably causing eutrophication. For example, the P loading rate of several freshwater lakes in the upper Barataria Basin is estimated between 1.5 and 4.3 $g \cdot m^{-2} \cdot yr^{-1}$, which may be from 4 to 11× greater than the loading limit for eutrophication. We do not know how these effects are quantitatively coupled to primary production, consumers in general, and fishery harvest in particular. But on the basis of preliminary data, we suggest that decision makers make full use of computer simulation models, of energy cost accounting, and of other more specific recommendations for marsh management.

Key words *Canals, coastal zone, eutrophication, hydrologic changes, impoundment, land loss, Louisiana management implications, spoil banks.*

INTRODUCTION

The Louisiana coastal ecosystem comprises a broad zone made up of wetlands and water bodies; it is characterized by low elevation and little natural relief. The coastal zone of Louisiana has recently been defined as extending landward from the Gulf of Mexico to the Pleistocene terrace, a distance ranging from about 30 to 150 km (McIntire et al., 1975) and encompassing an area of $\approx 31 \times 10^3$ km². Within the coastal ecosystem, 4 contiguous zones of emergent wetland have been distinguished, based on plant community composition (Chabreck, 1972): saline marsh, brackish marsh, intermediate marsh, and freshwater marsh. In addition, there are extensive areas of forested wetland that generally occur inland from the freshwater marsh zone. Figure 1 shows the full extent of the coastal ecosystem and the approximate boundaries between wetland types. The inclusion of all wetland types in a single coastal ecosystem is based on an array of data on exchanges of matter and energy across the entire zone. For example, tidal effects are sometimes detectable far inland from the point at which salinity effects are seen.

Because all wetland zones are interconnected by water bodies, water flow transports dissolved and particulate matter and organisms between different zones. This flow seems to be the primary regulator of the entire ecosystem, because the hydrologic and salinity regimes determine local plant community composition. Emergent plants in any given area integrate chemical and physical variations over time and reflect long-term average conditions. Water flow and alternating water levels perturb the wetland zones and maintain them in a successional state that allows net community production. Thus the hydrologic regime serves as a natural energy subsidy of significant importance. For these reasons, we normally do not view freshwater marshes as a separate entity in coastal Louisiana.

Man has imposed his activities on the Louisiana coastal ecosystem in a variety of ways, which usually affect the natural function adversely. We believe that management actions should reflect and complement, as much as possible, the natural function. We will restrict our discussion to the freshwater marshes of coastal Louisiana but we will indicate other aspects of the coastal wetlands when they relate to the freshwater marshes.

In this discussion our objectives are to:

1) Describe briefly the natural function of freshwater marshes in the Louisiana coastal ecosystem
2) Describe potential and actual changes from man's activities—such as canalling—to freshwater marshes
3) Illustrate how these changes affect and relate to the natural function
4) Draw implications and make recommendations for management and mitigation of these adverse effects in freshwater marshes.

We use the word "management" in its broadest sense—namely, those policy and day-to-day decisions affecting the use of air, land, and water in and about freshwater marshes.

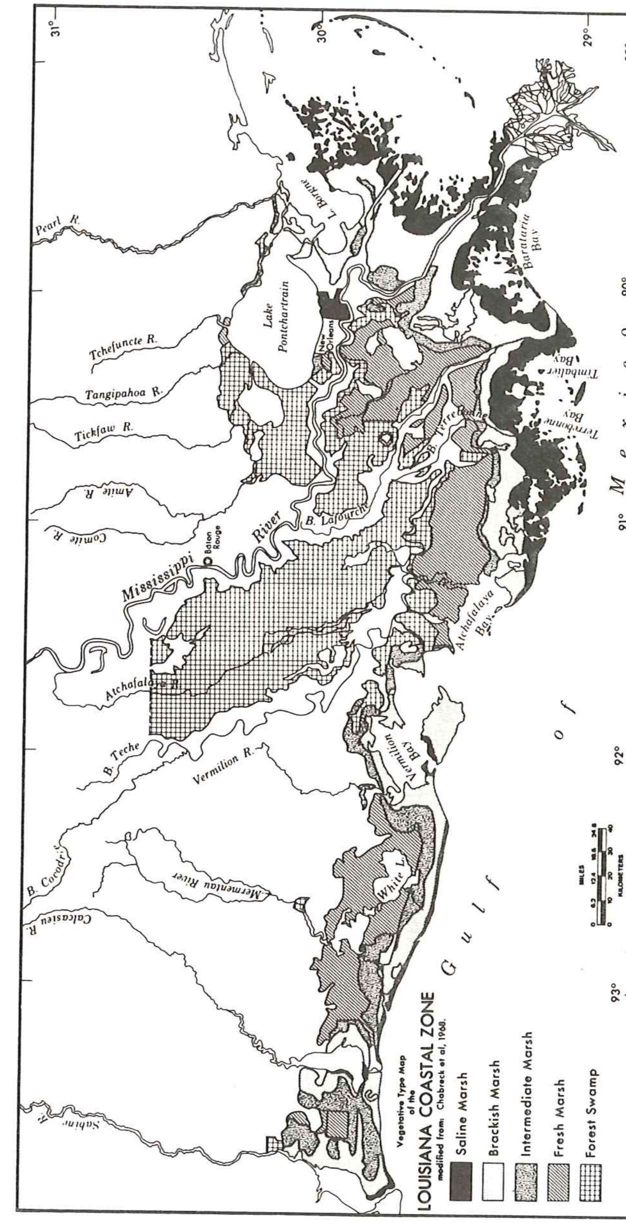

Fig. 1. Coastal zone of Louisiana divided into 5 vegetative types.

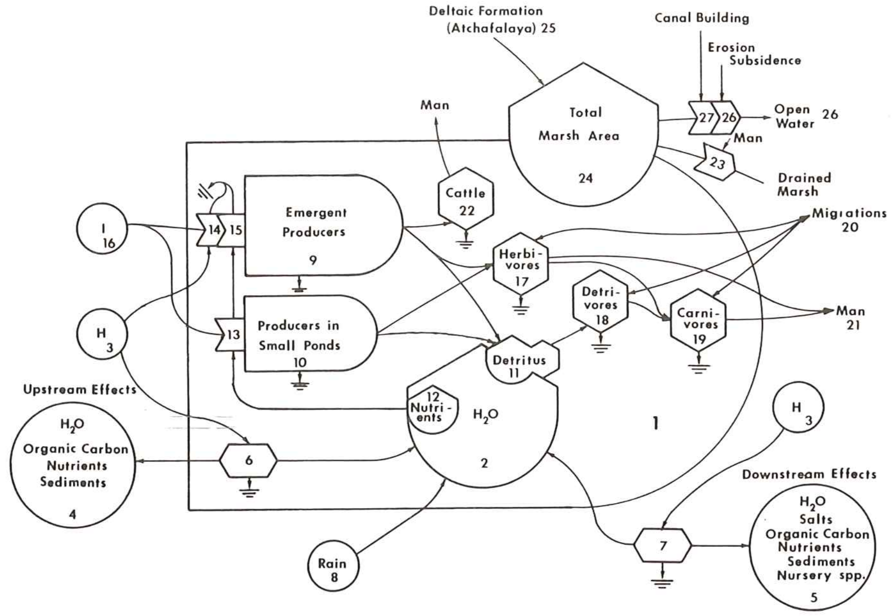

Fig. 2. Conceptual model of freshwater marshes in coastal Louisiana. H = hydrology which includes all hydrodynamic processes influenced by natural forces and man's activities.

Natural Function of Freshwater Marshes in Coastal Louisiana

The function of any complex ecosystem is most clearly and concisely described through the use of a conceptual model in which the major components, processes, and forcing functions are indicated schematically. Such a model for the freshwater marsh ecosystem in Louisiana is shown in Fig. 2. Symbols used in the model were developed by Odum (1971) as a way of depicting flows, storages, and interactions of energy and matter. **Each component in Fig. 2 is numbered, and these numbers are referred to in the following discussion of the model.**

The overall freshwater marsh ecosystem (**1**) is depicted with the symbol for a producer, because there is a net export of organic matter in the form of detritus from the marsh into adjacent open water bodies.

Water associated directly with the marsh is indicated with a storage symbol (**2**). Water (particularly water flow) has already been discussed as the primary integrator and forcing function of the entire coastal marsh ecosystem of Louisiana. The local hydrologic regime (**3**) is a function of water inputs from rainfall and terrestrial sources, slope, marsh "friction," the ratio of wetland to open water, and all natural and man-made relief features. Hydrology and man's effect on it are discussed further in the next section. In addition, Table 1 lists selected physical and biological characteristics for marsh types in coastal Louisiana.

Table 1. Selected Physical and Biological Characteristics of Coastal Marsh Types in Louisiana[a]

Marsh type	Salinity range[b] (‰)	Organic proportion of substrate (%)	Marsh: water ratio	Frequency of inundation (times/yr)	Net primary production rate (kJ m^{-2}yr^{-1})	Plant species (n)	Dominant producers[c]	Vertebrate species (n): Amphibia	Reptilia	Aves (yr-round)	Mammalia
Saline	5–35 (12.4)	5	0.5:1	160	56,480	17	(1), (2)	0	4	15	8
Brackish	0.5–16 (5.6)	23	3:1	40	82,840	40	(2), (3)	5	16	16	11
Intermediate	0.5–8 (2.1)	≈25	20:1	. . .	69,660	54	(3)	6	16	14	11
Freshwater	0–0.5 (<0.1)	usually >50	13:1	20	50,840	93	(4), (5), (6)	18	24	11	14

[a] Extracted from Bahr and Hebrard, 1976; C. B. Rainey, *personal communication*.
[b] Means in parentheses.
[c] Dominant producer species: (1) *Spartina alterniflora*; (2) *Distichlis spicata*; (3) *Spartina patens*; (4) *Sagittaria falcata*; (5) *Panicum hemitomon*; and (6) *Alternanthera philoxeroides*.

Two ecosystems normally border freshwater marshes in Louisiana. One is the inland upstream areas (**4**), either swamp forest with associated water bodies, or high land (Pleistocene terrace) and river basins; the other ecosystem is the downstream brackish and intermediate salinity marshes with associated estuaries (**5**). Both of these adjacent areas exchange matter and energy with the freshwater marsh, and these exchanges are indicated by bidirectional work gates (**6** and **7**).

Water (**4**) brings with it organic matter, nutrients, toxins, and sediments. Nursery species and salts (**5**) are also introduced to the freshwater marsh ecosystem via downstream areas; and some freshwater areas in Louisiana appear to serve as primary nursery areas. Of special importance are the export (via **7**) of organic carbon downstream from freshwater marshes and the migration of aquatic nursery species along the same pathway. Rainfall (**8**) represents a major source of water and a minor source of nutrients to the ecosystem.

Marsh producers are divided into the predominant emergent vascular plants (**9**) and less important pond algae and floating aquatic plants in small marsh ponds (**10**). Because the marsh trophic structure is primarily based on a detrital system, the pathway from (**9**) to a detritus—microbial storage module (**11**) is very important. Nutrients (**12**) stimulate primary production (**13** and **15**). The nutrient pool and man's effect on it are discussed in a following section. Hydrology (**3**) is a major determinant of community composition and primary production in marsh plants (**9**) as shown by work gate (**14**). Insolation (**16**), of course, provides the major energy requirement of all primary producers.

Natural consumers in the freshwater marsh ecosystem have been lumped in the model into 3 groups: herbivores (**17**), detritivores (**18**), and carnivores (**19**). Herbivores and detritivores comprise terrestrial and aquatic organisms including insects, gastropods, crustaceans, finfish, birds, and mammals. Carnivores are represented by a diverse assemblage of birds, insects, mammals, and reptiles.

It should be noted that many marsh consumers migrate either daily or seasonally into the marsh to feed and find shelter. This activity is indicated in the model by number **20**.

Man harvests various organisms that use the freshwater marshes and water bodies (**21**). These animals include waterfowl, furbearers, alligators, finfish and crayfish. This recreational and/or commercial harvest represents a major resource to Louisiana.

Cattle (**22**) are often allowed to graze in freshwater marshes in Louisiana. Natural marsh areas are usually marginal for cattle, however, and are therefore often impounded and drained to increase their agricultural value (**23**). Cattle grazing also probably disturbs natural marsh areas, although this is not documented for coastal Louisiana.

Total freshwater marsh area in Louisiana (**24**) is ≈282,000 hectares, but this area is changing because of the dynamic nature of coastal wetland areas and man's alterations. A newly emerging major delta is rapidly accreting wetlands in the Atchafalaya Bay region (Fig. 1). This sedimentation process is indicated in Fig. 2 (**25**). Loss of wetland (including freshwater marsh) occurs via natural processes of erosion and subsidence (**26**) and man-caused changes such as canal building (**27**) and draining (**23**). Some of these processes and the management implications they represent are the subject of the following section.

The conceptual model, represented by Fig. 2, allows us to identify the most important features of the freshwater marsh ecosystem, to view these features in relation to each other and to assign research priorities. Thus, we believe that changes in water flow and quality are 2 of the most important problems in coastal Louisiana, especially in the freshwater marshes. In the following section we illustrate this thesis by considering the effect of selected activities of man on hydrology, which in turn causes land loss and changes to the nutrient cycle.

Our conceptual model is derived from existing data on freshwater marshes and from the many years of our combined field experience. The model is only one of many possibilities but it illustrates and identifies the principal factors of how a freshwater marsh functions, what the control features are, and what the possible interrelationships and interactions are.

MAN'S ACTIVITIES AND THEIR IMPACTS IN COASTAL LOUISIANA

Eight use-issue categories of man's activities in coastal Louisiana are given in Table 2. A variety of activities are identified under each of these categories. This list is probably incomplete, but it is not our purpose to describe the various economic activities and their environmental impacts in the coastal zone (see Byrne et al., 1976; Conner, 1976; Grimes and Pinhey, 1976; and Van Sickle et al., 1976). However, Table 2 does allow us, to identify the most important environmental impacts of these activities. All of these activities require the use of land, air, and water. For example, oil and gas exploration entails several activities. Dredging of marshlands is required to clear right-of-ways, lay pipelines, and to prepare plant sites. Workmen and their families need places to live. Agricultural production requires the clearing of land, pest control, fertilization and a variety of harvesting techniques. As a result of these land uses, various chemical pollutants are often discharged into surrounding water bodies. All these activities occur in each of the vegetative zones of coastal Louisiana, including the freshwater marshes.

Below we discuss some of the environmental impacts in the freshwater marshes of coastal Louisiana due to the disruption of the marsh by man's activities, specifically as a result of digging canals, disposal of spoil, and the discharge of agricultural and urban runoff through these canals. These ac-

Table 2. Selected Use-Issue Categories and Man's Activities in Coastal Louisiana[a]

Use-Issue category	Activity
Mineral and energy extraction	Exploration Dredging Drilling Casing and cementing Treating oil field emulsions Pipe laying Brine disposal Drilling mud disposal Facility abandonment Oil spills
Navigation and transportation	Canal construction and maintenance Spoil disposal Dock construction Waterweed control Boat traffic Harbor-port development and use Airport construction and use Highway construction and use Railroad construction and use
Flood control and hurricane protection	Levee construction a) dredging b) spoil disposal c) right-of-way Channel improvement a) dredging (cutoff dredging, improvement dredging) b) revetments c) dikes Water control construction a) spillways b) pumping
Recreation and tourism	Sportfishing Beach, river and lake activities Camping Boating Outdoor games Hiking Hunting Tourism
Fishing and trapping	Harvesting (commercial and sportfishing) Boat operation Commercial processing Aquaculture Trainasse building (Trapper's Canal)
Wetlands maintenance	Weir construction Pesticide and herbicide application Mechanical tilling Marsh burning

Table 2. Continued

Use-Issue category	Activity
	Pothole, plug and ditch construction Cattle grazing Impoundment construction
Agriculture and forestry	Commercial harvesting Soil preparation Pest control Cultivation Irrigation Fertilization Land use conversion for agriculture Various management practices (flood and saltwater intrusion control)
Urban development	Sundry economic activities

[a] Extracted from Conner, 1976; V. R. Bennett, and W. W. Burke *personal communication*.

tivities result in 3 important and interrelated environmental impacts: hydrologic changes, land loss, and changes in nutrient cycling.

Changes to the Hydrologic Regime

Our model illustrates the importance of water to the function of the freshwater marsh. When a marsh is disturbed or removed, local hydrology changes. Because there is so much dredging and canalling activity in coastal Louisiana, we are repeatedly asked: how much hydrologic change occurs when a canal is dug? where does the change occur? how can we mitigate its effects? As a result of these questions, one of our workers helped us to model the water circulation within a small piece of marsh. This approach should give us—at least initially—a means for making an order-of-magnitude estimate on the effects and for planning mitigative procedures.

McHugh (1976) has created a two-dimensional hydrodynamic model for predicting water levels and current vectors within a small area of given size, shape and boundary conditions. It simulates water flow over a small piece of marsh by using a variable-size grid system. For each block of the grid, current speed and direction, water volumes, and water height are given for each time step. The time steps can be made to duplicate a tidal cycle. For this discussion we will present data only on water volumes. However, the model will eventually enable us to study the effects of winds, exchange rates, and dissolved or suspended materials. Basic assumptions of the model are:

1) There is a constant horizontal velocity at all depths
2) There is no vertical velocity

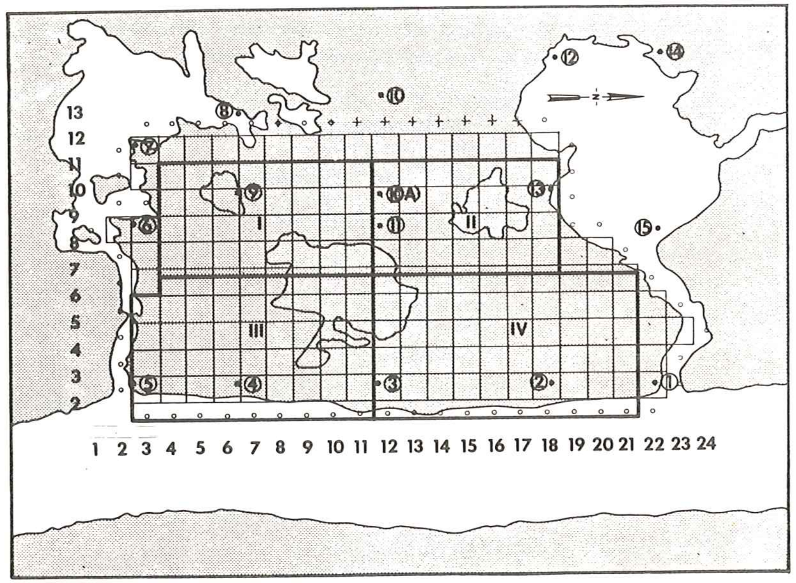

Fig. 3. Marsh layout and grid system used for testing, via McHugh's model, various physical disturbances to marsh. Black dots indicate elevation locations taken in field. Large grid (I, II, III, and IV) superimposed over smaller grids was used to calculate total water flow over a 20-h tidal cycle.

3) There is no vertical shear due to horizontal velocity gradients
4) There are no pressure and buoyancy forces due to variations in salinity.

The model uses an implicit method of solving the equations of water motion in alternating directions. The type of marsh used for testing the model is immaterial because it takes into account only the elevations or topography and the changes in water levels and velocities. For details of the model the reader is directed to McHugh (1976). The model has been tested on a small area (≈185 × 304 m) of brackish marsh located in Caminada Bay, Louisiana (see Fig. 3). We believe that we can generalize from the model because coastal wetlands geometry in Louisiana tends to be very similar—namely, dendrite or branching streambeds with a very gentle slope; however, field verification of the model is still underway. In addition, the model can be used to study almost any area of marsh with open and closed boundaries. However, it should be emphasized that our results are only preliminary and deal presently only with water volumes.

Figure 3 shows the general layout of the study area and the grid system used for calculating current vectors. The larger grid system (namely, the 4 sectors) superimposed on the small grids is used for calculating flow rates over 4 larger areas so that average and total values could be derived. We

Table 3. Results of Computer Simulation Studies of Water Flow over a Piece of Louisiana Brackish Marsh 185 m × 304 m for a Variety of Test Conditions[a]

Test condition	Total water flow ($m^3 \times 10^4$) per 20-h tidal cycle	Percent of normal
Normal circulation (Fig. 3)	6.0752	100.0
1) North to south canal and spoil bank (complete)	5.5385	91.2
2) No. 1 with openings in spoil bank		95.9
3) East to west canal and spoil bank (complete; Fig. 4)	5.7178	94.1
4) No. 3 with openings in spoil bank	5.8962	97.0
5) North to south canal and spoil bank (blind-ended)	5.6105	92.3
6) No. 5 with openings in spoil bank	5.8602	96.5
7) East to west canal and spoil bank (blind-ended)	5.7889	95.3
8) No. 7 with openings in spoil bank	5.9322	97.6
9) Levee surrounding on 3 sides	5.1109	84.1
10) No. 9 with vertical canal and spoil bank (partial, but not extending from levee)	4.8608	80.0
11) No. 10 (partial but extending from levee)	4.8962	80.6
12) No. 10 with openings in spoil bank	4.9682	81.8
13) No. 11 with openings in spoil bank	5.0039	82.4
14) Impoundment (31 m × 274 m)	3.9308	64.7

[a] A mean tide height of 0.14 m was used.

discuss here only the change in the water volume flowing over the marsh, before and after simulating physical modifications to the marsh.

Table 3 presents the preliminary results of computer simulations. We will discuss 3 types of physical disturbances: (1) canals and their spoil banks, (2) surrounding levees, and (3) impoundments. These are common to a variety of economic activities; however, for the actual alignment of each there exist many possibilities so they should be considered only as illustrative. The 3 types of physical disturbances and their variations are as follows:

Canal and Spoil Bank
- North-south alignment (cutting completely across marsh)
- North-south alignment with openings in spoil bank
- East-west alignment (cutting completely across marsh)
- East-west alignment with openings in spoil bank
- North-south alignment (not cutting completely across marsh)
- North-south alignment with openings in spoil bank
- East-west alignment (not cutting completely across marsh)
- East-west alignment with openings in spoil bank

Surrounding Level (three-sided)
- Surrounding levels (by itself)
- Surrounding levels with vertical canal and spoil bank (not next to levee)

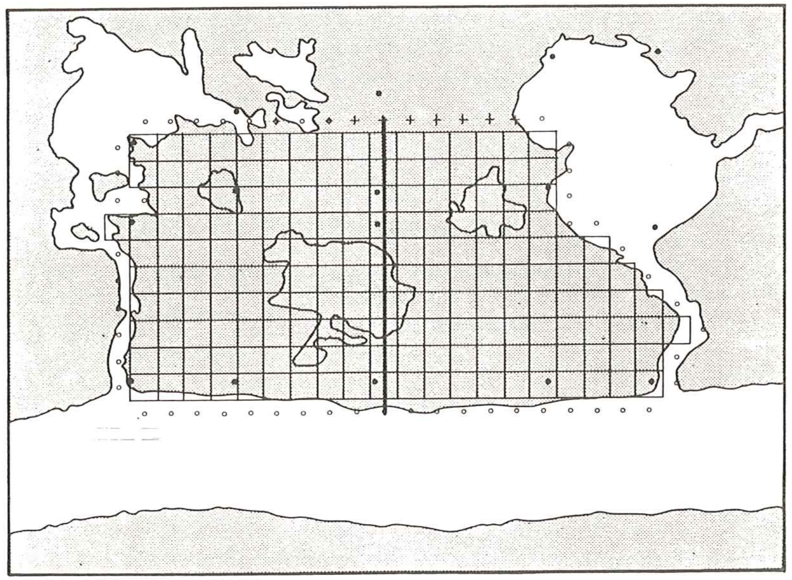

Fig. 4. An example of an east-to-west canal with spoil bank (barrier) cutting completely across marsh area.

Surrounding levels with vertical canal and spoil bank (not adjacent to levee) with openings in spoil bank
Surrounding levels with vertical canal and spoil bank (adjacent to levee)
Surrounding levels with vertical canal and spoil bank (adjacent to levee) with openings in spoil bank
Impoundment (four-sided)
Impoundment (by itself)

The canal was assumed to be 2.4 m deep and ≈30.5 m wide and the spoil bank assumed to be ≈30.5 m wide. In the north-south and east-west alignments, the canal cut completely across the marsh. A variation of these 2 alignments was made by simulating that the canal did not cut completely across the marsh; rather it extended about 80% of the way into the marsh then terminated. For all alignments, an additional experiment involved simulating 15.2-m openings every 15.2 metres. This allowed water to flow through the spoil bank or barrier. Figure 4 illustrates an east-west canal used for one of the simulations.

The surrounding levee was assumed to be a barrier on 3 sides of the marsh area (i.e., north, south and west). An additional simulation was made by placing a canal and spoil bank in the middle of the area surrounded by the 3 levees. In one instance, the canal and spoil bank abutted the levee while in another instance it did not; in neither case did the canal and spoil bank cut completely across the levee or marsh. The effects of creating breaks or openings in the spoil bank of the canal were also simulated.

The configuration assumed for the impoundment was a four-sided levee or barrier in the middle of the marsh, the area being ≈8.5 km².

Among the various canal alignments simulated, north-to-south canals produced the greatest hydrologic changes; water flow (cases 1 and 5) was decreased by approximately 9 to 8% below normal conditions. However, it should be emphasized that the values in Table 3 represent water flow over the entire marsh and some sectors (I, II, III or IV, as shown in Fig. 3) had larger hydrologic changes, but the change in total flow was not great. For example, the canal alignment illustrated in Fig. 4 reduced water flow to 94% of normal, but flow in sector II was 86% of normal and in sector IV, 90% of normal.

The alignments used for testing the effects of a three-sided levee showed more of a hydrologic change than did the canals. Water flow over a 20-hour tidal cycle was ≈80% of normal flow.

The impoundment showed the largest hydrologic changes as it reduced water flow 35% of normal.

Openings in the spoil bank (or barrier) were simulated for some of the alignments; in general, they increased the water flow closer to normal. For example, in Table 3, compare water flow in cases 1 and 2, 3 and 4, 5 and 6, 7 and 8, 10 and 12, and 11 and 13.

The implications of this preliminary work with a model that simulates water flow over a marsh are: first, hydrologic changes (at this stage only in terms of water volumes) do occur as a result of canalling and some of these changes appear to be quite significant; second, data on only 1 parameter are presented—data are needed on water heights, frequency of inundation, current speeds and directions, and distribution and abundance of dissolved and suspended material; third, this type of work should be coupled more closely with biological research such as nutrient dispersion, primary production, and consumers in general.

We believe that decision makers should use models such as the one above even in its rather incomplete state. Decision makers will be more able to identify the major impacts of an economic activity, to form initial rough estimates of these impacts, and, possibly to design mitigative procedures. For example, in the case of canals, they could select the direction of a canal that would produce the least amount of change or disruption.

Land Loss

The amount of available marshland is of considerable importance, as indicated in Fig. 2, because on it hinges the amount of primary production by the emergent producers. Because marshlands are under continued deterioration by both natural and man-made processes, and as the processes for forming new marshlands to augment these losses are now under man's control—with the exception of the new Atchafalaya delta—prevention of land loss is especially important. For example, Gagliano and van Beek (1970) estimate the total land loss for coastal Louisiana is 42.7 km^2/yr, and man's activities probably account for ≈35% of the total. Land loss for the coastal zone of Louisiana can be estimated from Barrett (1970), Gagliano and van Beek (1970), Chabreck (1972), Adams et al. (1976), and Day et al. (1976).

Regional subsidence and erosion of marshes and barrier islands are probably the most important natural causes of wetland loss; however, substrate type greatly influences the rate of loss. Other factors being equal, wetlands characterize by peaty, organic soils will erode faster than those with more mineral soils (Day et al., 1976).

Land loss due to man is associated with a number of activities; these include flood control, canal construction with attendant spoil banks, and land reclamation. Flood control levees along the lower Mississippi River have eliminated most sediment input from the river which historically offset natural erosion. Canal construction (for navigation, oil rig access, pipelines) eliminates wetlands directly (the canal itself as well as where spoil is placed). These canals widen over time leading to additional land loss. Both canals and spoil banks lead to hydrological changes as discussed in the previous section. These changes, in turn, can lead to salinity encroachment, which can cause death of marsh grass. Land reclamation has taken place principally as the result of urban and agricultural expansion.

Estimates on total land loss for each vegetative zone in coastal Louisiana are given in Table 4. About 491 hectares of freshwater marsh is lost annually (≈35% man and 65% natural) in Louisiana (≈18% of total wetland lost in the state). Brackish and saline marshes have experienced even higher rates of land loss, being 49% and 25% of total wetland lost, respectively. There are at least 3 possible reasons for the higher rates in brackish and saline marshes. First, tidal currents are more pronounced in these areas than in freshwater marsh. Second, there is much more open water in the brackish and saline zones. These conditions of tidal currents and fetch probably result in strong wave action. Finally, salinity intrusion is more serious in the brackish zone, which often results in the death of vegetation and, in turn, more rapid erosion.

The land loss data for each vegetative zone (Table 4) have not yet been broken down into the percentage of causal factors. However, data exist on some of man's effects, particularly canal widening in a freshwater marsh (i.e., the Rockefeller Wildlife Refuge in southwestern Louisiana). L. G. Nichols (*personal communication*) studied the erosion and widening of canals mainly used by petroleum interests in the refuge. One canal system (Humble Oil Co.) was dredged ≈20 metres wide for a length of 8.5 km in 1954 and has widened at the average rate of 0.36 m/month (1.2 ft/month) since. The total land loss for this canal, including the levee, amounts to 204 hectares of freshwater marsh. Another canal system (Superior) was also constructed

Table 4. Land Loss (hectares/year) per Vegetative Type and Percent of Total Land Loss for Management Units of Louisiana Coastal Zone[a]

Management unit	Marsh type: Saline	Brackish	Fresh	Swamp forest
Pontchartrain/St. Bernard	122.0 24%	430.0 64%	3.0 1%	72.0 11%
Mississippi River	1.5 1%	94.0 37%	116.0 62%	... ...
Barataria Basin	331.0 40%	365.0 44%	76.0 9%	58.0 7%
Terrebonne Basin	168.0 30%	184.0 31%	166.0 28%	68.0 11%
Atchafalaya River[b]	0.7 1%	4.7 9%	43.0 78%	6.6 12%
Vermilion Basin	5.2 3%	161.0 84%	11.1 6%	15.1 7%
Chenier Plain	11.3 6%	106.0 55%	76.0 39%	... ...
Totals	640.0 25%	1344.0 49%	491.0 18%	220.0 8%

[a] From Craig and Day, 1976.
[b] This does not include current delta building in the Atchafalaya Bay.

≈20 metres wide for a length of 24.6 km in 1952. By 1958 the average canal width increased by 23 m. Total land loss of freshwater marsh was 262 ha by 1958.

The data in Table 4 (and shown above on canals) indicate that land loss has several cumulative impacts, some of which are interrelated. First, land loss due to the construction of canals often results in rapid salinity changes. This causes a change in the species composition of the area. One example of this is a result of the construction of the Mississippi River-Gulf Outlet. Since its construction 20 years ago it has changed the biotic composition of at least 18,000 ha from that of a freshwater marsh to that of a brackish marsh. Freshwater flora and fauna have been eliminated from the immediate area (van Lopik and Stone, 1974).

Another negative result of land loss is due to the construction of straight canals, which creates a condition whereby runoff water, such as from agricultural and urban sources, is shunted through the marsh into open water bodies. Eutrophication probably results, which we discuss in the next section. In addition, straight canals result in less buffering of chemical discharges and a direct loss of habitat necessary for consumer and especially fishery species.

It is possible to see two implications in the data presented on land loss, especially loss due to canals: (1) canals cause a direct loss of land by removal of the marshland and they cause a cumulative loss of land because erosion at the banks of canals is quite rapid; (2) there is a considerable amount of natural land loss in freshwater marshes of coastal Louisiana, but man's activities can significantly amplify and increase this.

We strongly suggest that managers and decision makers require that all canals not used for navigation be refilled and refurbished to their prior or natural condition.

Nutrient Changes

Disruption or digging in any type of marsh produces local changes in the sediments and associated chemical species. For example, it has been estimated (Stone et al., 1976) that the construction of a particular pipeline ditch through 21.6 km of freshwater marsh in coastal Louisiana would produce $\approx 1 \times 10^6$ m^3 of spoil and potentially could add to the surrounding aquatic environment a total inorganic nitrogen component of 2,400 kg, a PO_4^{-3} component of 610 kg, a dissolved SiO_2 component of 4,000 kg, a BOD load of 4.1×10^6 kg, and a H_2SO_4 component of 2.0×10^5 kg.

To provide some relative measure of the importance of some activities (such as digging the above pipeline), we made extensive, basic field studies (during 1973–1974) on the hydrology, C, and nutrients of the upper drainage basin of the Barataria estuary (Craig and Day, 1976). This is a freshwater area consisting of bayous, lakes, swamp forest, and marsh (Fig. 1). Export of materials from this wetland watershed was calculated by dividing total output by total watershed area. Final estimates were 19.3 g C per square metre per year, 2.7 g N per square metre per year, and 0.4 g P per square metre per year. (By comparison litter fall in the swamp amounted to 600 dry weight grams per square metre per year.) These figures are not highly precise and should be treated cautiously. From these data we estimated that the annual export to the lower estuary calculated from water discharge and materials concentrations is 8,016 metric tons of organic C, 1,047 metric tons of N, and 154 metric tons of P. Thus, the pipeline, cited above, could account for 0.25% of the total N export and approximately 0.45% of the total P export. In 1974 alone, 128 dredging permits were issued for the Barataria Basin, which suggests that the total impact on nutrient cycling due to dredging and/or pipeline construction could be quite significant.

The annual export data on nutrients clearly indicate that the fresh waters in the upper Barataria Basin are rich in N and P, but we believe that some of these nutrients are derived primarily from terrestrial sources such as agriculture and urban runoff. If these waters could flood over wetlands, the nutrients would be taken up by plants and incorporated into detritus. (There are, of course, other important transformations that would also occur in wetland soils, such as the adsorption of P and denitrification.) Many canals allow

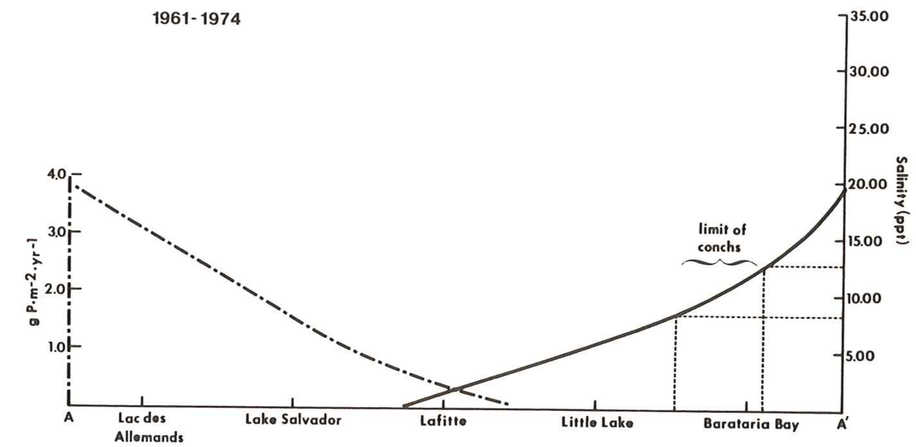

Fig. 5. Phosphorus loading rate (grams per square metre per year) and salinity levels (parts per thousand) at various locations in Barataria Basin, 1961–1974. Conch range illustrates southern limit of oyster production (Craig and Day, 1976).

runoff water to bypass wetlands and flow directly into water bodies. This eliminates the purging value of wetlands and may lead to eutrophication of water bodies.

Export of these materials represents an important source of raw materials to the lower estuary. And we know that there is a general trend of decreasing concentrations of total N, P, and organic C toward the brackish and saline marsh areas and the gulf (Happ et al., *In press*). This may indicate that part of the material supplied by the upper watershed is being consumed by the lower system. Water discharge from the basin is significant year-round, except during the summer when evaporation equals precipitation.

Research by Craig and Day (1976) indicates that the upper basin is eutrophicating. They estimate that the P loading rates into 2 of the largest freshwater lakes of the upper basin are 0.5 and 4.3 g per square metre per year, respectively, and that this may exceed the loading limit by about 4 and 11×, respectively (Fig. 5). Craig and Day believe that the primary sources for this P are natural background levels, plus runoff from agricultural and urban lands, and domestic sewage.

The freshwater system and marshes of the Barataria Basin serve as a major freshwater reservoir for maintenance of favorable salinities in the brackish and saline zones. The upper area thus contributes substantially to the productivity of the lower estuary. The major pulse of materials to the lower system begins in February and coincides with the time of high detrital formation and the arrival of migrant species which enter the estuarine area for growth and spawning purposes. An advantage of detrital export in spring is that it allows for overwinter enrichment of detritus by microbial action on the swamp floor. This probably produces a food of high quality for the

Table 5. Selected Recommendations for Management of Freshwater Marshes in Coastal Louisiana[a]

Management recommendations	Reference and/or derivation sources
A. Policy recommendations	
Managers should know the general features of the natural function of freshwater marshes. Decisions should reflect, complement, and reinforce natural function.	Fig. 2; Clark, 1974; Odum, 1971.
Managers should make full use of simulation models for estimating environmental impacts at order-of-magnitude level.	Fig. 3 and Table 3; Eckenrod et al. 1977; R. A. Hinchee (*personal communication*); Hall and Day, 1977.
Managers should evaluate environmental impacts by means of the energy-cost accounting technique or other suitable optimalization techniques.	Odum, 1972; Odum and Odum, 1976; Gilliland, 1975; Day et al., 1976; Stone et al., 1976; Zucchetto, 1975.
Managers should support research that will quantify impact assessment.	McHugh, 1976; Craig and Day, 1976; Day et al., 1976.
Managers should recognize the limits of technology and require those who propose environmental changes to demonstrate no effect or to refurbish.	Happ et al., 1976; Schumacher, 1973.
B. Operational recommendations	
Preventative procedures:	
Use existing canals (whenever possible).	CM No. 26; L. G. Nichols (*personal communication*); Gagliano, 1973; Craig and Day, 1976.
Restrict new canals to natural corridors or levees.	Gagliano, 1973.
Stop construction of canals that connect the edge of the hydrological basin to the middle.	Gosselink et al., 1976.
Stop construction of blind-end canals or finger-fill developments.	Barada and Partington, 1972.
Limit construction of impoundments in marsh areas.	MM No. 14.
Limit canals between different vegetative types.	Stone and McHugh, 1977.
Mitigative procedures:	
Perform dredging operations as fast as possible.	Gosselink et al., 1976.
Place periodic openings in spoil banks so water circulation is not impeded.	MM No. 2, 4, 5, 8, 12 and 13; Day et al., 1976.
Place water control structure on all existing waterways.	St. Amant, 1971, 1972.
Plug pipeline canals on seaward side until construction is finished.	St. Amant, 1971, 1972.
Dispose of spoil with special care; if possible, place in nonwetland areas.	Craig and Day, 1976.
Use special care during times of wildlife migrations, spawning, and nesting.	Gosselink et al., 1976; Bahr and Hebrard, 1976.
Shunt agricultural and urban runoff waters into marsh areas rather than into open water bodies.	Turner et al., 1976.
Construct spoil banks lower than tidal amplitude.	Cite coastal elevations.
Dig transportation canals only as deep as the euphotic zone and not deeper than water body where canal ends.	Barada and Partington, 1972.
Time application of fertilizer to time of maximum uptake (eliminate fall and winter applications).	R. A. Hinchee (*personal communication*).
Use manure to condition soil and to replace chemical fertilizers.	R. A. Hinchee (*personal communication*).
Plow fertilizers (if used) as deeply as possible.	R. A. Hinchee (*personal communication*).
Refill and refurbish canals.	Happ et al., 1976.

[a] Recommendations are divided into policy (A) and operational levels (B). Reference cited as CM No. 1 through 27 refer to the conceptual model and its various parts as illustrated in Fig. 1 and described in the text; references cited as MM No. 1 through 14 refer to the marsh model and the various simulation tests described in Table 3.

detrital-based food chains both in the swamp and the area below it. Enrichment of detritus over time has been well demonstrated (Odum and de la Cruz, 1967).

The implications of these data are that canals or dredging has several impacts, all of which are interrelated. For example, by digging a canal the water is often diverted away from the marsh proper and nutrients in these waters are not removed by the marsh grass; the consequence of this is unfavorable conditions for most fishery species, namely eutrophication.

Decision makers should consider the use of marshlands for removing excessive nutrient loads from agricultural and urban runoff. Pilot programs with the Louisiana Sea Grant program demonstrate the validity and effectiveness of this approach (Turner et al., 1976).

RECOMMENDATIONS FOR MANAGEMENT OF FRESHWATER MARSHES

Table 5 summarizes some of our recommendations for management of freshwater marshes in regard to canalling. These are segregated in terms of policy and operational recommendations, the difference between the two levels being that policy deals more with general items while operations deal more with specific, or day-to-day items. Operational recommendations are subdivided into preventative and mitigative measures. For each recommendation we have cited a reference and/or derivation source.

We believe that the policy recommendations, perhaps the most obvious, are the most important. For example, a decision maker should know the rudiments of how a wetland system operates; thus, for example, if he is aware of the importance and role of water in the natural functioning of the freshwater marsh, he may be cautious in deciding to change or modify the marsh. He should realize that the marsh is a product of many years of evolution, and not easily duplicated by man and that it provides many natural services to man. If a development cannot be stopped, then he should use a variety of simulation models to estimate the impacts and he should use some form of energy-cost accounting (Odum, 1972; Gilliland, 1975; Stone et al., 1976; Zucchetto, 1975) in order to derive representative benefit:cost ratios. If research is not supported, then almost any opinion will be valid in regard to proposed economic activities and the discussion is apt to be clouded by emotion rather than data. Technology does not have all the answers, but those who propose economic-return activities in freshwater marshes should demonstrate that there will be no adverse effects on the marsh or how any potential adverse effects may be mitigated.

Table 5 lists recommendations to develop guidelines for coastal zone management in Louisiana. The reference or derivation sources are not complete; others could be added to the table but our knowledge of freshwater marshes is incomplete and much work remains to be done in order to perfect these guidelines. We are not certain that as more data and knowledge become available that eventually we will reach performance standards, comparable to engineering specifications. It is more probable that something in between our recommendations and specific performance standards will evolve.

Perhaps a more serious problem is how to implement or transfer these recommendations into action. The outlook is not particularly sanguine, but as with many things it will probably be done by a combination of laws, education, and moral persuasion. The frustration of this approach is that it is inefficient, slow, and very tortuous in its workings. Many of our problems in the management of marshes are more immediate and demand resolution faster than we can do the necessary research. We must try, nonetheless.

ACKNOWLEDGMENTS

Part of the research reported herein was supported by the Louisiana Sea Grant Program, a part of the National Sea Grant Program maintained by the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce and by the Louisiana State Planning Office under the Coastal Zone Management program.

LITERATURE CITED

Adams, R. D., Barrett, B. B., Blackmon, J. H., Gane, B. W., and McIntire, W. G. (1976). Barataria Basin: Geologic processes and framework. Sea Grant Publication No. LSU-T-76-008, Louisiana State University Center for Wetland Resources, Baton Rouge, La.

Bahr, L. M., Jr., and Hebrard, J. J. (1976). Barataria Basin: Bilogical characterization. Sea Grant Publ. No. LSU-T-76-005. Louisiana State University, Center for Wetland Resources, Baton Rouge, La.

Barada, N., and Partington, W. M., Jr. (1972). Report of investigation of the environmental effects of private waterfront canals. Environmental Information Center of the Florida Conservation, Inc., Winter Park, Fla. 63 pp.

Barrett, B. B. (1970). Water measurements of coastal Louisiana. Louisiana Wildlife and Fisheries Comm., U.S. Dept. of the Interior Fish and Wildl. Serv., Bureau of Commercial Fisheries Proj. No. 2-22-T of P.L., 88–309.

Byrne, P., Borengasser, M., Drew, G., Muller, R. A., Smith, B. L., Jr., and Wax, C. (1976). Barataria Basin: Hydrologic and climatologic processes. Louisiana State Printing Office. Baton Rouge, La.

Chabreck, R. H. (1972). Vegetation, water, and soil characteristics of the Louisiana coastal region. Louisiana State University Agri. Expt. Sta., Baton Rouge, La. Bull. No. 664.

Clark, J. (1974). Coastal ecosystems: Ecological considerations for management of coastal zone. The Conservation Foundation, Wash., D.C. 178 pp.

Conner, W. H. (1976). Wetland use practices: Mineral and energy production. Louisiana State Planning Office, Baton Rouge, La.

Craig, N. J., and Day, J. W., Jr. (1976). Barataria Basin: Eutrophication case history. Louisiana State Planning Office, Baton Rouge, La.

Day, J. W., Jr., Craig, N. J., and Turner, R. E. (1976). Cumulative impact studies in Louisiana coastal zone: Land loss. Louisiana State Planning Office. Baton Rouge, La.

Eckenrod, R. M., Day, J. W., Jr., and Bahr, L. M., Jr. (1977). A simulation model of urban estuarine interactions. *In* "Proc. Marsh-Estuarine Systems Simulation Symposium" (R. F. Dame, ed.), Univ. of South Carolina (*In press*).

Gagliano, S. M. (1973). Canals, dredging and land reclamation in the Louisiana coastal zone. Hydrologic and Geologic Studies of Coastal Louisiana, Report No. 14. Louisiana State University Center for Wetland Resources, Baton Rouge, La.

Gagliano, S. M., and van Beek, J. L. (1970). Geologic and geomorphic aspects of deltaic processes, Mississippi River system. Hydrologic and Geologic Studies of Coastal Louisiana, Report No. 1. Louisiana State University Center for Wetland Resources, Baton Rouge, La.

Gilliland, M. W. (1975). Energy analysis and public policy. *Science* **189**, 1051–1056.

Gosselink, J. G., Miller, R. R., Hood, M., and Bahr, L. M., Jr., eds. (1976). Louisiana offshore oil port (LOOP): Environmental baseline study. 4 vols. LOOP, Inc., Harvey, La.

Grimes, M. D., and Pinney, T. K. (1976). Recreation potential of private lands in Louisiana Coastal Zone. Louisiana Agricultural Experiment Station. Sea Grant Publication No. LSU-T-76-010. Center for Wetland Resources, Louisiana State University, Baton Rouge, La.

Hall, C. A. S., and Day, J. W., Jr., eds. (1977). Ecosystem Modeling in Theory and Practice: An Introduction with Case Histories. John Wiley and Sons, New York.

Happ, G., Bennett, V. R., Burke, W. M., III, Conner, W. H., Craig, N. J., Hinchee, R. E., Bahr, L. M., Jr., and Stone, J. H. (1976). Impacts of outer continental shelf activities; Lafourche Parish, La. Louisiana State Planning Office, Baton Rouge, La.

Happ, G., Gosselink, J. G., and Day, J. W., Jr. (*In press*). The seasonal distribution of organic carbon in a Louisiana estuary. *J. Coastal and Estuarine Mar. Sci.*

McHugh, G. F. (1976). Development of a hydrodynamic numerical model for use in a shallow well-mixed estuary. Sea Grant Publication No. LSU-T-76-008. Center for Wetland Resources, Louisiana State University, Baton Rouge, La.

McIntire, W. G., Hershman, M. J., Adams, R. D., Midboe, K. D., and Barrett, B. B. (1975). A rationale for determining the Louisiana coastal zone. Sea Grant Publ. No. LSU-T-75-006. Louisiana State University Center for Wetland Resources, Baton Rouge, La.

Newsom, J. D., ed. (1968). Proc. of the Marsh and Estuary Management Symposium held at Louisiana State University, July 19–20, 1967. Louisiana State University Division of Continuing Education. Baton Rouge, La.

Odum, E. P., and de la Cruz, A. A. (1967). Particulate organic detritus in a Georgia salt marsh estuarine ecosystem. *In* "Estuaries" (G. H. Lauff, ed.), pp. 383–388. AAAS Publ. No. 83.

Odum, H. T. (1971). Environment, power, and society. John Wiley and Sons, Inc., New York.

Odum, H. T. (1972). Use of energy diagrams for environmental impact statements. *In* "Tools for Coastal Management," pp. 197–213. Proc. of the Conf. Marine Technology Society, Washington, D.C.

Odum, H. T., and Odum, E. (1976). Energy Basis for Man and Nature. McGraw-Hill, New York.

Schumacher, E. F. (1973). Small is Beautiful: Economics As If People Mattered. Perennial Library, Harper & Row, New York.

St. Amant, L. S. (1971). Impacts of oil on the Gulf Coast. *Trans. of 36th N. Amer. Wildlife and Nat. Res. Conf.* **36**, 206–219.

St. Amant, L. S. (1972). The petroleum industry as it affects marine and estuarine ecology. *Journal of Petroleum Technology*. **46**, 385–392.

Stone, J. H., Byrne, P. A., and Fannaly, M. T., III (1976). Selected environmental impacts of proposed Louisiana oil port project. *In* "Louisiana Offshore Oil Port: Environmental Baseline Study" (J. G. Gosselink, R. R. Miller, M. Hood, and L. M. Bahr, Jr., eds.), Vol. I, Chaps. 5–9. LOOP, Inc., Harvey, La.

Stone, J. H., and McHugh, G. F. (1977). Simulated hydrologic effects of canals in Barataria Basin: A preliminary study of cumulative impacts. Final Report to Louisiana State Planning Office, Baton Route, La.

Turner, R. E., Day, J. W., Jr., Meo, M., Payonk, P. M., Stone, J. H., Ford, T. B., and Smith, W. G. (1976). Aspects of land-treated waste applications in Louisiana wetlands. *In* "Freshwater Wetlands and Sewage Effluent Disposal" (D. L. Tilton, R. H. Kadlec, and C. J. Richardson, eds.), pp. 145–167. The University of Michigan, Ann Arbor, Michigan.

van Lopik, J. R., and Stone, J. H. (1974). Environmental Planning for Future Port Development. *In* "Port Planning and Development as Related to Problems of U.S. Ports and the U.S. Coastal Environment" (E. Schenker and H. C. Brockel, eds.), pp. 154–174. Cornell Maritime Press, Inc., Cambridge, Maryland.

Van Sickle, V. R., Barrett, B. B., Gulick, L. J., and Ford, T. B. (1976). Barataria Basin: Salinity changes and oyster distribution. Louisiana State University Center for Wetlands Resources, Baton Rouge, La. Sea Grant Publ. No. LSU-T-76-002.

Zucchetto, J. J. (1975). Energy basis for Miami, Florida, and other urban systems. Ph.D. Dissertation, University of Florida. 248 pp.

MANAGEMENT OF FRESHWATER WETLANDS FOR NUTRIENT ASSIMILATION

William E. Sloey,[1] Frederic L. Spangler,[1] and C. W. Fetter, Jr.[2]

[1] *Biology Department*
[2] *Geology Department*
University of Wisconsin–Oshkosh
Oshkosh, Wisconsin 54901

Abstract Nutrient transformation processes such as sorption, coprecipitation, active uptake, nitrification, and denitrification remove P and N from the free-flowing water of a wetland and transfer them to the substrate and biota for storage. Advantage is being taken of these processes by using wetlands to treat sewage in Germany, Holland, Finland and other European countries. In the USA, experimental application of cultural water (wastewater) to peatlands in Michigan, tidal marshes in Louisiana and New Jersey, cattail marshes in Wisconsin, cypress domes and sawgrass in Florida and many more have shown promising results. Denitrification may remove up to 3.5 kg $N \cdot ha^{-1} \cdot day^{-1}$ and as much as 20 g P/m^2 may be detained in a growing season. Natural release of nutrients between growing seasons, however, either restricts application periods, or demands management of the wetland systems to regulate such releases. The most obvious management tool, plant harvesting, removes only a few grams of P per square metre per year (<5) which is usually <20% of that detained. Most of the remainder is in the substrate-microbial compartment and is subject to between-season washout.

Other management techniques used and proposed, such as dikes, drains and intermittent application, relate to manipulating the hydraulics of the system to optimize conditions for assimilative biogeochemical processes and to prevent washout from reaching surface waters. Chemical treatment to reduce the surplus of P has also been considered.

Management options for a specific wetland will depend to a large extent upon that particular hydrologic regime. Riverine systems have different hydraulic patterns than lacustrine or palustrine systems. Flow-through systems cannot be managed like influent or seepage systems.

Already, changes in the biota of some experimentally treated wetlands indicate undesirable disturbances of these valuable natural resources. Caution in widespread use of natural wetlands to treat waste at this time is advised and careful monitoring of all biotic communities in experimental programs is essential.

Artificial marshes and peat filters offer feasible alternatives to other treatment methods for small systems and do not endanger natural wetlands.