# WETLANDS AND WATER QUALITY ENHANCEMENT

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## 1. Introduction

Prosperity for South Africa depends upon the sound management and utilization of many resources, with water playing a pivotal role. Located largely in a semi-arid part of the world, South Africa's water resources are, in global terms, scarce and extremely limited (Basson *et al.*, 1997). A key environmental problem facing South Africa is water pollution. This arises from many sources, including mining and industrial effluents, and runoff of biocides, nutrients and pathogens from agricultural lands, urban areas and informal settlements with poor sanitation. Its consequences are often severe, including among other impacts, habitat destruction, reduced oxygen levels, fish kills and loss of human life.

Wetlands are natural filters, helping too improve the quality of runoff water from urban and agricultural lands by trapping pollutants. Wetlands are particularly useful because they are generally located between land and open water. This allows them to intercept many pollutants before they enter the river system.

Wetlands have long been employed for the treatment of point-source wastewaters as well as non-point source pollution (Hammer, 1989). In Uganda, the National Sewerage and Water Corporation is supporting conservation of papyrus swamps and other wetlands near Kampala because of the role they play in purifying water supplies (Barbier *et al.*, 1997). By purifying water wetlands save us a lot of money. For example, in 1990 it was shown that without the Congarei Swamp in South Carolina, the area would need a $5 million waste water treatment plant (U.S. Environmental Protection Agency, 1995). Similarly, in Gotland, Sweden the restoration of wetlands was found to be substantially more cost effective in reducing nitrogen levels than expanding sewage treatment plants (Folke, 1990; Gren, 1995). This was despite including lost opportunity costs from agriculture foregone when the land was restored back to its original wetland state.

It is no co-incidence that the primary legislation protecting wetlands in the U.S. is contained within the Clean Water Act. In the U.S., wetlands are considered to be “essential to protecting water quality and

health of aquatic systems" (U.S. Environmental Protection Agency, 1998). In the U.S. and Europe, considerable resources continue to be dedicated to rehabilitating/restoring wetlands.
In the U.S. approximately 78 000 ha of wetland is restored annually (U.S. Environmental Protection Agency, 1998).

It is recognized that wetlands alone cannot solve all of our water pollution problems since every wetland has a finite capacity to assimilate pollutants and overloading it will reduce its ability to perform this and other functions. Nevertheless, wetlands have a key role to play in integrated catchment-based strategies to address water quality issues.

The objectives of this document are to:

- Describe the factors influencing the capacity of wetlands to enhance water quality.
- Describe how wetlands operate in reducing the levels of different types of pollutants.
- Discuss the value of wetlands specifically for urban stormwater pollution management.

## 2. Characteristics of wetlands which influence their ability to improve water quality

Wetlands may contribute substantially to improving water quality by modifying or trapping a wide range of substances commonly considered to be pollutants. These include suspended sediment (such as silt and clay), excess nutrients (most importantly nitrogen and phosphorus), toxicants (e.g. pesticides and excess heavy metals) and pathogenic bacteria and viruses. Wetlands have several attributes that enhance their capacity for improving water quality (Kadlec and Kadlec, 1979; Mitsch and Gosselink, 1986; Hammer, 1992) including the following.

- A high capacity for reducing the velocity of water flow (because of such factors as the resistance offered by wetland vegetation and the gradual slope of most wetlands) which results in suspended particles being more readily deposited.
- A generally high capacity for filtering out suspended solids in the water owing to characteristically dense plant growth and abundant surface litter.
- Considerable contact between water and sediments because of the shallow nature of the water column and the fact that wetlands are generally characterized by sheetflow, spread out across the wetland rather than just channel flow concentrated in a small area. This leads to high levels of sediment/soil-water exchanges. If should be added, however, that some wetlands may have considerably less favourable hydraulic conditions than others, with most of the flow being concentrated within a channel.
- A variety of anaerobic and aerobic processes that remove pollutants from the water, including: chemical precipitation, adsorption, ion exchange, nitrification and denitrification. Microbial activity in the wetland is particularly important for promoting nitrification and denitrification.
- The plant productivity of many wetlands, leading to high rates of mineral uptake by vegetation.

- Generally high soil organic matter contents (accumulated primarily as a result of anaerobic conditions) which favours the retention of elements such as heavy metals.

- Microbial decomposition of certain organic substances (including synthetic organics and pathogens). Wetland plants provide substantial surface area for the attachment of microbes, both above-ground and below-ground, due to the aerobic rhizosphere around roots.

Suspended sediments, toxicants and nutrients pass through a wetland as throughflow or are stored for varying periods in wetland storage compartments. In the case of nutrients, these compartments include plant tissue, microbial tissue, detritus, sediments, waters within the soil profile and ponded waters on the soil surface which have a longer residence time than the main throughflow (Howard-Williams, 1983). According to Howard-Williams (1983) the nutrient (or sediment/toxicant) output from a wetland can be calculated as:

Nutrients out = Nutrients in - (transfers into storage compartments - transfers out of storage compartments)

Two points arise from consideration of the above equation:

- the faster the rate of throughflow (i.e. the more channelled the throughflow and the steeper the gradient of flow) the lower will be the extent of pollutant storage (Gaudet, 1978; Day et al., 1982, as cited by Howard-Williams, 1983); and

- although wetland storage compartments have a substantial ability to absorb excess nutrients, they have finite boundaries, and once they are full, there will no longer be transfers into storage. This principle also applies to sediments and toxicants (Howard-Williams, 1983).

A wetland is considered a sink if the input of a given chemical or specific form of that chemical (e.g. organic or inorganic) is greater than the output. Conversely, if output is greater than input, it is considered a source. Through transformation, a wetland may act as a sink for an inorganic form of a nutrient and a source for the organic form of that same nutrient. Determining conclusively whether wetlands are sources or sinks for a given chemical is often hampered by the inadequacy of the techniques used to measure fluxes (Howard-Williams, 1983). In order to calculate nutrient fluxes, water budgets are needed and there are many difficulties inherent in measuring the hydrological components required for water budget determination (Carter, 1986). Thus, even with long term studies it is often difficult to assess how efficiently a wetland removes a given pollutant.

## 3. Effectiveness of wetlands in removing different pollutants

### a) Removal of suspended sediment

The higher the mean flow velocity, the greater the ability of water to transport particles of increasing grain size (Hjulstrom, 1935). Flow velocities through wetlands are typically lower than in river channels and the surrounding landscape, and wetlands thus provide important areas where the settling of suspended sediment may occur. Suspended sediment may be detrimental to water quality in itself and it may also carry other adsorbed pollutants (Boto and Patrick, 1979). Turbidity, caused by suspended particles, attenuates light penetration, thereby decreasing photosynthesis (and oxygen production) by submerged aquatic plants. Costly filtration and flocculation processes are generally necessary to free water of particulate matter before it can be used for industrial or domestic purposes (Begg, 1986).

High sediment loads are also costly in that they lead to storage capacity loss in dams, an important problem in South Africa (Conley *et al.*, 1987).

In New Zealand (Schouten, 1976 as cited by Begg, 1986) showed that all of the bedload and 50% of the suspended load were being deposited in the wetlands of a particular catchment. Mitsch (1993) reports an annual sediment accumulation from 6 to 20 mm/y, with high inflow wetlands having higher sediment accumulation rates than low inflow wetlands. In an analysis of the efficiency of 36 wetlands in the U.S., Strecker *et al.* (1992) found the median efficiency of wetlands in removing total suspended solids was 76%, clearly demonstrating the effectiveness of wetlands in trapping suspended solids.

### b) Plant nutrient removal

In water quality studies, nitrogen and phosphorus are the nutrients most commonly identified as pollutants (Adamus *et al.*, 1987). Wetlands which receive water with high nitrogen and phosphorus concentrations usually demonstrate high removal efficiencies, at least during the growing season (Van der Valk *et al.*, 1979; Begg, 1990). This is considered to be particularly valuable because excess quantities of these nutrients promote algal blooms and population explosions of other undesirable aquatic plants, such as water hyacinth (*Eichhornia crassipes*). These in turn often reduce oxygen levels in the water and detrimentally affect the suitability of water for domestic consumption and recreational activities (Sather and Smith, 1984). The impacts of increased nutrient concentrations is by no means confined to inland waters and is now having negative impacts on marine life on the Gulf of Mexico, the Baltic Sea and other large coastal systems (Mitsch *et al.* 2000).

Freshwater wetlands receive nitrogen and phosphorus from natural sources, such as runoff from vegetated watersheds, and anthropogenic sources, such as effluent discharge, and runoff from fertilized cropland (Hemond and Benoit, 1988). There are three processes by which nutrients are immobilized or removed from wetland waters: (1) accumulation by plants and microorganisms, (2) sedimentation, and (3) denitrification and ammonia volatilization (applicable only to nitrogen). Of these, only denitrification and ammonia volatilization actually eliminate nutrients from the system by releasing nitrogen to the atmosphere. The other two only immobilize and detain nutrients. Nutrients accumulated by plants are temporarily immobilized, after which, they may be re-mobilized or accumulated in the sediment, where they remain immobilized for an indefinite period in an adsorbed or particulate form. Nutrients in the sediment may be re-mobilized and transferred to adjacent waters if, for example, a wetland is disturbed through drainage (Nichols, 1983; Bailey *et al.*, 1985, Howard-Williams, 1985; Richardson, 1985; Richardson and Marshall, 1986).

Denitrification, caused by anaerobic bacteria, is the primary mechanism for nitrogen removal from wetland waters (Sather and Smith, 1984). The denitrification rate varies according to temperature, pH, organic carbon availability, and available surface area. High denitrification rates depend on a continuous supply of $NO_3$ (associated with aerobic conditions) to anaerobic areas. Wetlands are often suitable sites for this as they are generally characterized by anaerobic sediments (overlain by an aerobic sediment zone, a few millimetres thick), and shallow oxygenated surface water. This, combined with the aerobic rhizosphere that surrounds wetland plant roots, maximizes the aerobic/anaerobic interface where denitrification can occur (Hemond and Benoit, 1988; Hammer, 1992). Denitrification may be enhanced further in wetlands which are alternately wet (anaerobic) and dry (aerobic). High levels of nitrogen loss have been shown to occur under such conditions (Patrick and Wyatt, 1964; McRae *et al.* 1968; Reddy and Patrick, 1984).

Nitrogen may also be removed through uptake by vascular plants and subsequent "burial" when the plants die and organic matter accumulates in the sediments. DeLaune *et al.* (1986) showed that in a freshwater marsh, a large proportion of the nitrogen incorporated in the vegetation accumulates mainly as organic nitrogen in accreted sediment.

Phosphorus immobilization through the development of organic soils is less important than for nitrogen. Richardson (1985) found that wetland mineral soils had a greater phosphorus retention capacity than organic soils. Adsorption of phosphorus onto mineral sediments appears to be the most important mechanism accounting for the removal of this nutrient (Hemond and Benoit, 1988). Phosphorus may also be removed from solution by precipitation as insoluble iron, aluminium or calcium phosphate (Nichols, 1983) or through deposition of suspended sediment to which phosphorus is already adsorbed (Boto and Patrick, 1979). Thus, the ability of a wetland to retain phosphorus through adsorption and precipitation is related strongly to its capacity to trap mineral soils (Hemond and Benoit, 1988) as well as to the particle size distribution of the trapped sediment, which affects the total surface area available for adsorption (Corps of Engineers, 1988). Van der Valk *et al.*(1979) attribute the differences among wetlands in their nutrient-trapping capacity to be primarily the result of differences in hydrology and the interaction of seasonal fluxes of nutrients within a wetland. During the growing season there is generally a high rate of nutrient uptake from the water and sediments by emergent and submerged wetland vegetation. Increased microbial immobilization of nutrients and uptake by algae and epiphytes also leads to retention of inorganic forms of nitrogen and phosphorus. Thus, there is seldom a net export of nutrients during the growing season. Lee *et al.* (1975) consider this pattern to be beneficial because wetlands are most efficient at trapping nutrients during the growing season, the time when the potential for algal blooms to occur is at its highest.

A substantial amount of the nutrients taken up by rooted emergent plants may be lost to the water at the end of the growing season through litter fall and subsequent leaching. However, this is often less than may be expected because, by the time the above-ground parts of higher plants die, most of the nutrients have been translocated to the below-ground storage portions of the plant where they may be "buried" in the deep sediments (Hemond and Benoit, 1988).

Van der Valk *et al.*(1979) list the results of 17 different studies investigating the potential of wetlands to act as nitrogen and phosphorus sinks. These were listed according to whether the wetland in question acted as a nutrient sink for nitrogen and phosphorus and whether this was seasonal. All studies for which phosphorus data are presented indicate that wetlands remove phosphorus from the water passing through them at least during the growing season, and in some cases in all seasons. The same was shown to be true for nitrogen, except for the study conducted by Shih *et al.* (1978 as cited by Van der Valk *et al.*, 1979) which showed that the given wetland acted as a nitrogen source. Overall, Van der Valk *et al.* (1979) conclude that all 17 studies show that there was at least a seasonal net retention of phosphorus and/or nitrogen) clearly demonstrating the overall effectiveness of wetlands for assimilating nutrients.

Mitsch and Gosselink (1986) also list the results of 26 different studies of wetlands as nitrogen and phosphorus traps, using the same format as that of Van der Valk *et al.*(1979) and including six of the previously listed studies.

The overall results are very similar to those of van der Valk *et al.* (1979) in that in only one of the 26 studies was a wetland shown to be a net source of nitrogen and 4 were shown to act as phosphorus sources.

In summary, Van der Valk *et al.* (1979) conclude that the general picture to emerge from the studies reviewed is that wetlands are always good-to-excellent nutrient traps during the growing season, but in the non-growing season their efficiency declines.

Adamus *et al.* (1987) state that few quantitative models exist for evaluating the nutrient retention and removal capabilities of wetlands. Qualitative models include informal guidelines by Kiddy (1979) and more formal procedures by Reppert et al. (1979), Wolverton (1980) and Adamus *et al.*(1987).

## c) Toxicant removal

Toxicants are taken to include metals, organic pollutants, bacteria and viruses and BOD (Biological Oxygen Demand). No specific procedures have been developed for assessing the toxicant removal potential of wetlands, but general principles will be discussed for each group of toxicants.

### i) Metals

Metal pollution is often primarily anthropogenic in origin, with the greatest concentrations generally being found in areas with heavy industry or mining (Lazrus *et al.*, 1970). Metal removal efficiencies can vary greatly depending on the particular metals and wetland types involved (Tchobanoglous and Culp, 1980). Giblin (1985) summarized the findings of different studies investigating the passage of metals through various types of wetlands. Measured values ranged from 0% lead passing through an English bog to 100% zinc passing through a North Carolina salt marsh.

Metals may be removed from solution by adsorption onto suspended sediment (mineral and organic), and buried in the sediment when it settles. Metals may also be adsorbed directly onto already immobile sediment (Hemond and Benoit, 1988). The oxidation-reduction (redox) potential is a key factor influencing the retention of metals (Gambrell and Patrick, 1988). Certain metals, such as cadmium and zinc, are more strongly bound to humic material under anaerobic than under aerobic conditions. In contrast, other metals, such as iron (precipitated as ferric oxide under aerobic conditions) may be released back into wetland waters as ferrous iron with the onset of anaerobic conditions (Hemond and Benoit, 1988). The pH is another important factor influencing metal retention.

Most metals are sorbed more efficiently by organic than by mineral soils (Vestergaard, 1979). Since wetland sediments are usually rich in organic matter, they are likely to be better suited for sorption of metals than non-wetland soils with less organic matter. Some metal cations also appear to form organically bound complexes with soil organic matter; in such cases, sorption is essentially nonreversible provided the soil is not disturbed (Wieder and Lang, 1986).

Wetland plants are able to take up metals from the water and sediment. However, the degree to which this leads to the removal of metals depends on the extent to which the plant material is accumulated in organic sediment rather than being exported from the

system as detritus (Hemond and Benoit, 1988).
Plants may also accelerate the removal of mercury by emission into the atmosphere. Kozuchowski and Johnson (1978) found that there was a positive correlation between mercury emission into the atmosphere by *Phragmites australis* growing on the edge of a mercury-contaminated lake, and concentration of mercury in the sediment.

Another important mechanism by which metals may be removed is through precipitation as oxides, hydroxides, carbonates, phosphates and sulphides. Most transition metals are precipitated as sulphides. This occurs under anaerobic conditions and thus, provided wetlands contain appreciable sulphide ions, the conditions generally prevailing in wetlands tend to promote the precipitation of transition metals.

This process is usually more important in saltwater than freshwater because of the generally higher sulphate concentration in saltwater (Hemond and Benoit, 1988).

### ii) Synthesised organic pollutants

Freshwater wetlands may detain and/or chemically degrade synthesized organic pollutants, such as pesticides. The two processes may be linked, as when a pollutant is delayed in its passage through a wetland ecosystem long enough to allow degradative processes to occur. One mechanism for the detention of dissolved organic pollutants in wetlands is sorption onto sediments (Hemond and Benoit, 1988). Several different mechanisms may be involved in the degradation of organic pollutants. Wetlands, because of the shallow nature of their surface waters, provide an ideal opportunity for photodegradation to occur (Zafiriou *et al.*, 1984). The degradation of organic pollutants under anaerobic conditions has not been well documented. However, several workers (Parr and Smith, 1976; Sleat and Robinson, 1983; Suflita *et al.*, 1983; Gambrell *et al.*, 1984; Gambrell and Patrick, 1988) have shown that many organic compounds, such as halomethanes, are degraded far more rapidly under anaerobic than aerobic conditions. Thus, wetlands, which characteristically have anaerobic soils, may play a vital role in the degradation of these compounds.

### iii) Bacteria and viruses

Agricultural and urban runoff entering wetlands may contain large quantities of bacteria, particularly coliforms and pathogens such as *Salmonella* and *Enterococci*, all of which pose a potential hazard to human health. Wetlands have been shown to reduce pathogen counts entering in effluents (Rogers, 1983). Dejong (1976), for example, found bacterial contamination to be greatly reduced by a reed-pond, even during times of peak load.

Several factors may be responsible for the depletion of bacteria and viruses in wetland waters. These include adsorption onto sediments and subsequent sedimentation, exposure to solar radiation, and the presence of toxic substances such as root secretions which have been shown to kill pathogenic bacteria (Seidel, 1970; Rogers, 1983). In addition, one of the most important mechanisms for bacterial removal by wetlands is simply detention while natural die-back occurs. Pathogenic micro-organisms found in sewage effluent generally cannot survive for long periods of time outside the host organisms (Hemond and Benoit, 1988).

### iv) Biological oxygen demand

BOD (Biological Oxygen Demand) of water is a measure of the oxygen required for the degradation of organic matter. Wetlands decrease the BOD of introduced waters through the decomposition of organic matter during aerobic bacterial respiration (Hemond and Benoit, 1988). While wetland plant material is a source of BOD, the presence of wetland vegetation can also improve purifying capacity by trapping particulate organic matter and providing sites of attachment for decomposing micro-organisms (Hemond and Benoit, 1988).

De Jong (1976, cited by Hemond and Benoit, 1988) studied wastewater purification in a rush pond and found BOD reduction was a function of residence time in the pond. He concluded that removal resulted from infiltration of wastewater into the sediment followed by decomposition by soil bacteria, as well as purification of through-flowing waters by microbes in the pond.

## 4. When is it acceptable to use wetlands for pollution control?

Depending on its quantity and quality, stormwater runoff or wastewater discharge may have a high impact on wetland biota, especially in natural wetlands. Flow regimes in the wetland may be modified and pollutants accumulated, resulting in undesirable environmental effects. Thus, an important issue is whether natural wetland systems should be used as stormwater control measures. The use of natural wetlands should definitely not be seen as an easy substitute for addressing pollution at source, and any use of wetlands for pollution control would need to conform with the requirements of the Water Act.
A general consensus from the literature is that:

- As far as possible, pollution should firstly be controlled at source. However, with some non-point pollution sources, in particular, this is unlikely to be always achievable.

- The intentional use of a healthy natural wetland for stormwater and wastewater pollution control should be discouraged. In many cases, however, the exclusion of a wetland from urban runoff would deprive it of a key water supply. Thus, each case should be considered individually, taking into account the levels and type of pollution and nature and condition of the wetland.

- If a natural but degraded wetland is used it should be rehabilitated and careful attention should be given to ensuring the applied runoff receives sufficient pre-treatment (e.g. pond areas for settling suspended materials).

- The use of well designed constructed wetlands should be encouraged. The functioning of different elements of a constructed wetland can be manipulated to enhance the performance of particular processes. Thus, a constructed wetland can be tailored for the particualr pollutants it is recieving (Hammer, 1992). The U.S. Environmental Protection Agency encourages the use of constructed wetlands for water pollution control. Where availability of land is not limiting, the ability of constructed wetlands to treat water cost effectively and with little maintenance makes them ideal for small communities, leisure resorts, camping sites, rural schools and individual home-owners with no access to municipal sewerage systems (Archibald and Batchelor, 1992).

The use of constructed wetlands in South Africa has great potential and is increasing. Wood (1999) demonstrates that although the technology has in several instances been applied less than optimally, South African systems do demonstrate significant potential for wastewater treatment.

## 5. The use of wetlands for urban stormwater pollution control

In South Africa's urban areas, many wetlands have been destroyed or severely impacted. To a developer the value of a wetland may appear small relative to a development which will destroy the wetland. However, developers and the public often fail to consider the services which wetlands provide free of charge to the inhabitants of the town and to society at large. With wise management, wetlands are undoubted assets to the urban environment (Milstein, 1992). Water pollution is a universal problem in urban areas, and one of the most critical services provided by these wetlands is improving water quality. This is of particular value for downstream water users or sensitive downstream habitats such as estuaries. Besides, improving water quality urban wetlands also provide the following benefits.

- Flood reduction, which reduces the costs of flood damage
- Areas for recreation and education
- Habitat for wetland dependent plants and animals
- Enhanced beauty of the surroundings

As indicated in the previous section, wetlands need to be carefully selected for pollution control. Furthermore, it is usually best to use wetlands in combination with othernon-point pollution control methods (e.g.grassed swales, porous pavements and infiltration basins).

Several documents have been produced that provide practical guidance for using wetlands for controlling urban stormwater pollution (e.g. Woodward-Clyde Consultants, 1990; Strecker *et al.*, 1992; Horner *et al.*, 1994; Reeder, 1996). Many cases have been cited, such as those given in Box 1, where the water quality enhancement benefits alone more than compensate for the resources dedicated to wetland restoration, construction and management.

**Box 1** Wetlands as great assets to urban areas: example case studies

*Clear Lake Treatment Marsh - Waseca (Barten, 1987)*
Clear Lake, a 257 ha body of water located in southcentral Minnesota, is a heavily utilized recreational lake that became eutrophic because of the inflow of nutrient-rich runoff water from the adjacent city of Waseca. In 1981, 50% of the hydraulic load and 55% of the phosphorus load to the lake was diverted into a 21 ha marsh. The marsh system reduced the annual phosphorus load to Clear Lake by 34%. In 1986, construction was completed on a second marsh system that filters urban and agricultural runoff carrying 20% of the phosphorus load into Clear Lake. The mean total phosphorus concentration in the lake has been reduced by 31%.

*Lake Jackson Restoration Project in Tallahassee (Woodward-Clyde Consultants, 1990)*
The Lake Jackson Restoration Project uses a combination of detention ponds, sand filters and constructed marshes. In combination these have achieved the following removal rates.

| **Pollutant** | **Removal rate** |
|---|---|
| Inorganic solids | 96% |
| Organic solids | 94% |
| Total nitrogen | 76% |
| Ammonia | 37% |
| Nitrate | 70% |
| Nitrite | 75% |
| Total phosphorus | 90% |

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