Impacts of Freshwater Wetlands on Water Quality: A Landscape Perspective

DENNIS F. WHIGHAM
CARIN CHITTERLING
BRIAN PALMER
Smithsonian Environmental Research Center
Box 28
Edgewater, Maryland 21037, USA

ABSTRACT / In this article, we suggest that a landscape approach might be useful in evaluating the effects of cumulative impacts on freshwater wetlands. The reason for using this approach is that most watersheds contain more than one wetland, and effects on water quality depend on the types of wetlands and their position in the landscape. Riparian areas that border uplands appear to be important sites for nitrogen processing and retention of large sediment particles. Fine particles associated with high concentrations of phosphorus are retained in downstream wetlands, where flow rates are slowed and where the surface water passes through plant litter. Riverine systems also may play an important role in processing nutrients, primarily during flooding events. Lacustrine wetlands appear to have the least impact on water quality, due to the small ratio of vegetated surface to open water. Examples are given of changes that occurred when the hydrology of a Maryland floodplain was altered.

There is little doubt that freshwater wetlands can significantly improve water quality and, with few exceptions, most have been shown to perform that function (Kelly and Harwell 1985, Nixon and Lee 1988). However, numerous questions about the relationship between wetlands and water quality are still unanswered because many types of freshwater wetlands have not been adequately studied (LaBaugh 1986, Nixon and Lee 1988). Most water quality research projects have been short term and have not included input–output analyses (Whigham and Bayley 1979, Howard-Williams 1985, Nixon and Lee 1988), especially for hydrologic variables (Carter 1986, LaBaugh 1986).

The need for long-term studies and detailed input–output analyses has been recognized over and over again in recent reviews of the freshwater wetland literature (Kadlec and Kadlec 1979, Whigham and Bayley 1979, Zedler and Kentula 1985, LaBaugh 1986, Nixon and Lee 1979, Richardson 1988), and has been documented in recommendations to the National Science Foundation (NSF) and many other federal agencies (Larson and Loucks 1978, Clark and Clark 1979). To date the Long-Term Ecological Research Program (LTER), funded by NSF, is the only national program devoted to long-term ecological research, and wetland ecosystem research is the main focus of only two sites. Unfortunately, institutional support of long-term wetlands research has not moved very far from the initial pronouncements made in the late 1970s. There are many reasons for this, and our purpose is not to make yet another call for those types of projects; the need is still obvious. In this article, we hope to provide a framework that might be used to evaluate how cumulative impacts to wetlands might affect or alter water quality. We also hope that this framework may lead to suggestions about the types of research that should be conducted.

The approach that we use is an extension of the studies by Hemond and Benoit (1988) and Brinson (1988), who provide summaries that complement other recent reviews of the same topics by Howard-Williams (1985), Nixon and Lee (1988) and Richardson (1988). With few exceptions, data are insufficient to predict how an individual wetland will affect water quality. A landscape approach to wetland function can be used instead to make reasonable decisions about how any particular wetland might affect water quality parameters, and can even be used for whole landscapes (Risser 1985, Urban and others 1987).

Conceptual Approach

It is useful to view freshwater wetlands as being distributed along a continuum (Figure 1), much like the river continuum concept described by Vannote and others (1980) and Naiman and others (1987). As water flows from uplands, it first encounters wetland conditions in the riparian areas associated with small streams. As water flows into higher (second–fifth) order streams, most of it contacts wetlands during periods of flooding and when it enters areas where flow has been reduced (palustrine wetlands or impoundments). In some regions, natural topographic depres-

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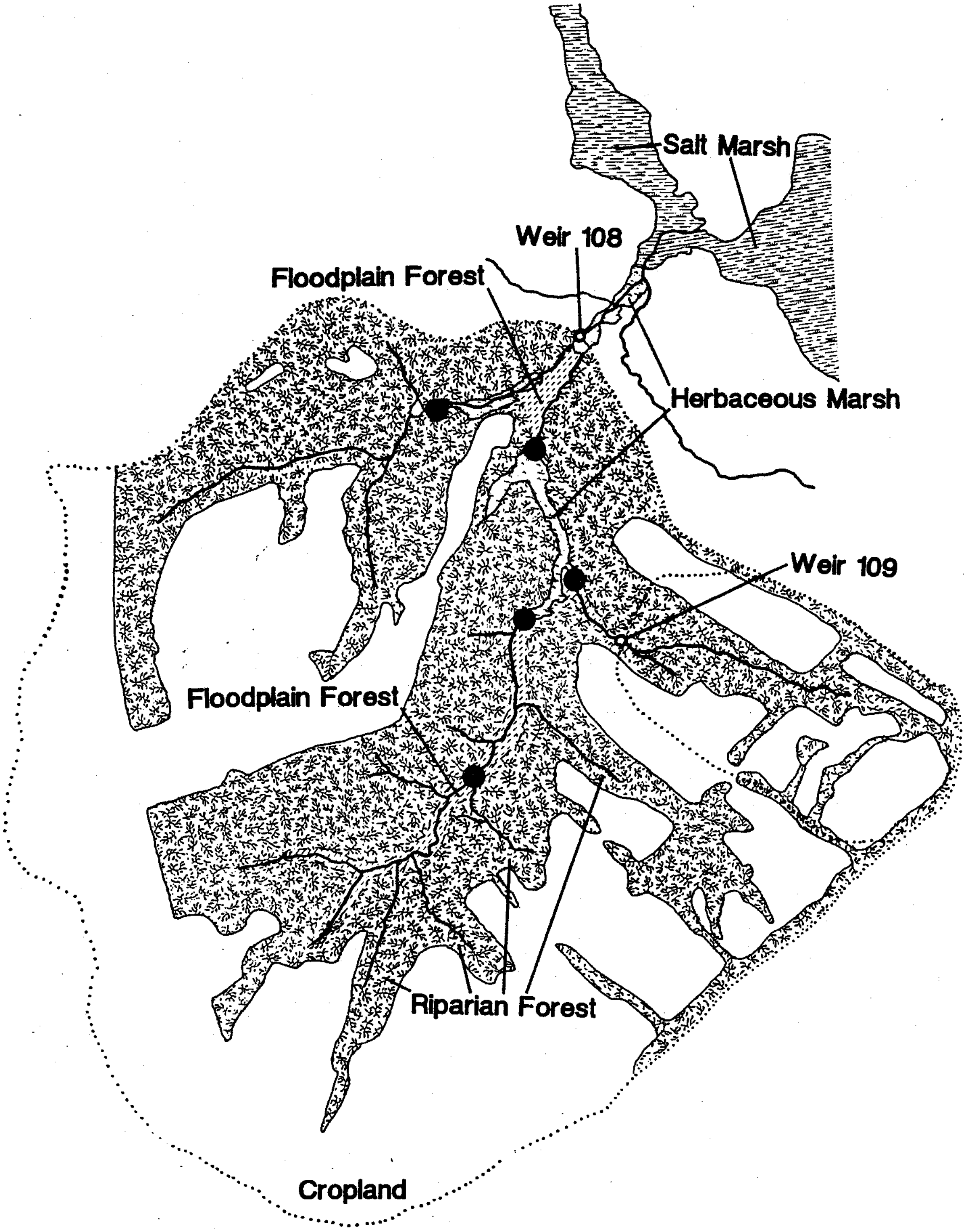

Figure 1. Diagram of subwatersheds 110 and 109 on the Rhode River watershed. The diagram was drawn from 1985 aerial photographs of the watershed.

sions dominate the landscape; for example, in glacial areas of the Northeast and Midwest, streams often flow from one depression in the landscape to another (Vitt and Bayley 1984). This hydrologic pattern also occurs in areas where beaver create impoundments on streams (Naiman and others 1986).

As water moves into higher order streams (rivers), the percentage of total flow that passes through wetland ecosystems decreases. We realize, however, that there are exceptions to this scenario, as when surface water moves slowly over the landscape (e.g., the Florida Everglades), or through blanket bogs (e.g., boreal areas and the Pocosin region of North Carolina), or where topographic conditions cause water to flow through large wetland areas (e.g., Great Dismal Swamp and Okefenokee Swamp). In general, however, the percentage of total river flow that contacts wetland environments decreases as stream order increases.

We suggest that this relationship can be used to determine the potential impact of wetlands on water quality. Accordingly, we will focus on the effects of cumulative impacts on wetlands, particularly on water quality as water moves into and through riparian areas that border first-order streams, and then to higher order streams that flow through different types of wetlands. Our hypothesis is that the amount of nutrient processing that occurs at any point along a hydrologic gradient is positively related to the total flow through wetlands. Maximum contact occurs in areas associated with smaller streams, and in areas where stream flow is constricted and water flows through wetlands. Water quality changes that occur when some floodwater flows over floodplains will be compared to situations where most streamflow passes through them. This situation will also be discussed in terms of what happens when flow patterns are altered so that a larger percentage of the flow passes through wetlands. Finally, we will suggest that a landscape approach may provide more information than a whole watershed approach.

Riparian Wetlands

In this section, we consider riparian areas that are topographically located between uplands and wetlands, and upstream of first-order streams. As water flows from upland systems, it passes through riparian zones before reaching first-order streams. The inclusion of these areas as part of the wetland continuum is problematic, but we believe that they should be included because of their sediment-trapping capacity and capacity to remove nitrogen, particularly nitrate, from phreatic water; these functions are characteristic of riparian areas (Johnson and McCormick 1979). Retention of sediments is primarily a physical phenomenon, while the ability to remove nitrate seems to be related to the presence of waterlogged soils, high organic matter inputs, and large inputs of nitrate in phreatic water.

Riparian vegetation has been shown to be particularly important in agricultural landscapes (Schlosser and Karr 1981, Lowrance and others 1984a, 1984b, Peterjohn and Correll 1984, 1986, Cooper and others 1986, Gilliam and others 1986), but also has a positive impact on water quality in landscapes not dominated by agriculture (Verry and Timmons 1982). Lowrance and others (1984a) showed that a riparian zone in the Piedmont area of Georgia removed large amounts of nutrients, especially nitrogen (68%). Eighty-nine percent of the nitrogen was removed by a riparian forest on the inner coastal plain of Maryland (Peterjohn and Correll 1984) and 86% by a riparian forest on the coastal plain of North Carolina (Cooper and others 1986). The paper by Cooper and others (1986) is particularly useful, because they compared different riparian zones as well as situations in which the riparian zone had been bypassed by drainage tiles. In drained areas, nitrate concentrations averaged 5.4 mg/l compared to 0.2 mg/l in areas where the riparian zone was intact. Similar results were shown by Gilliam and others (1986), who also studied riparian areas in North Carolina.

Cooper and others (1986) were also able to evaluate the movement of sediments and nutrients from agricultural uplands, through riparian areas, and into downstream alluvial swamps. They found that a riparian forest buffer only 16 m wide effectively removed most of the nitrate from groundwater. Peterjohn and Correll (1984) found similar results, but suggested that the efficiency of the riparian zone varies seasonally and with hydrologic conditions. Gilliam and his colleagues found that about 88% of the sediment that had eroded from cultivated fields over the past 20 yr had been deposited in the riparian zone. Whigham and others (1986) have also found that the litter zone of riparian forests is an efficient sediment trap. Gilliam and others (1986) further suggested that movement of most of the phosphorus from the fields is with sediment particles, and that most of the fine sediments move further down the hydrologic gradient, where they are retained in the floodplain swamps. Peterjohn and Correll (1984, 1986) and Whigham and others (1986) have found a similar pattern in their studies of the Rhode River system in Maryland.

In summary, riparian vegetation that borders first-order streams appears to efficiently remove nitrate and large particulate sediments from phreatic and surface water, respectively. Omernik and others (1981) are the only authors we found who disagreed with this conclusion. It has also been shown that nitrate and phosphate removal decreases when riparian zones are bypassed. Riparian areas do not appear to be as efficient in long-term removal of phosphorus, because it either moves through the riparian zone attached to fine sediments or is trapped as particulate phosphorus and then released as dissolved phosphorus.

Wetlands Downstream of First-Order Streams

Once water enters first-order streams, the nutrients and sediments that it carries contact downstream wetland surfaces mostly (1) during flooding events (riverine wetlands), (2) when the flow is directed to topographically low areas in the landscape (palustrine and, to a lesser degree, lacustrine wetlands), or (3) when the flow is altered to create impounded conditions. In this section, we consider these situations, recognizing that each of the aforementioned wetland types frequently has riparian wetlands at its upland boundary. We believe that the bordering riparian areas associated with higher-order streams are less important, because most of the surface and phreatic flow that contacts wetlands comes from riverine and/or lacustrine sources.

Impounded Areas

Numerous structures, both human-made and natural (Cooper and others 1986), can block the flow of water in smaller (first–fourth) order streams, where small and shallow impoundments can support emergent vegetation, either herbaceous and/or woody species. These types of systems are almost exclusively restricted to smaller streams. Robert Naiman and his colleagues recently published a series of papers that demonstrate the importance of in situ processing of materials in such streams (Naiman 1982, Naiman and others 1987). They also demonstrated that large-scale changes in carbon and nitrogen dynamics occur when beaver impoundments are created on smaller (second–fourth) order streams (Naiman and Melillo 1984, Naiman and others 1986), a condition that was undoubtedly very common in North America prior to the arrival of Europeans. We believe that their research is relevant to the present discussion, because beaver impoundments become sites where wetland succession occurs, and almost all of them eventually become emergent wetlands.

Their data (Naiman 1982, Naiman and others 1986) clearly showed that watersheds containing beaver impoundments retained 1000 times more nitrogen than unimpounded stream areas (Naiman and Melillo 1984). The rate of downstream movement of carbon decreased by 88% and the carbon turnover time increased by 21% in beaver-impounded areas (Naiman and others 1986). The changes that they measured are probably due both to decreased flow rates and the presence of wetland vegetation. Brown (1985) found similar results for a small (6.4 ha) wetland that had been slightly impounded so that runoff from a 284 ha watershed flowed through it. It is difficult to separate the impacts due to impounding of water and the presence of wetland vegetation, but since these conditions almost always occur together, the distinction is probably unimportant.

Riverine (Floodplain) and Palustrine Wetlands Associated with Streams and Rivers

Palustrine wetlands. Most of the palustrine wetlands studied have been shown to improve water quality and are sinks for nitrogen and phosphorus (Davis and others 1981, Howard-Williams 1985, Nixon and Lee 1988, Richardson 1988), even though the amount of retention varies with changing hydrologic conditions (Bayley and others 1985). It is important to note that palustrine wetlands seem able to retain more and more nutrients as inputs increase (Verry and Timmons 1982). The major exceptions are *Sphagnum*-dominated palustrine systems, which appear to have a limited capacity to store phosphorus (Kadlec 1983, 1985, Richardson 1985, Richardson and Nichols 1985, Richardson and Marshall 1986).

Riverine wetlands. Like palustrine wetlands, all riverine wetlands studied using the mass balance approach have been shown to remove nitrogen and phosphorus (Nixon and Lee 1988). The dominant feature of those systems is periodic flooding. During nonflooding periods, riverine wetlands have little impact on water quality and most nutrient processing occurs within the stream ecosystem. There are interactions between groundwater and the stream during nonflooding periods, but the magnitude and characteristics are not well known. How much of the total annual flow of riverine systems passes through wetlands, and what impacts do the wetlands have on nutrient flux? We could not find any studies in which those questions were addressed for an entire drainage system. Two studies, however, provide some insight into this issue. Mitsch and others, (1979) studying a riverine system in Illinois, found that the floodplain forest removed 4.5% of the phosphorus that flowed over it. However, removal efficiency dropped to 0.4% when total river flow was considered. Yarbro and others (1984) studied several floodplain systems on the coastal plain of North Carolina and calculated removal efficiencies as different amounts of the floodplains were inundated. They found that between 10% and 17% of total phosphorus was retained when less than 50% of the floodplain was inundated. Above 50% inundation, between 46% and 69% of the phosphorus was retained. Riverine systems thus appear to be able to retain phosphorus efficiently during flooding conditions. This capacity is undoubtedly related to their ability to trap and retain sediments.

As indicated earlier, fine particulates and phosphorus are not efficiently trapped in riparian areas (Cooper and others 1986). What happens as the sediments and attached phosphorus move further downstream? Cooper and others (1986) found that most phosphorus moved with fine clays and silts that were deposited on floodplain areas. Any structures that caused surface flow to become diffuse rather than channelized caused fine sediments and phosphorus to be deposited. We have found similar results in our studies of the Rhode River system (Whigham and others 1986).

Mill Swamp receives water from one of the largest Rhode River subwatersheds. Jordan and others (1986) used land-use patterns on the watershed to predict the amount of nitrogen and phosphorus that should have been measured at the automated station if Mill Swamp were not part of the watershed. They compared the predicted value to the measured value and found that the swamp retained both nitrogen and phosphorus, with most of the phosphorus retention associated with storm events. More recently, we have measured sedimentation in Mill Swamp and have found distinct differences between three habitats (Whigham and others 1986). The areas most relevant to the present discussion are (1) a forested wetland that floods frequently, and (2) an emergent wetland, in which water flows over the surface of the wetland primarily because of an abandoned beaver dam at the downstream end. We have measured water quality parameters in both systems and found that the greatest changes occur as water flows over the surface in the emergent wetland. These parameters are also altered in the forested wetland, but not as much as in the herbaceous area and only during flooding events. We measured sediment deposition rates during 1985–1986 and found that significant amounts of sediment and phosphorus are deposited in the two areas that flood. Figure 2 shows the depth of sediment accumulation, bulk density, and % organic matter for sites in Mill Swamp (Sites 1–4). The patterns for the two years are similar. The largest sediment accumulation occurs in Sites 1 and 2, the forested and freshwater herb-dominated areas that flood. Sites 3 and 4 are also in Mill Swamp, but in areas that hardly ever flood. The data also demonstrate differences in the composition of the sediment in the flooded areas. Larger sized materials are deposited in the upstream portion of the wetland (Site 1), bulk density is higher, and the flooded area associated with the herbaceous wetland has a higher organic matter content. Also, while the patterns of sedimentation for the two years are similar, there are differences in the composition of the sediment based on bulk den-

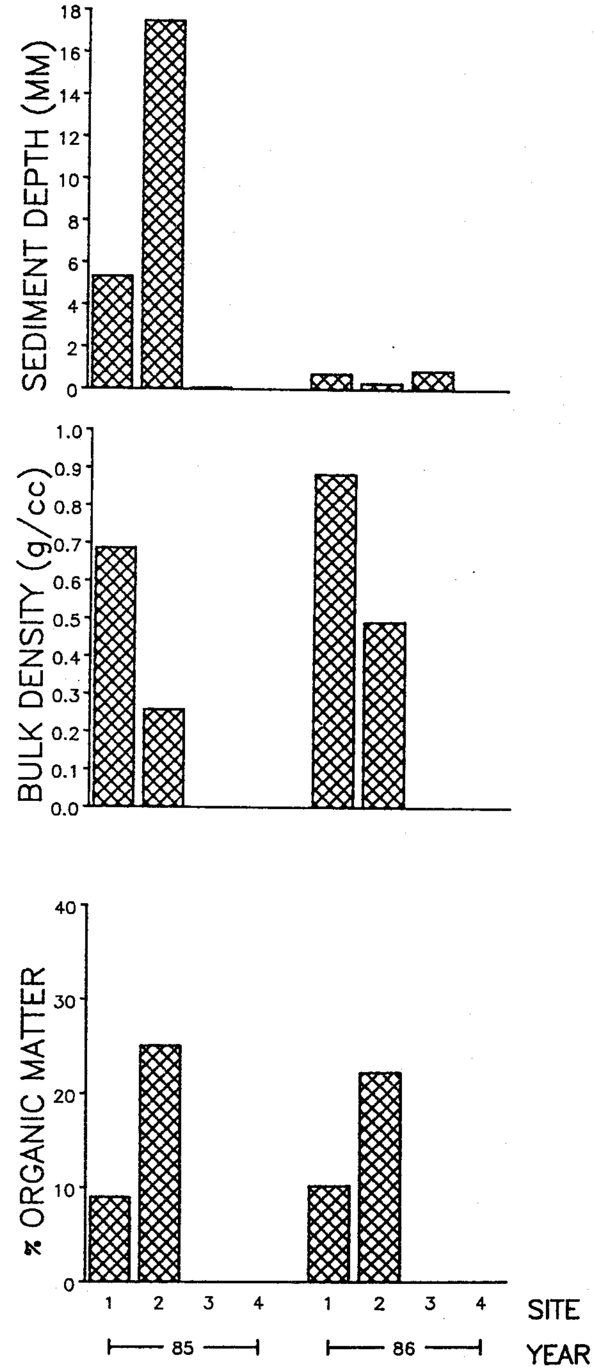

Figure 2. Depth of sediment, bulk density, and % organic matter for four sites in Mill Swamp during 1985 and 1986.

sity and organic matter content. Studies by Kuenzler and his colleagues (Yarbro 1979, Mulholland and others 1981, Yarbro and others 1984, Kuenzler and Craig 1986) and other researchers (Mitsch and others 1979, Brinson and others 1984, Kemp and others 1985) have shown that floodplains retain large amounts of sediment and phosphorus.

In summary, it appears that palustrine and riverine systems improve water quality, especially if most of the flow is directed through the wetland. In smaller streams the retention (e.g., burial of sediments) and removal (denitrification) potential of the system increases if flow patterns are altered so that water is retained behind natural or human-made structures. In larger riverine systems, wetlands have also been shown to improve water quality, although there is some evidence that the amount of retention may be related to the percentage of total river flow that comes into contact with wetlands. There are, however, other situations where water moves slowly over the landscape and there are extensive peat-dominated systems (boreal habitats, pocosins, the Florida Everglades, and cypress-dominated areas). In these areas, water quality improvement is most likely due to longer contact time between the water, vegetation, litter, and substrate.

Other Important Landscape Characteristics

What is the cumulative impact of having more than one wetland within a drainage basin, and does it matter whether or not they are different types? There have been so few studies that it is not possible to address this issue adequately. The question, however, is very important, because almost all watersheds contain more than one wetland, and alterations within the watersheds do not usually involve all wetlands in the system. Naiman and others (1986) have clearly shown that multiple wetlands within a system will slow the movement of materials downstream and will increase the overall system efficiency for nutrient processing. Odum (1982) has suggested that similar processes occur in wetland-dominated landscapes in Florida. Much more research must be done in this area.

Another key issue is the cumulative impacts of wetlands on water quality. Hemond and Benoit (1988) consider two aspects of this issue: (1) whether models can be used to predict the impact of a given nutrient loading or modification to a wetland, and (2) the estimation of the current status of a wetland based on measurements and observations. They suggest that there are problems with both approaches; adequate physical and biological data and understanding of the ecological processes are lacking. We agree with their assessment. There have been very few studies in which freshwater wetlands have been monitored for more than a year or two.

Richardson (1985) analyzed data from three wetlands and one upland site and found that the ability of the wetlands to assimilate phosphorus from wastewater decreased with time. He concluded that "The fact that many wetlands have accumulated massive quantities of phosphorus in peat over time has also been misconstrued as implying high phosphate retention." Kadlec (1983) found that significant retention of phosphorus in a Michigan wetland was followed by losses after 5 yr of wastewater addition. Boyt and others (1977) studied a wetland in Florida that had received wastewater for 40 yr. They found considerable uptake of phosphorus, but the annual hydrologic regime had a large impact on nutrient cycling. Clearly the database to evaluate cumulative impacts is not very large, and adequate answers to many questions will not be possible until a number of current research projects continue for longer periods of time.

Watershed Approach

What will be the cumulative impacts of a series of wetlands within a drainage system? As we have tried to demonstrate, we believe that wetlands in the upper parts of drainage systems have the greatest impact on water quality. Especially important are riparian areas and palustrine systems in which most of the flow comes into contact with the vegetation/litter zone. In most instances, we believe that the latter situation will also most likely be associated with wetlands in the upper parts of drainage systems. We are also aware that there will be many exceptions to this pattern, as some palustrine wetlands are associated with larger streams and/or dominate entire landscapes. We know of no instance where several wetlands along one drainage system have been studied simultaneously. The closest approximation is the beaver impoundments studied by Naiman and his colleagues. Even in that instance, the authors compared a generalized stream section with a generalized beaver impoundment rather than considering all the impoundments and wetlands along the drainage system. They clearly demonstrated, however, that the Beaver Creek system, with its series of wetlands/impoundments, conserved nutrients more than the other watersheds they studied.

Are the cumulative impacts on wetlands in any way related to the percentage of the drainage system occupied by wetlands? If a relationship can be shown between these two variables, then it may not be necessary to consider all of the wetlands along the hydrologic gradient. Oberts (1981) used a multiple regression ap-

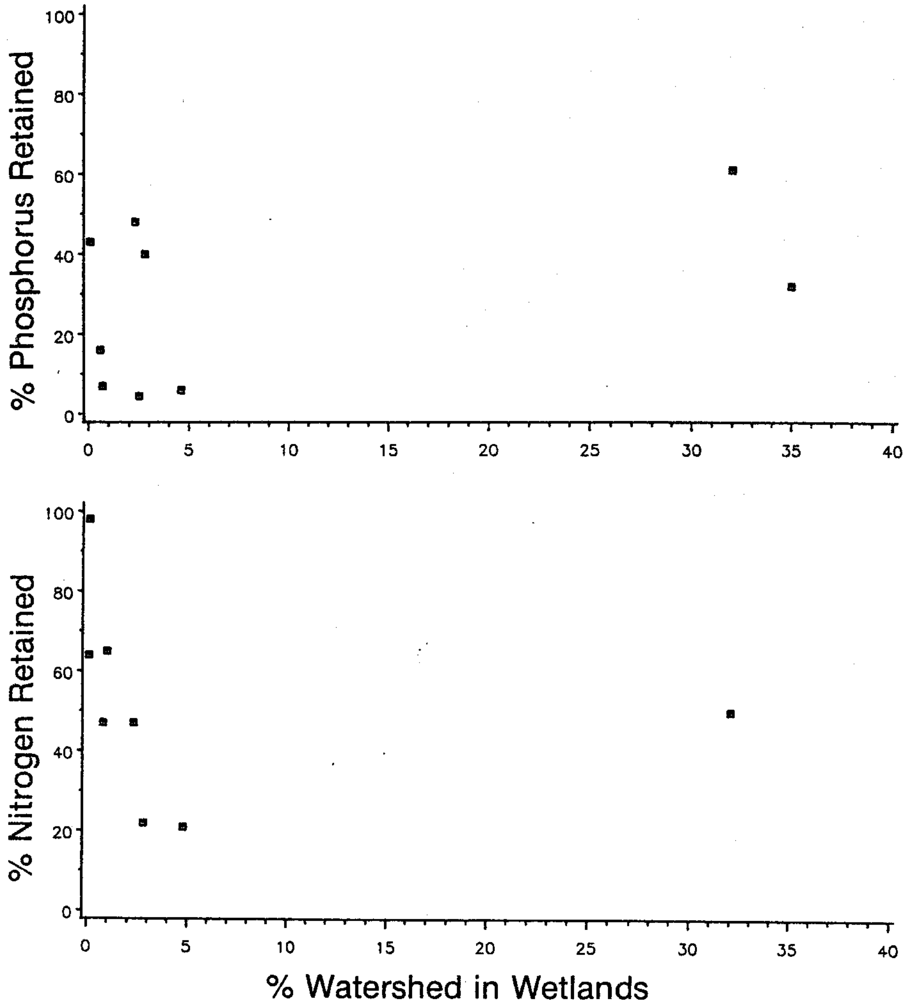

Figure 3. Comparison of % retention of total phosphorus and total nitrogen related to % of watersheds covered by wetlands. Data compiled from Rykiel (1977), Fetter and others (1978), Mitsch and others (1979), Monke and others (1982), Patten and Matis (1982), Verry and Timmons (1982), Naiman and Melillo (1984), and Yarbro and others (1984).

proach to characterize the importance of wetland area as well as other parameters in urban and rural watersheds in Minnesota. While wetland area was an important variable in many of his equations, others were also important, suggesting that wetland area within a watershed cannot be used as a simple predictor of water quality characteristics. Aside from Obert's study, there are few data available for such a comparison. We have reviewed the literature for studies that give total watershed area, total area of wetlands within the watershed, and % retention (or release) of nutrients from the system. We were able to find nine data points for total nitrogen and eight for total phosphorus (Figure 3). There appears to be no pattern for phosphorus, and the variability is quite high for lower wetland percentages. The two data points associated with large wetland areas relative to watershed areas are both greater than 30%, but data are insufficient to show that efficiency increases with wetland area within the watershed. The variability for nitrogen is even greater, and there is no hint of any relationship between wetland area and watershed area. We believe, however, that this approach deserves further study, because the present analysis is very tentative.

Conclusions

We have attempted in this article to take a different approach toward analyzing the available data on water quality and freshwater wetlands. Our hope was that a landscape approach to the subject might enable us to assess the water quality functions of wetlands relative to their position within the landscape. There is strong evidence that riparian areas are important for nitrogen processing and retention of larger sediment particles. Phosphorus removal appears to occur farther downstream in watersheds; the most important areas are those in which water flows through the vegetation/litter zone. Most wetland types in this category are palustrine. These systems are probably most important as sites for processing surface water, while riparian areas are important for nutrient processing in phreatic water. Riverine systems are also efficient processors of nutrients, but they are primarily important during flooding events. Lacustrine wetlands have less impact on water quality compared to other types, because the ratio of vegetated surface to open water is comparatively small.

Can any of this information be translated into research objectives? We believe that the landscape approach is useful and wetland researchers should attempt to focus on this issue. Sites where wetlands are distributed along a continuum within one or more drainage systems should be chosen. Emphasis should be placed on changes in water quality, both qualitative and quantitative, that occur as surface and subsurface water move along the wetland gradient. This will allow for the identification of landscape components critical to the water quality functions of wetlands. Focusing on sites where long-term studies are in progress will also produce data to answer questions related to cumulative impacts.

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