Evaluating the Cumulative Effects of Alteration on New England Wetlands

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ABSTRACT / In New England, patterns of glacial deposition strongly influence wetland occurrence and function. Many wetlands are associated with permeable deposits and owe their existence to groundwater discharge. Whether developed on deposits of high or low permeability, wetlands are often associated with streams and appear to play an important role in controlling and modifying streamflow. Evidence is cited showing that some wetlands operate to lessen flood peaks, and may have the seasonal effect of increasing spring discharges and depressing low flows. Wetlands overlying permeable deposits may be associated with important aquifers where they can produce slight modifications in water quality and head distribution within the aquifer. Impacts to wetlands undoubtedly will affect these functions, but the precise nature of the effect is difficult to predict. This is especially true of incremental impacts to wetlands, which may, for example, produce a change in streamflow disproportionate to wetland area in the drainage basin, i.e., a nonlinear effect as defined by Preston and Bedford (1988). Additional research is needed before hydrologic function can be reliably correlated with physical properties of wetlands and landscapes.

A model is proposed to structure future research and explore relationships between hydrologic function and physical properties of wetlands and landscapes. The model considers (1) the nature of the underlying deposits (geologic type), (2) location in the drainage basin (topographic position), (3) relationship to the principal zone of saturation (hydrologic position), and (4) hydrologic character of the organic deposit.

The freshwater wetlands of New England have formed since the last glaciation, and their distribution and characteristics are controlled by glacial deposits. A Massachusetts survey (Table 1) shows that 67% of the state's wetlands overlie deposits that generally are quite permeable or are associated with aquifers. This is contrary to the common expectation that associates wetlands with deposits of low permeability. The nature of glaciation in the region explains this phenomenon.

Glacial deposition in New England was quite different from that in other areas because of the presence of northeast-trending ridges and the manner in which the ice melted back. This latter process, called stagnation zone retreat, involves the formation of dead (nonflowing) ice, typically 5–8 km (3–5 mi) wide, along the glacier margin that melted over a period of 1–50 yr (Koteff and Pessl 1981; also see Gustavson and Boothroyd 1987). Behind this zone the ice was still active, or flowing, and supplied meltwater and debris that washed over the stagnant ice. Much of the debris was caught in the low areas between the northeast-trending ridges; because drainage to the south was often blocked, lakes formed along the margin of the ice. This process, repeated many times as the ice retreated, produced a series of complex, discrete, and often isolated deposits of stratified drift in lowland areas.

KEY WORDS: Freshwater wetlands; Wetland hydrology; Streamflow modification; Groundwater; Cumulative impacts

In the lowland areas wetlands could be formed, for example, in a kettle hole, on poorly permeable lake bottom deposits, or as a thin veneer over permeable material where groundwater was near the surface. In such a setting wetlands are usually the result of groundwater discharge and are often a part of the local stream system (Figure 1). Wetlands on till tend to occupy higher elevations, and as a result are often linked to the headwaters of streams. This juxtaposition of wetlands with streams and permeable materials associates them with aquifers and raises the potential for moderating streamflow.

In a national discussion, it is important to understand the regional differences that exist not only in the formation of wetlands but also in their potential hydrologic function. For example, other regional wetland types (e.g., pocosins, prairie potholes, southern river swamps) differ from New England wetlands and from each other not only in their origin and climatic setting but also in their potential effects on the hydrologic cycle. Considerable care should be exercised in comparing studies between regions, and in extrapolating results from one region to another. A similar injunction holds true when comparing wetlands within regions. Any regional discussion attempts to produce a coherent picture through generalization. Yet any generalization, by its very nature, may be an incorrect characterization of specific circumstances.

The following sections draw upon studies from New England and similar regions to develop a gener-

Table 1. Geology and wetland occurrence in Massachusetts

Deposit	Land area underlain by deposit (%)	Wetland area underlain by deposit (%)
Stratified drift	35	48
Till and bedrock	56	32
Alluvium	2	13
Lake bottom	3	5
Other	4	2

Source: Motts and O'Brien 1981.

alized picture of the hydrology of New England's wetlands and the important factors that control their function. We know that anomalies must exist, although we lack the detailed information to determine when and where they occur. Therefore, a research model is proposed to test parameters that seem to be the major determinants of hydrologic function. This article is a synthesis of earlier works, most notably O'Brien (1983, 1987) and O'Brien and Motts (1980).

Hydrology of New England Wetlands

Wetlands and Flood Reduction

The role of wetlands in the runoff cycle has been a subject of considerable debate. It is widely believed that wetlands reduce flooding effects and serve as a "sponge" to absorb water in the wet season and then slowly release it to streams during the dry season. While reduction of flooding can be demonstrated in some cases, the "sponge" theory of wetlands is almost certainly false. Research does show, however, that wetlands have a significant impact on streamflow and that the impact may vary considerably with the region and the specific wetland.

In a series of publications on flood assessment, the U.S. Geological Survey showed that in New Jersey (Tice 1968) wetlands and lakes have a significant effect on lowering the size of the mean annual flood (MAF). Statistical analysis showed that, if 2% of the drainage area were covered by swamps or lakes, the MAF was reduced 50%, while a 20% coverage of the area produced a fivefold decrease in the size of the flood. A parallel study conducted for New England (Green 1964), however, does not report any modification in the MAF resulting from an increase in the percentage of wetlands (or lakes) in the basin. Moreover, in a detailed statistical analysis of factors that determine the size of the annual floods in New England, Benson (1962) identified five parameters that influenced flood size but could not report any effects due to wetlands or lakes.

While it may be difficult to show statistically that wetlands reduce floods in New England, one study of a specific river does illustrate the effect. In a now famous study, the U.S. Army Corps of Engineers concluded that a substantial reduction of floodwaters resulting from the 1955 hurricane occurred along the Charles River because of the natural storage effect of wetlands flanking the channel (Childs 1970). In comparison to the Blackstone River, which is similar but lacks natural storage, the hydrograph of the Charles River showed a slow rise and long recession, with a peak discharge ⅕ as great as the Blackstone's.

Seasonal Effects

Studies from the U.S.S.R. and northern Europe show (Klueva 1975, Zubets and Murashko 1975, Ivanov 1981) that when wetlands are drained, spring flows are considerably reduced, while summer and fall streamflow is greater. Some areas, however, are exceptions to this generalization (Moklyak and others 1975). The bulk of the research suggests that wetlands produce a variable discharge with high spring runoff and depressed low flows, an effect noted by O'Brien (1977) in a detailed study of two wetlands in Massachusetts as well as by other U.S. hydrologists (Vecchiolo and others 1962, Miller 1965, Bay 1966).

Conditions that favor high spring runoff, yet serve to reduce floods, would appear to be mutually exclusive. A study by Novitzki (1978), however, presents empirical evidence that such may in fact be the case. In a statistical analysis of streamflow in Wisconsin, Novitzki reports that basins containing wetlands produce lower flood flows, higher spring discharges, and lower fall baseflows than areas with no lake or wetland. This confirms much of the research showing that, in general, wetlands appear to produce flashy streamflow, yet function to reduce high magnitude floods.

Several tentative and highly general conclusions can be drawn from the preceding studies:

1) Wetlands may have an important effect on high-magnitude floods.
2) Wetlands play an extremely important role in determining the characteristics of streamflow.
3) The degree to which wetlands affect streamflow and the nature of that effect depend upon a number of as-yet unquantified factors.

Generation of Streamflow

Research linking the physical characteristics of wetlands with streamflow is perhaps most advanced in the

Figure 1. Topographic map showing wetlands. The wetlands developed on glacial outwash filling the low areas around till-mantled higher terrain. In such areas wetlands may have an important association with streams and groundwater (U.S. Geological Survey, Concord Quadrangle, Massachusetts 1:24,000).

U.S.S.R., where wetlands are numerous and are actively being modified to conform to the needs of a planned economy. The Soviet research is best summarized by Ivanov (1981), who notes that water flows very quickly through a highly permeable upper layer of peat (acrotelm) but extremely slowly through an underlying layer of decomposed and compacted peat (catotelm), which has a much lower permeability. Because the acrotelm is generally quite thin (7–70 cm), small reductions in water level can drop the water table into the catotelm, causing a virtual cessation of streamflow. This mechanism is cited by Soviet scientists as the chief cause of the flashy nature of streams draining wetland areas.

In the United States research on wetlands has been less focused. There has, however, been a virtual revolution in our understanding of the pathways by which precipitation becomes streamflow, leading to a better understanding of the relationship of wetlands to streamflow.

Runoff and Streamflow

It was previously believed that a fraction of the total rainfall accumulated on the surface and spilled downslope to streams, where this overland flow produced a storm peak on the hydrograph. However, it is now known that in humid areas such as the Northeast, the storm peak is "mainly the product of contributions from a *fraction* of the drainage basin" (O'Brien 1983) and is the result of "hydrologic processes *other than overland flow* which contribute the bulk of the water that produces the stormpeak" (O'Brien 1983).

The role of wetlands in the runoff process is not completely clear, but several studies have cited wetlands as key elements. The U.S. Forest Service (1961), the Tennessee Valley Authority (1965), Hewlett and Hibbert (1967), and Dunne and others (1975) have stressed that runoff is generated from saturated areas in valley bottoms, along streams, and in swales. Although not specifically cited, wetlands are often found in these settings, under physical conditions described by these researchers.

Further, a significant body of research from the Soviet Union and northern Europe shows that when wetlands are destroyed by drainage there is a marked change in streamflow characteristics (Burke 1975, Mikulski and Lesniak 1975, Mustonen and Seuna 1975). It seems likely, therefore, that wetlands play a significant role in modulating streamflow.

Shallow groundwater also appears to play a key role in the generation of stormflow from wetlands. Crouzet and others (1970), using tritium to index floodwaters, found that the flood produced at the mouth of a marsh was largely the result of rapid groundwater discharge. Similarly, O'Brien (1980) found that two wetlands in Massachusetts served as efficient groundwater discharge areas and that the rapid discharge of groundwater was the major mechanism producing peak flows. As Ivanov (1981) stresses, flow through the highly permeable upper layer of peat, which maintains streamflow, is strongly affected by small changes in groundwater level.

Finally, wetland structure and microtopography may also play an important role in modulating streamflow. In addition to the Soviet research (Ivanov 1981), O'Brien (1980) and Weyman (1970) have found that water may be discharged to streams through natural pipes that develop in peat or muck. Although research in this area is still lacking, it also seems likely that the presence of a strong microtopography (that is, hollows and hummocks in the organic deposit) may influence a wetland's capacity to contribute to streamflow.

We cannot rely on standard techniques because we are not simply examining excess rainfall running off a saturated surface (such as a parking lot). The effects of incremental impacts to wetlands can only be assessed when the mechanisms by which wetlands contribute to streamflow are understood.

Wetlands and Groundwater

Wetlands may be elevated above or depressed below the regional potentiometric surface, and thus may stand in a variety of relationships to groundwater. These relationships, illustrated in Figure 2, may be further complicated by deeper confining layers. It is generally true that wetlands perched above the main zone of saturation are in a position to recharge the groundwater, while those in contact with the main groundwater zone serve as discharge areas for aquifers. These effects have been noted in several studies (Williams 1968, Southeastern Wisconsin Regional Planning Commission 1969; see also Maryland State Planning Department 1970, Kiselev 1975). In addition, some wetlands may change during the course of an annual cycle from receiving groundwater discharge to providing recharge. O'Brien (1977) demonstrated this effect on a deep, peat-filled wetland surrounded by till, in which he estimated that the organic material recharged the underlying deposits with 26,000 m^3 (7 million gal) of water over a 6-wk period in August and September.

The reasons for investigating the relationship of wetlands to associated groundwater bodies are: (1) they may be associated with aquifers and play an auxil-

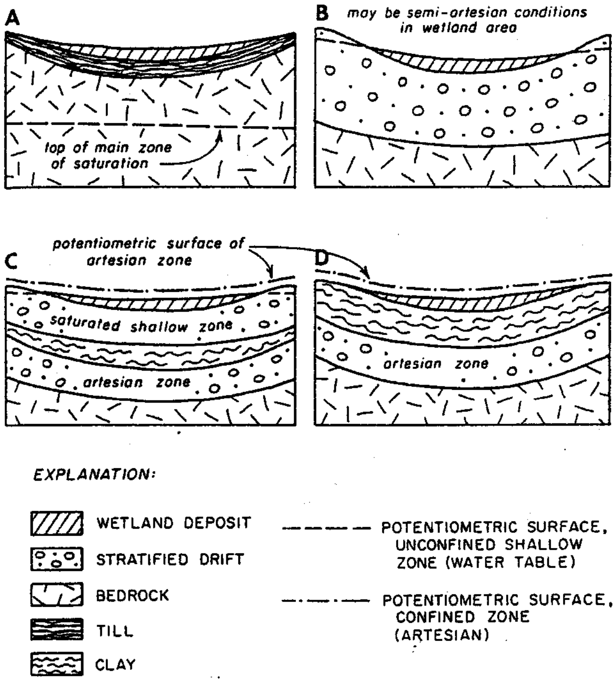

Figure 2. Diagrammatic cross-sections showing the relationship of wetlands to the principal zone of saturation (hydrologic position) for several geologic conditions. (A) Perched wetland. (B) Watertable wetland. (C) Watertable/artesian wetland. (D) Artesian wetland. (O'Brien and Motts 1980)

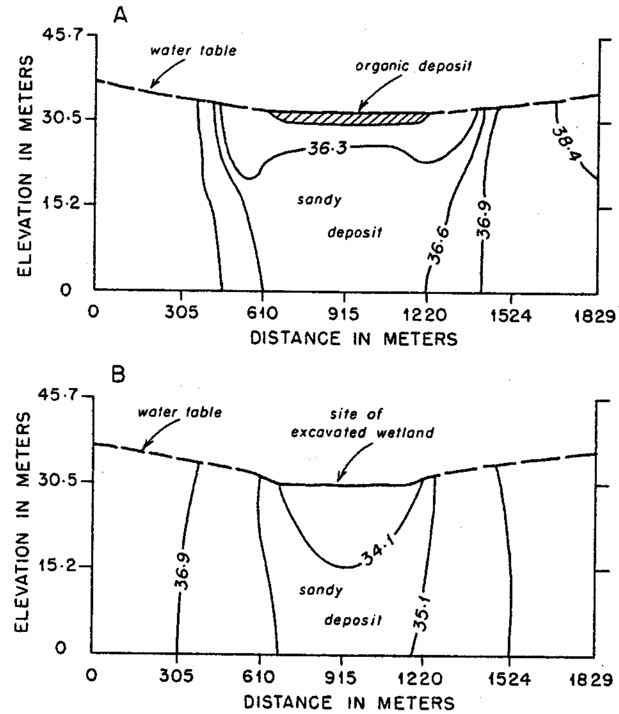

Figure 3. Head distribution in an ideal sand and gravel aquifer (A) with a wetland 1.5 m thick and (B) after organic deposits have been excavated. 36.3 and 34.1 represent lines of equal hydraulic potential, in meters above a standard datum. Vertical exaggeration: 20:1. (O'Brien 1987)

iary role in the water resources of a region; and (2) by moderating groundwater discharge to streams they may have an important impact on the quantity and quality of water that drains from a region. These concepts are discussed more completely in the following sections.

Water resources. Wetlands may play an auxiliary role in the water resources of a region. This may be particularly significant in New England, where aquifers are composed of relatively small deposits of sand and gravel and a wetland may have a good hydraulic connection with, and occupy a significant fraction of, the top of an aquifer. A Massachusetts survey has shown that about 67% of the state's wetlands overlie permeable materials that are commonly associated with high-yield aquifers (Table 1).

While wetlands are not aquifers, they may exert some control on the head distribution and recharge/discharge characteristics of aquifers (discussed in the following section), as well as water quality.

The relationship of wetlands to groundwater quality is a complex issue. The quality of groundwater associated with a wetland is highly dependent upon whether the wetland is in a recharge or discharge position (Goode and others 1977, Ivanov 1981). Further, the confining effect of wetlands, and the attendant groundwater circulation pattern, may concentrate iron and possibly other constituents in the aquifer under a wetland (Motts and O'Brien 1981). In addition, well development may induce infiltration from peat deposits, leading to a change in redox potential and pH in an aquifer and a consequent change in water quality at the wellhead. Consequently, wetlands may exhibit considerable control over water quality in an aquifer.

Groundwater and streamflow. The relationship of wetlands to groundwater may have a significant impact upon the quantity and quality of the water that drains from a region. Freeze and Witherspoon (1967) have indicated that in small aquifers where the water table is near the surface, the recharge area tends to be large in proportion to the discharge area. Therefore, a wetland that overlies a discharge area is in a position to exercise considerable control over groundwater discharge.

The importance of groundwater discharge to streamflow has been illustrated in several studies (Crouzet and others 1970, Zubets and Murashko 1975, O'Brien 1980). Moreover, groundwater levels may be particularly critical to streamflow; several researchers have shown that a small decline in groundwater level can lead to a cessation of streamflow (Goode and others 1977, O'Brien 1977, Ivanov 1981). For these reasons, it is important to develop an understanding of the role of the unaltered wetland in its associated aquifer systems. Subsequent alteration of the wetland may lead to changes in water quality and head distribution within the aquifer.

The effect of the wetland on head distribution can be shown by digital models developed from a U.S. Geological Survey finite difference model (Trescott and others 1976) and is illustrated in Figure 3. Figure 3A shows a cross-section of a sand and gravel aquifer containing a wetland deposit 1.5 m thick. If the permeability of the aquifer is 40 $m^3/d^{-1}/m^{-2}$ and that of the organic deposit is 0.04 $m^3/d^{-1}/m^{-2}$, groundwater gradients are as shown, and the ratio of horizontal to vertical permeability is 100:1, then the head distributions and flow patterns are calculated as shown. If, however, the organic matter is removed but all other factors are held constant, head beneath the wetland area drops approximately 2.1 m and the flow pattern and head distributions are as shown in Figure 3B. While the model is subject to certain limitations, it does illustrate the potential importance of an organic layer in influencing head distribution and flow pattern within an aquifer.

The effect of wetland destruction, therefore, may be to lower head potential within an aquifer, which could lead to a decline in the water table and a readjustment of groundwater gradients. In response to the lowered water table, the area may become dryer at the surface. The effect of these adjustments on streamflow is difficult to predict but would, at the least, require knowledge of the mechanisms responsible for streamflow generation and the critical areas that contribute to streamflow. While total annual runoff from the region may not change, stream response to spring runoff and rainfall events could be significantly altered. Conversely, the development of a replacement wetland, through excavation of permeable materials and replacement by organic deposits, may increase head potentials in the wetland areas, as demonstrated by the digital models. That the alteration of wetlands can have an effect on groundwater should not be doubted, as numerous studies from the Soviet Union show that the drainage of wetlands can affect both phreatic and confined groundwater (Zubets and Murashko 1975).

The difficult tasks of a groundwater investigation are: (1) to define the role of the wetland in the larger groundwater regime, (2) to show how alteration will affect that regime, and (3) to predict the effects of alteration on groundwater.

GEOLOGIC TYPE I

BEDROCK OVERLAIN BY TILL OR THIN ALLUVIUM

Topographic Position \ Hydrologic Position	A Perched Wetland	B Water-Table Wetland	C Water-Table / Artesian Wetland	D Artesian Wetland
1 Wetland near Basin Mouth	com	com		
2 Wetland on Floodplain	com	com		
3 Wetland on Basin Divide	com	com		

GEOLOGIC TYPE II

STRATIFIED DRIFT

Topographic Position \ Hydrologic Position	A Perched Wetland	B Water-Table Wetland	C Water-Table / Artesian Wetland	D Artesian Wetland
1 Wetland near Basin Mouth		com*	com*	com*
2 Wetland on Floodplain		com*	com*	
3 Wetland on Basin Divide	com	com*		

Figure 4. A proposed classification of wetlands for defining hydrologic response. COM = type occurs commonly in Massachusetts. * = Groundwater development from wetland-associated aquifers is favorable given sufficient transmissivity, saturated thickness, and recharge combined with adequate water quality. (O'Brien and Motts 1980)

Wetland Classification

While a general knowledge of the hydrologic function of wetlands within a given region is important, more specific information is needed to predict function for specific wetlands. It is likely, for example, that not all wetlands control flooding, or act to the same degree. At present we do not know the physical factors needed to predict this function. Answers to such questions require detailed studies of individual wetlands (Carter and others 1984, Hollands and others 1987). Yet to regulate land use activities in and around wetlands it is important to be able to correlate hydrologic functions with easily measured physical features. To this end, I propose a hydrologic classification that takes into account the diversity of wetlands as well as their role as part of a larger hydrogeologic unit—the drainage basin.

The classification proposed in Figure 4, based on the work of O'Brien and Motts (1980), permits prediction of the major hydrologic functions discussed above. This classification includes four factors: (1) geologic type of associated deposits, (2) hydrologic position, (3) topographic position, and (4) nature of the organic mat (not shown in the diagram). The resulting matrices produce 24 major categories; 13 of these are believed to be common types in New England (O'Brien and Motts 1980).

Geologic Type

The two geologic categories represent a synthesis of the many possible types. Geologic Type I (bedrock overlain by till or thin alluvium) would be expected to contribute only small quantities of groundwater to the wetland, whereas Geologic Type II (stratified drift) could contribute large quantities of groundwater. Therefore, the two major types are distinguished by their ability to contribute discharge to (or accept recharge from) the wetland.

Hydrologic Position

This factor classifies the wetland according to its relationship to the principle zone of saturation (see Figure 2). Wetlands perched above the main zone of saturation are commonly in a position to recharge the regional aquifer, whereas those in contact with the major groundwater zone generally serve as a discharge area for the regional aquifer. Actually, types A–D are part of a continuum in which the wetland is elevated above or depressed below the regional potentiometric surface during the wet season; some depressed wetlands may become perched as the regional potentiometric surface declines (O'Brien 1977). Types C and D have been found to be common and distinct types in Massachusetts (Heeley and Motts 1976).

Topographic Position

The ability of a wetland to modify runoff from the basin and the recharge/discharge function depends significantly on its topographic position. For example, a wetland near the mouth of a basin is in a position to control runoff from the entire basin, whereas wetlands near the basin divide can only impact a small fraction of the runoff. It is also likely that wetlands on the basin perimeter are part of the recharge zone, whereas those at the mouth occupy the discharge zone.

Nature of the Organic Mat

This factor is not easily related to the other factors

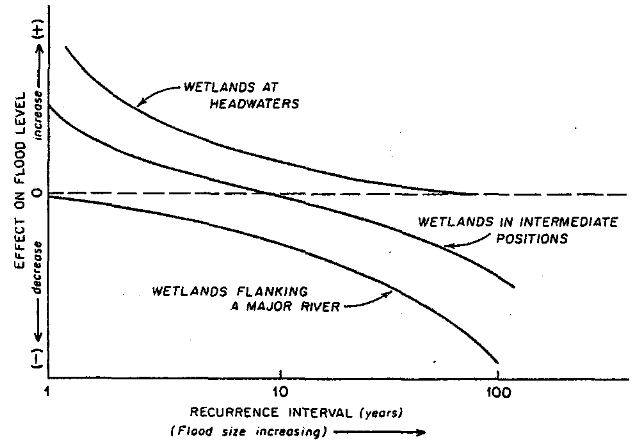

Figure 5. Theoretical diagram showing the possible effects of wetland location and flood frequency on storm discharge. Wetlands in headwaters areas are shown as increasing the discharge of the higher frequency storms (two-year floods), whereas wetlands flanking a major river slightly decrease the discharge of similar storms. This may be contrasted with lower frequency storms (25-year floods) in which wetlands in the headwaters of a stream act to increase the discharge slightly, whereas wetlands flanking rivers produce a major decrease in flood discharge. Thus the action of wetlands on floodwaters may depend on both location in the drainage basin and size of the flood.

of Figure 4, but its proper quantification is no less significant. The organic mat may have a uniformly low permeability (common with muck) or contain highly permeable zones as in the acrotelm or pipes. In addition, the surface may have essentially no relief or may contain hummocks. These factors may be described as: (a) uniformly low hydraulic conductivity, (b) presence of pipes, (c) presence of a permeable upper layer, or (d) presence of hummocks (see the earlier discussion of microtopography). Thus a wetland containing a highly permeable upper layer might contribute significantly to streamflow but be highly sensitive to changes in groundwater levels, whereas an organic mat with an overall low hydraulic conductivity might have very different effects on streamflow.

Discussion

The above classification is presented as a research tool, with which the effects of the various factors may be rigorously tested at many wetlands. Some of the factors are reasonably well known whereas others have been little investigated. For example, it has long been known that wetlands along floodplains near the mouth of a basin are in a position to control flooding, while those at the headwaters can only control a small volume of the basin's floodwaters (Langbein 1947). Recently Ogawa and Male (1986) were able to refine these concepts by numerically modeling the flood storage characteristics of wetlands with respect to location and size, a type of "toy" research (Preston and Bedford 1988). The role of wetlands in generating flood peaks has received much less attention, and may be seen as conflicting with data on flood control. However, this is not necessarily the case, because flood storage and flood peak generation may be seen as separate functions that depend on location and scale.

Consider a wetland lying downstream along a major river. The volume of water that may flood from the channel onto the wetland is far greater than the runoff that can be produced from the wetland. Consequently, the runoff-producing and runoff-conveying function of the wetland is overridden and storage capacity becomes the dominant function, leading to a reduction in the flood peak. Where a small tributary stream originates in a wetland, however, there is no major volume of water flowing overland to be stored on the wetland. In this setting all runoff is generated in the wetland and the immediate environs, and will flow away as rapidly as channel conditions allow, producing the flashy conditions described earlier. For wetland-flanked streams that are between these extremes, the wetland function may depend on the magnitude of the flood, with the runoff function dominant for the higher frequency storms, and the storage function dominant for lower frequency storms. These concepts are summarized in Figure 5, in which the effect of wetlands on various-sized floods is related to wetland location.

Although Figure 5 is preliminary, it summarizes a conceptual model of how wetlands in different landscape positions act in flood desynchronization and storage. More data will be required to establish thresholds, define the shapes of the curves, and provide a more quantitative assessment. The importance of the diagram lies in showing that the effect of wetlands on floodwaters may depend on both location in the drainage basin and size of the flood. It illustrates a potentially greater role for wetlands in controlling streamflow than previously suspected. In addition, the diagram provides a framework for detailed future studies designed to investigate the different effects that are proposed for wetlands at headwaters vs those flanking major rivers. Interestingly, statistical studies incorporating a range of wetland types would be expected to yield results similar to the intermediate wetlands of Figure 5; this is not unlike the findings of Novitzki (1978), which were described earlier.

Both the literature cited and the author's formulations suggest that wetlands in the New England region may have a synergistic effect (Preston and Bedford 1988) on streamflow. That is, wetlands may have far greater effects than their areal percentage in the drainage basin would indicate. Consequently, alteration of wetlands could produce effects disproportionate to their size.

It is my recommendation that, at present, the way to determine the approximate effect of cumulative impacts to wetlands and the subsequent impact on the regional hydrology is to conduct a thorough investigation of the basin-wide hydrology and the role of the wetland in that hydrology. Future research should allow us to better define the function of wetlands in the regional hydrology and to link key physical factors to important wetland functions. This research must be carefully targeted by regions and must focus on key hydrologic processes in those regions to produce the practical results required by cumulative impact assessment.

Acknowledgments

The author gratefully acknowledges the support of the Fund for New England and the Environmental Institute, University of Massachusetts, for funding an earlier report upon which much of the current article is based. Special thanks are due to Dr. Joseph Larson and the members of the Wetland Mitigation Workshop for stimulating discussions and helpful criticisms of many of the ideas in this article.

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