Water Regimes and Principles for Management of Wetland Systems

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INTRODUCTION

The water regime is the dominating influence in the ecological functioning and human values of wetland ecosystems. This statement may be considered the Hydrological Control Theory of Wetland Function. To the extent this theory holds, management of wetlands should concern itself in large part with management of the water regime, particularly the hydropattern. This paper defines what is meant by water regime, notes some of the fundamental roles played by the hydrological regime in determining the human values and the ecological functions of wetlands, and derives management principles for consideration when planning for the conservation and management of wetlands.

Eight principles for management of wetland systems include: wetlands are wet lands; wetland hydrology can be managed; no wetland is an island; manage for specific goals; know the hydrology; manage the hydropattern; do not manage for the mean; seek no net loss of hydrologic function or value within the watershed. These principles suggest that, to the extent that the hydrologic regime determines much of a wetland's ecological functioning and human values, preservation and management of appropriate hydropatterns may be essential to preserve these functions and values in the landscape. It is unfortunate but generally the case that management will be required in most wetlands in order to achieve a wise use of resources. The most functional level for goal setting is at the watershed scale, with individual wetlands becoming but one component of management of the entire watershed.

It is well accepted, that water is the dominating influence in the ecological functioning of wetland ecosystems (Mitsch and Gosselink, 1993; Kushlan, 1989a; Junk et al., 1989; Lugo et al., 1990). Hydrology is also intimately related to many of the important human values that wetlands serve in the landscape. Owing to its prevalence in the literature and thinking about wetlands, I suggest identifying this view be formalized as a paradigm we could call the "Hydrological Control Theory of Wetland Function." To the extent to which this theory is correct, it is reasonable to suggest that management of the hydrologic regime must be a fundamental factor in the conservation and management of wetland systems.

In this paper I will discuss several topics related to the dominating role of water in wetlands. First, I will define and characterize what is meant by "water regime". Then I will briefly document some of the fundamental roles played by the hydrological regime in determining the human values and the ecological functions of wetlands. Finally, I will derive management principles to be considered when planning for the conservation and management of wetlands.

DEFINING THE "WATER REGIME"

That wetlands need water is a truism and something of a logical circularity given that it is the presence of water and its effects on plants and soil that defines and delineates a wetland in the first place. So by definition, water is required for wetland development, persistence, and management. This definition sets a lower boundary for wetland management: wetlands cannot be drained and still retain all their ecological functions and human values.

The presence of water is a necessary, but not a sufficient condition for maintaining wetland function. Other aspects of hydrology are required as sufficient conditions, but these may be more subtle than wetness alone.

By way of example, one might consider how the amount of water present in a wetland would be a critical determinant of its ecological functioning. This is implied by the textbook view of the importance of the wetland water budget. Difficulty of determining any wetland water budget notwithstanding, the number of acre-feet being retained in a marsh is seldom by itself a critical aspect of ecological functioning (although it may be important to some wetland values, such as flood control). What a specific amount of water does do in a specific wetland is to create flooding conditions that are characterized ecologically by specific depths, durations, timing, and patterns of change. These factors are what affect ecological functioning.

Of these factors, depth is the most fundamental. A wetland that has developed under moist soil conditions is different from one that has developed under one foot of water. And these are different from a wetland that developed under two meters of permanent water. The depth of water, or depth to water, determines such critical features of a wetland as the type of plants present, their size and structure, the animals present, the redox potential of the soil, and the microbial consortia that occur there. Duration of flooding and the timing of variation can be crucial to ecological functioning.

A combination of depth, duration, timing, and periodicity is the "hydropattern" of a wetland. Hydropattern is depicted by a plot of depth by time, the "hydrograph" (See Figure 1). The hydropattern over a period of years sufficient to account for inter-annual variability is the "hydrological regime" or "water regime" of a wetland (See Figure 2). It is proposed that it is the hydropattern that should be one important basis for wetland water management.

HUMAN VALUES ASSOCIATED WITH THE WATER REGIME

Many of the human and economic values generally ascribed to wetlands are the result of water conditions that prevail in the wetland. Human value can emerge from the water regime in several ways. Wetlands may supply water for human use. Water and the materials water transports may be stored, removed, transformed, or attenuated by the wetland. Or water may support wetland resources of value or use to humans. Additional background may be found in Greeson et al., 1979, Sather and Smith, 1984, and Adamus et al., 1991.

Human Values Associated With the Water Regime

The amount of surface water in a wetland and its periodic fluctuation determines that wetlands role in human water use. The surface water in a wetland can recharge the aquifer where ground water flow can make it available for human use elsewhere, via wells or springs. In some wetlands, surface water is perched above the aquifer separated by an aquiclude of relatively impermeable rock, clay, or organic layer. In this situation, recharge occurs primarily along the edges of the wetland where the relatively impermeable depositional material meets a more permeable terrestrial soil. In some wetlands the connection between wetland surface water and groundwater is more intimate, such as in karst topography where the wetland may be created by the groundwater emerging at the surface. The amount of water held by wetlands accepting groundwater discharge determines how wetland retards water loss from the watershed through stream flow.

The amount of water and its fluctuations determine how and when water in a wetland can be used for human consumption. Such water may be used directly by humans, agriculture, livestock, or industry, or indirectly from recharged well fields or reservoirs. Wetlands can be expressly managed for their water supply function through retarding the down gradient movement of water in the watershed, thereby holding the water for when it is needed by humans. In this way wetlands themselves can function as shallow reservoirs for human use.

The amount and level of water in a wetland can affect its functioning in influencing the duration and amplitude of flooding within a watershed. The flood control value of wetlands results from their ability to store water within the watershed. Without such natural detention features, surface flows quickly proceed down gradient. With such detention features, the amplitude and rate of change of surface water are reduced, thereby lessening adverse downstream effects on human developments. An economic value of the water holding capacity of wetlands can be to avoid installing expensive artificial detention or distribution structures (levees, dams, canals, and spillways). Another value of water retention may be to increase recharge to the aquifer. The degree of flood control is in large part determined by the hydropattern characteristics, size, and location of the wetland relative to the size and hydraulic characteristics of the watershed.

The water regime of a wetland influences the fate of water-borne sediment. Water entering a wetland is slowed by the head of existing water and aquatic plants allowing suspended sediment to settle out. Within the watershed, basin wetlands particularly can serve as sediment catchments and riverine wetlands can build a rich depositional substrate provided they are not overwhelmed by the amount of material. In deltaic regions, wetlands can progressively colonize depositional environments.

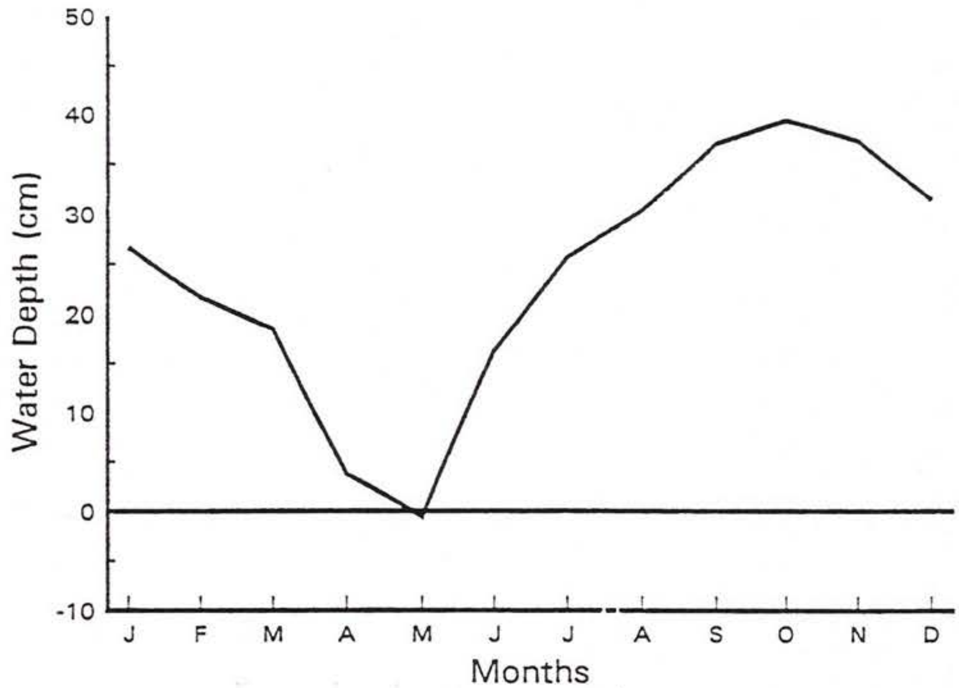

Figure 1. Example of an annual hydrograph showing fluctuations in water depth over a one-year period in a wetland.

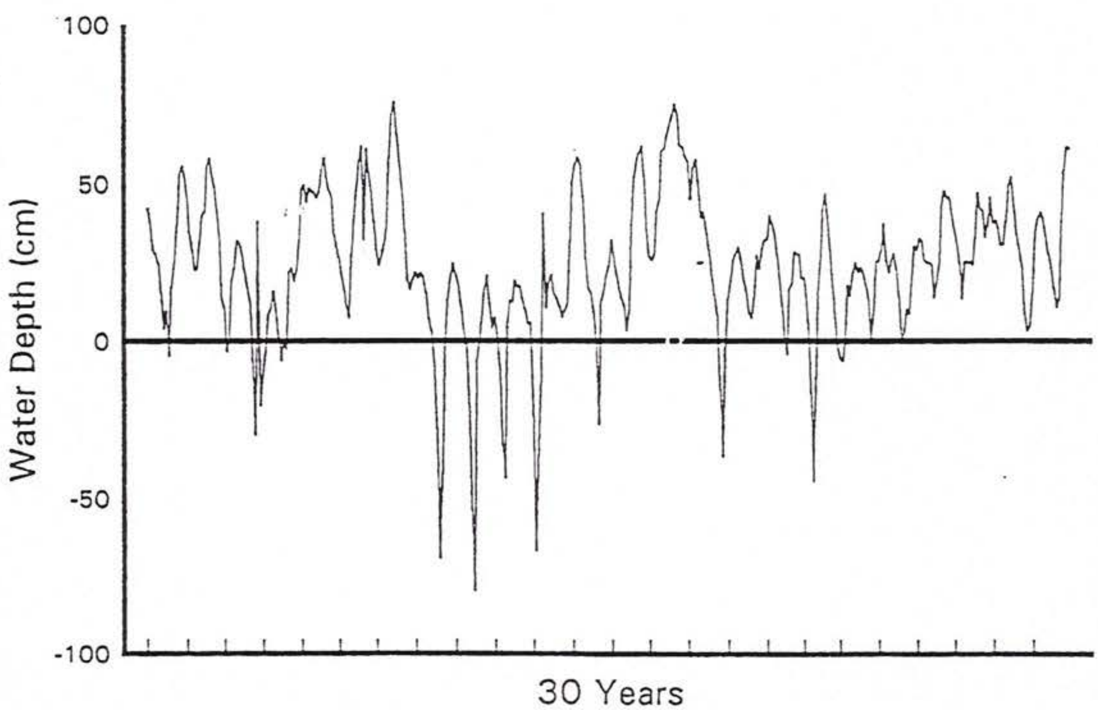

Figure 2. Example of a multi-year hydrograph showing fluctuations in water depth over 30 years in a wetland.

The water regime similarly influences how wetlands receive and process dissolved and particulate organic materials and inorganic contaminants. Natural organic material, pesticides, nutrients, and other organic and inorganic pollutants move down gradient from application sites dissolved in the water or adsorbed to sediment or particulate organic matter. Wetlands have well-demonstrated abilities to retain nutrients, thereby maintaining downstream water quality. Nutrients are taken up by plants or sediments or transformed by microbes. Wetlands also are likely to function similarly in retaining and transforming certain pesticides, metals, and other artificial materials. The passage of materials through a wetland depends on water depths and the resulting speed of water passage.

To the extent to which water moves out of a wetland via surface flow or stream flow is also determined by the water regime. Such effluent carries with organic materials, a feature thought to be an important function in some wetlands. Particulate and dissolved organic matter can be flushed out of wetlands by high water or heavy rain events and into receiving systems such as rivers or coastal lagoons, where it may support fisheries and other aquatic resources.

In developed countries, the waters of wetlands provide recreational opportunities, nearly all of which are hydroperiod dependent. Users enjoy recreations such as hunting, fishing, nature study, and water sports. Users may pay for access and enhance the economy by purchases of the tools and toys of recreation. For nature study, people are often interested in the rare or sensational plants or animals found in wetlands. Or they may just be interested in the aesthetics of vistas or vignettes of wild places. The extent and timing of water depth fluctuations generally determined which activities may take place in a wetland.

The waters of wetlands also provide forest, wildlife, and fisheries harvests, which depend on certain patterns of water fluctuation. Forest resources are directly harvested in wetlands worldwide, where wood products and fuel wood (including charcoal) are important industries. Sustainability of forest biomass harvest is not well understood, although the economic imperative is great in underdeveloped countries. Reed beds and peat, which require specific water conditions for development, are harvested for fuel in many parts of the world. Depending on the local culture, harvested wildlife resources may include such wetland species, such as crocodilians, muskrat, mink, nutria, deer, antelope, wild cattle, capybara, and many species of wildfowl and their eggs. Fisheries resources that are in some way dependent on wetlands are economically important in that many estuarine, river, and open water sport and commercial fishes and crustaceans use fringing wetlands for spawning and nurseries grounds. All these resources depend on specific characteristics of the water regime.

Although wet lands and agriculture are generally incompatible, as the extensive worldwide drainage of wetlands for agriculture demonstrates, critically important foodstuffs are grown in flooded wetlands. This particularly is the case for the most important of the world's grains and rice. The water regime on active or past wetlands determines the success of agricultural practices there.

Not all wetland resources of value to humans are harvested. Plants and animals dependent on wetland conditions include some of the world's most endangered and popular species. Many valued waterbirds that are not hunted depend on the wet conditions of wetlands. Migratory waterbirds use a succession of wetlands along their migratory routes and for wintering grounds. Among the more notable wetland mammals and birds are tigers, jaguars, storks, cranes, and crocodilians. Again, water conditions determine their use of wetlands.

The natural harvest available in wetlands has led to the development of wetland cultures throughout the world. Although the marsh peoples of the lesser developed world usually come to mind, developed countries, such as the United States and France, have historic subcultures that traditionally have depended on wetland resources. Thus human heritage values are associated with resources made available by the water regime of wetlands.

WETLAND FUNCTIONING ASSOCIATED WITH THE WATER REGIME

Many of the human values of wetlands derive from their ecological functioning. Many of these are directly associated with the water regime. Here, I will provide a few examples of how variables associated with the hydropattern (depth, duration, timing, and periodicity) directly and indirectly affect wetland plants and animals. Additional and supplementary information may be found in Van der Valk and Davis, 1978; Weller, 1981; Fredrickson and Taylor, 1982; Reimer, 1984; and Kushlan, 1987, 1989a, 1989b, 1991.

Depth

Depth is often the most critical variable because it determines what plants and animals can use a wetland. Plants have specific depth ranges. Indeed, growth forms of aquatic plants have predictable relative depth ranges. It is well known that along a transect from shallow to deeper water, emergent plants are replaced by floating leaf plants that are in turn replaced by submersed plants, which are finally limited by the depth of light penetration. On the other end of the transect, at some point very shallow water depths fail to provide an advantage to typically aquatic plants and may result in invasion by upland or facultative wetland species. The importance of water depths may be seen in the visible changes that occur in almost any wetland where, by artificial (dams, canals) or natural (beavers) means, water depths have been altered.

Specific depths are required for the use of a wetland by various animals. Many species of animals wade, and the water cannot be above their wading depth. Examples include wading birds, such as herons, storks, ibises, cranes, and shorebirds, and mammals, such as deer and mountain lions. Cranes and large herons can feed in deeper water than the smaller ibises, which can feed in deeper water than the even smaller shorebirds. Birds that swim require relatively deeper wetlands. Grebes, anhingas, and diving ducks that feed by swimming underwater use deeper wetlands than dabbling ducks that feed from the surface by upending.

To the extent that water depth controls vegetation development in wetlands, it also controls much of the use of wetlands by many animals. Specific vegetation structure is required for certain species to use a wetland or inhibits others from using the habitat. Marsh-nesting song birds require emergent vegetation, as do reed-nesting species, such as rails, cranes, terns, and ducks. Some wetland nesting birds, such as storks and herons, require trees or bushes growing overstanding water for nesting.

Depth, of course, determines the suitability of a wetland for various species of fishes and macroinvertebrates. Small fishes may live well in very shallow wetlands, whereas larger species may require deeper habitats. The interaction of prey populations and water depth can affect predators. For example, the snail kite is found primarily in deep water marshes where populations of its snail prey have been able to build up.

Duration

Wetland plants have differing and specific flood tolerances. As a result, length of flooding (hydroperiod) in addition to depth can determine what plants can invade and persist in a wetland and also determine development of plant associations. Different plants also have different requirements for dry periods (the complement of hydroperiod). Some require dry periods for germination and their seeds may wait many years for proper drying conditions to occur.

Duration of flooding also affects long-term survival of aquatic plants. Long-term high water depths lead to the eventual death of emergent plants and their replacement by submersed or floating leafed plants. Long-term low water depths have the opposite impact, and even the invasion of more mesic plants and shrubs.

Duration affects animal populations similarly. Many aquatic species occur only where water depths are appropriate for a sufficiently long period of time for invasion and reproduction to occur. For example, after a wetland floods, fish populations must invade the site and then have a sufficient period of time for growth, maturation, and reproduction to establish viable populations. This is also the case for invertebrates. However, population size and stability of smaller invertebrates and fishes may be affected by the ability of larger predator populations to develop. Thus invertebrates tend to dominate the fauna of isolated, short flood-duration wetlands.

Timing

Timing of water depth changes may be critical for plant establishment and survival. This is especially the case for the aquatic plants that require seasonal drying for germination. The drying period must correspond with a favorable season and temperatures. Drying in the winter months may not permit germination or survival. Water depths must also fluctuate with appropriate timing after germination, such that depth does not outdistance the growing seedling.

Surprisingly precise seasonal water depth changes may be required for the successful reproduction of fish, birds, and reptiles. In fluctuating wetlands, fish populations become concentrated by decreasing water depths and disperse on increasing water depths. The rate of decrease may be crucial to the pattern of survival of the fishes over the drying period. Predators that depend on accessing the food available in drying wetlands similarly depend on precise timing of water level changes. The successful nesting of wading birds, for example, may depend on very specific rates and timing of water level decreases. Similarly, water level rises affect wetland use. If water depths increase rather than decrease, wading birds can abandon nesting, or marsh-nesting species can have their eggs flooded.

Periodicity

The depth, duration, and timing create a periodicity of fluctuations in most wetlands. Often this is seasonal, with dry periods expected at one or more specific times of year. Periodicities also occur over cycles that cover multiple years. It has been shown that multi-year wet and dry cycles occur, and that these affect the depth and duration of water cover. Such periodicities are an inherent part of the water regime of a site.

PRINCIPLES FOR THE HYDROLOGICAL MANAGEMENT OF WETLANDS

The previous discussion has provided examples of how many of the human values of wetlands depend on water conditions, and similarly how the characteristic plants and animals of wetlands require specific water conditions for reproduction and survival. To the extent that the hydrological regime entrains the values and ecological functioning of wetlands, hydrology should be a principal focus in the establishment and carrying out of management policies for wetlands. I suggest seven principles to be considered in managing wetland hydrology.

Wetlands Are Wet Lands

This principle derives from the fundamental definition of wetland ecosystems. Wetlands develop where soil has been saturated with shallow water for sufficient periods to develop anaerobic conditions leading to the creation of hydric soils and the invasion and persistence of aquatic plants, animals, and microbes.

Without water, wet-lands become up-lands and succeed to an entirely different ecological endpoint in which both functions and values differ fundamentally from those of wetlands. The purposeful change from wetlands to dry land, of course, is the history of wetlands worldwide, as they are drained to support alternative human uses for the land. Wetlands can be dewatered by subtle means, local ditching (such as farm or mosquito control ditches), lowered water tables, diversion of flood and nonflood inflows, retention of flows up gradient, changes in landform, or water withdrawal for consumptive use. Dewatering does not require drastic alterations at the wetland site but can result from changes occurring elsewhere in the watershed or aquifer.

Wetland Hydrology Can Be Managed

The preservationist ethic tends to dominate considerations of wetland conservation in North America. Faced with the vastness of the North American continent, there remains hope that wetland wilderness would persist if only human interventions would cease. While we hope there remain such places as the northern tundra and mountain wet meadows, most North American wetlands are but a remnant of their historic size, occur in watersheds that have been altered, and are subject to human use of water and water-related resources. It is an unusual wetland that need not be subjected to some sort of explicit, planned, and thoughtful management in order to persist as a functional and valuable component of its watershed. Appropriate hydrologic management may be highly preservationist or it may be highly interventionist, depending on the situation.

Outside North America, the need to manage wetlands may be more widely accepted. The management strategy accepted for wetlands worldwide is their "wise use," which means their sustainable use by humans in ways that protect their function and values and the future availability of these resources. Use requires management; wise use requires careful, scientifically valid and culturally sensitive management. In face of the need for economic development throughout the world, the wetlands that will persist will be those that provide recognized and appreciated values to humans. If a wetland is to be used for any of its values, its hydrology will need to be managed to protect those values over time.

No Wetland is an Island–Manage Wetland Hydrology Within the Watershed

The hydropattern of a wetland is a dependent variable of a highly multivariate system. Important independent variables include external forcing functions. Thus, water depth depends in part on how much water comes into the wetland and on what schedule and how much leaves and on what schedule. Such surface and groundwater inflows and outflows depend on what happens outside the wetland in the watershed, both up gradient and down gradient of the wetland itself. The only way to manage hydropattern in the wetland is to manage controllable external forcing functions; that is, to manage wetlands within context of their watershed.

It should be noted that this principle is not reflected in all of current wetland management practice in North America. Presently, each wetland tends to have independent regulatory standing. Its value is assessed; the relative economics of its preservation vs. development are calculated; its public profile is noted; its location, size, and connectiveness are measured; and a decision is made as to its future. The larger watershed view tends to come into play when a wetland's connectiveness makes it of greater perceived value than if it were more isolated, when development of a wetland is considered in the regional context of cumulative impacts, or when its development will require offsite mitigation.

Somewhat surprisingly, the no net loss goal tends to support the individualized approach to wetland management, because each wetland patch is considered as contributing the inventory of wetland area. This need not be the case, if no net loss were viewed from a perspective of preserving overall wetland functions and values within a watershed.

Manage for Specific Goals

To manage requires a goal towards which management should proceed. It is likely that the single most difficult aspect of wetland management is settling on management goals. If there are few interest groups involved in a decision as to management goals, the goal-making step often is ignored. If there are many interest groups involved in a decision concerning management goals, the goal-making step may flounder on incompatible expectations. In neither situation are goals set.

Each wetland has many values, some more important to certain stakeholders than they are to other groups. Significant conflicts among the primacy of certain values can hamper setting common goals. Compromising fishery, hunting, and passive recreation values for the sake of water use, for example, is likely to lead to impasses unless carefully resolved through negotiation.

A goal for a specific wetland might be to restore natural functioning. In such a situation, managers would need to be able to define natural functioning in ways to assure that they had met their goal. A goal of natural functioning may secure multiple values but would not explicitly enhance any one value, such as waterfowl management. Alternatively, a wetland could be managed to enhance one of its values, such as water supply, realizing that other values may be compromised. The important point is that goals for a wetland must be set in advance.

To achieve any management goal, the functional aspects of the wetland needed to produce these values need to be understood. As previously argued, for biological value this will probably involve hydropattern management. Then the engineering needed to produce these goals must be put in operation. Only then can successful management be engaged.

Goal setting should extend beyond the wetland to the watershed. It is possible that the loss or alteration of some wetlands would not adversely affect the overall values wetlands have in a watershed. Or differential management of remaining wetlands might mitigate the loss of value of the developed wetland. In this way some development or alteration might be approved without a net loss of wetland functioning. Without a common goal for the watershed management accepted by the major interests, achieving a management goal for a particular wetland is likely to fail.

In addition to goals, a manager should provide assessment tools in order to determine whether the goals have been met. Assessment tools should relate as directly as possible to the expected outcomes of management. That is, they should suggest whether the management goals have been achieved. Assessment tools may relate to the achievement of a hydropattern or to the preservation of specific wetland values. The point here is that assessment must follow management action, and this assessment should be related to the goals.

Know the Hydrology

To manage the hydropattern, the hydrology of a site and its watershed should be known. It should be understood whether the system is a moist soil wetland, a shallow fluctuating wetland, or a deep permanent wetland. If fluctuating, a manager needs to understand the usual seasonal hydropattern, the timing of wet and dry, inter-year variability, the normal hydroperiod, the normal drydown period, and the usual rates of change. A also needs to know how conditions in the watershed and variation in rainfall affect water depths, and whether there are predictive relationships that can guide management decisions.

Knowing the hydrology may be difficult if historic data are unavailable. However, if rainfall and stage monitoring stations exist in a watershed, it may be possible to model historic water depth changes in a specific wetland and to predict future water depths under various management scenarios.

With such hydrological information, one can set out to develop a plan of water management. Usual and long-term hydrographs before alteration provide a hydrologic baseline for management. This information can then be related to the important values that management has placed on this wetland, and decisions may be made as to what hydropattern will deliver desired values and services. If the watershed and wetland are relatively unaltered, perhaps protection of inflow waters rather than active management is required. If the watershed has been significantly altered, inputs and outputs may need to be actively controlled to produce a certain hydropattern.

Manage the Hydropattern

The hydropattern of a wetland determines much of its biological functioning and its value in the landscape. In order to achieve goals related to these functions or values, the hydroperiod must be managed.

Variation in water depth integrates the effects of all other input and output variables. For example, rainfall is certainly an important variable in wetlands, but rainfall really is important only to the extent that it effects depth, duration, and timing of flooding. A similar argument applies to evapotranspiration, inflow, recharge, and discharge.

Furthermore, these variables are often related statistically. Rainfall data in some cases can be used to predict inflow and resulting water depth. Stage-discharge relations predict outflow. Stage-duration curves can be used to predict the return time of certain stages, but these do not show the time course of variation that is a critical variable to plants and animals.

The effect of inflow and discharge on the hydropattern reinforces the importance of considering wetlands within the context of their watershed. The size, shape, slopes, and contours of the watershed, its hydrological connectiveness and "roughness," the relative importance of stream, surface, and ground flows, ambient rainfall and snowmelt patterns, soils, bedrock, and aquifer characteristics, and human development in the floodplain all determine how much water enters and leaves wetlands and on what schedule. The water regime of a wetland cannot be defined or understood apart from the casual relationships with variables in the larger system of which it is a part, the watershed.

Do Not Manage For the Mean

This discussion has focused on the need to understand the usual hydropattern and the need to take this understanding into consideration when setting goals and establishing outcomes assessment tools. However, the error of managing for the mean must be avoided. While a mean annual hydropattern will suggest the overall water regime of a wetland, it is unlikely that under natural conditions any year would match that mean. Thus replicating a mean hydropattern each year will likely not achieve the management goals of the wetland.

Of course, this depends on the goals. If the wetland value to be managed is only water supply, then achieving a specific hydropattern each year might be a valid goal. This is the management strategy for reservoirs, where discharges are made to match a regulation curve (a stage hydrograph). This curve is derived after consideration of the annual needs for water supplies, under best management practices, and also the upstream and downstream effects of discharge on flooding conditions in the watershed. Water managers then try to match this curve as closely as possible. Similarly, a specific, unnatural hydropattern might be required in a greentree reservoir to achieve appropriate flooding and drying conditions.

If, on the other hand, preservation of natural ecological values is the goal, a consistent mean hydropattern is seldom appropriate. Many wetlands are highly variable from one year to the next, and their ability to support a diversity of plants and animals may require difference in the hydropattern from one year to the next. In these cases, management should retain the inherent variability of the hydrology and allow excursions that reflect relatively high water and low water years.

Seek No Net Loss of Hydrologic Function or Value Within the Watershed

The no net loss approach to wetland conservation has both advantages and disadvantages. However, when carefully applied, it can provide guidance for management. If the goal is to lose no more wetland area, then an aerial approach to no net loss is justified. However, given the impossibility of protecting every wetland patch and the difficulties faced in creating wetlands for mitigation purposes, an areal goal is probably not achievable.

The alternative is to consider the no net loss goal in context to the value of wetlands in the landscape. Unlike a surface area approach, a value driven approach does not equate all wetlands as having equal importance. Thus the goal can be stated that in the management of the entire watershed an attempt will be made to achieve no net loss of wetland values.

Of course it is not yet possible to understand all wetland values, nor relate them fully to hydrological conditions. On the other hand, such an approach sets the search for management goals and assessment in a different context in which all the wetlands of a watershed are conceded together rather than in isolation.

CONCLUSION

For most wetlands, the hydrologic regime determines much of their ecological functioning and human values. Thus, the preservation and, perhaps, management of hydropattern is essential to preserve these functions and values. It is the unfortunate case that active management will be required in most wetlands to achieve the wise use of their resources. Management requires that goals be set, management be accomplished, and outcome assessed to evaluate whether the goals were achieved. The most appropriate scale for goal setting and management action is at the watershed, with individual wetlands becoming one aspect of management of the entire watershed.

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