

# Artificial wetlands and water quality improvement

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## Abstract

This paper illustrates the role of plants to assist the treatment of water pollution in man-made wetlands in tropical and temperate climates. It also considers the potential for environmental education of these wetland systems. The management and natural treatment of pollution is described in the Mai Po Marshes, Hong Kong and a wetland in London which is also an important site for birds. The design of the Putrajaya Lake and Wetland system in Malaysia is compared with a constructed wetland and lake for the treatment of urban surface runoff in a new residential development in the United Kingdom. The benefits of these natural systems are discussed in the context of the global trend for introducing sustainable methods of environmental management and low cost pollution treatment systems. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

### 1.1. Wastewater treatment by aquatic plants

The ability of large aquatic plants (macrophytes) to assist the breakdown of human and animal derived wastewater, remove disease-causing microorganisms and pollutants has only recently been scientifically investigated (Kadlec and Knight, 1996).

A range of plants have shown this property, but the common reed (*Phragmites australis*), and the reedmace (*Typha latifolia*) are particularly effective. They have a large biomass both above (leaves) and below (underground rhizome system) the surface of the soil or substrate. The subsurface plant tissues grow horizontally and vertically and create an extensive matrix which binds the soil particles and creates a large surface area for the uptake of nutrients and ions. Hollow vessels in the plant tissue enable air to move from the leaves to the roots and to the surrounding soil. Aerobic microorganisms flourish in a thin zone (rhizosphere) around the roots and anaerobic microorganisms are present in the underlying soil. Natural filtration in the substrate also assists the removal of many pollutants and pathogenic microorganisms.

### 1.2. Artificial or constructed wetlands

Constructed wetlands were initially developed about 40 years ago in Europe and North America to exploit and improve the biodegradation ability of plants. The advantages of these systems include low construction and operating costs and they are appropriate both for small communities and as a final stage treatment in large municipal systems (Cooper et al., 1996). A disadvantage of the systems is their relatively slow rate of operation in comparison to conventional wastewater treatment technology.

Constructed wetland designs include horizontal surface and subsurface flow, vertical flow and floating raft systems. Surface flow wetlands are similar to natural marshes as they tend to occupy shallow channels and basins through which water flows at low velocities above and within the substrate. The basins normally contain a combination of gravel, clay- or peat-based soils and crushed rock, planted with macrophytes.

In subsurface flow wetlands, wastewater flows horizontally or vertically through the substrate, which is composed of soil, sand, rock or artificial media. The purification processes occur during contact with the surface of the media and plant rhizospheres. Subsurface flow systems are more effective than surface flow systems at removing pollutants at high application rates. However, overloading, surface flooding and media clogging of the media of subsurface systems can result in a reduced efficiency.

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The lifespan of constructed wetlands has been demonstrated as being approximately 20 years for organic waste treatment. They can be designed to form an aesthetically pleasing and functional landscape which can be incorporated into residential developments. In addition, they provide a valuable ecological habitat for wildlife.

The performance of these systems is influenced by their area, length to width ratio, water depth, rate of wastewater loading and the time for it to pass through the wetland. For the removal of disease-causing microorganisms, an efficiency above 90% is normally achieved, for organic material and suspended solids 80% removal may be expected but nutrient removal efficiency is normally below 60%.

Constructed wetlands have also been designed to treat urban and highway runoff (Shutes et al., 1997, 1999). The variable quality and quantity of urban and highway runoff requires a more complex design for a constructed wetland treatment system. Fig. 1 shows the use of pretreatment structures including an oil separator, silt trap, spillage containment basin and settlement pond in an idealised highway runoff treatment system incorporating a horizontal subsurface flow constructed wetland. A final settlement tank provides posttreatment followed by discharge to a receiving water body. An overflow structure from the settlement basin prevents excessive flows passing through the wetland and damaging the plants.

The treatment of airport surface runoff, industrial waste and mine drainage, landfill site and composting system

leachate and the drying of sludge are also applications of constructed wetlands.

These natural systems are often referred to as examples of green technology because of the use of plants. However, ‘green’ is a widely used and often misleading label attached to any product or system which claims to reduce the impact on the environment. The factors which need to be considered when assessing how ‘green’ a waste water treatment system is have been listed by Brix (1998):

- treatment performance in relation to effluent standards;
- robustness of process;
- emissions of various pollutants to environment;
- waste production (e.g. sludge);
- recycling or reuse potential;
- energy consumption, including source of energy used;
- use of chemicals;
- area use;
- environmental nuisance;
- environmental benefits.

Brix suggests that an environmental life-cycle assessment approach, which quantifies energy and resource inputs and outputs at all stages of the life cycle, could be applied to constructed wetland systems. However, he emphasises that it is very difficult to quantify some of the parameters included in the assessment and that the impacts and benefits will have to be weighted for each system.

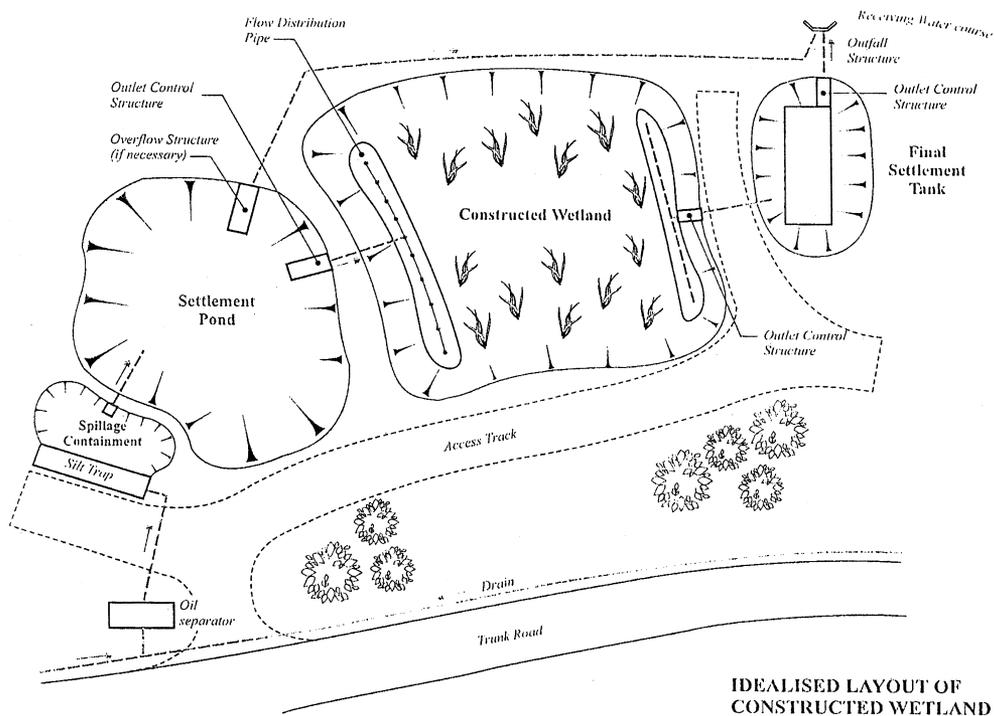


Fig. 1. Idealised layout of highway runoff constructed wetland system (Shutes et al., 1999).

### 1.3. Local agenda 21

Agenda 21, a Global Action Plan for the next century, was adopted at the United Nations Conference on Environment and Development) summit meeting in Rio de Janeiro on 14 June 1992 by the UN General Assembly (UNCED, 1992). The principal aim of Agenda 21 is to integrate environmental concerns across a broad range of activities.

The local Agenda 21 Initiative aims to develop a planning framework for local sustainable development and stresses the importance of environmental considerations when assessing planning applications, and the need to increase community involvement in water issues.

The use of plants in natural systems to treat wastewater and other sources of pollution is a simple and attractive example to create interest and raise public awareness of water pollution sources and treatment. The wetland treatment processes and wildlife present in wetlands provide an opportunity for environmental education in the community.

### 1.4. Sustainable waste treatment in China

Sustainable agriculture systems which treat organic wastes derived from crops, livestock and humans have traditionally been used for several millennia in Asia and are particularly well developed in China. Historically, wastes have been treated as valuable resources that are recycled and returned to the environment.

The China dike pond system is an example of traditional agricultural technology which integrates vegetable, fish and livestock production. Shallow wetlands and marshes in coastal areas are excavated to 2.5–3 m depth to enable fish to survive. Organic waste fertilisers are fed to the ponds including plant material and human and animal wastes. The production of 10 t of fish per hectare may consume up to 75 t of manure and ducks traditionally share part of the pond with the fish (Korn, 1996). The fish yields of the established ponds, which are typically stocked with four to five species of carp, are five to six times higher than in other countries.

The ponds are colonised by floating and rooted species of plant which contribute to the processes of organic waste breakdown. They provide a simple wastewater treatment system for small communities, but the efficiency of the system is dependent on the experience of the farmer and there are potential health hazards from the consumption of fish contaminated by pathogenic microorganisms.

The soil excavated from the ponds is used to create elevated dikes that prevent flooding and protect land for crop and livestock production. The complete dike pond system is typically 0.2–0.5 ha in area. The ponds are a reservoir for irrigation water and are normally managed without water being discharged except when fish are harvested or sediment is removed for use as a land fertiliser.

These traditional systems have recently been improved by the introduction of modern technology. Biological digesters breakdown organic wastes and produce biogas which can be used as a source of energy for the community. Integrated farming systems which include modern technology have recently been established in China to improve the efficiency of nutrient cycling and energy flows, obtain benefits in food production and recycle the residues completely and economically (Chan, 1993). These systems are examples of Ecological Engineering which involves the design of human activities using locally available natural resources in ecologically balanced systems.

The survival of the dike pond system is being threatened by urban and industrial expansion especially in the Pearl River Delta Region of South China. Contamination of pond water and fish by pollutants is currently a serious problem. The use of selected species of plants in constructed wetland systems is being developed as a method of treating wastewater for the dike pond system and for large-scale wastewater treatment in the towns and cities of China.

## 2. Examples of constructed wetland systems

The following examples of artificial or constructed wetland systems were designed for aquaculture (Section 2.1), water storage (Section 2.2), urban surface runoff treatment (Section 2.3) and stormwater treatment (Section 2.4). The colonisation of 2.1 and 2.2 by wetland plants has resulted in their ability to improve water quality.

### 2.1. Mai Po Marshes, Hong Kong

Mai Po Marshes Nature Reserve, situated at the north-western corner of the New Territories of Hong Kong (Fig. 2), is the largest wetland in Hong Kong and occupies an area of 381 ha. In 1983, Mai Po Marshes was declared a Nature Conservation Area, and the World Wide Fund for Nature, Hong Kong (WWF HK) took over the responsibility of managing and developing the area for conservation and education. In 1995, an area of 1500 ha of wetland around Mai Po and Inner Deep Bay was listed as a Wetland of International Importance under the Ramsar Convention.

Much of the area was converted to ponds (local name *gei wais*) by enclosing the intertidal marshlands to earthen dikes fitted with a sluice gate to allow for alternating entry and drainage of tidal waters. The ponds (each about 10 ha, and 1–1.5 m deep), are the only traditionally operated *gei wais* remaining and are good examples of how coastal wetlands can be managed sustainably. Juvenile shrimps are washed into the pond with the incoming tide through a wide meshed net, which keeps out predatory fish. By closing the sluice gate, the shrimps remain in the pond until they grow to marketable size. Fish of economic importance, such as grey mullet (*Mugil cephalus*) are caught as fry in Deep Bay

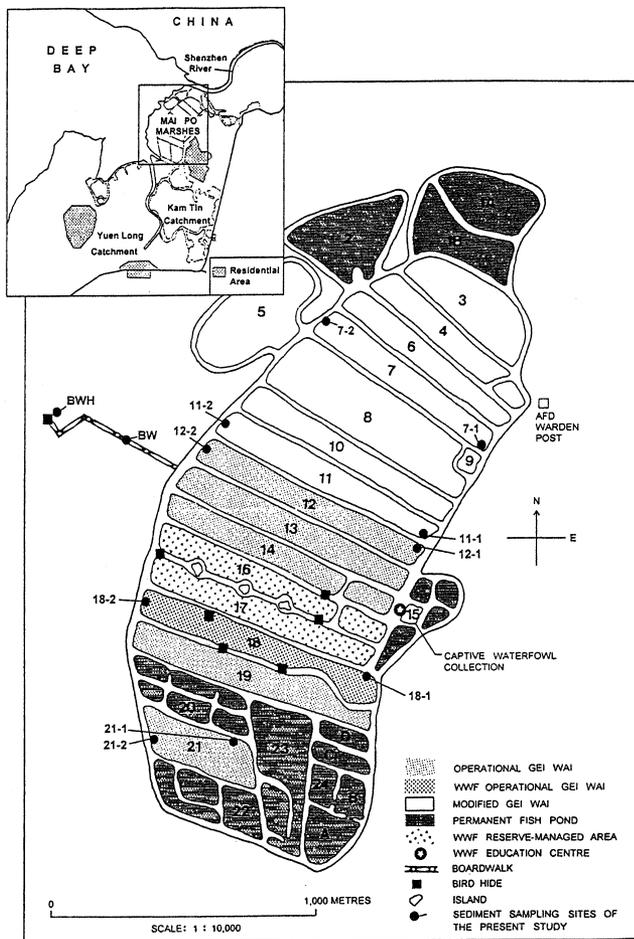


Fig. 2. Mai Po Marshes Nature Reserve, Hong Kong (Liang et al., 1999).

during the months of December and March and introduced into the *gei wais*. In addition, shrimps and fish with less economic value are also present in *gei wais* such as Tilapia. During the shrimp and fish harvest period (April–October or November), up to 1600 wintering birds, as well as fish eating otters, may be attracted into *gei wais* and consume shrimps and fish trapped in the pools and sluice gates of the ponds. Moreover, the large area of vegetation in the *gei wais*, principally mangrove trees and reeds (*P. australis*), provides ideal nesting sites for birds.

However, the Mai Po Marshes now face unprecedented threats and pressures from both landward and seaward sides. On the landward side, the rural landscape is rapidly being removed to make way for industrial development and the associated infrastructure (Young and Melville, 1993). On the seaward side, the water quality of Deep Bay is declining due to increasing pollution loads from the Shenzhen River and Yuen Long–Kam Tin catchments. There has been a decrease in shrimp production at Mai Po Marshes as a result of lower juvenile shrimp stocks from the polluted Deep Bay and the absence of other aquatic organisms. Cadmium concentrations (2.1–2.4  $\mu\text{g/g}$ ) in some oysters (*Crossostrea gigas*) collected from Deep Bay exceeded the

limit of 2.0 g/g for human consumption (Phillips et al., 1982). The calculated PCB concentrations in water ( $0.646\text{--}9.95 \times 10^{-3}$  ng/l) were considered safe for aquaculture according to US EPA guidelines, but PCB in grey mullet (*M. cephalus*) exceeded this guideline (Liang et al., 1999). Tilapia and shrimps collected from Deep Bay and Mai Po were also contaminated by Cd, Cr and Pb but were fit for human consumption. Reeds have colonised the *gei wais* and assist the natural processes of pollution treatment. The adaptation of *gei wais* specifically to treat pollution is currently proposed.

## 2.2. Welsh Harp Reservoir, north-west London, UK

The Welsh Harp Reservoir is a body of open water (96 ha) located in north-west London, which was constructed in the mid-nineteenth century to provide water for two canals and to act as a flood alleviation basin. The area surrounding the reservoir was originally countryside but is now urbanised. The original open water has been reduced by the growth of, reedbeds, marshlands, willow carr woodland and grassland which provides habitats for resident and over-wintering waterfowl populations and the reservoir was designated a Site of Special Scientific Interest in 1950. Floating rafts have been constructed in recent years to provide additional nesting sites. These rafts or platforms have attracted several pairs of common Tern, *Sterna hirundo* (Batten, 1989; Johnston, 1990).

The management of these wildlife habitats is the responsibility of the Welsh Harp Conservation Group, which consists of volunteers who carry out tasks, such as the coppicing of willow, harvesting of reeds and building of nesting rafts, especially during winter weekends. They contribute to the management plan of the reservoir, which is agreed to by a management committee including the local authorities. There is also a fully staffed Field Centre that offers day visits and short courses for schools, colleges and teachers. Two countryside rangers lead guided walks, liaise with the local community and protect the conservation interests of the site. However, the conservation management of the reservoir's habitats is limited by local authority funds and as there is no additional central government support, it is largely dependent on the activities of the volunteers.

The Welsh Harp is fed by the Silkstream in its northern arm and the Dollis Brook from the east. Both streams receive urban runoff that consists of a cocktail of heavy metals, hydrocarbons and pesticides. The downstream sediments become increasingly contaminated and their remobilisation during storm events and transport into the reservoir presents a threat to organisms including macroinvertebrates and via the food chain, fish and waterfowl. Oil booms have been installed at the inlet of both streams and at the Silkstream inlet, a trash screen and automated 'grab' collector has been added. The oil boom consists of an inflated plastic cylinder with a skirt protruding below the water surface to

provide additional oil retention during storms. Initial monitoring by Jones (1993), a year after its installation, showed a reduction in hydrocarbon concentrations in the water immediately below the oil boom on the Silkstream but negligible reduction in sediment concentrations. The extremely effective natural treatment processes which occur within the Welsh Harp basin are clearly demonstrated by the 50–80% reductions recorded in both water and sediment mean total hydrocarbon levels and 97% reduction in suspended solids between the boom and the northern limit of the reservoir.

The natural colonisation of the marginal areas of the northern and eastern limbs of the reservoir by two species of *Typha* has been complemented by the planting of *P. australis*, the common reed. *T. latifolia* has been shown to tolerate water and sediment concentrations (mg/kg) of Pb (36.2, 841), Cu (59.6, 219.8), Zn (136.6, 778.9) and Cd (8.9, 12.5) that have been recorded in discharges to the Welsh Harp (Shutes et al., 1993). Furthermore, the plant rhizome, or subsurface stem provides a matrix for contaminated sediment to accumulate and a sink for heavy metals. The 54–61% of Pb, Cu, Zn and Cd taken up by *T. latifolia* were shown to be stored in the rhizome (Shutes et al., 1993). The reeds create a valuable wildlife habitat for waterfowl but require maintenance and long-term control of succession to willow carr development. The long-term accumulation of silt requires its costly removal and the reservoir has recently been extensively dredged.

### 2.3. Great Notley Garden Village, south-east England, UK

The increasing demand for housing in Britain has led to the continued development of greenfield sites in locations around the cities. There is also a need to observe the UK Environmental Policy (DoE, 1992) when designing these

developments and to add features which may enhance their landscape, wildlife and conservation value. Great Notley Garden Village (188 ha) is located near Braintree in south-east England on former agricultural land and by the year 2000 will contain 2000 homes. Its design by Countryside Properties includes a country park with an ornamental pond, wetland and surrounding woodland and grassland providing wildlife habitats and a central focus for community relaxation and recreation (Oldham, 1995). The constructed wetland (7900 m<sup>2</sup>) and adjacent recreational pond (16,000 m<sup>2</sup>) at the site have been designed to provide treatment and act as a balancing pond to store surface water runoff from the catchment and discharge it into the outfall system of ditches at a controlled rate.

The base of the reed bed was constructed in the impermeable boulder clay, to minimise any seepage, with a slope less than or equal to 1% to assist the water flow through the bed. The discharge from the inlet passes to two sediment trenches to allow settlement of suspended solids (Fig. 3).

A soil bed of 150 mm was planted with *T. latifolia*, *Scirpus lacustris* and *Iris pseudacorus*. The topsoil was previously used for farming and has sufficient nutrient content to encourage initial plant growth. The triangular gravel area (comprising over a third of the surface area of the wetland) that extends from the settlement trenches below the inlet was planted with 10,000 *Phragmites*. The remainder of the wetland was planted with *Typha*, *Iris* and *Scirpus* with alternating species in front of the six outlet pipes. A total of 33,750 plants have been introduced to the wetland.

The water passes through the subsurface system of the *Phragmites* bed planted in gravel. This system will assist the control of weed growth although the water level will periodically rise above the surface of the gravel. However, during dry periods, water will flow through the base of the bed encouraged by the slope.

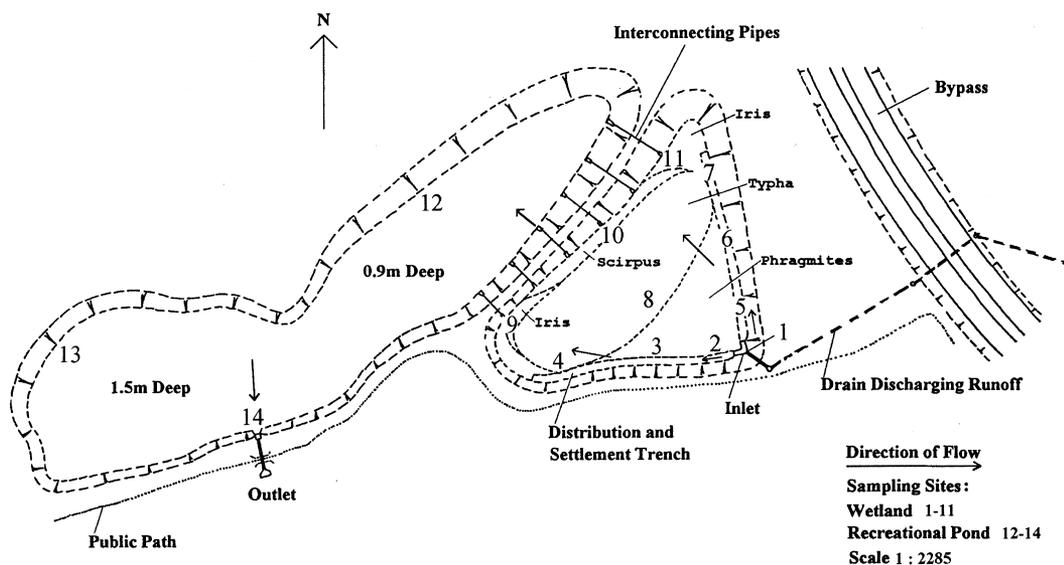


Fig. 3. Constructed wetland and recreational pond, Great Notley, Garden Village, south-east England (Mungur et al., 1999).

The water will then reach the soil bed which represents the surface flow system. Due to the poorer hydraulic conductivity of the soil compared to the gravel, surface flow will dominate through this section of the wetland containing *T. latifolia* and *S. lacustris*. Finally, the water passes through six outlet pipes into the recreational pond from which it is subsequently discharged via a narrow outlet into the local river channel (Mungur et al., 1999). The recorded results for the first year of operation show ranges for Cd of 10–99%, Cu of 94–97%, Pb of 89–97% and Zn of 10–99%. It is essential to remove silt each year from the settlement trenches in order maintain this metal removal performance.

The introduction of this constructed wetland to a substantial residential development represents an innovative example of environmental engineering that utilises plants as an ecological method for treating pollution from surface runoff.

#### 2.4. Putrajaya Lake and constructed wetlands, Malaysia

Putrajaya is the new Federal Government Administrative Centre in Malaysia, located south of Kuala Lumpur, north of the new International Airport (KLIA) and along the Multimedia Super Corridor (MSC). It will consist of government departments, commercial offices, residential premises and recreational parks as well as water bodies. Green space will occupy 30% of the land area of the city. In balancing the ecosystem and the future population of Putrajaya, one of the most distinctive features is the development of the lake that covers a total of 650 ha and has been created by the construction of a dam at the lower reaches of the River Chuau. An important component of the lake is the creation of 23 constructed wetlands (Fig. 4). The wetlands act as a natural treatment system that filters most of the pollutants in the river water before it enters the lake.

Located in the middle of Putrajaya, the lake provides a landscape feature and varied recreational activities for the population as well as creating wildlife habitats. An interpretation centre describes the design and operation of the lake and wetland system and their role in the developing ecology. The ultimate goal of the development is a self-sustaining and balanced lake ecosystem set in the Garden City of Putrajaya.

The water in the lake must be suitable for recreational activities and aesthetically attractive to the public. It is therefore expected that the lake will be free of floating debris, algae, weed, objectionable odour as well as safe and healthy for humans and freshwater fauna. In achieving this, the general objectives are:

- the existing environment is sustainable;
- the lake does not become eutrophic;
- the water quality is suitable for body contact recreation;
- the lake creates a natural and pleasant landscape, enhancing ecotourism and attracting wildlife;

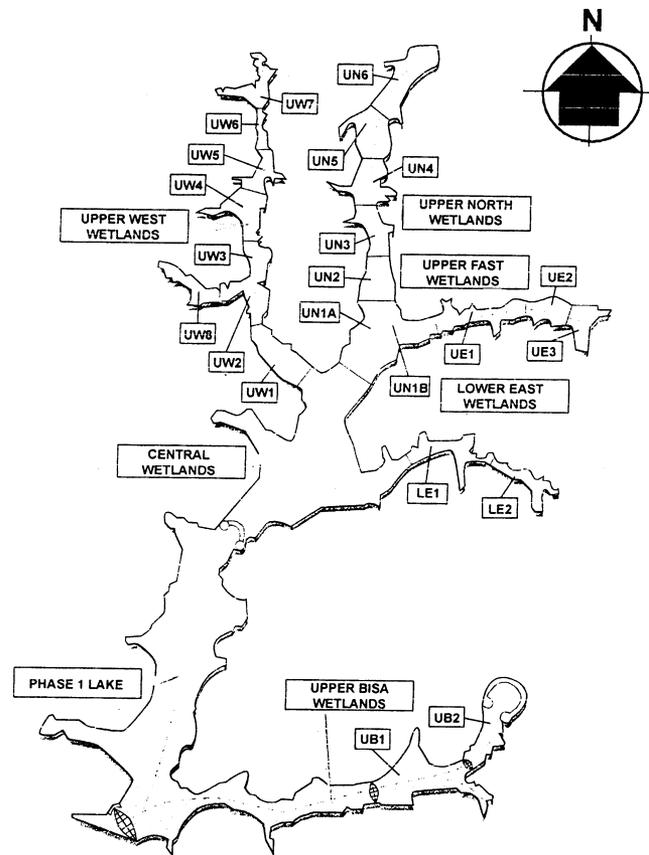


Fig. 4. Putrajaya Lake and Wetland system, Malaysia (Ariffin, 1998).

- the lake provides a suitable environment for education and scientific research.

Each of the 23 wetland cells (total area 130 ha) is separated by a weir and has a similar design to the wetlands systems shown in Figs. 1 and 3. An initial settlement forebay is followed by a surface flow wetland and a final settlement pond. The raised walls at the inlet, outlet and sides of the wetland allow water storage following storm events. The vegetation types in the wetlands comprise emergent macrophytes (large plants), rheophytes (floating plants) and freshwater swamp species. A total of 70 plant species have been selected for the wetlands and their seeds obtained from locations throughout Malaysia. The 12 million plants have been grown in a nursery that is 5 ha in area.

The wetlands were designed using the multicell, multi-stage approach, with different water levels at each cell as the water flows across the wetlands. The advantage of the design is that it provides good flow distribution, thus maximising shallow areas required for the successful growth of macrophytes and facilitates a more cost-effective maintenance including the management of weeds and insects.

A comprehensive water quality monitoring programme will be introduced following the completion of the Putrajaya Lake and Wetlands system in 2000.

### 3. Conclusion

The use of constructed wetlands to treat wastewater and other sources of water pollution is a valuable and appropriate technology to be used alone or in combination with other systems. It is especially suitable for small communities in developing countries, where the potential health benefits from pathogen removal are considerable. The rapid recent increase in the number of wetland systems in Britain alone, although concentrated in two regions, is an indication of their acceptance by water engineers and managers. However, although there are established design criteria for wetland wastewater treatment systems, criteria for urban and highway runoff treatment systems have yet to be agreed upon.

The management and maintenance of the systems require trained and experienced staff. The long-term efficiency and sustainability of these systems is critically dependent on an integrated understanding of their biological, chemical and hydrological processes. Management plans and budgets need to be prepared at the design stage and provision should be made for resolving unforeseen operational problems. Both natural and artificial wetlands are dynamic systems that change with time unless human intervention arrests these processes.

Domestic and agricultural wastewater, which is uncontaminated by toxic compounds, can theoretically be treated by constructed wetlands without replacing the substrate for several years. Urban and highway runoff systems will accumulate heavy metals and hydrocarbons in their substrate and this will ultimately require disposal to a landfill site.

The recycling or the reuse of water in these systems needs to be addressed. They lose water by evaporation and evapotranspiration through the plant leaves. Although this is an advantage for drying sewage sludge (90% water) and in regions with high rainfall, water shortages will stress the plants. The use of the treated effluent for the irrigation of crops is a desirable recycling application.

Public curiosity into how these wetland systems operate is complemented by an interest in their wildlife. The use of Information Technology has opened up new opportunities for providing information to the public. Clearly, the objectives of Local Agenda 21 including community education are being applied in different regions of the world.

There is a global trend for more stringent environmental standards and legislation. The current economic climate encourages the introduction of relatively low cost pollution treatment systems. The benefits of natural systems are becoming more apparent as they become successfully used. Developing countries are realising that natural systems may

be preferable to energy demanding conventional technology for wastewater treatment.

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