CREATING ENVIRONMENTAL KIDNEYS: WETLAND ECOSYSTEMS AS POLLUTION FILTERS AND HABITAT RESTORATIVES

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ABSTRACT

Wetlands are now recognised as important wildlife habitats and as ecosystems which enhance the quality of water that flows through them. Wetland creation and restoration are forms of ecosystem manipulation requiring a scientific understanding of wetland function. This paper reviews the concept of the ecosystem in general and how it applies to wetlands in particular. Wetlands, because of seral processes, are transitional and dynamic features of the landscape. The rate of successional change varies from wetland to wetland but may be rapid enough to challenge wetland conservation efforts. Human-induced disturbances and perturbations can also alter wetlands significantly and three case studies: Bool Lagoon, South Australia; Waigani Lake, Papua New Guinea and the Norfolk Broads, England are presented to illustrate the impact of alterations in features such as water level and nutrient supply. In constructing and rehabilitating wetlands, clear objectives and goals should be set. Wetlands constructed for water quality enhancement will need to be assessed on their nutrient removal performance and how, or whether, this performance can be sustained. A thorough understanding of wetland hydrology, nutrient uptake dynamics by selected plant species, biofilm function and sediment-water column interactions will be needed. Wetlands constructed with conservation goals will largely be assessed on their biodiversity. Greater consideration will need to be paid to features such as life-history strategies, seasonality, inter- and intra-specific competition and maintenance of biodiversity. Environmental impact assessments of developments affecting wetlands should not merely seek to minimise the impacts but should actively pursue ways to maintain and restore them. In many cases, reversing the trend of wetland degradation and destruction can achieve both an enhancement of downstream water quality and the provision of attractive wetland habitats. This is the challenge, the capability exists to meet it.

WETLAND HABITATS

Wetlands are rapidly losing their reputation of being wastelands and are being recognised as intrinsically important wildlife habitats as well as ecosystems which enhance the quality of water that flows through them. The mammalian kidney functions to remove wastes and restore water and salt balances. Similarly, wetlands have been shown to act as nutrient sinks and sediment filters and have, therefore, been regarded as kidneys of the landscape (Mitsch & Gosselink 1993). It has been suggested that this analogy be extended to compare wetlands with kidneys and liver (P. Adam *in litt.*). The liver has particular roles in detoxifying substances and wetlands can similarly effect chemical transformations which serve to protect the wider environment. Nutrients entering wetlands may pass through unchanged, but are usually processed in two main ways: released to the atmosphere (e.g. nitrogen and carbon but not phosphorus) or stored, either temporarily or permanently, in the biomass or sediments. In recognition of this nutrient and pollutant removal capacity, wetlands (both natural and constructed) are being utilised for wastewater treatment.

Heightened environmental awareness of wetland values has led to programmes designed to rehabilitate and restore wetlands and thereby reverse the trend of wetland loss. Wetland loss can be halted through even more intense efforts to conserve these habitats, but reversing the trend can only be achieved through the creation of new wetlands or the restoration of drained or degraded wetlands to their previous ecological glory and size. Both wetland creation and restoration require a thorough scientific understanding of wetland ecosystem function.

WETLAND ECOSYSTEMS

Tansley (1935) first advanced the concept of the "ecosystem" and defined it in terms of interactions of the biotic community and its environment. The concept was soon tested and applied by ecologists and was recently ranked by members of the British Ecological Society as ecology's most important (Cherret 1990). Ecosystem ecologists have not only discovered significant interactions between communities and their environment, but have also found that ecosystems may have a predictable structure and development sequence. Furthermore, ecosystems respond to disturbances in ways that can be forecast (Golley 1991). The capacity to predict ecosystem change is, however, often limited by inadequate information, to generalities. More specific predictions can only be made following detailed study.

The success of the "ecosystem concept" has also resulted in abuse of the term and subsequent loss in clarity of its meaning. Attempts by some early users of the concept to give ecosystems physical boundaries further undermined its usefulness. Rowe (1991) quoted in Reynolds (1993) has restored some semblance of order. Rowe (1991) recognised three functional levels: ecosphere, ecosystem and environment. The 'ecosphere' includes the land, ocean, atmosphere, organisms and their interactions: an entire ecological system of planetary proportions. Each organism interacts with the biophysical system that surrounds it and this system was designated the 'environment' by Rowe (1991). In between these two extremes lies the 'ecosystem' consisting of a subdivision of the ecosphere in which organisms interact with both their environment and with each other.

In more functional terms, the ecosystem has been defined in terms of (1) the trophic levels that make up its biotic community and the flow of energy through them and (2) the cycling of materials between the biotic and abiotic components within the system. Identifying a boundary to an ecosystem has presented problems because of the import and export of both energy and materials into and from it. The magnitude of these imports and exports vary widely, but nonetheless form important inter-ecosystem linkages. Such linkages affect function in both donor and recipient ecosystems. A physical boundary to a wetland can be drawn based on the presence of free water, but such a boundary completely ignores the significant transfers that occur across it. These linkages between aquatic and terrestrial systems have led to the concept of Total Catchment Management and the consideration of each drainage basin as a manageable ecosystem.

The importance of these linkages has been recognised through the careful assessment of mass balances. How much of an element, phosphorus for example, is entering the system? What is its fate within the system and how much is exported? Using the ecosystem concept we have an accounting system which allows us to study, quantitatively, the transfer of energy and materials between black boxes (adjacent ecosystems). While this capability opens a treasure trove of management options, the internal workings of the 'black boxes' are far from simple. Ecosystems need to be studied with due regard to internal interactions such as competition between and within species, succession, life-history strategies, seasonality, limiting factors and resource allocation.

Current conservation efforts aim at ecological sustainability and wetlands have been identified as ecosystems that may help us achieve sustainability. Wetlands have frequently been shown to reduce suspended matter, bacterial contamination and the biochemical oxygen demand of waters flowing through them. However, it must be assumed that these wetland systems have a finite capacity to carry out these functions. What are these limits? How can we extend them? How can we manage a system sustainably when one of its intrinsic properties is change (succession)? These, and other questions, need to be addressed if we are to construct wetlands effective as water purification systems or even create sustainable wetland habitats to fulfil conservation goals.

SUSTAINABLE WETLANDS

Wetlands, given their precarious position in the hydrosere, are transitional features of the landscape undergoing change that may ultimately convert them to an ecosystem that no longer falls within any definition of a wetland. Although the driving force behind succession is usually a reduction in water depth, the process and successional stages vary significantly from site to site. This natural, successional change in wetlands has been well-documented in many parts of the world and presents a challenge to the long-term management of smaller wetlands, as well as those undergoing rapid sedimentation.

We have experience of three natural wetlands that have been significantly altered by changes in catchment management practices. We briefly review this experience below because changes in these wetlands provide pointers as to how we might sustain their constructed or rehabilitated counterparts.

Bool Lagoon

Hacks and Bool Lagoons comprise a wetland area with five major, plate-shaped basins in South Australia with a surface area of 2,690 ha. In the 1960's, levees were constructed to increase the capacity of the lagoon as a means of flood mitigation. The increased detention of stormwater significantly altered the water regime of the lagoon. It is now a deeper and more permanent water body. Rea (1992) showed that this alteration resulted in an expansion of the range of the semi-emergent plant *Triglochin procerum* within Bool Lagoon. Rea and Ganf (1994) were able to delineate the growth performance of *T. procerum* and *Baumea arthrophylla* with what they called the sum water regime of particular growing sites. *T. procerum* reacts quickly, matching changes in depth whereas *B. arthrophylla* has a more tolerant strategy, resting through changes in water depth. This study was made possible by having surveyed elevation gradients and daily water level records. In other words, hydrological conditions, both past (integrated) and present, were precisely known. Rea and Ganf (1994) were thus able to show that *T. procerum* thrived within a wider water level range and that *B. arthrophylla* performed better in areas that dried out each year.

Rea (1992) and Rea and Ganf (1994) have thus shown that the increase in water level favoured one species (*T. procerum*) over another (*B. arthrophylla*). It would be very reasonable to predict that the impact did not end with this switch. Other organisms would also have been affected by the change in hydrology, either directly or through alterations in their habitat brought about by the change in aquatic plant distribution.

Waigani Lake

Waigani Wetland, near Port Moresby in Papua New Guinea, drains into an extensive swamp/river system drained by the Brown and Laloki Rivers. The wetland consists of a mosaic of emergent herbaceous plants and areas of open water. *Phragmites karka*, *Typha domingensis* and *Hanguana malayana* dominate the emergent littoral vegetation. Sewage disposal into Waigani Lake began in 1965 and the settling ponds were subsequently enlarged to cater for the rapidly expanding population of Port Moresby (now approximately 200,000).

Major changes in the distribution and abundance of aquatic plants in Waigani Lake and its surrounding emergent vegetation wetland have occurred over the last forty years. The main lake is now devoid of submerged and floating-leaved plants, but in the late 1960's and early 1970s nymphaeids (*Nymphoides indica*, *Nymphaea pubescens* and *Nymphaea dictyophlebia*) dominated the area which is now open water. In 1942, the central area of the Waigani Lake basin was covered with emergent vegetation (Osborne & Leach 1983). The increase in sewage effluent disposal correlates with the decline in floating-leaved plants and by 1974 only a few small stands remained. By 1978, no floating-leaved plants could be found in the main lake and their decline in Waigani Lake was accompanied by a regression of the surrounding reedswamp. This decline in the area of the emergent reedswamp has continued subsequent to the work by Osborne and Leach (1983) (Osborne & Totome 1992). From an analysis of sediment cores, Osborne and Polunin (1986) argued that, although an increase in water-level is an obvious contributing cause of what they characterised as a partial reversal of the hydrosere, it can not explain all the vegetation changes observed. The timing of changes in the features measured suggested nutrient enrichment was likely to have played a significant role, but the effects of changes in water level could not be ruled out. The demise of the native, aquatic flora opened the system to invasion by two exotic plants. *Salvinia molesta* colonised areas of open water in 1985, but was subsequently controlled through the introduction of a host-specific insect. In 1990, *Eichhornia crassipes* infested open water areas and dense mats now choke this wetland. Three biological control agents have now been released to control this prolific weed. Polunin *et al.* (1988) clearly demonstrated that the Waigani Lake sediments not only recorded the nutrient enrichment of this wetland, but also increases in sediment concentrations of lead, manganese and zinc.

This study of a tropical wetland disturbed through massive disposal of inadequately-treated sewage effluent demonstrates that the capacity of unmanaged wetlands for nutrient removal is finite. Furthermore, it also demonstrates that perturbed wetlands may undergo a cascade effect with lost species being replaced by opportunistic species.

The Norfolk Broads

The Norfolk Broads are a series of shallow lakes, rivers and wetlands in eastern England. The lakes in this system are mainly flooded peat workings excavated between the tenth and twelfth century. More recently, a process of nutrient enrichment starting in the mid-nineteenth century has seen, by the 1960's, the replacement of once diverse submerged and floating-leaved aquatic plant beds with large phytoplankton populations (Osborne & Moss 1977, Osborne 1981, Moss 1989). Early attempts to restore this wetland system to its former diverse, plant-dominated state first centred on reduction in phosphorus loadings. This was based on the premise that the change from plant-dominance to phytoplankton-dominance was driven by nutrient enrichment and that the process could be reversed through phosphorus limitation. Although reduction in the phosphorus loadings to some of these lakes was accompanied by a reduction in the magnitude of spring and summer phytoplankton populations, the change was inadequate to affect the desired switch in dominance of the primary producers.

Subsequent restoration efforts have taken a wider ecosystem approach and combined nutrient income reductions with manipulations to promote the development of zooplankton grazers. Manipulations have included removal of zooplanktivorous fish, the introduction of zooplankton refuges and the artificial re-introduction of aquatic plants. This more sophisticated approach has met with greater success (see Moss 1992, Reynolds 1994). This case study serves to illustrate the importance of viewing wetlands at an ecosystem level rather than at the level of nutrient use by plants and algae.

REVERSING THE TREND: WETLAND REHABILITATION AND CONSTRUCTION

We have shown, in the case studies described above, that alterations in features such as water level and nutrient loading can significantly change the make-up of wetland ecosystems. These alterations in the environment may induce a chain reaction that eventually leads to re-organisation of the ecosystem both in terms of its species composition and functional processes. It cannot be assumed that a reversal of the links in the chain reaction can be achieved simply through a reversal of the process that initiated the response.

Reversal of the trend in wetland loss must be tackled on two fronts. Firstly, efforts must continue towards conserving the wetlands that remain. Secondly, we encourage a more pro-active role: wetland rehabilitation and creation. The current perception that environmental impact assessments should demonstrate minimal or no impacts on the environment, needs to be changed to one that answers the question: 'In implementing a proposed development, how can the environment be improved'? In this paper, we wish to address ways in which this second front may be attacked.

WETLAND CREATION AND REHABILITATION

Constructed wetlands consist of water-saturated sediment with emergent vegetation, areas of open water with submerged vegetation and a range of wetland animal species. These wetland systems have five principal components (Hammer & Bastian 1989):

1. substrates with various rates of hydraulic conductivity;
2. plants adapted to water-saturated anaerobic substrates;
3. a water column;
4. invertebrates and vertebrates; and
5. aerobic and anaerobic microbial populations.

The design of constructed wetlands varies depending on site characteristics: climate, land availability, native plant populations and local environmental regulations pertaining to the site. Designs can be categorised on the basis of the life form of the dominant vegetation (Brix 1993):

1. Free-floating plant systems
    - Water hyacinth (noxious weed in Australia)
    - Lemnaceae

2. Emergent plant systems
    - Surface flow
    - Horizontal subsurface flow
    - Vertical subsurface flow

3. Submerged plant systems

4. Open water systems.

A combination of different designs (e.g. open water modules alternating with planted systems) has been found to be very effective with stages designed to promote, in sequence, solids removal, nitrification, BOD reduction, denitrification, nutrient removal and oxygenation. Currently, we are designing constructed wetlands in which the biotic components are being provided with an environment in which they will thrive. These designs are site-specific, but nutrient removal performance criteria can be predicted using a wetland modelling/decision support system (SWAMP™) (Roser & Bavor 1994). Designs are further refined to incorporate features that provide wetland wild-life habitat and passive recreational benefits.

Within constructed wetlands, plants have two important functions:

1. in the water column, stems and leaves (live and moribund) significantly increase surface area for the attachment of microbial populations (biofilms); and

2. wetland plants transport atmospheric gases, including oxygen, down into the roots and the sediments that surround them (rhizosphere).

Furthermore, the plants also require nutrients and trace elements and therefore play a direct role in pollutant removal, but this role may not be sustained unless plant harvesting is undertaken. Aquatic plants also act as filters and reduce suspended solid loads as well as physically stabilising the sediments through root development. However, wetland treatment of pollutants is principally undertaken through microbial transformations. The juxtaposition, on a microscopic scale, of an aerobic region surrounded by an anaerobic region is crucial to nitrification-denitrification and numerous other desirable pollutant transformations.

Similar scientific principles and design criteria can be applied to rehabilitation of degraded wetlands. Wetland degradation (as opposed to destruction) has occurred through a number of mechanisms. In urban areas, perhaps the most common is alteration of the natural flow of water through the system to aid stormwater disposal. In other cases, water flow has become channelised. This reduces the area that is inundated for a period long enough to support wetland organisms. Water depth, flow and the duration, and frequency, of flooding play major roles in determining wetland species composition and function. Rehabilitation of such wetlands will require earthworks and designs are available for both in-stream and by-pass wetland systems.

The ideal constructed or rehabilitated wetland would be biodiverse, aesthetically-pleasing and with an infinite capacity for nutrient or pollutant removal. It is clear, from the case studies presented above, that wetlands lack such a capacity and that constructed or rehabilitated wetlands will require ongoing maintenance. Hammer and Bastian (1989) concluded that 'constructed wetlands offer an economical, largely self-maintaining, and therefore preferred alternative to conventional treatment of a variety of types of contaminated water'. We, however, are advocating the construction of more complex systems than those discussed by Hammer and Bastian (1989) and these systems cannot be regarded as self-maintaining. Continued acceptance, by regulatory agencies, of the use of wetlands for the treatment of waste- and stormwaters will require demonstrations that these systems can be managed on a sustainable basis. Therefore, operation and maintenance issues for each wetland will need to be addressed. These wetlands will require technical competence in their design and active management to retain design performance. Management issues include pest and weed control, water quality, habitat management and water flow characteristics.

Weed infestations and the biodiversity of both constructed and rehabilitated wetlands will need to be monitored and corrective measures (weed eradication, replanting) undertaken. We recommend that constructed wetlands be planted with multiple species (eighteen species in one recently-planted wetland). Not only does this serve to enhance biodiversity, it also makes the system more responsive to change. For example, some species maintain active growth throughout the year; others are more seasonal. Furthermore, by using a variety of wetland plant species, wetlands can be designed to include areas with different operating water depths. Influent and effluent water quality will need to be monitored (at least monthly) and the flow characteristics of the wetland assessed annually. The design of the wetland can facilitate wetland management and one with a series of independent or parallel modules will permit staged servicing and greater water depth control.

In conclusion, wetlands (both natural and constructed) are complex and largely biologically-controlled ecosystems. Effective management of these systems will, therefore, require sound scientific understanding of the inter-relationships between the organisms and their environment. We must apply our current knowledge and through both setbacks and successes enhance it.

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