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THE EFFECTS OF DREDGING SALT MARSH CREEKS

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A WORD OF THANKS

The authors wish to thank the countless individuals who assisted us in identifying and collecting the materials that went into the preparation of this report. Without exception--though their efforts of the moment were certainly interrupted by our calls--they went out of their way to search their files and memories for reports that would help us and to suggest others who might come closer to the mark. When possible they sent us copies of the reports they had on hand, or, if not, they told us where they could be obtained. Not one of the over-half-a-hundred people contacted failed to try to help us--even when we called back for more information or clarification. We expected to succeed in our efforts; we did not expect such a gracious response from so many. We hope that someday we will be able to reciprocate. For now, the best we can do is say: Thank you.

an examination of . . .

THE EFFECTS OF DREDGING

SALT MARSH CREEKS

INTRODUCTION

The question has been asked:

"What happens when you dredge the small meandering creeks in a salt marsh?"

The short answer is:

"You hurt the environment."

The long answer is not so easily found.

Evidence abounds, however, that without great care in their design and construction, canals dredged in tidal salt marshes not only may destroy the productivity of the excavated area, but also the canal itself may become a net consumer of the production from the undisturbed remainder of the marsh: It may consume nutrients and organic matter while giving nothing in return. And, the marsh itself may be exported out to sea.

This may not mean that canals can never be dredged without adverse effects. It does mean that the way they have been made traditionally is not how they should be made in the future. In addition to the drain on productivity, the banks of such canals may continue to erode indefinitely, the waters of the canal may threaten the health of those who live alongside and/or use them for work or recreational purposes, and the unhealthy conditions in the canals may spread into nearby estuarine and bay waters with a consequent closing of shellfish beds and the prohibition of human contact.

Recent work indicates that it may be possible to construct canals in which many of these hazards are minimized or possibly even eliminated. Even though these techniques might prove out in one part of the U.S. coastal zone, that does not mean that they could simply be transferred to another part of the coast without prior rigorous analysis, prototype demonstration projects and possible modification.

This report covers these and other related topics in a narrative, non-technical manner. The objective is to inform those who must set policy and make decisions on such matters, but who, themselves, may not be marine scientists, engineers or oceanographers. Though the editorial style is more in the form of a feature article, the substance of this report is nevertheless based on hard data gleaned from study of the scientific literature and from talking directly with those who have carried out the research. First we take a brief look at the marsh itself.

The Salt Marsh

It is important to remember that these small salt marsh creeks were laid down and shaped over long periods of time in response to natural processes working on the marsh--tidal flow, waves, drainage, salinity, wind, rain, summer sun, winter storms, the occasional hurricane and, over geologic time, the changing levels of the sea. They are configured to the natural hydrographic demands of the system. In turn, they have been populated by living plants and animals which not only occupy their individual and unique habitats but also by the very fact of their being there help to define and shape the physical, chemical and biological complex that is the marsh.

Too, it is important to remember that it is a system which--though it experiences cyclical changes with the tides, the sun and the seasons -- is in dynamic balance. Left alone, it will remain as it is, continuing to perform the multiple services that it does virturally forever...for man and beast alike. Since it is in dynamic balance, however, any significant modification of it by man or nature cannot but alter that balance. Whether the tilt of the scale is great or small depends on how much is done and how. There will be a change. Whether that change is for the better or for the worse is a subjective view that varies with the perspectives and objectives of the beholder.

The natural environment has no constituency. It has no voice. It does respond, however; it responds to what is done to it, and it responds according to the laws of the natural system which are universal and immutable. It is with the nature of those reponses that this question is concerned.

Values of The Marsh

The values of the coastal wetlands are widely publicized and generally well known. However, in the interests of perspective, it is worth briefly noting again. Aside from their contribution to aesthetics, coastal wetlands perform many functions, including but not restricted to: Filtering and cleansing freshwater runoff on its way to the sea, providing an energy-absorbing buffer against severe ocean storms, slowing saltwater intrusion, giving shelter and sustenance to waterfowl, supporting a large and highly profitable recreation industry and providing the essential underpinnings to valuable coastal and offshore fisheries.

The role of Spartina salt marshes is critical. According to the National Marine Fisheries Service[1], some 31 species of commercially valuable fin and shell fish are directly estuarine-dependent -- ranging from menhaden, drum, seatrout and Spanish mackeral, to oysters, clams, crabs and shrimp. These estuarine-dependent species account for more than 88% (both by weight and by ex-vessel dollar value) of the total fishery landings of the Southeastern U.S.--and account for more than 30% of the total U.S. landings from all sources.

Some of these valuable species spend their entire lives within the estuary, while others are part-timers. Shrimp, for example, hatch and go through their various larval stages offshore, but as very small juveniles they return to the marsh where they remain until they are nearly fully grown. The famous blue crab is virtually entirely estuarine-dependent; only the female heads briefly towards the more stable conditions of the nearby ocean to hatch her young. Oysters and clams never leave the estuary. Neither does the diamondback terrapin. Many species of fish enter the marsh creeks as juveniles -- where there are fewer predators, cover is good, and food is abundant -- and remain there until they have grown enough to increase their chances of survival outside. Others, of course, return only to spawn, though their young hatchlings remain there through the first period of their growth as fully-formed members of their species. Anyone who has walked the tidal creeks in a salt marsh with a fine-mesh (shrimp) cast net knows the rich abundance of marine life to be found there.

Also important are the many species which man does not harvest but which are food for the species he does harvest--fiddler crabs, mud minnows, the many marine worms and other members of the benthic community, a sometimes-dense "soup" of phytoplankton, zooplankton (the tiny plants and animals that constitute the base of the marine food chain) and bacteria, and , of course, the Spartina itself.

THE SEARCH

In an effort to gain more information--the "long answer" above-- we have talked to more than 60 people--virtually all of them professional scientists concerned with coastal wetlands and directly involved in research and/or regulation. They represent over three dozen federal, state, academic and private organizations in 13 states and the District of Columbia, stretching from Rhode Island to Florida to Texas to Oregon. We not only picked their brains but also asked if they had heard of any directly-relevant work done by others. Considering the extent to which researchers and regulators in this highly specialized field closely follow each other's work and communicate with one another, it is safe to say that by this route alone we covered the majority, if not virtually all, potential sources of information.

We also obtained and searched the cumulative Sea Grant Publications Index covering the 14-year life of the program along with a list (prepared for National Sea Grant Office internal use) of all environmental projects currently underway throughout the Sea Grant program network. In addition, we have scanned numerous bibliographies, reference lists, etc., and obtained and read many reports and papers, the titles of which indicated that they might have addressed the specific issue in question.

As a final check of the thoroughness of our effort, we have run a key-worded computer search of the 145,000 citations currently stored in the Selected Water Resources Abstracts data bank compiled by the U.S.

Department of the Interior's Water Resources Scientific Information Center.

Specific Issue Not Examined

As a result of this effort we are forced to conclude that to this date no study has been reported which compares the before-and-after effects of dredging the small meandering creeks in a salt marsh.* This does not mean, however, that our search has been entirely fruitless. We have encountered some excellent studies and reports of the effects of other types of dredge modifications to the coastal environment. These, at the least, warn us of the kinds of environmental effects which might be expected; they, at the most, may tell us quite accurately what will happen; and they, in either case, provide clues for minimizing adverse impacts. These are studies of:

(1) Finger-fill canal residential developments in Florida and North Carolina, where bays and/or coastal wetlands (Spartina or mangrove marsh) are dredged and filled into frequently complex and extensive systems of dead-end canals to provide mass-produced waterfront property for homeowners.[(2)(3)(4)(5)]

(2) The channels or canals dredged in the extensive salt marshes of Louisiana's Mississippi delta in order to provide access for barge-mounted oil rigs to drilling sites in the marshes.[(6)(7)]

(3) Field and modelling research reports aimed at identifying ways to mitigate the hazards encountered in traditionally designed, man-made canal developments.[(8)]

The finger-fill canal studies show what happens to the underwater biological environment (the marine habitat) when channels are introduced whose depth and configuration are not what would obtain if they had been formed over an extended period by natural processes. The Mississippi delta studies show what happens when comparatively narrow, artificially-

(*If a proposal submitted to both the U.S. Environmental Protection Agency and the Office of Sea Grant by two University of South Carolina marine scientists in 1979 had been approved and funded at that time, the answers to the specific question being asked most likely would have been in hand at the moment of its asking.)

cut channels in a salt marsh are subjected to a fairly regular passage of power boats. These channels differ from the finger-fill canals in that the banks of the latter are almost invariably bulk headed, rip-rapped or otherwise artifically stabilized, whereas the former are not. The canal-design studies indicate that mother nature, after all, may know best.

SUMMARY OF IMPACTS

What follows is a synthesis of the findings of these reports with initial emphasis on finger-fill canal developments in Florida and North Carolina. They deal with several developments in as many different locations. One site, for purposes of this analysis, is ignored. That is located in the Florida Keys where water, geology and biology are quite different from those encountered in the kinds of coastal areas of concern to us. Comparatively few of the problems that are recounted below are found in the Keys. As one of the authors of the reports remarked to us: "If there is going to be any future for this type of waterfront development, that is where it will be." He paused and then continued, "But wherever they are, if a hurricane comes ashore they will be wiped out."

Each of the reports represents extensive field measurement and sampling programs, some extending for a year, as well as some computer simulation analysis. They were each cited by several of the scientists we contacted and recommended as being the closest thing they knew to what we sought. Included in the synthesized material are the results of surveys of the long-term responses of the oil-rig channels dredged and extensively used in the vast expanses of *Spartina* and *Juncas* marsh common to the outer Mississippi delta region. The design study is treated more or less separately under the section entitled "Discussion".

<u>Man-Made Canal Hazards In Brief</u>

Here is a summary of typical physical, chemical and biological conditions found in many dead-end artificial canals studied in U.S. coastal bay and wetland areas:

(1) There is poor water circulation -- thus poor flushing -- due mainly to excessive canal depth, but aggravated by the great length of some of them.

(2) Center troughs of canals act as traps for silt and organic detritus -- the result of poor flushing -- with adverse effects on biota and water quality.

(3) Where banks are unstabilized and there is power boat traffic, the sides slough into the canal, thus causing it continually to widen.

(4) Excessive suspended solids in the water column cause high light extinction rates, preventing light from reaching lower water levels much of the year.

(5) The water column is sharply stratified with frequently very low-to-zero dissolved oxygen levels in the bottom water layer.

(6) Elevated levels of ammonia nitrogen, a sign of anaerobic conditions, increase longitudinally from the mouth to the head of the canal.

(7) Elevated levels of organic nitrogen (amino acids <u>e.g.</u>) indicate high rates of bacterial activity, again increasing towards the head.

(8) High sulfide levels are found in bottom sediments, the result of the activity of anaerobic sulfate-reducing bacteria.

(9) High coliform bacteria counts rise toward the canal head, frequently exceeding safe shellfish harvesting and human contact levels.

(10) Nutrient (inorganic nitrogen and phosphorus) levels are elevated, causing extended plankton blooms in upper water levels and (sometimes) seasonal algal slimes; both effects worsen towards the heads of the canals.

(11) Number of species and total populations of macroinvertebrates (clams, mussels, oysters, crabs, shrimp, marine worms, etc.) decrease from the mouth to the head of the canal and from the surface to the lower depths.

(12) Finfish species diversity and total populations are lower in the canals.

(13) The canals are net importers of organic carbon and, thus, are "negative producers" -- that is, they consume more biological material than they produce, the result of an interrupted food chain.

(14) Without prior groundwater and geological investigations, the cutting of artificial channels may seriously degrade local freshwater aquifers -- including both loss of well pressure and saltwater intrusion.

Marsh Creeks Not Stressed

In contrast, naturally-formed creeks isolated in tidally-washed Spartina and mangrove marshes exhibit none of these defects. Their shapes and depths provide for easy in-and-out flow of water. There is good circulation and regular flushing, with no signs of oxygen depletion. Elevated ammonia nitrogen levels are not found. Bacterial counts and types are what would be encountered in any normal, healthy environment of the type. There is a net export of organic carbon, meaning they are positive producers. While the mid-channels of the tidal creeks are able to assimilate silt and organic detritus, good flushing prevents any appreciable build-up. During much of the year light extinction rates are high, especially on an ebb flow, but regular tidal changes of water, the general lack of excessive deeps and a continual exchange of top and bottom waters assures that dissolved oxygen levels remain high-to-adequate.

There is a healthy species diversity and total population numbers are high, among both finfishes and macroinvertebrates, among both periodic visitors and permanent residents. If the creeks are large enough, however, to accommodate power boats and if such traffic is excessive, bank erosion will occur even as it does in an artificially-cut canal. This is an unnatural perturbation, a tilting of the dynamic balance, and the system responds to adapt. Its response to waves (including those produced by wakes) is to provide a gently sloping beach to absorb their energy, which, ultimately, the sloughing of the creek banks will do.

ANALYSIS

PHYSICAL CHARACTERISTICS

Typical Example of Residential Canals

A typical finger-fill residential canal is from 40-to-100 feet in width, a few hundred to over 2,500 feet long and with uneven depths ranging from less than five to perhaps 20 feet below mlw (mean low water). The shallowest depth almost invariably forms a sill at the mouth of the canal, while deeps occur at various points along the canal's length, with the deepest portion frequently occurring close to or at the canal's head. Almost without exception, these canals dead end, that is, they connect to another body of water only at one end. The canal is straight, its sides are vertically bulkheaded (most common because it is most economical) or sloped and stabilized with riprap (or occasionally with plants indigenous to the region), and it is lined with as high a density of residential housing as the law permits.

Frequently the waste from these residences does not go into municipal sewer systems -- and thus be transported from the canal site* -- but rather is processed by individually-owned and maintained septic systems. The high ground where the houses are located is typically five feet above mlw, and the direction in which the canal runs is not in line with prevailing winds. The canal is set perpendicular to the body of water (often another canal) to which it is connected. Water depths may be greater than the controlling depth of the water outside. And, finally, the local tidal regime is "microtidal", that is, one meter or less.

It looks great on a developer's model, with its lush little green sponge trees and shrubs, sparkling foil waterways and gaily-colored cardboard houses, and it promises waterfront homes for hundreds of families who might not otherwise have them. In practice, however, it is turning into something of an underwater ecological nightmare, affecting

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(* Even if it is, the treatment plant's main outfall may be close by the finger-fill development -- with the unfortunate results that might be expected.)

not only local marine biological productivity, but also threatening the health of those who live alongside the canals and/or use them for recreational purposes. The health-threatening effects of some such developments extend beyond the finger-fill canal complexes themselves and out into adjoining bays and inlets.

The adverse impacts of such systems may not stem so much from the basic idea of artificially-created, canal-based waterfront property as they do from the ways in which such projects are executed. What follows is a brief examination of those adverse impacts and the reasons why they occur.

WATER QUALITY

The main problems have to do with water quality -- which is often in violation of Federal standards -- and derive almost totally from the location, configuration and bottom topography of the canals. The first problem is their depth which, with the exception of those cut out of hard marl in the Florida Keys, is often uneven, and which, frequently, have depths greater than those needed to accommodate the types of boats that use them.

The "Fjord Effect" The fact that the canal is perpendicular to its associated body of water produces a back-eddy at its mouth with every flow of the tide. This encourages suspended solids to drop out of the water column. Thus, if the dredge didn't leave one there originally, this soon produces a sill at the mouth of the canal. On a small scale, this results in what oceanographers have dubbed the "fjord effect" (Figure 1) -- after the great mountain-lined fjords of the west coast of Norway, which are long bays perpendicular to the shoreline and featuring great depths behind shallow sills at their mouths.

In the fjord effect the water below the controlling depth of the sill almost always develops properties quite different from those of the surface waters. Usually this water is "dead" - devoid of oxygen and all but bacterial life. The Black Sea is a very large and striking example of this phenomenon: From a couple of hundred meters below the surface

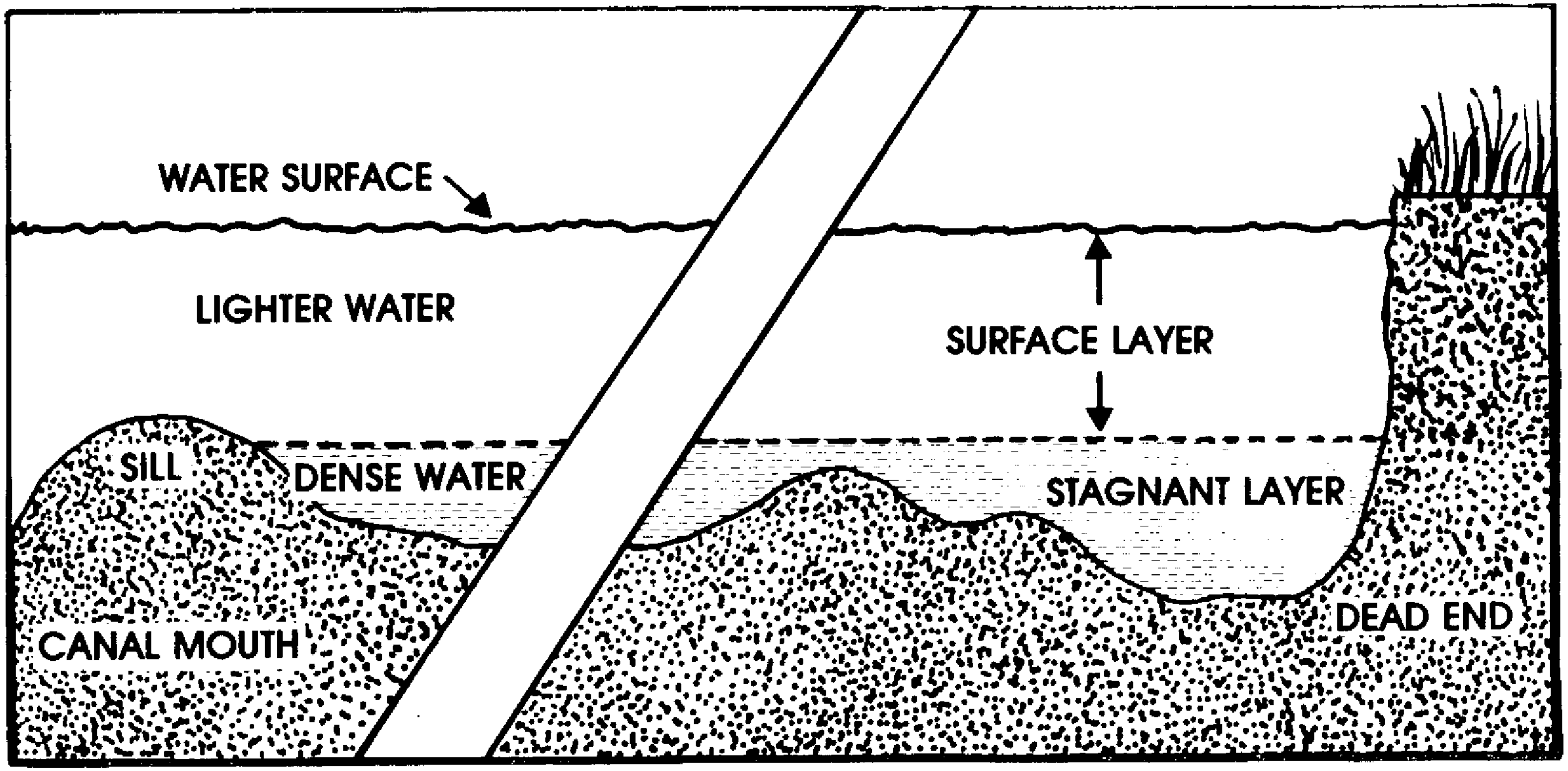


Figure 1: The Fjörd Effect

to the bottom, hydrogen sulfide, not oxygen, is the dominant dissolved gas. In every case of the fjord effect there is virtually no mixing of surface with bottom water. The latter is stagnant and seldom, if ever, changed. In many ways it acts like a false bottom to the water above.

The fjord effect occurs in the first place because the bottom water is heavier than the water above it. This may happen because the surface water is made lighter by freshwater from run-off, rain or rivers -- the case in both the Norwegian fjords and the Black Sea. Or, under the influence of the hot summer sun, freshwater may evaporate from the water's surface, leaving that thin top layer of seawater even saltier than it was to start. Being saltier, it is heavier. Being heavier, it sinks. If it sinks into a hole from which it cannot flow out (blocked by the sill at the mouth), it stays there. Keeping in mind that normal seawater the world over has a salinity of 35 o/oo (parts per thousand) and that water in bays where it is diluted with freshwater will be less than that, it is revealing that salinities in some of the finger-fill canal deeps have been measured at over 40 o/oo.

<u>Stratification</u> When surface water has characteristics quite different from, and is lighter than, the water beneath it, it doesn't mix with it and, in general, moves independently of it. That body of water is said to be "stratified". Fjord waters are stratified. Stratification in residential canals may be severe and, for such small bodies of water, of quite long duration. In one set of Florida canals studied, it was relieved only during a brief period in March-April. It is this stratification that is at the root of many of the canals' problems. It is caused by the sill at the mouth and aggravated by the occurrence of deeps along its length. Without these, stratification would at least be minimized by regular tidal flushing.

<u>Flushing</u> The effectiveness of tidal flushing is a function of tidal range, bottom topography and canal length. Under the conditions of severe stratification we have described, the heavier, stagnant water below acts as a false bottom. The flowing rise and fall of tidal water takes place essentially only in the surface layer, with virtually no mixing with, or disturbance of, the bottom water (Figure 2). It is analogous to oil sliding in over a layer

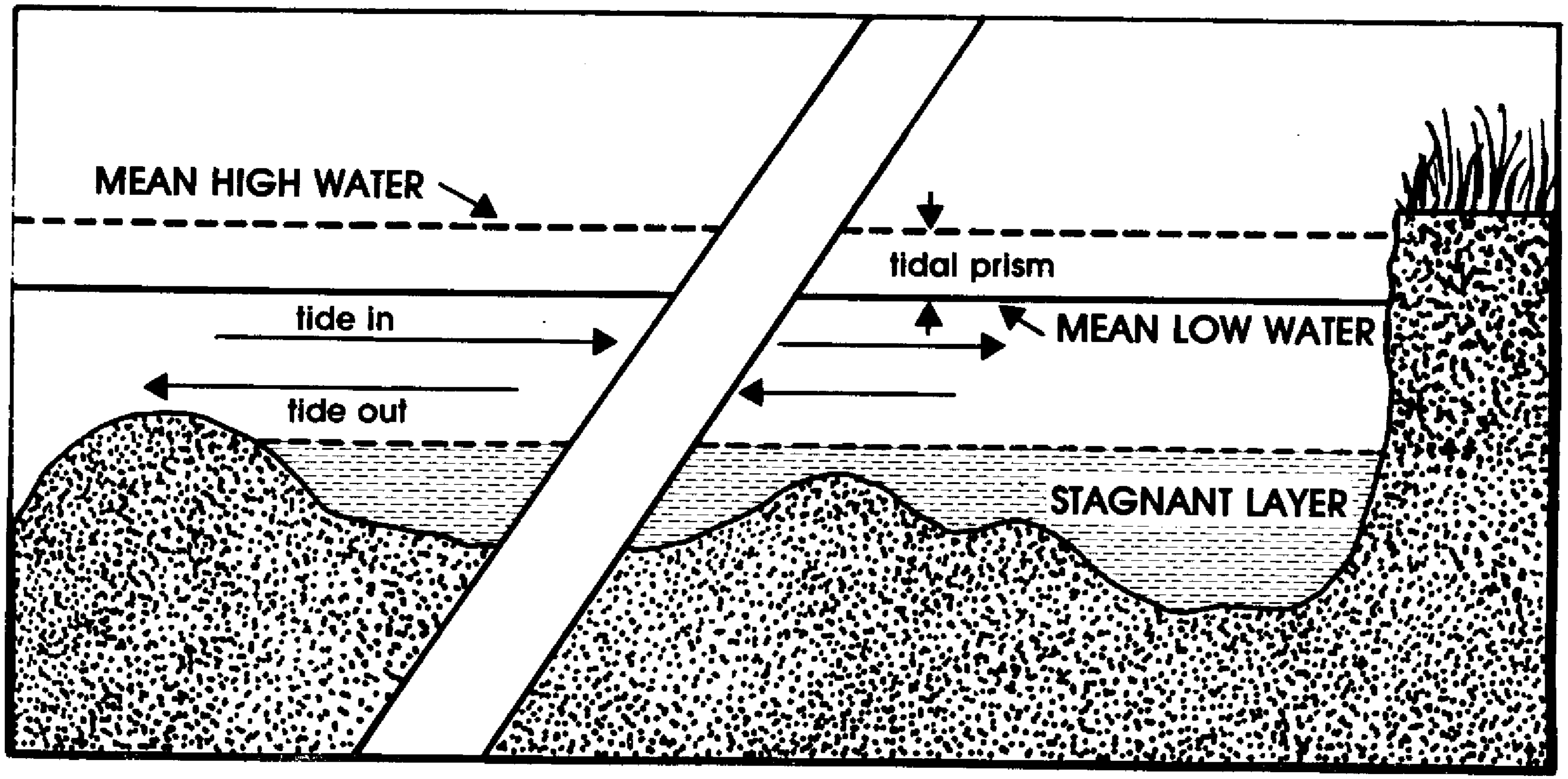


Figure 2: In a stratified system tide goes in and out essentially only in the surface layer.

of water and out again. This is over-simplified, but it is basically what happens.

Effect of Length

But, even flushing of surface water may be greatly degraded. Take a long canal in a microtidal regime where the range between high and low tide is only a couple of feet. Now imagine a parcel of water located at the head of a dead-end canal at high tide. As the tide goes out, that parcel of water will be moved towards the mouth of the canal. If is fast enough and lasts long enough, that parcel will escape out the mouth of the canal. But, with a microtidal regime and a long canal the parcel of water will only be moved part way down the canal before the direction of the tidal flow reverses, and the water parcel is carried back towards the head of the canal (Figure 3). This effect has been checked using both current meters and dye dispersal techniques. In the latter technique a known quantity of dye is injected at a point location in the canal, and then sensitive instruments are used to measure how rapidly it disperses, how far it moves in a given period of time. In one such measurement, it took 285 hours (over 11 days) for the canal to be 90% cleared of the dye. With good tidal flushing in a natural creek, it usually would be done in one or two tidal cycles.

Dispersion Coefficient

One measure of the mixing and flushing characteristics of a body of water is the "dispersion coefficient". This tells over how large an area a point-injected source of pollutant or dye will spread in a given period of time. One way dispersion coefficient units are expressed is in square miles per day (24 hours). In one study(9) the dispersion coefficients of wetland creeks were two-to-three orders of magnitude (100-to-1,000 times) greater than those of nearby canals. The two natural systems had dispersion coefficients of 0.7-to-6.0 square miles per day for one and 2.0-to-2.7 for the other. Of seven canals examined one had a dispersion coefficient of 0.011; all the rest ranged between 0.001 and 0.007 square miles per day. In these respects even the marl-cut canals of Big Pine Key in Florida fared poorly.

Thus, the longer the canals are, the slower is the flushing process, and only the surface water may be affected. Since they are dead-ended, unless there is a freshwater stream flowing into them or there is

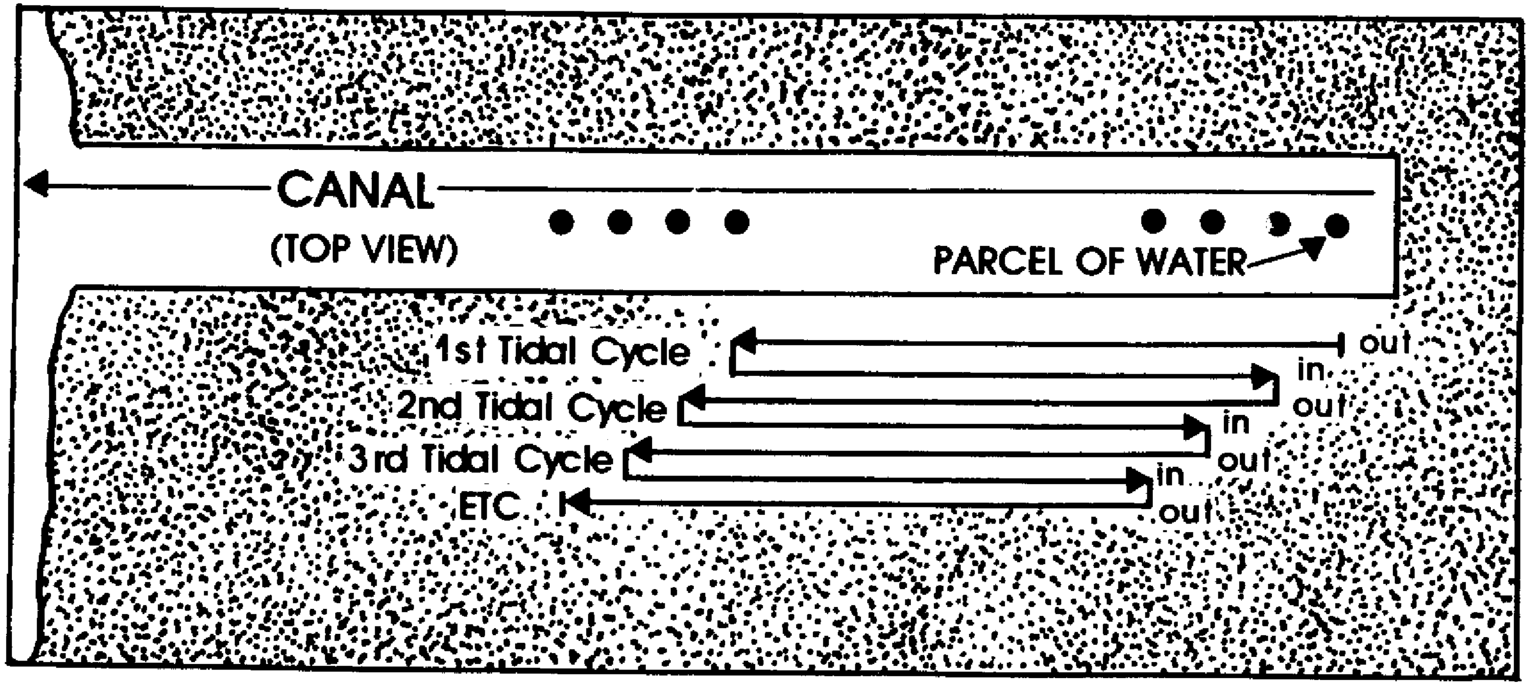


Figure 3: Oscillation Effect in very long canal in a micro tidal regime, where tides carry parcel of water back and forth many times before it is finally ejected from the canal.

runoff from a rain storm, the main mechanisms for flushing are tidal action and the wind*. For the wind to be effective, its direction must align with the longitudinal dimension of the canal, which is infrequently the case. This leaves the tide as the main source of flushing; in a microtidal regime, it is not enough.

So Blows the Wind

If canals are constructed in line with the prevailing winds, waves built up on the surface will contribute to surface mixing and oxygen entrainment. Such mixing will not likely be felt deeply enough, however, to affect stagnant bottom layers. There is another wind effect, though, which can have an appreciable and beneficial bottom influence. It is friction of wind on the water that makes waves. That friction also pushes water before it. Wind blowing down the length of the canal will push surface water out. The water thus removed must be replaced, especially at the upwind head of the canal where removal will be the greatest. The only source of replacement water is the bottom layer, and a phenomenon known as "upwelling" occurs for as long as the wind continues to blow (Figure 4). The dead water is brought to the surface and blown out of the canal. The bottom water is replaced by outside water "sneaking in" over the sill and under the exiting surface water.

There is a similar effect when the wind is blowing up the canal towards the head. The wind literally piles water up at the dead end. Responding to the interplaying forces of buoyancy and gravity (water seeks its own level), that accumulated water has to go somewhere, and the only way it can do is down. The effect is known as "downwelling" (Figure 5). The sinking surface water displaces the bottom layer, pushing it ahead and out of the canal. Winds blowing up the canal, however, may have one disadvantage -- namely the accumulation of wind-driven materials at the head of the canal. This may be especially troublesome if the canals are lined with trees and shrubs which drop their leaves into the water.

(* Under some circumstances density gradients also contribute to flushing, but they do little or nothing to relieve fjord conditions.)

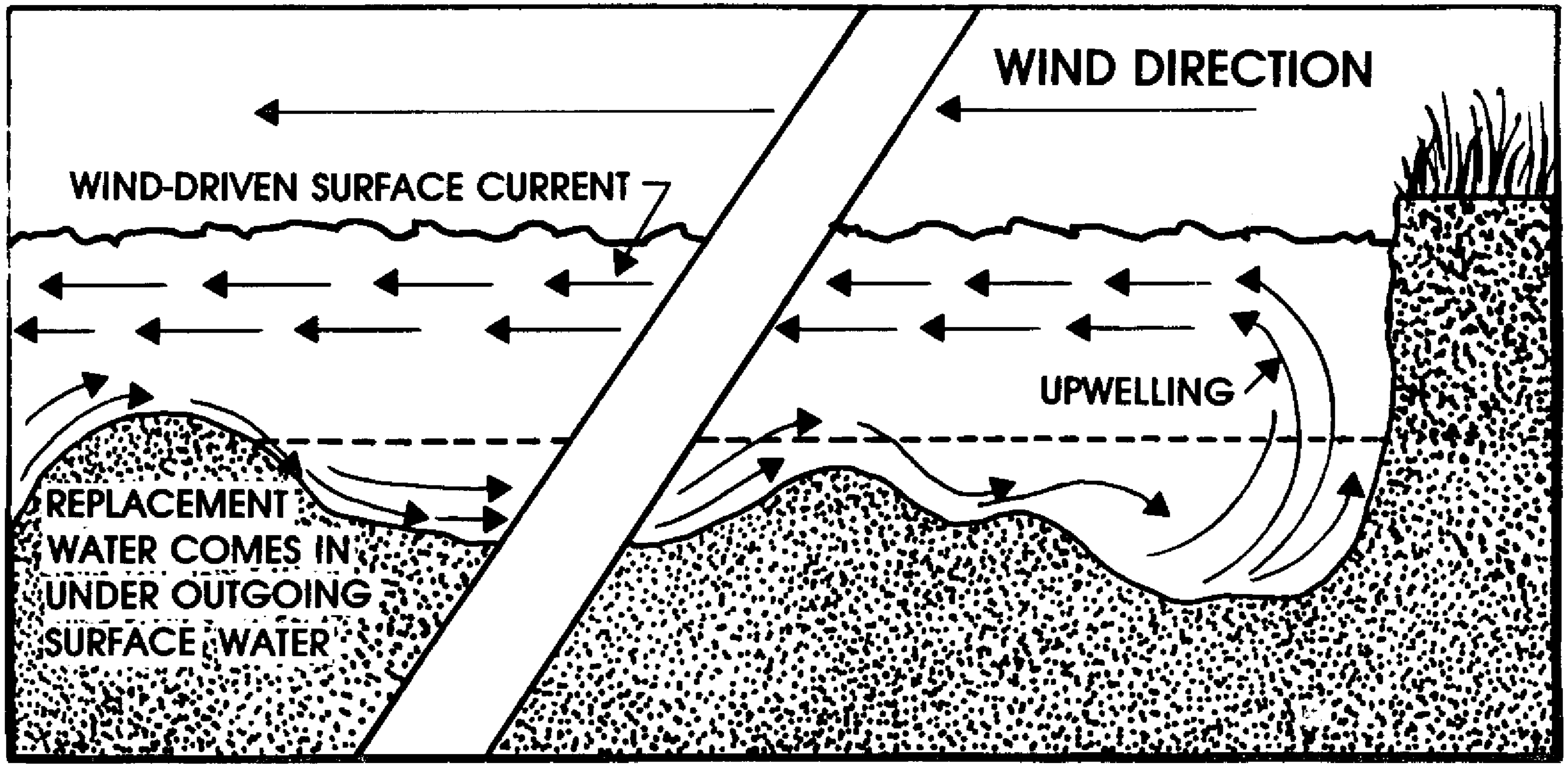


Figure 4: Wind-Driven Surface Current down canal drives surface water out of canal, causing "upwelling" of stagnant bottom water which, in turn will be driven from the canal

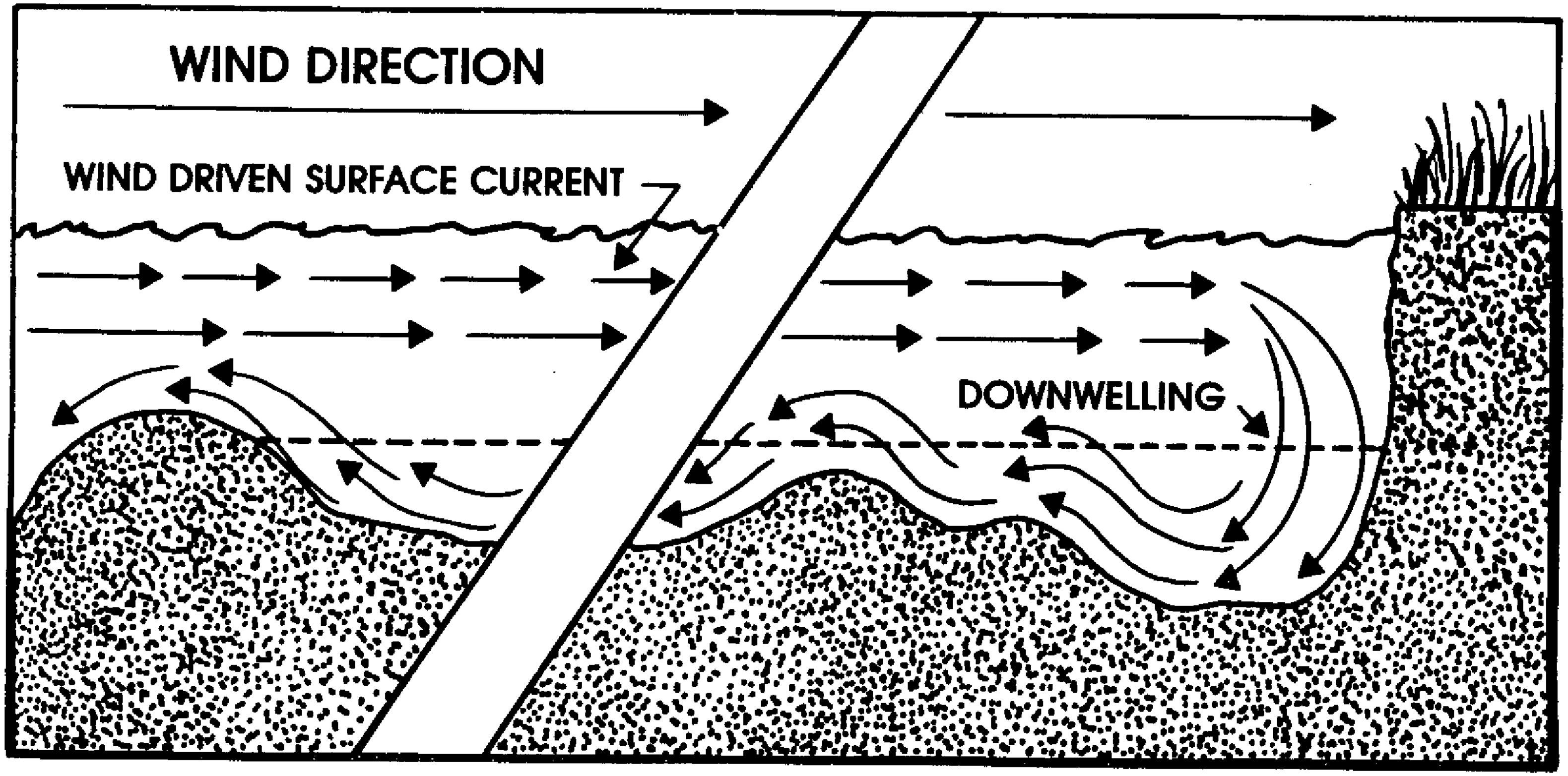


Figure 5: Wind Driven Surface Current up canal piles surface water at the head of the canal causing "downwelling" which pushes stagnant bottom water our of the canal.

<u>Power Boats Inneffective</u> Some may ask: What about the water mixing effects of power boats? The answer is that in most canals (as they have been built) it is not likely to be significant. First of all, the stagnant layer is probably six or more feet below the surface. Further, the interface between the two layers of water -- the surface layer and the heavier bottom layer - acts in a manner similar to that of the air-sea interface. A current in the upper layer, such as that produced by a boat's propeller, will create waves in the lower layer, just as the wind produces waves on the water's surface (Figure 6). But, unless those "internal waves" in effect break, there will be little or no mixing between the two layers. The water will move up and down (actually in a circular motion) and gradually return to rest, as stagnant and intact as it was before the disturbance. Thus, unless passing boats are quite big, moving very fast, or both, they are not likely to have much effect in breaking the anchor lock of that stagnant bottom layer.

<u>Aquifer Damage</u> Carelessly cut canals may degrade local water supplies. There are several ways man-made residential canal developments can endanger shallow freshwater aquifers: (1) The canals may actually cut into them with an immediate loss of pressure and salt-water intrusion; (2) so much of a water-permeable overburden may be removed that the aquifer leaks with a consequent loss of pressure; and (3) if the aquifer is subject to recharging with surface water, contaminants peculiar to the development may find their way to the aquifer and into the wells that use it.

One report[10] mentions specifically Canal No. 13 in Port Royal near Naples, Florida, which in 1959 was dredged to a depth of 20 feet. A number of local wells promptly salted up. The canal had apparently cut into an aquifer. In other cases where there was no saltwater intrusion, there was a widespread loss of pressure. The same report states: "Careless dredging to depths of more than 15 feet in the coastal area of Collier County did great harm and affected local fresh water pressures and lowered them dangerously everywhere." Of course, if it is a large, high-density development and each house has its own well, the aquifer will lose pressure not only from seepage, but also because of the greater demand from the new wells. The ultimate danger from this kind if situation is also salt-water intrusion.

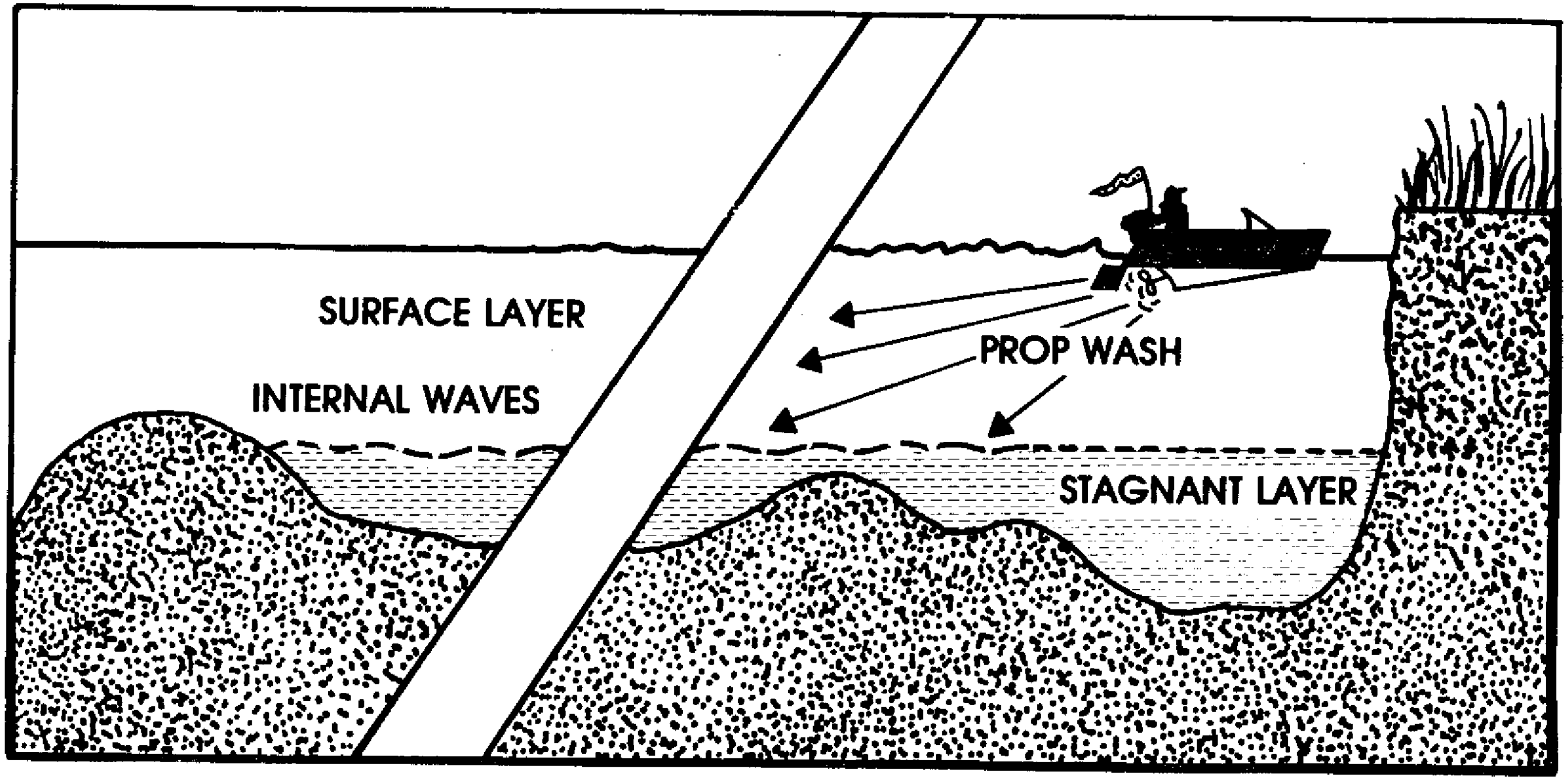


Figure 6: Prop Wash from small boats may set up internal waves at interface between surface layer and denser bottom layer, but there will be little or no mixing.

So, the local groundwater regime as well as the superjacent geology are important considerations when weighing the pro's and con's and decisions with regard to man-made canals in the coastal region.

<u>Surface Run-Off Pollutes Canals</u> Common to the finger-fill canal reports we examined was a concern for the pollution potential of surface run-off discharging directly into the canals. In some instances it could have a more severe impact on water quality than malfunctioning leach fields -- collecting and transporting petroleum products, pesticides, fertilizers, other chemicals, heavy metals, etc., directly into the canals. Not only are the canals polluted thereby, but also the surface water thus discharged is lost as a source for recharging shallow aquifers. It is better that storm runoff be controlled and contained -- by swales, catchment basins, holding ponds, etc. -- or discharged off-site so that (a) its pollution load doesn't reach the canals and their associated marine environment; and (b) the water can slowly percolate through the ground (and thus be purified) and into the aquifer. In addition to contributing to the health of the canal system, this would help maintain pressure in the aquifer by offsetting, in part at least, the higher rate of water drawdown caused by the many new wells drilled because of the development.

<u>Not All Canals All the Time</u> Not all these horror stories are found in all residential canals all the time. They probably occur in most canals some of the time, in response, for example, to particularly unfavorable combinations of conditions which are purely transient in nature. They may occur in many canals much of the time and are known to occur in some canals most of the time. If the reports we have examined are any indication, most of these canal developments have been built the same way with the same objectives in mind. The unfortunate bottom topography of the canals, for example, with their down-canal sills and up-canal deeps, is almost certainly not there because the dredge operator was careless or incompetent, but simply because the need for fill determined how deep he excavated at any particular location. And, most were probably built without any more than a casual consideration of underwater environmental factors. Awareness of the dangers and the levels of knowledge were much less then than they are today. At the time it was a non-problem, and any consideration of it would have been submerged in enthusiasm for new construction jobs, developers' profits,

expanded tax bases, more customers for local merchants and the dreams of prospective home buyers of living on the water.

Bank Erosion The finger-fill canal developments, upon which most of our information to this point is based, have waterways with banks that are bulkheaded, riprapped or otherwise protected from erosion forces, such as power-boat wakes. This would not be the condition that would obtain in a canal or channel dredged in a salt marsh. It could, of course, be a specific requirement of the permitting process that such protection be provided. This, however, might create problems of its own, interfering with both the tidal flooding of the marsh and its normal drainage -- both of which are necessary to the health and survival of the marsh.

The dangers inherent in dredging channels in Spartina marshes and then using them for power boat traffic are well documented[11][12] in studies of the lingering effects in the salt marsh portion of the Mississippi delta. While some canals were dug originally to facilitate the passage of small, muscle-powered boats (pirogues that were poled or paddled) and may be over 100 years old, the greatest impact comes from canals dredged to provide access by barge-mounted oil rigs and their support craft to drilling sites. Some of these date from the turn of the century.

The immediate effect of such activity is to diminish the marsh by the area of the canal plus that of the spoil disposal sites. Experience in this region shows that for every square foot of canal area originally dredged, two additional square feet are destroyed through spoil disposal. These canals also speed the drainage of freshwater flowing into the estuary. This has the effect of degrading overland or "sheet' flow, which deprives the marsh of nutrients, silt and detritus it otherwise would extract from the run-off. By the same reasoning, the water also by-passes the filtering effect of the marsh. Conversely, the tidal prism (the volume of water flowing in and out on each tidal cycle) is increased by the amount of marsh removed and by the fact that the way is expedited for tidal saltwater to push farther inland. In a large and complex estuary such as the Mississippi delta this can have large-scale and serious secondary effects[13], as traditionally-brackish marsh becomes saline, intermediate marsh becomes brackish, and freshwater marsh becomes intermediate. The effect is not dissimilar to what happened to the flora and fauna of the Santee River Delta when the bulk of its freshwater flow was diverted to the Cooper River system.

Canalization of the marsh also degrades its function as a storm buffer, offering less interference to storm waves and making it easier for more water to come in faster and farther. Finally, as the area of man-made canals increases, measurements have shown that the area of natural channels diminishes, "reflecting a change in hydrology as canals are built."[14]

The most serious long-term effect of these canals, of which there are now many, is that they continue to widen[14]. The banks slough in, and the resulting sediment tends to be carried out to sea: The marsh itself is thus "exported". The rates at which this widening occurs vary with the amount and kinds of boat traffic, the speeds of tidal currents, wave effects, storm damage and -- of first-order significance -- "the condition of the marsh substrate; the softer or more fluid and organic the marsh, the more susceptible it is to erosion."[14]

The results of monitoring these canals over long periods of time show that they are widening at rates ranging from 2% to more than 14% per year, yielding doubling times of from 60 to as few as five years. It could have a very large impact in the years ahead. Louisiana is currently losing about 0.3% of its coastal lands each year. The contribution of the canals to this is 2-to-4%, a rate that is an order of magnitude (10 times) greater than the total land-loss rate. If the trend continues, the canals will eventually become the dominant factor in Mississippi delta wetlands loss. Meanwhile, in localized areas the impact is already much greater: Some 10% of the wetlands in Barataria Bay have been lost as a direct result of canal construction[14].

Another problem arising from the dredging of canals or channels in salt marshes is that it has been a common practice to dispose of the dredge spoil in a dike-like "windrow" alongside the canal. This interferes with regular tidal flooding and drainage of the marsh.

BIOLOGY OF THE CANALS

Benthic Desert As might be expected, the altered physical properties of finger-fill residential canals produce an altered biota -- and "altered" in this case usually means much reduced and out of balance. Biologically the conditions of the water in the canals constitute a stressed environment. The canals are frequently murky with particulate matter, both living and dead. Light quickly fades with depth; oceanographers say that it has a "high rate of extinction". Little or no light reaches the bottom water layers. This means that no plants can grow there, neither macrophytes, large plants, nor phytoplankton, the small, microscopic plants that form the main base of the oceanic food chain. Plants cannot live without light, so that source of oxygen is absent. If that bottom layer is stagnant, as it may well be, it gets little or no oxygen from mixing processes or by replacement with oxygen-rich water from the surface. And, what little oxygen may be present is soon consumed by the decomposition of organic matter that falls from the upper water layer. Animals cannot live without oxygen, and the rich benthic community that occupies an undisturbed salt marsh creek is not found in such canals. The deeper parts of the fjord-like canals are anaerobic, no oxygen, which makes them azoic, no life.

Clamming Up If the anaerobic condition is intermittent, not lasting for more than a few days at a time, and if bottom conditions were suitable (a fairly firm substrate with a clearly delimited sediment-water interface) some molluscs might be able to "make do". Oysters, clams, mussels and other bivalves can literally "clam up" (analogous to hibernation) and simply wait it out if salinity or oxygen levels get too low...so long as water temperatures don't go too high. Most bivalves can close themselves off from the environment -- no feeding, no breathing -- for a matter of days. Some, such as oysters, can remain self-isolated for rather longer periods. But, it is an emergency procedure designed to overcome an unusual threat. All members of the community are weakened; some don't make it. If the animals are required to invoke this escape mechanism at frequent intervals, the mortality rate will be high. Those individuals that survive will be few in number and in a weakened condition. And, even if adults survive such conditions, reproduction is greatly reduced, and their progeny most likely will not reach maturity.

Silt Traps — Even where some oxygen is present in the bottom waters, other factors may stress the benthic community. The deeps in the canals serve as traps for silt and detritus. The bottom may be almost impossible tc define as water laden with particulate matter grades gradually into soft muck. The result is a floccule. Bivalves, the filter feeders, cannot tolerate such conditions: Their filter mechanisms become overloaded with silt, and they suffocate. Crustaceans (crabs, shrimp, etc.) meet a similar fate as their gills become clogged. Virtually all finfish will avoid such bottoms for similar reasons and because of the lack of any food. If the bottom were subject to regular periodic flushing, these conditions could not develop.

Organic Carbon — One of the great values of the salt marsh -- or its more tropical analog, the mangrove marsh -- is the contribution it makes as a primary producer: The solar energy, carbon and nutrients it captures and compounds into organic matter that can be eaten by animals. One way to measure this contribution to the local marine environment is to assay the rate at which the marsh exports organic carbon (e.g., fragments of decaying Spartina or mangrove, plankton and the larger animals that come in there to feed or that mature there and then leave).

Natural coastal wetlands are net exporters of organic carbon. They produce more than they consume and donate the balance to food chains beyond the marsh. When a portion of the marsh is destroyed -- by finger-fill residential canal developments, for example -- that production is lost. But, the total adverse impact appears to be worse than that. Not only do these modifications displace natural production, but frequently they become net consumers of what production remains. In a word, they are scavengers.

Measurements of total organic carbon (TOC) in canal waters and in their sediments indicate that they serve as sinks for organic matter. It comes in with the tides, settles out of the water column and is incorporated into the sediments. TOC concentration tends to increase towards the heads of the canals. If they were occupied by a vigorous benthic community, the organic carbon would be metabolized into clams, oysters, crabs, etc., and ultimately into fish. The canal would be a net organic producer. But, because of the benthic anaerobic conditions that frequently prevail, by and large this doesn't happen. While it may be metabolized by bacteria, there the process stops because successive links in the food chain simply are not there.

Nitrogen and Phosphorus

Inorganic nitrogen and phosphorus levels tend to be high, especially with leach fields nearby. This produces plankton blooms which tend to persist longer than they do in the nearby natural environment. While absorption of oxygen from the atmosphere and the photosynthetic activity of the phytoplankton during the daylight hours may keep oxygen levels high enough to support a vigorous zooplankton population, at night when photosynthesis stops oxygen levels drop with a possibly high mortality among the zooplankton. This high level of bio-activity is all taking place in the surface layer; the stagnant, anaerobic bottom layer remains non-productive. If the nutrient load is particularly high and other conditions are favorable (high, bright sun, warm temperatures), it is not unusual to see signs of eutrophication in the form of heavy growths of algal scum. Again, these conditions tend to increase as one moves towards the head of the canal.

Organic nitrogen (in the form of amino acids, the building blocks of proteins) and ammonia (NH_3) both tend to increase in the up-canal direction. This is proportional to the rate of bacterial metabolism taking place in the water column and sediments. Phosphorus levels tend to follow ammonia trends.

Thus, the canals are not only sediment traps but nutrient traps as well. They side-track and permanently remove inorganic nutrients and organic materials that would otherwise continue to be cycled through the marine food chain.

No Intertidal Communities

Finally, the very fact that in many canals there are vertical bulkheads lining both sides will, of itself, restrict species diversity and population densities of a whole class of marine life -- namely the whole of the intertidal and other shallow-water benthic plants and animals. There can be no shallow-water community because there is no shallow water. From this point of view, the ideal canal should have gently sloped banks that are stabilized by plantlife indigenous to the region. Figures 7 & 8 show a comparison of the two approaches.

CLOSER TO HOME

Similar Results

An unpublished paper[15] of the North Carolina Division of Marine Fisheries compares dredged canals and nearby natural creeks in three salt marsh locations along the state's southern coast (below Cape Lookout). Unfortunately the field work consisted of one-time-only spot checks conducted during May 1973, and detailed bottom profiles do not appear to have been taken of the artificial channels. For these reasons the work is considered to be incomplete, and there are no plans for formal publication. Despite these shortcomings, the results are at least interesting, for in many respects they parallel those encountered in the finger-fill canal studies.

Physically, tides in the study area are just barely in the meso-tidal range -- slightly more than one meter. The depths of the artificially-cut box (dead end) channels were greater than those of the natural channels. Bottom sediments were much finer in the artificial channels -- dominated by silts, while sand dominated in the natural channels. There was greater turbidity in the bottom waters of the artificial channels. These also contained hydrogen sulfide, whereas the natural channels did not. Dissolved oxygen levels in the surface waters of both regimes were approximately the same, but the oxygen demand of the dredged channel substrate was twice that of the natural creeks. Total populations and species diversity of the benthic communities of the artificial channels were sharply below those of the natural channels. The number of demersal nekton (near-bottom) species (including shrimp as well as finfish) was much lower in the artificial channels, though total numbers of individuals showed rather lower variations. Lowered species diversity accompanied by increased populations of certain species is a commonly accepted indicator of a stressed environment

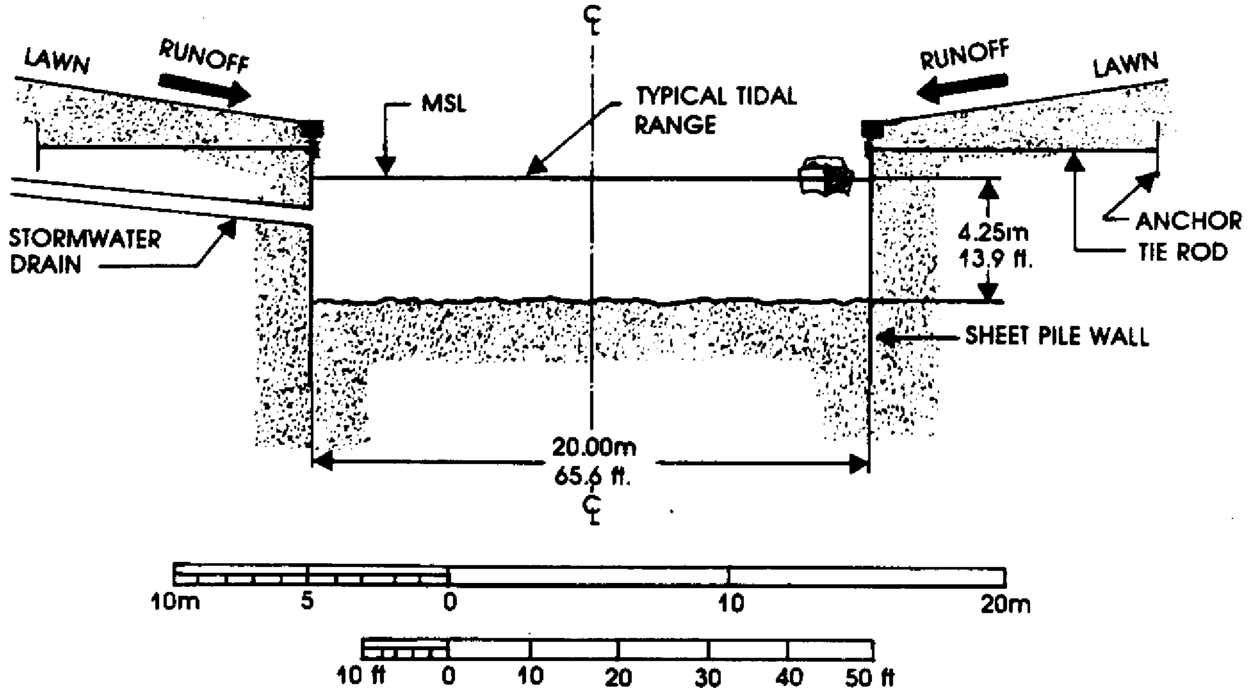


Figure 7: Conventional Bulkheaded Rectangular Canal Section

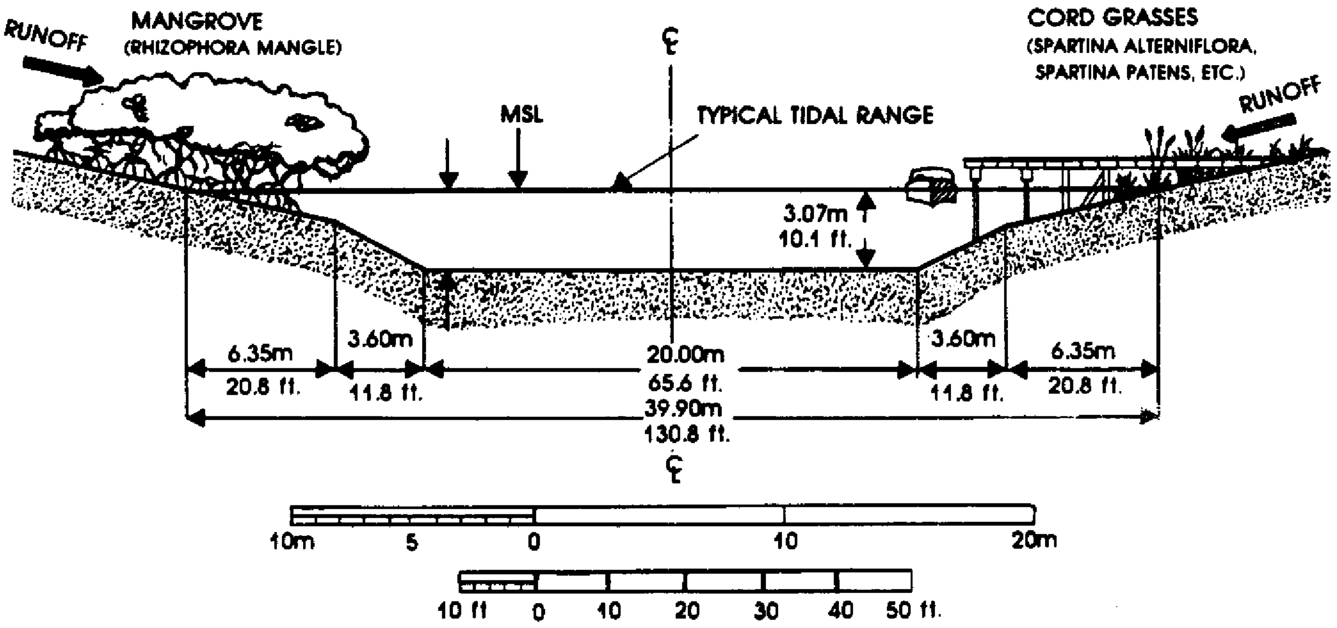


Figure 8: Vegetated Sloping Bank Trapezoidal Canal Section

and is frequently the final phase before total biological collapse. Some minor salinity stratification was noted in both regimes, though it tended to be greater in artificial channels. In a word, the severe fjord effect conditions found in the finger-fill canal studies in Florida and North Carolina do not show up in these measurements. This could well be a function of the fact that only one data set was taken and the fact that it was taken in the spring. It is quite possible that if measurements were to be made monthly throughout the year, some rather sharp differences might be found between natural and artificial channels -- as they have been in other, more extended studies of similar areas a few miles up the coast.

HEALTH THREATS

Anaerobic Bacteria Almost the only life forms that can survive in a marine environment devoid of oxygen are anaerobic bacteria. They are the organisms that process the organic materials that find their way into this otherwise azoic zone. Some are sulfate reducers which explains why such sediments, when disturbed, may give off a strong odor of rotten eggs (from hydrogen sulfide). Other bacteria produce methane; still others, ammonia. Since there are no other consumers in this environment -- to eat the bacteria, for example -- that is the extent of the local food chain. In a normal oxygen-based environment, microscopic meiofauna and zooplankton would consume bacteria along with equally-small phytoplankton. These, in turn, would be consumed by larger animals and so on up the food chain to the fish, shrimp, etc., that are consumed by man.

Enteric Bacteria While larger life forms are depleted in many of the canals much of the time, coliform bacteria counts may be high, especially towards the dead-end heads of the canals. One of the studies[16] reports that: "dead-end stations had fecal coliform densities which exceeded their respective background stations (nearby creeks with good flushing and no abutting residences) by: 43% at Punta Gorda; 1,200% at Big Pine Key; 33,000% at Panama City (Woodlawn

Canal); 50% at Panama City (Hentz Canal); 37,000% at Atlantic Beach; and 3,500% at Spooners Creek."

Coliform bacteria, a major component of animal and human feces, are usually harmless. They are easy to detect and measure, however, and "their presence serves as an indicator of any of the scores of disease-producing microbes found in feces and in water polluted by feces... Waters (with coliform numbers over the legal limit) are not considered safe for body contact or drinking. There is a high probability that they contain other microbes which can cause disease if they enter the body through nose, mouth, eyes, ears, genital organs or cuts."(17) Among the dangerous varieties which may be found in waters with high total coliform counts are (with harmful effects in parentheses):

* Clostridium welchii (severe food poisoning, potentially lethal intestinal infections, gas gangrene).

* Psuedomonas aeruginosa (urinogential infections and burn and wound infections).

* Fecal Streptococci (blood poisoning, sore throats, pneumonias, other infections).

* Staphylococcus (boils, carbuncles, impetigo, other skin infections, pneumonias, blood poisoning, food poisoning).

* Salmonella (Typhoid, other serious intestinal infections, food poisoning).

Some of these species are anaerobic, some are aerobic, and some can thrive in either condition. Whatever their preference, however, all can survive unfavorable conditions (for them) for substantial periods of time before succumbing. Thus, anaerobic species may be contracted in the upper oxygenated water and vice-versa.

Various species of Vibrio, some of which are ubiquitous (e.g., Vibrio parahaemolyticus, a common source of seafood poisoning) throughout the marine estuarine environment, were commonly detected; some strains can cause cholera.

Good Culture Conditions

High bacteria counts in the canals derive from two conditions: (1) poorly functioning leach fields, and (2) favorable culture conditions. In one series of tests it took as little as four hours for dyes injected into household systems to be detected in the adjacent canal. Once the bacteria are in the canals, the high organic carbon content of the suspended particulate matter and of the sediments provide culture points which the bacteria quickly colonize. Higher-than-normal temperatures in the canals further encourage their growth.

In studies of developments with individual septic systems a seasonal variation in the severity of the bacteria problem in the canals was noted and not unexpected. In Florida, for example, counts rose sharply in the late fall and winter -- when seasonal residents returned and when permanent residents had increased numbers of vacationing visitors, frequently overloading their septic systems. The danger, thus, was greatest while the greatest number of people was present to risk infection.

DISCUSSION

SOME RULES OF THE ROAD

If coastal canal developments are going to be permitted, the beginning, at least, of a set of rules for minimizing their adverse impacts is nicely summarized in one of the publications(18) which served as a basis for this report. A much more detailed checklist is reproduced as Appendix I of this analysis. Appendices II and III show the sequences and interrelationships of causes and effects in ill-considered (II) and improved (III) approaches to canal design. Keep in mind that in large measure these summaries are based on studies carried out in coastal areas which vary somewhat from those of much of South Carolina. While they are almost certainly relevant in principal, their specific application under different environmental conditions would almost certainly require some modification.

Here follow the summary recommendations for future finger-fill canal developments, as developed and promulgated by the Athens, Georgia, office of the U.S. Environmental Protection Agency:

(1) Coastal canal developments should be restricted to non-wetland areas. Access canals should be routed from housing developments to

the parent body of water by the shortest and least environmentally damaging course.

(2) During the planning phase of a coastal canal development, a hydrologic investigation should be made to determine the presence of, and project effect on, shallow aquifers. In addition, with consideration of surrounding hydrologic features, circulation patterns of the proposed canal system should be described.

(3) As part of the permitting process, the party responsible for maintenance of water quality standards and/or correction of water quality violations in coastal canal developments should be designated.

(4) Canal depths should not be governed by fill requirements. An appropriate canal depth for shallow draft pleasure craft should be no more than four-to-six feet below mean low water.

(5) Centralized waste collection and treatment systems are necessary in coastal canal housing developments.

(6) No sewage treatment plant effluent or other point source discharges should be discharged directly into finger-fill canal waters. Discharge into surface waters should be sufficiently distant from the canals to ensure that the effluent is not carried into the canal systems by tidal currents.

(7) Surface drainage patterns should be designed with swales to minimize direct runoff into canal waterways.

(8) The grade of canal bottoms should be such that no sills are created at any point in the system, especially at the confluence with the parent water body.

(9) Orientation of the canals should take into account prevailing wind direction so that flushing/mixing would be enhanced and wind drift of floating debris minimized.

(10) To the extent possible, dead-end features should be eliminated from canal system design.

The essence of the recommendations in the Mississippi delta studies is best summed up in one word: "Don't!" Recognizing the reality that some canals will continue to be dredged, however, the exhortation is that it be done in such a way as to "avoid the disruption of wetland hydrology." One of the most recent papers[19], while stressing the inadequacies of the present understanding of all relevant coastal processes, makes the following recommendations:

(1) Construct no new canals that connect (a) the edge and the center of a hydrologic basin, and (b) fresh and saltwater areas.

(2) Plug pipeline canals wherever possible at both ends and at intervals in between in order to reduce water flow and eliminate boat traffic and to decrease the annua. rate of widening. If a canal crosses a natural creek bank, plugs should be placed where the canal intersects the natural tributary.

(3) Build no new wetland impoundments.

(4) Minimize new canal construction by multiple use of existing canals, integrated planning, common use of pipeline canals, directional drilling, etc. The alignment of canals should take advantage of the existing natural or man-made channels.

(5) Reserve adequate spoil disposal sites and easements on high, dry land (nonwetland areas) for future dredging; or use the spoil to build "new" marsh.

(6) Avoid "fingerfill" development in wetlands by restricting residential development and canals to nonwetland areas.

Considering the different purposes for which the two types of canals (residential and oilfield) are intended and the somewhat different coastal regimes in which they are built, there is mutually reinforcing coincidence in the two sets of recommendations. The two bodies of experience should provide a general basis for understanding the potential implications of similar projects in the South Carolina coastal regions.

<u>Need To Look At South Carolina</u>

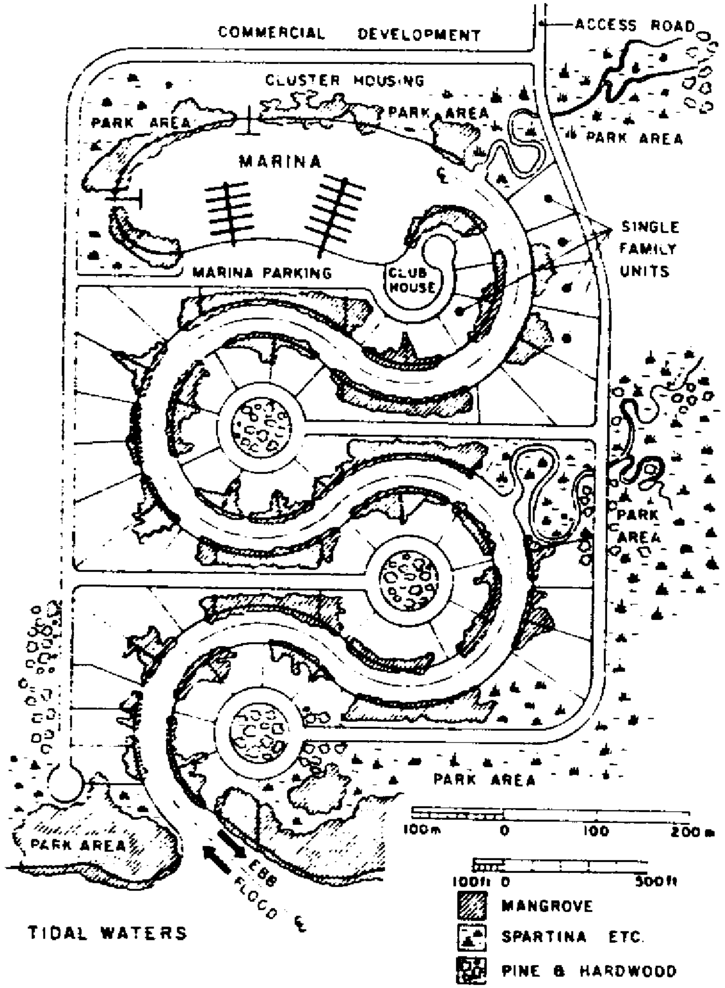
What, in the final analysis, may be needed, however, are specific investigations of conditions as they actually exist along the South Carolina coast -- higher tides, for example, and perhaps different marsh substrates. A number of artificial canals have already been dredged. They are of different ages and varying configurations and built in different locations. As a first step in determining how South Carolina fits into the canal scheme of things, a representative group of these canals -- including the maximum spread of ages -- should be examined to determine what conditions exist in them now, how these compare with natural marsh creeks and how, if at all, canal conditions change with age. Do bottom sediments after years of flushing, sifting and grading, for example, finally approximate those of natural creeks? Does the biota finally achieve a more or less normal balance?

Next, and ideally, a demonstration canal should be constructed, using the best know-how available in pre-construction planning and site selection, in canal system design and specification, in construction and in quality control. A thorough base-line data set should be established before construction, and a regular and extended period of post-construction monitoring should be undertaken of both the canal and the surrounding area.

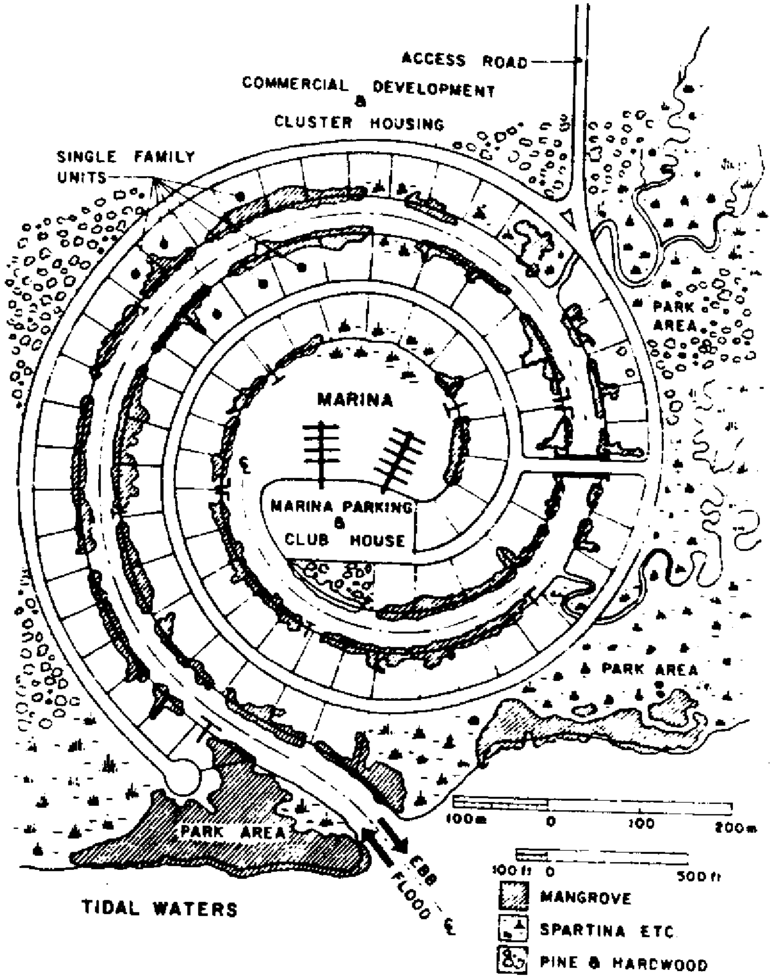
Following In Nature's Way

Recent field research and computer modelling investigations show that the meanders in salt marsh creeks are not without their advantages[20]. They may point the way for constructing artificial canals that do not suffer from the stagnation problems found in existing systems. In addition to depth and bottom contour control, the results of this work stress the advantages of (1) constructing a large pond or reservoir at the head of dead-end canals, and (2) laying out the canal itself in a series of meanders or bends (Figure 9).

The reservoir would assure a stronger tidal current in the canals, especially important in microtidal areas, by causing more water to flow in and out of the canal with every turn of the tide. In a word, it would increase the tidal prism. Tidal range in conjunction with canal length and width would determine the necessary surface area of the reservoir. So long as there is an adequate main tidal current, the meanders produce secondary helical currents which move surface water to the bottom and bottom water to the surface. Stagnation would not get the opportunity to occur, and, thus, anaerobic conditions could not develop from this cause. Why this secondary flow is established is really quite simple. It also provides a rationale for the river-boat pilot's long-standing dictum: "Take the long way home", why the deep water is always on the outside of the curve. As the flowing water passes through a meander, it pushes against the outer bank of the creek or canal and tends to pile up against it. Indeed, there is an upward slope to the water's surface measuring from the inside to the outside of



Canal System With Reversing Bend



Canal System With Spiral Bend

Figure 9.

AFTER MORRIS [8]

the curve. In response to gravity and more water pushing against it, the water piled up against the bank takes the only route open to it: It goes down. In so doing it pushes the water in front of it out of the way, and bottom water, having nowhere else to go, rises to the surface. All the while the whole water mass is moving up (incoming tide) or down (outgoing tide) the creek (Figure 10).

If you were to follow one single parcel of water, you would see that it followed a helical path -- traveling from the surface to the bottom on one side of the canal, across the bottom and up to the surface on the other side, across the surface and down again, and so forth -- as it also moved along the length of the canal. If you were to take the meanders out, the water parcel's path would look like a stretched coil spring, or a barber's pole, lying on its side.

CONCLUSION

It may be possible, then, to construct artificial canals that replicate in many ways the ecological benefits of natural channels. In *Spartina* marshes, however, erosion will remain a threat. In this case it is not so much a matter of canal design and construction techniques as it is the purpose for which the canal is built -- namely boat traffic. Will this cause erosion of the marsh? It depends on the nature of the marsh's substrate and the kind and intensity of boat traffic.

If there is erosion and flushing rates are high enough, the navigability of the channel will be maintained while the substance of the marsh is swept seaward. If there is erosion and flushing rates are not great enough, the channel will silt up, and a program of maintenance dredging will be required. As noted earlier, artificial protection of the bank (bulkheading, riprap, etc.) would probably cause unacceptable interference with normal flooding and drainage of the marsh. Other problems of canal design and construction, however, appear to have been solved. Perhaps with more research and inspiration, this one will be too.

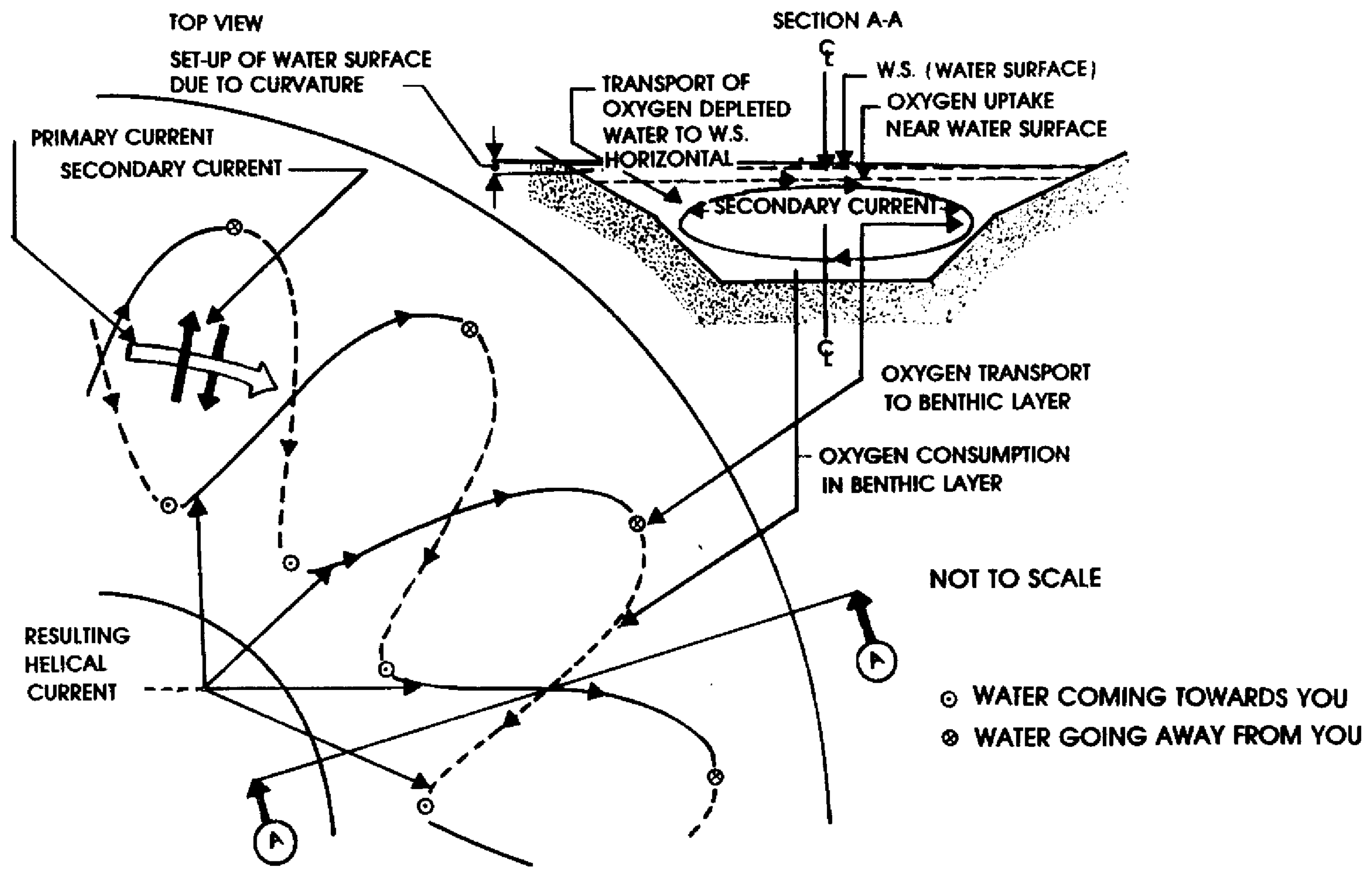


Figure 10: Idealized Helical Flow in a Bend.

FROM MORRIS [8]

There remain other potential problems, however, such as modification of rates and patterns of the flow of seawater towards the freshwater regime of high and fast land and, conversely, of freshwater to the sea (both previously noted). Spoil disposal is an ever-present and frequently contentious problem.

How these factors are weighted in the decision-making process and treated in the establishment of permissible design specifications (if any) depends in large measure on the particular conditions that prevail in the region where such projects are proposed to be undertaking. With its 1-to-2-foot tidal range and tremendous seaward expanse of wetlands (upwards of 150 miles in places) grading from Spartina to Juncus to increasingly freshwater ecologies and with its many streams, lakes, swamps, etc., the Mississippi delta is quite different from the southeast Altantic coast environment which, for one, is an alongshore rather than an offshore system, which may have tides 2-to-3 times as great and which, in general, has a proportionally lower input of fresh water.

The rules of physics, chemistry and biology are the same in South Carolina as they are in Louisiana or Florida, but the milieu in which they operate is different. For this reason there is a need to investigate how both the problems and the solutions apply. Differences will likely be of degree rather than substance. But a lack of understanding of differences of degree can easily produce results that differ in substance and in their application produce the very adverse impacts one seeks to avoid. However, there appears to be a sound knowledge base upon which to build. It is on such a foundation of understanding that any workable and acceptable program of balanced and ecologically-acceptable development or conservation depends. With understanding there may not be any reason why one day development and conservation cannot be synonymous.

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Appendix I

FROM MORRIS (8)

Design Element	Specific Characteristics	Guideline
Banks	Stablization	S.oping, vegetated banks should be used along as much of the canal as practical to provide protection against erosion.
	Slope	Slope should be determined for protection against the highest practical design flow. Multiple slopes are one possible alternative. Geotechnical slope stability must be assured. Piping to be avoided.
	Protection	Vegetation provides most economic bank protection.
	Aquatic life	Sloping banks provide habitat for shallow-water fish and wildlife.
	Curvature	Curvature of banks induces secondary flows which assist in vertical mixing.
	Discontinuities	Banks should transition gradually from slopes to bulkheads.
Beds	Holes	Beds should not have discontinuities such as dredge holes or sills. Deep depressions act as nutrient traps and do not easily flush.
	Stabilization	Beds can be protected against erosion, in some instances, by introducing aquatic vegetation. Deposition can be controlled to some degree by smoothing discontinuities in the geometry that can cause local low velocities, or reducing erosion in other parts of the canal network.
	Roughness	Bed roughness may be artificially increased to increase vertical mixing, which utilizes more of the total energy in the flow and may thereby reduce flushing in other parts of the network.
Boats Basins and Marinas	Flushing	Basins should be designed with a smooth entrance transition, same depth as canals, and favorable circulation for flushing. Proper orientation with prevailing wind substantially assists flushing.

	Access channels	Basin access channels should be designed to maximize flushing and avoid stagnant or recirculating areas.
	Existing shoreline configurations	Basins should be planned to minimize the extent of excavation, shoreline alteration, and disturbance of vital habitat areas.
	Waste handling	Marina design must incorporate facilities for proper handling of sewage, refuse, and waste.
	Siting	Basins should be sited to avoid boat traffic across shallow grass flats or in locations where boat wakes could be harmful to vegetation or unstabilized banks.
Bulkheads	Usage	Use of vertical bulkheads should be minimized in canal networks.
	Siting	Bulkheads, if used, should always be located shoreward of wetlands.
	Permeability	Bulkheads are often collapsed by infiltration and erosion onthe land side. Proper drainage, or a permeable structure, and footing extending far enough below the bed need to be considered.
	Reflection of wakes	The adverse effects of reflected boat wakes may be minimized by alternating bulkheads on both sides of a canal (facing each bulkhead with a vegetated sloping bank directly across the canal).
Circulation	Overall in network	Circulation throughout the canal network is enhanced by smooth transitions and increased tidal prism at inland extremity of canal network.
	Vertical circulation	Vertical motion of water is caused by turbulence,wind, bends, salinity gradients, and large rougness elements.
Curvature	Canals	Curvature of canals induces helical secondary flow which enhances vertical mixing and persists some distance downstream of the bend.
	Aesthetics	Curved channels can provide a more natural appearnce, especially if banks are sloped and vegetated.

Dead-ends	Circulation	Dead-end reaches have substantially less circulation than flow-through canals.
	Wind	Dead-end reaches must be aligned with prevailing wind to provide an opportunity for intermittent flushing. Orientation should be with wind away from dead-end. Opposite orientation permits wind driven waters to carry debris into canals, which can settle to bottom, decay, and increase local BOD.
Depth	Photic limit	Excessive depth precludes light penetration to the bed, where aquatic vegetation can grow under proper conditions.
	Transitions	Depth of canal should be the same as, or gradually transition from, other adjacent sections in the canal system.
	Geometry	Depths, widths, and other parameters need to be determined by comparative simulations using a numerical model. Depths cannot be determined independently.
Detention	Design	Detention reservoirs should be designed for a specific design storm and drainage plan.
	Control structures	Detention systems permit controlled amounts of infiltration and release at a flow approximating the predevelopment volume.
Drainage	Saltwater intrusion	Drainage of wetlands decreases freshwater storage capacity, both at the surface and in the aquifer, which may permit further intrusion of the saltwater interface.
	Patterns	Before development occurs, natural drainage patterns of the site and the surrounding region should be identified and incorporated into the site design. This will avoid interrupted flows and will enable the new design to work with established drainage patterns, which should not be modified any more than necessary.
	Wetlands	Wetland areas should not be drained or developed. These are too valuable in their natural conditions as nurseries for aquatic life.

Dredging	Canal beds	Hydraulic dredging can result in uneven canal bottoms, and therefore must be used with skill and caution.
	Wetlands	No dredging should be permitted in productive wetlands.
	Aquifer	Dredging into a shallow freshwater aquifer will accelerate the loss of freshwater to the sea and the intrusion of the saline interface farther into the aquifer.
	Canal entrances	Canal entrances should be located so as to minimize destruction of fish and wildlife habitat. An entrance must be sited so that the channel, and boat traffic, will traverse the smallest amount of productive wetland vegetation or shallow productive bottom substrate.
	Navigation channel size	Navigation channel dimensions should be kept to the minimum size consistent with circulation requirements in the system.
	Dredging operations	Dredging operations should be stopped during critical periods of fish migration and feeding. If the operation interfers in such migration and feeding.
	Dredge types	Dredge types should be selected so as to minimize environmental disturbances during operation.
	Dredge spoil	Dredge spoil should not be disposed of in open estuarine or receiving waters or in vital areas. Curtains should always be used.
Entrance Design	Location	Canal entrances should be located to minimize destruction of fish and wildlife habitat during construction.
	Minimizing erosion	Entrances and associated offshore channels should be situated and marked so as to minimize erosion of adjacent or opposite shoreline by boat traffic.
	Gradual transition	Entrances should have a gradual hydraulic transition from the interconnecting waterbody.
	Stabilization	Entrance banks should be sloped for shoreline stabilization.

Erosion	Stable cross-sections	Beds and banks should be designed with stable cross-sections to prevent erosion.
	Vegetation	Beds and banks should be stabilized with vegetation to prevent erosion.
	Construction details	Bulkheads should be properly designed with filter cloth, graduated fill, tie-backs, wingwalls, adequate toe penetration or other firm foundation, and adequate drainage to prevent erosion.
Fill	Wetlands	Fill should not be placed in wetlands.
	Foundations	If fill is to be used for foundations, it must be properly graded and compacted with minimal destruction to surrounding vegetation.
	Raised foundations	Raised foundations (piles) will eliminate the requirement for additional fill, if this technique is acceptable to permitting agencies.
	Dredging	Fill should not be dredged indiscriminately from canals, and preferably should be obtained from offsite. The canal designer must provide appropriate instructions to the contractor regarding the depth and uneveness of dredging that will be permitted.
	Drainage	Fill must be placed and prepared with adequate drainage.
Flushing	Transitions	Design channels with gradual transitions for lowest energy loss.
	Tides	Small amplitude tides have limited effectiveness in flushing.
	Length of canals	Canals extending long distances from canal entrances will require additional energy sources (such as moderate or high prevailing winds) to provide adequate flushing.
	Wind effect	Flushing effectiveness of winds is maximized by orientation of channels in direction of prevailing winds.
	Bends	Channel bends increase flushing through induced vertical circulation.

	Roughness	Local flushing may be increased by increasing the size of roughness elements in the channel. The use of roughness must be balanced with the available energy budget.
Groundwater	Offsite supply	Consider off-site supply to minimize groundwater withdrawal.
	Drainage plan	Maximize groundwater supplies by an appropriate drainage plan.
	Saltwater intrusion	Limit groundwater withdrawal to minimize saltwater intrusion into the aquifer.
	Subsidence	Limit groundwater withdrawal to avoid subsidence of land.
	Absorption fields	Design septic tank absorption fields for adequate filtering before seepage into groundwater supplies and canals.
Mangroves	Preservation	Mangrove areas bordering coastal waters or tidal channels should be preserved as buffer zones to maintain water quality and shoreline protection. Mangroves also help to retard runoff, maintain aesthetic values, and maintain habitat for aquatic life and birds.
	Permitting	Mangroves should be preserved to minimize permitting problems.
	Re-establishment	Mangroves should be re-established in shallow areas suitable for their propagation.
Mixing	Roughness	Use roughness elements to increase local turbulent mixing.
	Bends	Channel bends can be used to produce local vertical mixing through the action of helical flows.
	Wind	Use channel alignment with the prevailing wind to increase vertical mixing.
Natural Preserves	Protection and Aesthetics	Allocate a significant portion or portions of the site for natural preserves to protect wildlife and retain aesthetic appeal.

Recharge	Drainage	Design drainage plan to retain all runoff for recharge to the aquifer.
	Retention and Detention	Direct-runoff to vegetated swales and retention or detention ponds rather than to curbs, gutters, and storm drains.
	Paved areas	Minimize paved areas and roof area to maximize area available for recharge.
	Wells	Avoid the use of deep wells into the Floridian Aquifer unless the wells are properly cased and sealed. Otherwise deep wells may contaminate the shallow freshwater aquifer.
	Criteria	Use the following criteria for delineating an area suitable for aquifer recharge: 1. Geologic formation must be permeable. 2. Water must be available in the form of rainfall or runoff. 3. Maximize area of permeable surface. 4. Provide recharge area sufficient to balance depletion of water through evaporation, runoff into canals (if any), and usage. 5. Recharge area should be relatively pristine. Agricultural lands and areas near sewage outfalls are least desirable.
Retention	Runoff	Provide storage areas to retain runoff which cannot be handled by detention.
	Volume	Retention volume should be calculated by considering a suitable design storm and the drainage plan for the site.
Revegetation	Preservation	Minimize requirements for revegetation by preserving as much vegetation as possible during construction.
	Construction	Revegetate areas needing vegetation for runoff control as soon as possible after construction.
	Indigenous species	Revegetate shallows and banks with appropriate plant species.
	Plant communities	Provide for plant communities that are mutually compatible.

Roughness	Distribution	Distribute bed and bank roughness as required in the canal network to avoid stagnant areas.
	Energy losses	Control unwanted energy losses by minimizing local roughness as necessary.
Runoff	Control	Control site drainage by means of vegetated swales, filter mounds, re-tention or detention ponds, and vege-tation to preclude runoff into canals.
	Erosion	Control drainage so that runoff cannot cause erosion.
	Septic drain fields	Control drainage so that runoff cannot affect operation of septic absorption fields.
	Separation	Separate stormwater drainage from waste water disposal systems.
Saltwater Intrusion	Groundwater table	Maximize the potentiometric head (elevation of the groundwater table) on. and in the vicinity of, the site to minimize saltwater intrusion.
	Drainage	Retain as much drainage water as pos-sible on site to minimize saltwater intrusion.
	Off-site supplies	Use off-site water supplies to minimize effects of well drawdown.
	Hydrologist	Use the services of a competent hydro-logist to obtain measurements on site if saltwater intrusion is a problem.
Sedimentation	Water velocity	Design canals for adequate velocities to carry suspended sediments out of canals.
	Banks and beds	Design canals with stable banks and beds to minimize the amount of eroded material in suspension.
	Sediment control: · canals	During construction, use sediment blankets or barriers in the canals to avoid sedimentation of offshore areas.

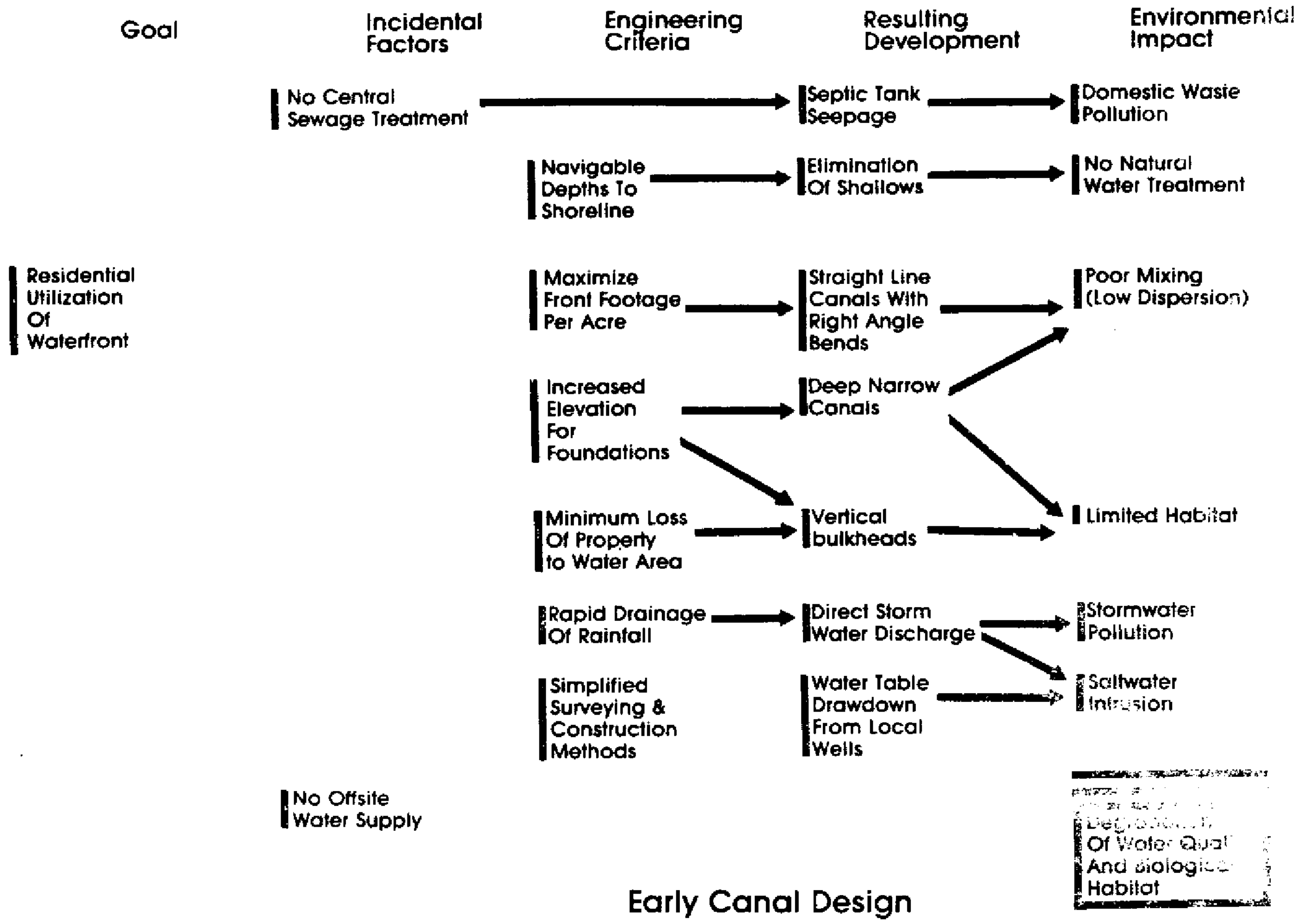
	• land	During construction use preventive measures, such as sediment basins, to keep sedimentation from runoff out of canals, and after construction promptly replant cleared areas.
Septic Tanks and Drain Fields	Alternatives	Consider alternatives, such as offsite waste treatment or onsite package treatment plants, as substitutes for septic tank systems.
	Location	Do not install septic tanks or drain fields close enough to canals to permit leaching into the canals or high water flooding of drain fields.
	Tests	Test borings should be conducted prior to construction to determine soil types and hydrologic conditions.
	Soils	"Septic tank systems should be installed only when soil characteristics are suitable" [Clark, 1977, p. 505].
	Setback	"The absorption field of a septic tank system should be set back at least 150 feet from the annual high water line" [Clark, 1977, p. 503].
	Groundwater level	"Septic tank systems should be installed only when the highest annual groundwater level is at least four feet below the absorption field" [Clark, 1977, p. 504].
Shallow areas	Vegetation	Include large shallow areas in the canal system where practical to provide space for re-establishment of intertidal vegetation, which provides nutrient uptake and a varied habitat for aquatic animal species.
Sills	Plug	Do not permit a sill to remain at the mouth of a canal after a plug has been removed.
	Communicating waters	Do not dredge canals deeper than the depth of the communicating waters. If this is necessary, provide a gradual transition from the entrance into the canal.

Site Characteristics	Before purchase	Determine hydrology of site and surrounding area, and hydraulic characteristics in the communicating waterbody, before purchase of the site.
	Before construction	Determine site characteristics on both long and short term bases from available information and extensive measurements before construction.
Slopes, Bank	Stability shallows wind	Use gently sloping banks to provide channel stability, intertidal shallows and greater canal surface area for wind-induced flow and for oxygen transfer from the surface.
Soils	Before purchase	Determine characteristics of soils at the site before purchase.
	Bearing capacity	Check soil bearing capacity prior to moving heavy equipment on to the site.
	After construction	Make certain that all soils that can sustain plant life are revegetated as soon as possible after construction.
Stabilization	Methods	Stabilization is best provided by vegetated sloping banks, then rip-rap on a sloping bank, and least, by bulkheading.
	Inlet	Provide a smooth transition from the communicating waterbody into the canal and integrate it with a mild sloping bank while providing the required protection against storms.
	Control erosion	Control erosion during site preparation and construction by planting buffer strips of natural vegetation, and providing artificial detention systems and runoff diversions.
Tides	Differential	Use more than one tidal entrance especially if they will be sufficiently separate to provide an elevation difference.
	Neap tide	Base design calculations on neap tide amplitude which provides the lowest amount of tidal energy to a canal system.
	Tidal prism	Use tidal prism as a design tool to increase flow through interconnecting channels and basins such as marinas.

Vegetation	During construction	Do not destroy or remove any more native vegetation than necessary during construction.
	Native varieties	Plant native, indigenous vegetation in preference to exotic species.
	Stabilization	Use vegetation to stabilize beds and banks, control runoff, provide habitat and aesthetic appearance, take up nutrients, and provide screen between dwellings.
Waste Disposal	Control	All waste waters should be controlled until they have been either treated, or disposed of offsite in an environmentally safe way.
	Mixing	Waste waters and storm waters should not be mixed, since only waste waters require treatment before recycling.
	Aquifer, septic tank systems, package plants	Improper disposal of solid and liquid waste can contaminate the aquifer. Septic tanks normally are not suitable for coastal development. Package treatment plants may be considered and must be placed above the 100-year flood level.
	Marinas	Marina designs must incorporate facilities for the proper handling of sewage and waste.
Winds	Alignment	Channels with poor flushing characteristics should be aligned in the direction of the prevailing wind.
	Water surface width	The effectiveness of wind in developing vertical secondary mixing circulation is increased by increasing the width of the water surface in the canals
	Trees	Since trees along canal banks retard the lower layers of wind, which decreases the mixing effect, their screening effect should be reduced if there is no other way to provide mixing in an existing channel.
	Simulations	In testing different canal configurations it is important to use typical variable winds for the site during simulations.

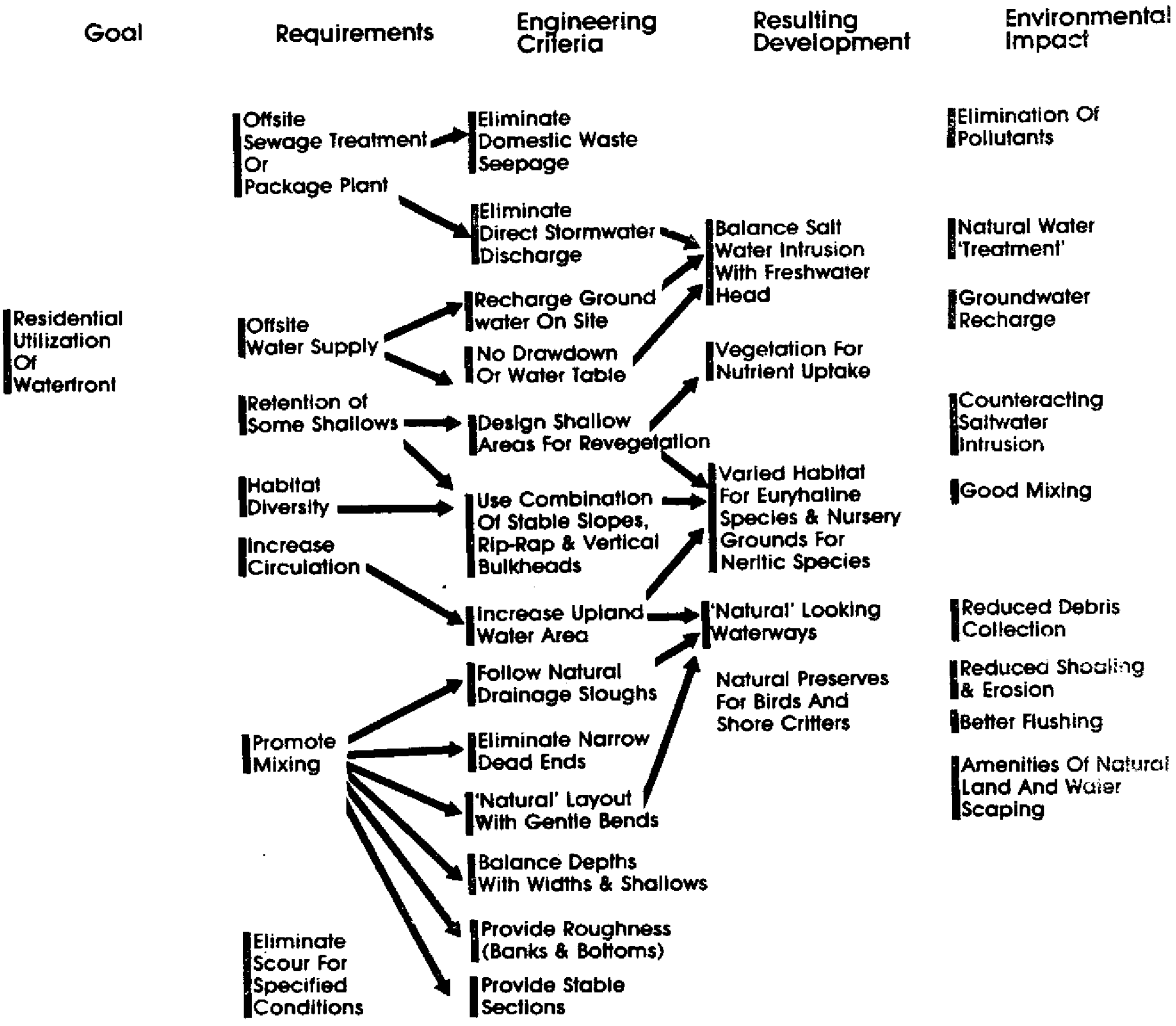
Appendix II

AFTER SNYDER (21)



Early Canal Design

Appendix III
AFTER SNYDER (21)



The Rational Approach to Canal Design