Ecological Effects of Highway Fills on Wetlands: Examples from the Field

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To establish a more comprehensive base of empirical evidence on interactions between highways and wetlands, case studies were conducted at eight highway sites in wetlands at various U.S. locations. Selection of the study sites was based in part on a comprehensive review of literature on highway-wetland interactions. The conclusions drawn from the case studies also reflect information obtained from the literature review. Since all case studies involved analyses of wetlands in which highway-induced changes had already taken place, the effects that were observed or deduced were largely limited to major, long-standing changes resulting from the continuining physical presence of a highway facility. Four classes of effects appear to dominate: (a) altered drainage, the most common effect; (b) interrupted tidal exchange, a manifestation of altered drainage found in tidal areas; (c) physical obliteration of wetlands resulting from the placement of highway fill or disposal of dredged material; and (d) habitat creation, included not because of its general occurrence but as an example of what can be done in many instances.

Wetlands are among the most biologically productive ecosystems in the world, often surpassing forests and managed farmlands. Like all ecosystems, wetlands can be partly understood by studying their most prevalent or dominant vegetation and interrelated animals and microbes. These biological features are dependent on the physical environment and thus vary widely according to climate, physiography, and soils or other substrate features. But, regardless of other variations in physical conditions, wetlands occur because there is water present on a permanent or reliably recurring basis above or within the surface soils, and it is the presence or absence of this water that exerts the greatest single influence on wetland ecology.

By altering the hydrologic regime, and through other means, the placing of highway fills on wetlands can have significant physical and biological effects on the natural environment and the ecological processes of the affected area. In addition to the direct physical alterations that result from construction activities, there are often physical, chemical, and biological effects that extend well beyond the construction and right-of-way corridor. This cascading of effects beyond the immediate site of impact is much more likely to occur when wetlands (in contrast to uplands) are involved, since wetlands are, almost by definition, those units of the landscape that receive, detain, retain, and discharge both surface and groundwater flows. As such, each wetland may reflect even the smallest change in the waters that feed it, and these changes may in turn be transmitted to other wetlands downstream.

Both coastal and inland wetlands have been well studied by biologists for many decades. The resulting literature provides a comprehensive, but essentially static, picture of wetland biota in terms of individual species and biotic communities and their distribution by geographic area and type of wetland. Within the past decade or so, the study of wetland dynamics—the interaction of wetland species and biotic communities over time—and associated changes in wetland productivity has been greatly aided by improved scientific theory and extensive use of computer simulations. From these relatively recent advances in ecosystem modeling there has emerged a growing understanding of how wetlands interact with other ecosystems and of the relationship between wetlands and local and regional hydrology.

In an effort to establish a more comprehensive base of empirical evidence on highway-wetland interactions, a set of case studies was conducted at highway sites in wetlands across the United States. The choice of field sites and the conduct of the studies were strongly influenced by the resources available to the investigators and by the lack of documented information on which instructive case studies could be based. There are few instances in which the physical and biological characteristics of a wetland have been documented before, during, and after construction of a highway facility. Since our resources did not permit the acquisition and analysis of primary data, we were almost wholly dependent on secondary information, supplemented by our own after-the-fact, on-site observations. Further contributing to the problem is the fact that relatively few highways are built in pristine wetlands—that is, wetlands unaltered by the prior construction of railroad embankments, water control and drainage structures, and other works of man. Thus, the effects of the highway are often confounded, if not totally obscured, by the effects of prior, or subsequent, alterations. For these reasons, what is reported here is a forced compromise between what we would have preferred ideally and what was actually possible.

As can be seen in the map of the lower 48 states shown in Figure 1, a reasonable approximation to geographic comprehensiveness was achieved. The eight case study sites range from Oregon to Massachusetts and from Minnesota and North Dakota to Florida. A wide range of wetland classes is represented, including examples of both tidal and inland situations. The studies include a variety of highway types, from gravel roads 50 years old or older to Interstate highways. Nevertheless, vast areas of the country, particularly the West Coast and south-central and southwestern regions, are not represented. However, the nature of the effects that are reported on is such that, in many instances, experience in one area can be transferred to another.

The various study locations and wetland classes and the primary effect or effects caused by the highway in question are given below:

Location	Type of Wetland	Effect of Highway
Whately, Massachusetts	Borrow pit ponds	Habitat creation
Fairfield, Connecticut	Estuarine salt marsh	Interrupted tidal exchange
Philadelphia, Pennsylvania	Freshwater marsh	Obliteration by fill
South Florida	Freshwater marsh and wooded swamp	Altered drainage
Roscommon, Michigan	Wooded swamp over organic soils	Altered drainage
Northeast Minnesota	Wooded swamp over organic soils	Altered drainage
Jamestown, North Dakota	Prairie potholes	Altered drainage, obliteration
La Grande, Oregon	Cattail-bulrush marsh	Altered drainage

Figure 1. Case study sites.

The information derived from each case study is organized according to type of ecological effect. Emphasis here is on those effects that tended to predominate in several studies or that are most graphically illustrated at one or more study sites. Since all of the case studies involved a retrospective analysis of a wetland in which highway-induced changes had already taken place, the effects that were observed or deduced were largely limited to major, long-standing changes resulting from the continuing physical presence of a highway facility. There was no opportunity, given the nature of these studies, to observe such significant, but relatively transitory, effects as erosion and sedimentation resulting directly from ongoing construction activities. The absence of such effects from these case studies, therefore, reflects not their lack of importance but the practical limitations of the case studies themselves.

Of the many effects of highways on wetlands that were identified in the case studies, four classes of effects appear to predominate:

1. The most common effect by far is altered drainage; indeed, to a greater or lesser extent, all of the case studies (with the exception of the Whately borrow pits) provide evidence of this class of impact.
2. In total area, the effects of altered drainage are manifested as interrupted tidal exchange, and this class of effect is placed in a separate category.
3. The physical obliteration of wetlands as a result of the placement of highway fill or disposal of dredged material was also a commonly identified effect of highway construction.
4. The fourth class of effect, habitat creation, is included not because of its general occurrence but as an example of what can be done in many instances.

ALTERED DRAINAGE

Wetlands are defined in various ways; in each case, however, it is the presence of water in and on the soil that is critical to the definition—and the existence—of wetlands. Thus, for example, the U.S. Fish and Wildlife Service defines a wetland as "land where water is the dominant factor determining the nature of soil development and types of plant and animal communities living at the soil surface" (1). The U.S. Army Corps of Engineers defines wetlands as "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions" (2).

The hydrologic regime is the controlling feature in wetland ecology, and alterations in this regime will have profound effects on the environment. Wetland plant communities are dependent not only on the presence of water but also on the frequency and amount of inundation. Changes in community structure can be expected when any of these characteristics are altered. The exact nature of the change will depend on the new water regime, the species composition of the former community, the available seed sources, and other factors. In most parts of the nation, the occurrence of water in wetlands is the result of seasonal patterns of precipitation, freezing, thawing, and the rate at which plants use water (transpiration). The duration and timing of these influences are a stochastic phenomenon particular to a given geoclimatic area. Thus, the concept of "normal flow pattern" in wetlands is understood as a pattern of flow probability with volume, time, location, and duration of occurrence.

Highways and analogous structures impound the flow of surface water and groundwater to a greater or lesser degree and thus tend to raise water levels on the upflow side of the structure and lower levels on the downflow side. Conversely, directing water around and at specific places through the structure may concentrate the flow from the affected watershed to specific aquifers, channels, and wetland areas, thus raising water levels in those areas. These effects are usually most apparent where sheet flow is intersected by the highway embankment. Attempts to accommodate the interrupted flow by means of culverts are generally successful only in protecting the highway structure. The change from diffused to concentrated flow results in a significant disruption of the hydrologic regime, which is reflected in alterations in the associated ecological system. Two types of sheet flow should be distinguished: surface and subsurface.

Subsurface Flow

Subsurface sheet flow is essentially ubiquitous, representing as it does the manner in which groundwater typically moves through the earth. But it is in organic soils, which underlie many classes of wetlands, that the interruption of subsurface flows often presents a problem. The Roscommon, Michigan, and northeastern Minnesota study sites exemplify this situation. In both cases, the highway embankment interrupted the movement of subsurface flows, which led to the elevation of the water table on the upstream side of the highway. Where culverts were installed, they were generally placed too high and too far apart to significantly affect the upstream buildup of water.

Large areas of the several states and Canadian provinces that border the Great Lakes are overlaid to various depths with peat and other poorly drained soils. These areas are typically dominated by various species of wetland conifers, the harvesting of which is a major economic activity. Extensive damage to timber has been observed on the upstream side of highways and other embankments crossing peat wetlands. The U.S. Forest Service estimates that in northern Minnesota alone more than 30 000 areas of swamp conifers have been so affected.

The nature of the problem is shown in Figures 2 and 3, which are taken from the Minnesota study. Figure 2 is a planimetric view of a typical wetland crossing and the area in which flooding occurs. The road is shown running parallel to the contours of the land and positioned so as to cross the wetland at its narrowest point—a typical situation. The cross-hatched area upland from the highway represents the location of inundation caused by the blockage of drainage. Because of the geometry of the basin, the extent of this zone of inundation is usually considerably larger than the area immediately adjacent to the road.

Figure 3 shows a profile view of the area shown

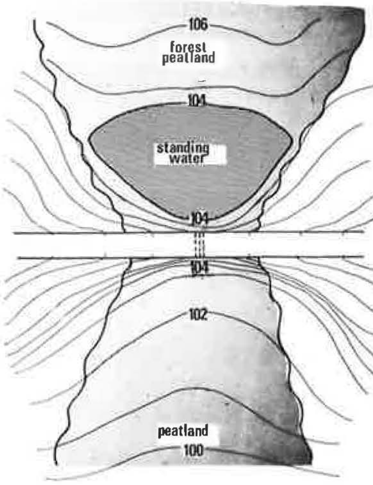


Figure 2. Planimetric view of typical peat wetland crossing showing area in which flooding occurs.

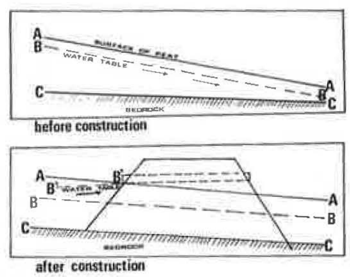


Figure 3. Hydrologic problem and water table relations in roads crossing peat wetlands approximately parallel to the contour.

planimetrically in Figure 2. In part A of the figure, the level and direction of flow of the water table are shown by the broken line from B to B. In undisturbed peat wetlands, the water table tends to be located 10-50 cm below the surface during much of the growing season, and it is in this zone that most of the horizontal movement of water through the soil takes place. Below 50 cm or so, the soil is consolidated because of the weight of the overlying soil, and little, if any, movement of water occurs in this near-impermeable medium.

Part B of Figure 3 shows the effect that the construction of the road has on the level of the water table. In the first instance, the road fill acts as a dam, blocking the movement of water along and below line B-B. The peat immediately below the fill is consolidated by the weight of the overburden, and this effectively reduces its hydraulic conductivity to zero. Since only the upper 50 cm of the peat is hydraulically active, almost any combination of fill, displacement, and consolidation will impede the movement of water across the line of fill regardless of the depth of the peat layer. The water that is impounded by the fill will rise at the embankment to the level of the culvert; the level of the water table will assume a position along line B^1-B^1, intersecting the undisturbed water table B-B some distance uphill from the road.

The invert elevation of the culvert relative to the undisturbed water is the most important design feature affecting the inundation caused by construction of the road. Typically, the culvert is located at or above the point of intersection of the embankment with line A-A so as to intercept surface flow in a more or less defined channel. Although this practice may suffice to prevent overtopping of the roadway by storm runoff, it does not provide adequately for subsurface flow, which is the primary means of drainage in peat wetlands during much of the year. Flooding and damage to timber in the area above the road are almost inevitable. (Highway-induced flooding may also have a beneficial effect on wildlife by providing open water, standing dead trees, and other favorable habitat. Because of these and other wildlife benefits, fish and wildlife agencies periodically request the creation of highway impoundments.)

The extent of the damage that results from highway-induced flooding and the road design and location features most frequently associated with such damage were investigated in 1965 by the North Central Forest Experiment Station of the U. S. Forest Service (3). A systematic random sample of 70 forest wetland crossings in seven contiguous counties in northeastern Minnesota was studied to determine the extent of damage done to trees by the damming effect of roads. The roads studied had all been in place for a considerable period of time, many for 50 years or more, and all could be classified as low standard in terms of design features such as width, surface type, foundation, and drainage. Eighty percent of the crossings were on peat, the rest on mineral soil. The timber involved was mainly black spruce and tamarack. Northern white cedar, black ash, red maple, and associated species were also present.

Tree damage was classified into three categories: (a) no damage, (b) trees killed or weakened within 15 m of the road, and (c) trees killed beyond 15 m of the road. Of the 70 sites included in the sample, 55 percent showed some degree of damage. All of the 39 crossings that showed damage were within 45° of being parallel to the contours along which they ran; that is, they tended to run across rather than along the drainage flow. The apparent rise in water table in the zone of most serious tree damage averaged about 28 cm for the 39 crossings, the greatest rise being 76 cm.

A comparison of U. S. and European practice in the design of road drainage features in organic soils suggests several steps that can be taken to prevent the damming action of roads that cross peat wetlands. European practice calls for the excavation of a collector ditch along the upstream side of the road. Culverts are placed so that their inverts are at or near the bottom of the collector ditch, 1 or 2 m below the original level of the swamp. A discharge ditch, perpendicular to the roadway, to carry water beyond the influence of the road is also recommended. A perpendicular entrance ditch on the upstream side of the road and an additional discharge ditch running parallel to the downstream side may also be used. Figure 4 shows the location of the various ditches (3).

The location of these drainage features in profile and their effect on the water table are shown in Figure 5. The dimensions and location of the various drainage features will, of course, vary with conditions at the site.

The converse of the blocked-drainage problem observed in the Michigan and Minnesota cases is found at Ladd Marsh, in La Grande, Oregon, where the water table has been lowered as a result of highway construction activities. The manner in which both the surface and subsurface water regimes have been altered by highway activities at this site is shown in Figure 6. The Foothill-Ladd Canyon Road was constructed with borrow. Drainage for the road is provided by a ditch along the uphill (west and south) side of the road. In the absence of lateral culverts through the road embankment, the surface sheet flow that formerly fed the marsh is now diverted around it. A secondary source of sheet flow from the north is intercepted by a pre-existing drainage ditch at the end of the marsh. The deprivation of water for the marsh is compounded by the borrow ditch along the west side of I-80N, which has lowered the subsurface water table in the marsh

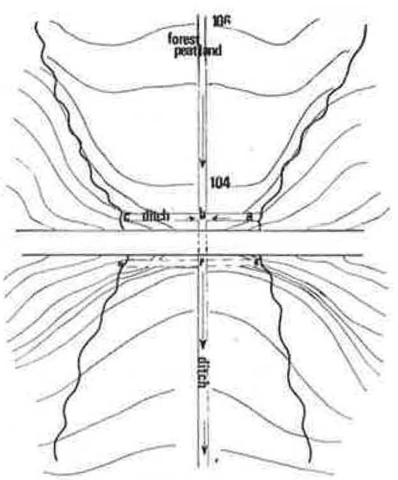


Figure 4. Location of various ditches to ensure proper drainage of peat wetland road crossing.

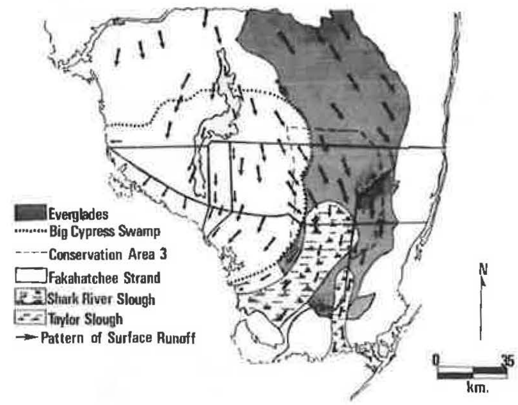


Figure 7. Everglades and Big Cypress wetland complexes in southern Florida.

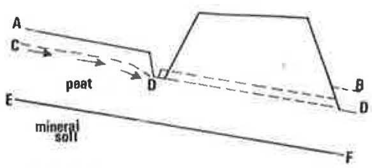


Figure 5. Collector ditch.

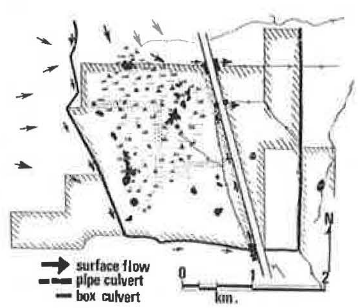


Figure 6. Ladd Marsh, Oregon.

by reducing the base grade at which groundwater discharges.

The combined effect of these hydrologic changes has been to lower the water table in the marsh during all seasons, thus changing the vegetation from wetland to upland and slowly eliminating areas of open water that are important to waterfowl and other marsh animals. Despite attempts by the Oregon Game Commission to divert runoff back into the marsh, over the past 29 years wetland area has been reduced by 15 percent.

Diffused Surface Flow

The effects of highway construction on wetlands that are dependent on diffused surface drainage are most dramatically illustrated in the Everglades and Big Cypress complexes of South Florida. The marsh and swamp systems of these two vast wetlands receive the bulk of their water from surface runoff and sheet flow over shallow aquifers. The natural flow is generally from the latitude of Lake Okeechobee on the north, south through the Everglades and Big Cypress, and exiting through the mangrove forests that border Florida Bay and the Gulf of Mexico (see Figure 7). Although highways occupy only a minute fraction of this vast area and generally do not block critical flow points, their construction has contributed to significant changes in portions of the region.

These changes stem principally from two aspects of the highway construction process. In the first instance, the presence of roadway embankments across the axis of primary flow has the potential for blocking sheet drainage, much as in the cases of the Minnesota and Michigan peat wetlands discussed earlier. In Florida, however, the bulk of the flow is above the aquifer and can often be effectively accommodated by proper culverting. Where this has been done—as in the case of FL-27 between the Everglades Park entrance and Flamingo—the drainage-related impact of the highway embankment is negligible. Where provisions for surface drainage are not adequate—as along the western portion of Alligator Alley—backwater conditions develop on the upstream side of the highway and are reflected in the drawdown of the water table on the downstream side. These hydrologic alterations inevitably produce changes in vegetation.

The effect of highways in the Everglades-Big Cypress environment is very much a function of the presence or absence of drainage canals associated with the construction of the roadway embankment. Unlike FL-27, which was constructed with borrow from sites well removed from the right-of-way, the other Florida roads in our study were constructed on fill obtained from borrow-canal spoil excavated along the right-of-way. Although these canals are used as flood-control structures at critical periods during the year, they also serve to collect sheet drainage on the upstream side of the highway and to facilitate the reestablishment of sheet flow on the downstream side. Where the combination of parallel canals and adequate culverts at all natural drainage channels is sufficient to reestablish natural drainage immediately downstream from the highway—as along the Tamiami Trail and the eastern portions of Alligator Alley—little if any ecological effect is observed.

It is important that a balance be struck between too little and too much drainage. For example, connecting the borrow canal along Alligator Alley to the south-running Barron River and Turner River Canals has accelerated flows south of the alley and directed water away from the historic pattern. Similarly, the borrow canals along FL-29 and FL-840A, which run parallel to the north-south drainage axis between Alligator Alley and the Tamiami Trail, intercept substantial amounts of surface water and divert it directly to the estuaries of Florida Bay. There is evidence that the reduction in freshwater head that has resulted from this diversion has led to inland migration of saltwater.

The Flamingo Road demonstrates that, if highways must be constructed across sheet-flow wetlands, extensive use of culverts without borrow canals can have minimal effects. The original construction of the Tamiami Trail suggests that borrow canals in combination with culverts need not have adverse effects but that they lay the foundation for subsequent disruption of the wetland ecosystem. Alligator Alley illustrates that, even when attention is given to the effect on hydrology, modern techniques of road and borrow-canal construction need further refinement if uniform desirable results are to be obtained. FL-29 and FL-840A are examples of a straightforward effort to use a combination of canals and no culverts in conjunction with a spoil-bank base to drain a wetland, with questionable economic and adverse ecological effects.

Appropriate drainage features are obviously necessary for avoiding ecological damage in the Everglades-Big Cypress environment. But, given the destructive effects of many of the activities associated with roads such as the Tamiami Trail, it is clear that proper drainage alone will not suffice. Rigid control of access is also essential to preventing adverse impacts and further inappropriate uses of these vast wetlands. Reconstruction of Alligator Alley to Interstate standards will provide an opportunity to develop a major demonstration of compatible road construction and wetland protection.

INTERRUPTED TIDAL EXCHANGE

Interruption, by embankments and other structures, of the tidal exchange in coastal and estuarine marshes is an important, special case of altered drainage. The twice-daily ebb and flow of tidal waters is essential in maintaining the level and salinity of these salt and brackish marshes and in carrying detritus from marsh areas to the marine environments that rely on this source of nutrient. Highway drainage structures are typically designed to accommodate storm flow from upland sources. The capacity of the culvert, its invert elevation, and the erosion protection measures associated with it are characteristically based on the need to convey storm waters that flow down from upland locations. Insufficient attention is often directed to the passage of tidal waters, which, during part of their cycle, move through these structures in a direction opposite to the design flow. The result of such "unidirectional design" is often the alteration of the tidal regime within the marsh.

The ecological effects of restricted tidal exchange are illustrated by the Fairfield, Connecticut, study. Pine Creek Marsh is a 9.6-km^2 estuarine salt marsh on Long Island Sound in the town of Fairfield. A storm- and flood-control dike was constructed in 1970. The location of this dike and changes in the dike and culvert system that have been proposed in an effort to mitigate effects of tidal interruption on the marsh are shown in Figure 8.

The interruption of tidal flows by the dike has resulted in an average 23-cm reduction in tidal elevations within the marsh and a reduction of as much as 46 cm during spring tides. Groundwater levels have receded well below that required to support two common species of marsh grasses. The reduction in tide height has reduced the total marsh area that is exposed to saltwater and, in combination with lowered groundwater levels, has resulted in a shift of vegetation from salt marsh to fresh; at the landward margins of the marsh, upland species have begun to replace the wetland biota. Where upland or freshwater species have become established, the peat soils of the original salt marsh have become compacted and less permeable. As a consequence, even if current efforts to restore the historic tidal hydrology are successful, the capacity of the marsh to support salt marsh species would be reduced.

The restriction of saltwater intrusion into an estuarine system by a highway acting as a barrier to or restrainer of tidal inundation will greatly affect a wetland. Where saltwater intrusion is prevented by a highway barrier, plant populations will show slow but significant changes. Many estuarine plants actually grow well in freshwater but cannot compete successfully with freshwater species in that environment because of slow growth and lack of viable seeds. Some estuarine plants require salt for growth and will die in freshwater conditions. The estuarine species of macroscopic algae and microscopic diatoms will be replaced by freshwater species.

PHYSICAL OBLITERATION

The physical obliteration of wetland habitat by the highway embankment itself is an unavoidable consequence of that form of construction. When such loss of habitat is unacceptable—for example, when a unique wetland may be lost or rare or endangered species may be threatened—rerouting of the highway or open-pile construction may be the only alternative. However, there are many situations in which loss or alteration of habitat through physical obliteration extends well beyond the highway fill. The construction of I-95 through Tinicum Marsh in Pennsylvania is a case in point (4).

Tinicum Marsh occupies the lowlands along Darby Creek in Delaware and Philadelphia Counties in southeastern Pennsylvania. Before construction of I-95, the marsh covered about 200 km^2 between PA-291 and the Tinicum Wildlife Preserve of the city of Philadelphia (see Figure 9). Though the marsh area has been greatly disturbed and considerably reduced in size over the past 300 years, it was, and still is, an important, tidally inundated freshwater environment. No rare or endangered species consistently live or breed in Tinicum Marsh, but the habitat itself is rare, being the last remaining tidal wetland in the state of Pennsylvania.

In the initial planning phase for construction of I-95, a compromise between the Pennsylvania Department of Highways and local conservation groups in 1963 provided for the routing of the highway along the southern edge of the marsh, where it would have interfered least with tidal flows and would have obliterated the least amount of marsh habitat. This compromise, however, was not included as a restriction when construction bids were advertised in 1968. The project contractor, unencumbered by the earlier compromise, negotiated contracts with the private owners of the marshland to obtain sand and gravel lying under the marsh for roadbed fill. These contracts also obligated the contractor to fill other parts of the marsh to a level above the highest tide so that light industrial facilities, high-rise apartments, or shopping centers could be erected. Even though this filling was not a direct result of roadbed construction, the entangling contracts tied it intimately with highway construction. The location and extent of the marsh areas destroyed or altered by these related activities are shown in Figure 10.

CREATION OF NEW HABITAT

Highway construction may result in the creation as well as the destruction of wetland habitat. Habitat creation is often the unplanned result of borrow-pit excavation or the inadvertent blockage of surface or subsurface drainage by a highway embankment. Increasingly, however, provisions for the creation of new habitat are being in-

Figure 8. Proposed restoration of Pine Creek Estuary, Fairfield, Connecticut.

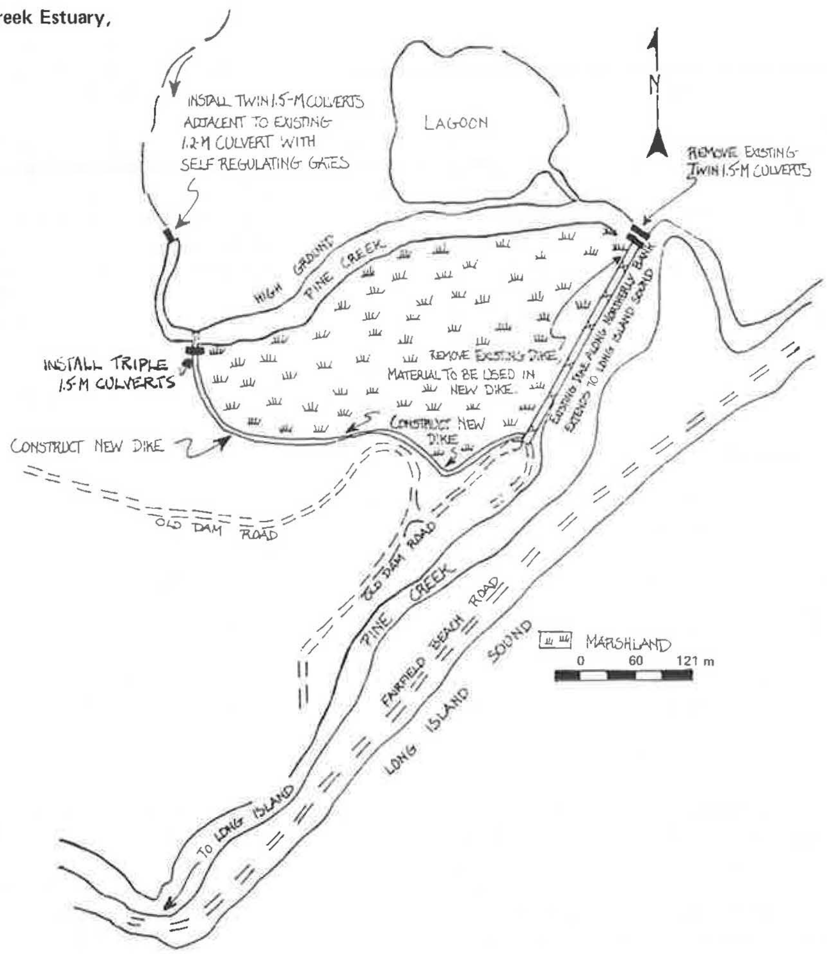


Figure 9. Pennsylvania's Tinicum tidal marshlands in 1968.

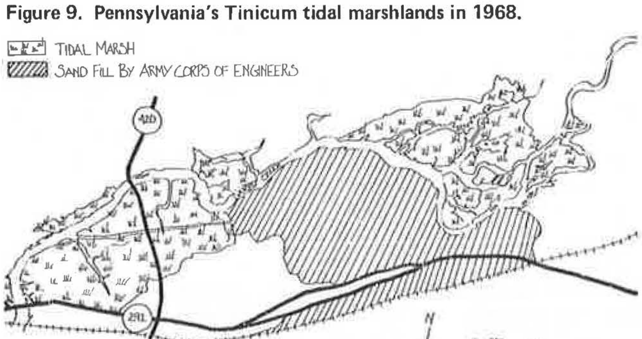
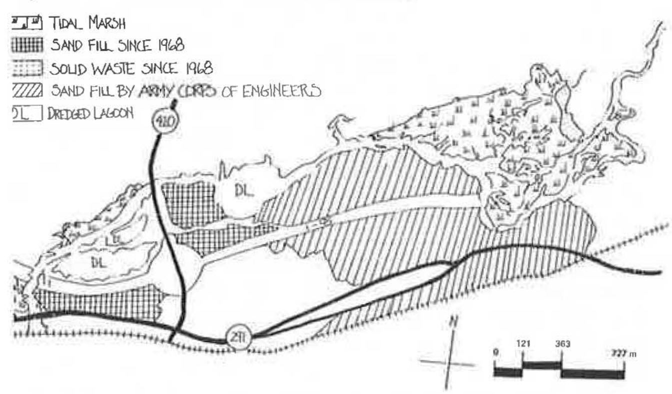


Figure 10. Tinicum tidal marshlands in 1971.



corporated explicitly in highway location and design plans as highway agencies gain experience with the advantages that can accrue from such practices to both highway users and the public at large. Early and continuing coordination between highway agencies and state natural resource or wildlife departments is essential if the full benefits from the creation of new wetland habitats are to be realized. Of the many highway features and construction activities that can be used in this capacity, three—use of ditches and culverts, construction of borrow pits, and disposal of dredge material—appear to offer the most extensive opportunities for habitat creation. The material dredged from a wetland or removed from an upland site can be used to create new wetlands or extend existing ones.

The ecological uncertainties involved in the accidental creation of wetland habitat are exemplified by a series of borrow pits excavated in 1959 and 1960 along I-91 in Whately, Massachusetts (5, 6). Figure 11 shows the location of the larger of these pits and identifies four that are the subject of the present case study. In this instance, location of the various borrow areas and the excavated configuration of each pit were dictated by the availability of appropriate borrow material and ease of excavation and haul to the construction site. Consideration was not given to the ecological potential of one location or excavation procedure relative to another.

The four borrow-pit ponds are very similar in most respects. All four ponds have predominantly granular bottoms (as would be expected, given the purpose for which they were excavated), and all four are fed mainly by groundwater supplemented to a degree by surface drainage from I-91 and the surrounding fields. The principal differences between the ponds lie in their basin configuration (a and b have greater average depths and considerably less shallow margin than do c and d), the composition of the surface flows into them, and, directly related to these two factors, their biological productivity.

Borrow-pit productivity is strongly related to nutrient availability, substrate composition, runoff characteristics, and basin morphology. Because of the nature of borrow pits, the bottom sediments are primarily sand and gravel, contributing little to wetland fertility. Upland seepage and runoff is characteristically slow and, although it does exert a major control over water chemistry, it usually does not encourage rapid eutrophication. Growth of aquatic vascular plants depends on the extent of shallow areas in the basin. Borrow-pit morphology often results in either extensive shallows or no shallows at all.

Of the four sites discussed, 91 South and 91 North exhibited the highest productivity. The 91 South pond exhibited extensive growths of algae and a dense population of cattail (Typha spp.). Both shallow water and agricultural drainage contributed to this condition. Shallow water was also a contributing factor in the higher productivity of 91 North, but the absence of agricultural drainage leads to most of the pond's energy being cycled through the benthic flora rather than through an extensive plankton population. The 91 Swim pond lacked both shallow areas and nutrient-rich upland drainage. As a result, this impoundment was more deficient in plant nutrients (oligotrophic) than 91 North and 91 South. In addition, because of its use as a swimming area, 91 Swim was highly turbid throughout the growing season, which inhibited the penetration of light in the water column. Drainage entering 91 Woods came primarily from a pine-mixed hardwoods swamp, and the resultant pH range was 4.9-3.7. This pond had very little emergent vegetation, a very small plankton population, and no fish. All of this emphasizes the importance of site to subsequent wetland characteristics.

In marked contrast to the strict highway-function orientation that characterized construction practices a decade ago, an increasing number of highway agencies are making explicit provision for creating or replacing wetland habitat in the course of highway construction. The practices of the North Dakota State Highway Department (7) and the state of Minnesota are instructive in this regard.

A number of artificial wetlands have been created by the North Dakota State Highway Department as an integral part of the construction of I-29. Borrow areas are designed specifically to create marsh habitat and include the flat slopes and shallow areas necessary for the establishment of marsh vegetation. Figure 12 shows the type of plan and basin configuration used. It is reported that, within one year after construction, marsh vegetation appeared along the periphery of the borrow area and waterfowl were observed.

In addition to making good use of the opportunities for wetland creation provided by borrow excavation, the North Dakota State Highway Department has used a substantial number of highway embankments as dams for the deliberate impoundment of surface drainage. The management of the lakes and other wetlands so created is coordinated with the North Dakota State Water Commission and State Game and Fish Department to provide the fullest possible ecological and recreational benefits from these areas.

The policies of the state of North Dakota with regard to the replacement of wetland habitats lost through highway construction are also worthy of note. A memorandum of understanding between the North Dakota State Highway Department and the U. S. Fish and Wildlife Service establishes a basis of exchange for the replacement of wetlands beyond the highway right-of-way covered by easement agreements between the U. S. Fish and Wildlife Service and private owners. Wetland filled or drained as a result of highway construction is replaced by alternative land as agreed to by both agencies. Exchange options are reviewed during the loca-

Figure 11. I-91 borrow-pit ponds, Whately, Massachusetts.

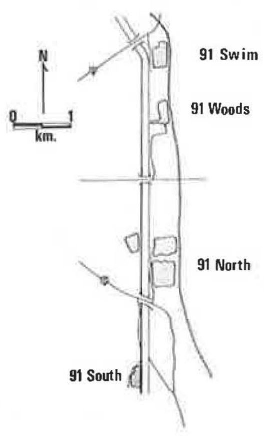
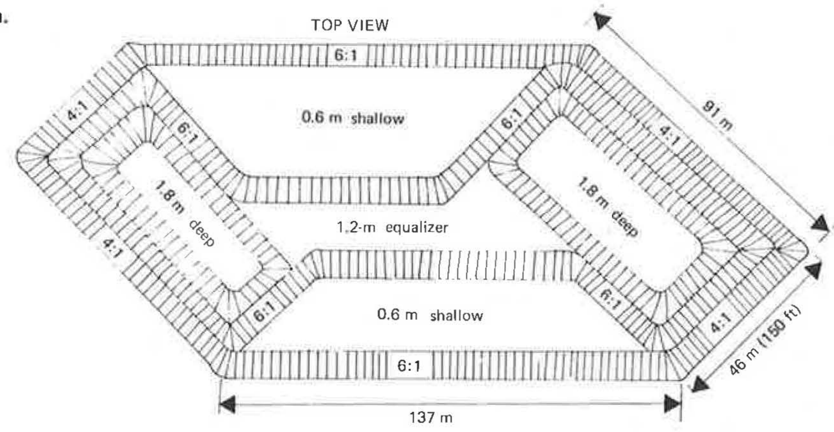


Figure 12. Basin configuration used in North Dakota.



tion and predesign phase of the project, the range of options is narrowed during the preliminary design phase, and the final choice is made in conjunction with the final project design. Twelve types of wetland for which replacement may be required under the federal-state agreement are specified, along with six replacement options. The ratio of replacement area to affected area varies depending on the type of wetland that is to be lost, the type of area with which it is to be replaced, and the biotic region in which the replacement land is located. Replacement ratios range from 0.25, when the replacement wetland is considered to be of a higher type than that to be replaced, to 8.0, when tame grassland is to replace prime wetland in another biotic region. The Minnesota Department of Transportation (DOT) has also entered into such a memorandum of understanding with the U. S. Fish and Wildlife Service and uses borrow pits and control structures to create new habitat.

CONCLUSIONS AND RECOMMENDATIONS

The effects that highway fills have on the wetlands in which they are constructed depend primarily on the extent to which the surface and subsurface hydrology of the affected wetland is disturbed. Standard design and construction practices do not appear to provide adequately for the unimpeded flow of groundwater through the fill. The result is that the water table on the upstream side of the embankment is raised, and this leads to the destruction of timber and to other ecological changes. In coastal wetlands, drainage facilities designed to accommodate surface flow from upland sources often do not adequately handle tidal ebb and flow; the level and salinity of the waters within these tidal marshes are reduced, which results in changes in marsh biota. Restriction of tidal exchange also reduces the amount of nutrients that can be exported from the marsh to other, dependent, environments.

The extent of physical obliteration of wetlands that results from embankment construction and disposal of dredge spoil can be limited by careful location and construction practices. With the assistance of ecologists and other environmental specialists, highway construction can also be designed to create new wetlands. The extent of damage or enhancement that results from highway construction is, in the final analysis, determined not so much by the nature of wetlands or by the construction process itself but by the perceptions and objectives of those responsible for location and design decisions.

Our understanding of the effects on the hydrologic regime of various highway construction activities and design features is incomplete, especially with reference to induced changes in the movement of groundwater at the local and regional scale. Our knowledge of how the ecology of specific types of wetlands will respond to a given change in the hydrologic regime is also badly deficient. It is recommended, therefore, that the following steps be taken to increase our knowledge of the effects of highway construction on local and regional hydrology and the response of various wetland ecosystems to changes in the hydrologic regime:

1. Research should be undertaken to further our knowledge of the geophysical factors that govern the movement of surface and subsurface waters at both the local and regional scale. Particular emphasis should be given to studies of groundwater movements at the regional scale.

2. Studies of local and regional hydrology, including both surface and subsurface flows, should be incorporated in the preliminary engineering studies that precede highway location and design decisions.

3. Research should be undertaken to increase our understanding of the responses of various wetland ecosystems to the changes in the hydrologic regime associated with each wetland class.

Identifying and assessing the probable effects that highway activities will have on wetlands require the application of knowledge that is in a state of active evolution. Considerable progress has been made in recent years in understanding how wetlands function and how highways and other engineered works affect those functions; considerable further progress is both necessary and feasible. For many decades highway engineers have been refining and applying their knowledge of soils, hydrology, and other elements of the geophysical environment to the construction of structurally sound and economically efficient highway facilities. It is now essential that this knowledge be more fully merged with that of biologists, ecologists, and other natural scientists so that the integrity of the environment through which a highway passes is as carefully protected as the integrity of the highway itself.

ACKNOWLEDGMENT

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The investigators on the case studies were as follows: Whately, Massachusetts, borrow-pits synthesis by Richard Newton, adapted from theses by Heusmann (5) and Moulton (6); report on Fairfield, Connecticut, and investigations of Jamestown, North Dakota [with reference to reports by Nilson (7)], and La Grande, Oregon, by Carl A. Carlozzi; Philadelphia report by Richard Clarke, adapted from reports by McCormick (4); South Florida investigation performed by Joseph Larson, with reference to unpublished data compiled by Frank C. Craighead, Sr.; Michigan investigation performed by Dale F. Cope, with assistance from the research team at the Department of Natural Resources, Michigan State University, and especially Phillip B. Davis; northeastern Minnesota investigation performed by Paul W. Shuldiner, with reference to research by Stoeckeler (3) (special thanks to Mary Quilling, who located sites and preliminary contacts). The original figures were drawn by Caren M. Caljouw.

The opinions and conclusions expressed or implied are ours and not necessarily those of the sponsors or the individual states that participate in the National Cooperative Highway Research Program.

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State Practice and Experience in the Use and Location of Truck Escape Facilities

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One phase of a study undertaken to develop warrants for the use and location of truck escape ramps is described. A questionnaire submitted by mail to state highway agencies sought information on (a) the type and number of escape facilities constructed, (b) variables considered in determining the need for escape ramps, (c) factors that affect ramp location, and (d) operational experience with escape ramps. The study results indicated that, although most ramps are located on four-lane divided and two-lane highways, they can also be found on three-lane routes, in medians, and at the end of freeway off-ramps. Only two states indicated that a rational technique was used to determine the need for ramps. Both techniques made use of accident rates. Other important factors in determining the need for escape ramps included length and percentage of grade, percentage of trucks, and conditions at the bottom of grades. Topography was cited as the primary factor in ramp location. Examples of satisfactory and unsatisfactory ramp location are described.

On long, steep highway downgrades, there is the possibility of brake failure on large commercial vehicles. In such situations trucks often accelerate uncontrollably, endangering not only the lives of truck drivers but the lives of occupants of other vehicles as well. Residences and business enterprises adjacent to or at the foot of long, steep downgrades may be damaged or destroyed by runaway vehicles. A large percentage of runaway-vehicle accidents result in fatalities.

Highway agencies in states that have roadways in rugged terrain (primarily the Appalachian region and the mountainous western states) have attempted to mitigate the problem by using various types of truck escape facilities. Until recently, there had been little formal research and development in the design and construction of truck escape ramps. Since the mid-1970s, however, there has been increasing interest in all facets of truck escape facilities.

No single type of truck escape facility has been adopted nationwide, but four general types of escape facilities can be identified (see Figure 1): (a) ascending-grade ramps, (b) horizontal-grade ramps, (c) descending-grade ramps, and (d) sandpiles.

The ascending-grade ramp is probably the most common type of escape facility now in use. In general, these ramps consist of a roadway that is composed of layers of loose gravel or uncompacted sand and ascends at a very steep grade, using the force of gravity to stop moving vehicles. The length of ascending-grade ramps tends to vary considerably, depending on percentage of grade, the type of aggregate used in the arrester bed, and the land available for ramp construction.

Horizontal-grade ramps are the newest type of truck escape ramp to be constructed. They use only the resistive force of the aggregate arrester bed to stop vehicles. Horizontal-grade ramps are primarily used where the terrain precludes the construction of other types of ramps.

Descending-grade ramps, like horizontal-grade ramps, depend entirely on the resistance of the aggregate bed to stop runaway vehicles. Because of the adverse effect of the negative grade, they are generally longer than ascending or horizontal ramps.

Of the four types of escape ramps, sandpiles are probably the easiest and least expensive to construct. An inclined pile of loose, dry sand provides the resistive force. The use of sandpiles is currently confined to several eastern states.

The state of the art of escape-ramp construction has advanced in recent years, but the same cannot be said of escape-ramp warrants. In most cases, the use and specific location of truck escape facilities are based on subjective judgment rather than formal engineering analysis. As resources for highway construction and maintenance become more limited, a "seat-of-the-pants" approach to locating and installing truck escape facilities is no longer justified. There is a need to develop methodologies by which optimum use and location of truck escape ramps can be determined.

The West Virginia Department of Highways, in cooperation with the Federal Highway Administration (FHWA), has sponsored a research project at West Virginia University, the overall objective of which was to develop warrants for the use and location of truck escape ramps. To accomplish this general objective, a number of detailed objectives were developed. These included

1. Use of a mail questionnaire to determine the experiences and practices of state highway agencies in re-