**Maintaining Biodiversity in Constructed Wetlands**

Abstract:
*Natural wetlands have been dramatically reduced due to development and modern agricultural techniques. In addition, wetlands are becoming an increasingly popular means of bioremediation and treatment of wastewater. In an effort to protect the wetland ecosystem while utilizing its intrinsic filtering capabilities, multi-objective constructed wetlands are popping up across the world. However, limited knowledge of the processes and relationships that govern such ecosystems means that constructed wetlands may not be an equivalent replacement for natural wetlands. Some researchers fear losing natural wetland biodiversity through overly eager attempts to construct simplified wetlands that are exploited for their industrial applications. Instead of offsetting only the direct losses of wetland area, wetland mitigation programs should also strive towards protecting wetland functions.*

## INTRODUCTION

Constructed wetlands represent a collaborative effort among biologists and engineers to create systems that mimic the intricate behaviors of natural wetlands. Wetland construction programs have become increasingly popular with the establishment of regulatory initiatives. However, knowledge of wetland design that incorporates nutrient and pollution reduction as well as biodiversity is still rather limited (Hansson et al. 2005). The balance between biology and engineering is difficult to achieve. If engineers are left alone in the design of constructed wetlands, their plans often reflect a lack of understanding of fundamental biological processes. Yet, biologists are not trained to integrate engineering and hydrological designs into their wetland projects (Benyamine et al. 2004).

There is a growing amount of research concerning the impacts of constructed or restored (partially constructed) wetlands on natural ecosystems. There is danger in believing that the comparatively simplistic human-constructed wetlands can truly substitute the natural wetlands they replace. This literature review will discuss the rising interest in wetland preservation and then examine recent research that has compared the functionality of constructed wetlands versus natural wetlands.

## STATE OF WETLANDS

Marshes, swamps, bogs, and fens all fall within the broad category of wetlands. In the contiguous United States, approximately five percent of the land area is categorized as wetlands according to a fact sheet published by the United States Environmental Protection Agency (EPA) in 2001. This same publication reported that this small proportion of land area, however, hosts 31 percent of plant species and nearly one-half of bird species in the United States. Wetlands are particularly sensitive to environmental changes, and sadly, the current rate of wetland loss in the United States is 60,000 acres each year (EPA 2004).

Worldwide, wetland degradation has accelerated with industrialization and modern agricultural practices. Citing Innis et al. (2000), Benyamine et al. (2004) used the fact that 60 percent of the world's wetlands have disappeared in the last century to spur their research into what defines a "good" wetland ecosystem. The loss of wetland habitats has contributed significantly to species extinction. Additionally, the reduction in wetland area paired with the increased use of fertilizers has led to severe eutrophication problems in both freshwaters and coastal waters (Hansson et al. 2005).

## VALUE OF WETLANDS

Wetlands supply several vital functions to natural ecosystems. In addition to providing unique fish and wildlife habitats, wetlands store floodwaters, maintain surface water flows, protect water quality through natural filtration, and serve as centers of biological productivity – much like tropical rain forests or coral reefs. The human value of these functions is difficult to determine in terms of an exact market price. However, as is often done when valuing common property resources, an examination of consumer behavior and opportunity costs can generate approximate figures. According to the EPA, wetland-related ecotourism contributed approximately $59 billion to the national economy in 1991. The United States Army Corps of Engineers estimated that protection of wetlands along the Charles River saved the Boston, Massachusetts area $17 million in avoided flood damage (EPA 2001). A majority of commercial and recreational fishing depends on wetland-dependent species, generating nearly $79 billion annually according to the Pacific Coast Federation of Fisherman's Associations (EPA 2001). These contributions translate to a significant value that wetlands provide society.

## GOVERNMENT INVOLVEMENT

The Clean Water Act was one of the first effective pieces of federal legislation to establish government responsibility for maintaining and protecting natural waters in the United States. In recent years, the United States government has expressed its re-commitment to wetland protection through various programs. During his presidential campaign in 1988, President George Bush pledged to achieve a "no net loss" of wetlands. Section 404 of the Clean Water Act was clarified in 1990 to establish clear guidelines for wetland mitigation. The EPA and Department of Army established the following hierarchy for mitigation decision-making:

(1) **Avoid** – Practical alternatives should be fully considered prior to initiating a project that will adversely impact a wetland area.

(2) **Minimize** – If an impact cannot be entirely avoided, efforts should be taken to limit the negative effects of such a project on a wetland area.

(3) **Compensate** – Appropriate actions should be taken to offset the unavoidable adverse impacts.

(EPA 2002)

In 2000, the EPA's Office of Wetlands, Oceans, and Watersheds established two priorities: state-level wetland monitoring programs and improvements on the success of compensatory mitigation (Brooks et al. 2004). In a collaborative effort among several federal agencies, the National Wetlands Mitigation Action Plan was established at the end of 2002. The EPA recognizes the creation, restoration, enhancement, or preservation of wetland areas as appropriate means of compensatory mitigation (EPA 2002).

As a result, it has become relatively simple to justify development by agreeing to construct an equivalent area of wetlands to replace any impacted natural habitat. Most recently, President George W. Bush announced a new national goal of not only maintaining but also expanding total wetland areas. This places even more emphasis on the use of human-designed and constructed wetlands.

Brooks et al. (2004) reported that opponents of wetland development believe mitigation is simply a license to impact natural wetlands, and that the constructed system is a scant resemblance in terms of function to the natural ecosystem it replaced. In 2001, the National Research Council reported that the goal of no net loss of wetland functions was not being met due to a variety of suboptimal and operational decisions. In other words, there is plenty of room for improvement. Brooks et al. (2004) continue on to propose that losses of wetland function should be considered in addition to direct losses of wetland area.

## WHY CONSTRUCTED WETLANDS?

Wetlands are natural cleansers. By slowing down water movement, suspended solids settle while pollutants and nutrients are absorbed by the dense vegetation. Scientists and engineers have used natural wetlands as a model to construct systems of their own to treat storm water and, more recently, wastewater. The EPA defines constructed wetlands as "treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality" (EPA 2004). Constructed wetlands are praised for often being less expensive to build and maintain than conventional wastewater treatment facilities, while effectively removing odors and other pollutants in an aesthetically pleasing manner. There are currently around 1000 constructed wetlands treating wastewater in the United States and nearly five times as many operating in Europe (EPA 2004). Such systems treat industrial wastes such as landfill leachate, pulp and paper wastewater, mine drainage, and wastewater from petroleum refineries, electroplating industries, and textile production (Benyamine et al. 2004).

To promote their use, the EPA has established guidelines for the successful design of constructed treatment wetlands. There is even mention of the importance of creating a diverse foundation of species. However, there remains an underlying sense that this goal should never precede the human appreciation of the created system:

> Where appropriate, design your constructed treatment wetland to provide habitat with a diversity of native species comparable to similar wetlands in the region. Maximize vegetative species diversity, where appropriate, without increasing the proportion of weedy, non-indigenous, or invasive species at the expense of native species. Project plans should include mechanisms to control or eliminate undesirable species….Developing a wide variety of wetland types will provide a range of diversity for different types of wildlife. Considerations may include seasonal hydroperiods, depth-flow changes, vegetative succession, and accumulation of sediments.
>
> (EPA 2000)

Beyond treatment, there are several other potential applications for successful wetland construction methods: (1) improvement of degraded sites; (2) re-construction of wetlands on the site in which they were destroyed; and (3) creation of new wetlands where they previously did not exist (Keddy 1999). However, in terms of biodiversity, the construction of wetlands has not been met with wide success. Natural wetland ecosystems are difficult mimic because they are too complicated to be modeled analytically yet small enough not to be properly modeled through statistical analysis (Keddy 1999). Oftentimes, constructed wetlands are designed as simplified versions of their natural counterparts. The true performance of these systems is uncertain.

## MEASURING SUCCESS

Undoubtedly, constructed wetlands have become a valuable technology. However, the question still remains whether they serve as an appropriate replacement for natural wetlands. Certainly wetland mitigation programs would not be considered successful if they failed to protect the features that make natural wetlands unique.

Keddy (1999) identified three appropriate indicators for monitoring wetland function, which in turn may be used to measure the success of constructed wetlands. These indicators were chosen on the basis of five criteria: (1) ecological significance; (2) scale; (3) practical application; (4) sensitivity; and (5) simplicity. As Keddy explains, a good indicator should represent some ecologically significant function or environmental process within the wetland, reflect the performance of the wetland as a whole (as opposed to one minor aspect), be experimentally measurable, adjust quickly to environmental stresses or other ecological changes, and be easy and inexpensive to monitor.

There are three types of indicators that sufficiently meet these requirements: damage responses, abiotic environmental factors, and biota. Keddy (1999) defined damage response indicators as factors which become apparent in stressed environments, such as increased respiration or nutrient loss. Abiotic factors include dissolved oxygen levels, salinity, water level fluctuations, or other physical features which have been shown to affect wetland function. Biota-based measurements are the third type of indicators. They seem to have received the greatest research attention in recent years. These measurements focus on elements of wetland composition, such as biomass, biodiversity, or the incidence of certain species.

Biodiversity and other biota-based measurements serve as an excellent gauge of the health of a wetland system, since they account for wetland processes as a whole. Unlike purely structural or functional indicators which may inadequately represent the true effects of environmental disturbances, biodiversity measures are able to characterize ecosystem integrity on a broader scale (Mayer and Galatowitsch 2001). Several methods are available to assess biodiversity.

Likely one of the easiest methods of measuring biodiversity is simply through visual inspection. When Hansson et al. (2005) chose to compare the functionality of constructed wetlands, they gathered most of their data through multiple biological samplings – netting random samples of fish and amphibians, identifying plants within sample areas, and bird watching. On a smaller scale, bird inventories alone can serve as a measure of biodiversity. Benyamine et al. (2004) relied on historic bird counts to characterize biodiversity in their examination of multi-objective constructed wetlands. Inventories of plant species or benthic invertebrates are yet other alternatives. Brooks et al. (2005) used a combination of invasive plant counts, invertebrate indexes, and bird inventories to relate natural, degraded, and constructed wetlands in terms of species diversity.

Plant production-diversity relationships are yet another method, though more indirect. Mayer and Galatowitsch (2001) developed this novel method as a tool to compare the functionality of natural and constructed wetlands. Production was measured in terms of diatom biomass as a function of the quantity of observed plant species. Biota-based methods like these have allowed researchers the opportunity to examine how biodiversity is related to wetland structure, production, geography, and multi-objective designs.

## STRUCTURE

Brooks et al (2004) examined how constructed wetlands function in comparison to degraded natural wetlands as well as healthy (reference) wetlands. The analysis was able to make some important connections between the structural functionality and biodiversity of wetlands. Initially, the experiment compared degraded wetlands to reference wetlands. There were obvious structural differences. Degraded systems showed higher sedimentation rates, lower levels of organic matter, and greater susceptibility to invasive plant species.

The next step in the analysis was to relate constructed wetlands to healthy natural systems. Indeed, Brooks et al. (2004) found observable differences here as well. Constructed wetlands had higher amounts of sand and lower amounts of organic matter than reference wetlands. These observations suggest that constructed wetlands are physically most equivalent to degraded wetlands. Brooks et al. (2004) cited a study by Campbell et al. 2002 that drew a similar conclusion.

Using these observed relationships, Brooks et al. (2004) designed an illustrative model to distinguish the three types of wetland structures studied. Figure 1 shows how site stressors, buffer type, and surrounding location may lead a reference wetland to become degraded. The characteristics of a constructed wetland can be considered most closely equivalent to a degraded wetland environment. The model clearly suggests that the exact replication of a natural land is not possible, even under the most advantageous circumstances.

Once the general relationship between the three wetland types was identified, biodiversity provided another form of comparison. Brooks et al. (2004) used macroinvertebrate index of community integrity and bird community index scores – both measures of animal biodiversity – to evaluate 16 degraded wetlands, seven reference wetlands, and seven constructed wetlands. The biodiversity measures indicated that species variation was greatest for reference sites and lowest for degraded sites. Constructed wetlands ranked most similar to degraded wetlands in terms of animal biodiversity, once again supporting the Brooks model of structural similarity between those two types of wetlands.

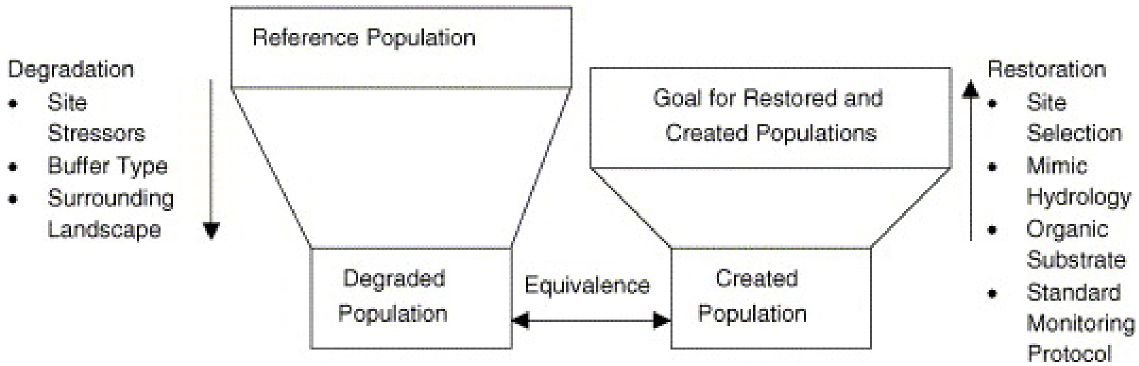


**Figure 1.**
*Visual representation of the equivalent relationship between degraded wetlands and constructed wetlands. The goal of mitigation projects is to create constructed wetlands which function closely to the level of reference, or natural, wetlands. (Brooks et al. 2005)*

An examination of invasive plant species among the three wetland types is summarized in Figure 2. Constructed wetlands showed a greater proportion of invasive plant species than both degraded and reference wetlands (Brooks et al. 2004). Two studies by Moss (2000) and Loreau et al. (2001) suggested that an existing high biodiversity of native species helps to ward off invasive species (Hansson et al. 2005).

The tendency of constructed wetlands to perform similarly to degraded wetlands can be reasoned in several ways. First, the plant species for constructed wetlands are chosen to meet specific project objectives, not necessarily to represent a local biodiversity. Second, the artificial soil composition of a constructed wetland may favor particular plant species. Constructed wetlands often are either too dry or too wet, both of which tend towards a highly homogenous population (Brooks et al. 2004). Lastly, neither constructed wetlands nor degraded wetlands have the luxury of a dense, established population to help defend against invasive species. Consequently, both may easily become overridden by foreign species, which in turn disrupts healthy diversity.

Another study by Taylor and Middleton (2004) found that natural wetlands and constructed wetlands exhibit different rates of decomposition. The study compared the decomposition of leaves from four different plant species within natural wetland sites and constructed wetland sites, specifically reclaimed coal-slurry ponds. In each case, the decomposition rates were observably lower for natural wetlands.

Taylor and Middleton (2004) explained the discrepancy by pointing to organic matter accumulation. The concentration of organic matter within a wetland is tied closely to ecosystem function – habitat quality, production, and finally, decomposition rates. Taylor and Middleton (2004) noted seven times greater organic matter accumulation within the selected natural wetlands, echoing the findings by Brooks et al. (2004). High organic matter is correlated with low pH, which slows the decomposition process within a system. This relationship is cyclical since slower decomposition rates yield greater organic matter accumulation.

In a wetland system, the accumulated organic matter forms an interface between the soil and plant structure. The level of organic matter directly impacts soil nutrient and water capacities, seed germination, and plant production (Taylor and Middleton 2004). Since organic matter levels and decomposition rates impact the quality of plant growth in a wetland, they must also play a role in plant diversity. The authors cited another study by Zedler and Callaway (1999), which identified insufficient levels of organic matter as one of the largest obstacles for the successful performance of constructed wetlands.

On the plus side, Taylor and Middleton (2004) mentioned several studies in which researchers have tried to artificially increase organic matter levels in constructed wetlands. Some wetlands have responded well, while others have not. Wetlands also require time to accumulate organic matter, which could explain why constructed wetland performance typically improves with age (Taylor and Middleton 2004).

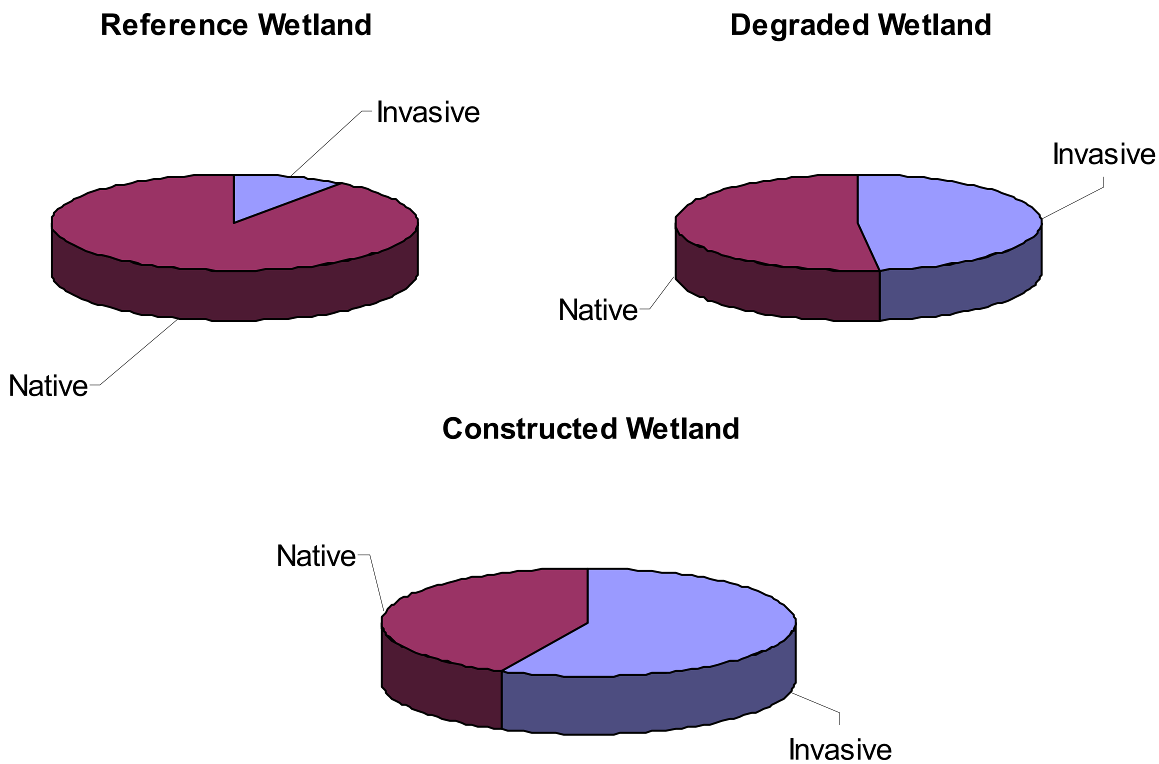


**Figure 2.**
*Comparison of the approximate proportions of native and invasive plant species within reference, degraded, and constructed wetland sites as examined by Brooks et al. (2005). Reference wetlands showed the greatest resistance to the invasion of foreign species, followed by degraded sites and finally constructed sites.*

PRODUCTION

Mayer and Galatowitsch (2001) approached the biodiversity question from another angle. Instead of comparing species richness between natural and constructed wetlands, the authors examined diatom production as a representation of wetland function. Interestingly, among the 33 wetlands that were studied, Mayer and Galatowitsch (2001) found no significant difference in overall plant diversity between constructed and natural sites. In fact, for the most part, the same species were found in both. Total diatom production was comparable between constructed and natural sites, since statistical analysis revealed that production was dependent on species type rather than wetland type. However, the authors also reported an observable difference in species production between natural and constructed wetlands.

The real discovery came when Mayer and Galatowitsch (2001) determined that production was negatively related to plant diversity only within constructed wetlands – there was no such correlation within natural wetlands. In other words, diatom production was highest for the constructed wetlands that had the lowest diversity. In this situation, *Rhopalodia gibba* and *Epithemia* species were responsible for the greatest production, suggesting that these species are particularly aggressive given the artificial conditions of a constructed site (Mayer and Galatowitsch 2001). Owing to this difference, Mayer and Galatowitsch (2001) suggest that the production-diversity relationship can be used to distinguish natural and constructed wetlands.

Mayer and Galatowitsch (2001) also conducted a transplant experiment in which plant species were relocated from natural wetlands to constructed wetlands and vise versa. The plants adopted the same production-diversity relationship to match their new environment. For instance, plots of diatoms moved from a constructed wetland to a natural wetland lost the negative production-diversity relationship. The opposite was true for plots of diatoms moved from natural to constructed sites. Mayer and Galatowitsch (2001) use this observation to argue that low-diversity constructed wetlands operate with an "impaired ecological integrity." In this way, high diatom production indicates a poorly functioning wetland system.

GEOGRAPHY

The health of a wetland is also a function of the geography in and around the site. Constructed wetlands tend to have a simpler, more geometric shape than their natural counterparts (Brooks et al. 2004). This aids in constructability and lowers construction costs but may discourage species richness. Hansson et al. (2005), on the other hand, found that complex shorelines favor bird and plant diversity. Figure 3 illustrates the linear relationship observed between the number of plant species and the shape of the wetland. Shoreline complexity was calculated as a function of shore length and wetland area. The authors concluded that shallow wetlands exhibit higher diversity than deep, lake-like systems.

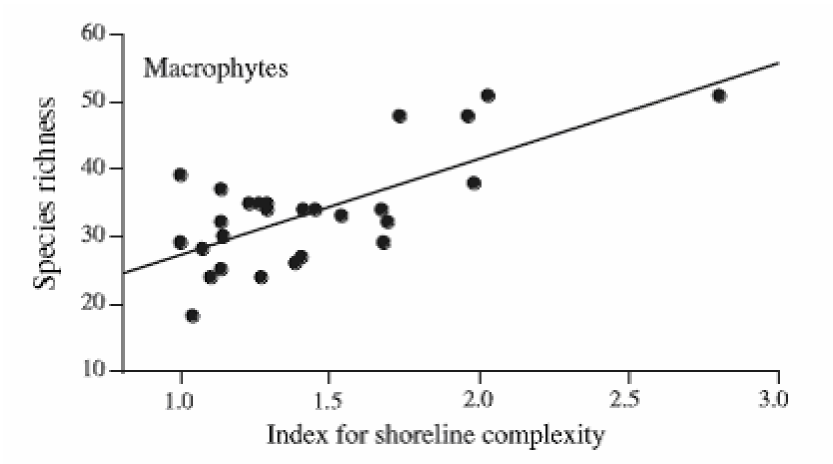


**Figure 3.**
*Linear relationship between shoreline complexity and species richness (Hansson et al. 2005).*

Additionally, bird and invertebrate diversity is directly proportional to the size of the wetland area and the wetland age (Hansson et al. 2005). Figure 4 illustrates the positive relationship between bird populations and wetland area up to a certain size. While there are no known studies to examine the average area of a constructed site versus a natural one, many existing constructed wetlands are relatively young. One would expect, however, that biodiversity would improve over time, therefore size and age should be considered important design parameters for constructed wetlands.

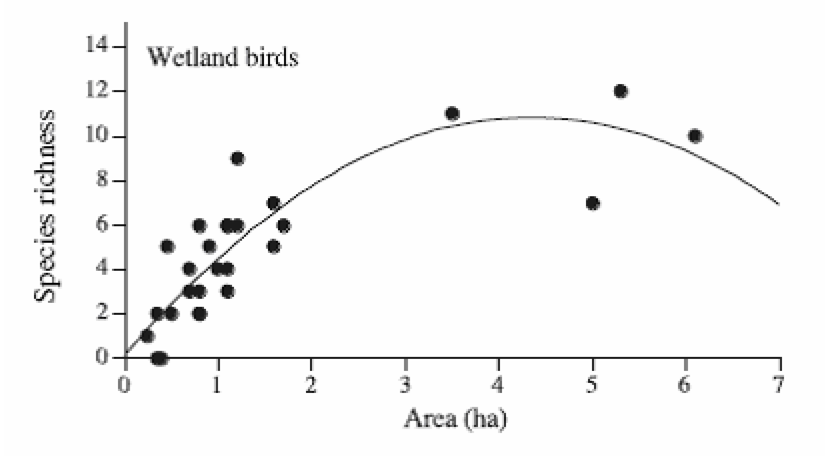


**Figure 4.**
*Near linear relationship between wetland area and species richness. Bird diversity increased directly with area up to about 4 ha (Hansson et al. 2005).*

During their examination of constructed and natural wetlands, Hansson et al. (2005) investigated the effects of nutrient loads on ecosystem function. While no negative relationship was observed, the authors cited previous studies in which high nutrient levels were shown to reduce biodiversity. Hansson et al. (2005) did find a correlation between nitrogen and phosphorus removal rates and wetland geography. Nitrogen removal is favored in large, shallow wetlands, while phosphorus removal performs best in small, deep wetlands. Hansson et al. (2005) acknowledged the difficulty in designing a wetland system that treats both nitrogen and phosphorus pollution. The challenges in designing multi-objective wetlands that both maximize biodiversity and nutrient treatment will be addressed in the next section.

Whited et al. (2000) found a relationship between the surrounding landscape and wetland biodiversity. The authors cited several studies suggesting that urbanized or agricultural landscapes within a wetland watershed have a significant impact on plant, bird, and invertebrate diversity. This could be partially attributed to nutrient and pollution drift as well as the general disturbance these areas impose on wildlife. Whited et al. (2000) identified site size and nearby road density to be the greatest landscape predictors for bird populations. The authors also concluded that large tracts of natural surrounding landscape lessen the chances of land use stressors on wetland processes and allow for more stable and diverse plant and animal populations.

## MULTI-OBJECTIVE DESIGN

Proposals for constructed wetlands frequently impose strict expectations on the designed system. For instance, the conversion of a municipal landfill in Örebro, Sweden to a constructed wetland was publicized for creating additional recreational areas, increasing biodiversity in and around the site, and managing leachate from the aging landfill (Benyamine et al. 2002). These objectives are typical for many modern constructed wetlands. Some researchers question whether it is feasible to create a system that adequately meets all these goals.

In particular, the system requirements for pollution removal and biodiversity may conflict. Though substantial research has been done on the use of constructed wetlands to treat high nutrient and pollutant loads, comparatively little is known about maintaining biodiversity within such man-made systems (Hansson et al. 2005). In the case of the Örebro constructed wetland, no attempts were made to mimic natural hydrological conditions; therefore, the wetland experienced severe drying-out and flooding as a result of the requirements for leachate treatment (Benyamine et al. 2002). Such a pattern should not be expected to promote biodiversity.

There are other conflicts as well. Benyamine et al. (2002) pointed to studies by Horne ad Dunson (1995) and Mensing et al. (1998) that suggest that the concentration of pollutants in a treatment wetland affects amphibians and other sensitive species, thereby reducing biodiversity. Optimal water treatment conditions may require specific plant species which are foreign to an area, limiting the diversity of native plants. Or, water treatment designs may even call for homogenous vegetation, disrupting the biodiversity balance further. Hansson et al. (2005) noted that the size and shape requirements for wetlands managing phosphorus loads are entirely opposite of those necessary for maintaining species richness. They continued that phosphorus treatment performs best in new wetlands, while biodiversity is observed to improve with the age of the wetland.

With such contradicting requirements, it seems nearly impossible to balance multiple objectives within a single constructed wetland. As suggested by Benyamine et al. (2002), a hierarchy inevitably emerges within the design. Biodiversity goals compete with treatment objectives and recreational designs. With that in mind, it seems advisable that constructed wetlands be designed with a single objective: either to promote biodiversity *or* treat pollution.

## BIODIVERSITY AND DESIGN

Designing constructed wetlands that promote species richness is difficult since there is a limited understanding of all the factors that affect biodiversity. Successful constructed systems are those which mimic the structure and function of natural wetlands as close as possible. In the least, design of appropriate hydrological patterns, development of adequate organic substrate, site selection, and proper monitoring can help constructed wetlands achieve a more natural level of functioning (Brooks et al. 2004). Yet, more research needs to be done to establish a more thorough understanding of how diversity can be emphasized in wetland design.

When considering the design of constructed wetlands, Keddy and Fraser (2000) identified management strategies for maintaining biologically diverse wetlands, primarily in terms of vegetation. These guidelines were established to regulate the fundamental controlling factors for wetland function. Keddy and Fraser (2000) initially named six environmental factors: water level, soil fertility, disturbance, salinity, grazing, and burial. However, their management strategies address primarily two of these. Keddy (1999) selected water level and soil fertility as the most important factors in determining wetland composition.

Keddy and Fraser (2000) found frequent water level fluctuations to be correlated to high plant diversity. This can be explained by the observation that variations in water level favor different plant species at different times. Therefore, varying water levels support a wetland with diverse plant representation. The Keddy and Fraser management model recommends fluctuating water levels year to year within a 10-year cycle, as well as changing water levels from season to season in order to facilitate plant growth. Such a model should mimic natural fluctuations.

The second factor considered by Keddy and Fraser (2000) was soil fertility. Enhanced fertility increases the competitive edge for more dominant plant species. This yields a more uniform population. Keddy and Fraser (2000) cite their previous study in which 12 wetland types were modeled and the effects of fertilizer application on biomass were examined. The fertilized wetlands were simply treated with levels of nitrogen, phosphorus, and potassium. Regardless of type, all wetlands responded to the fertilizer by yielding significantly greater biomass but at some cost to plant biodiversity. The findings are summarized in Figure 5. This points to the importance of monitoring nutrient levels within the organic substrate of constructed wetlands.

Site selection is another necessary consideration for constructed wetland design. As Whited et al. (2000) reported, the surrounding landscape and wetland size play a critical role in attracting and maintaining diverse species. Geographically speaking, large, shallow wetlands with complex shorelines are most favorable for bird and plant diversity (Hansson et al. 2005).

Finally, site monitoring enables wetland function to be documented and provides indications when ecological integrity begins to decline. Wetland biodiversity should be expected to improve over time (Hansson et al. 2005). Site monitoring may also offer insight into ecosystem function that could improve future design techniques for constructed wetlands.

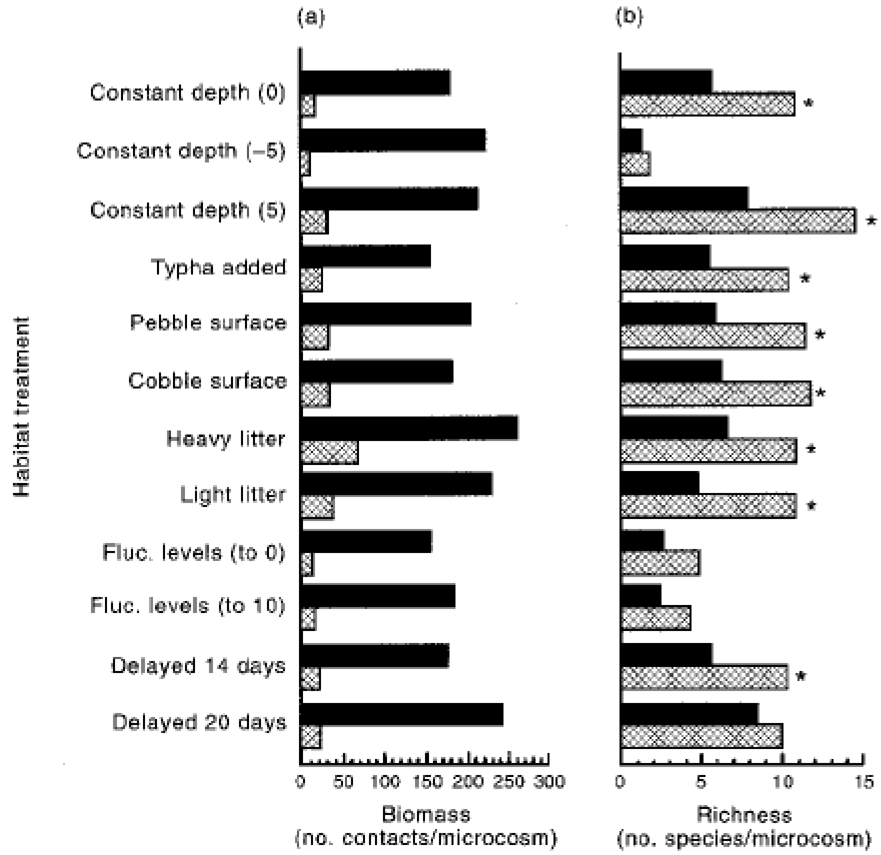


**Figure 5.**
Impact of fertilizer application on (a) biomass and (b) species richness for 12 wetland models. (▨) represents unfertilized wetlands, while (■) represents fertilized wetlands. (Keddy and Fraser 2000)

CONCLUSION

This literature review has examined the importance of wetlands systems to the global ecosystem – including the growing interest in expanding wetland areas as a resource – as well as the challenges that face constructed wetlands. The struggle to maintain biodiversity in man-made systems represents the limited knowledge available about the intricate relationships that dictate natural habitat function. Until advancements in this understanding can be made, the decision to replace natural wetlands with constructed ones should be made with caution.

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