CHAPTER 9

CHAPTER 9

CONSTRUCTED PONDS AND WETLANDS

9.1 INTRODUCTION

A growing public awareness of environmental issues in recent times has elevated water quality issues to the fore in public debate in several areas of Australia. Urban developments as well as agricultural activities in rural catchments all contribute to increased pollutant loadings into the receiving waterbodies. The nature of pollutants emanating from different landuse is different and as a consequence treatments to improve the stormwater quality would necessarily involve a number of measures. It is well documented that urban stormwater runoffs are generally of poorer overall quality than runoffs from a rural catchment and there have been a number of significant studies into developing appropriate treatments for the range of pollutants generated from urban catchment activities. Agricultural activities in rural catchments and urban developments can often lead to high inputs of nutrients into the receiving waters which could lead to excessive algal growth, particularly of toxic blue-green species such as Nodularia, Anabeena and Microcystsis. For example frequent outbreaks of blue-green algae in many water supply reservoirs and ornamental lakes have highlighted the effects of progressive build-up of sediment-bound nutrients in receiving waters over a number of years.

Issues concerning pollution that endangers the sustainable utilisation of the nation's water resources have focused government authorities towards integrated catchment management where both causes and effects of pollution are addressed. Constructed and natural wetlands have been promoted as effective means of improving the quality of stormwater runoff from both rural and urban catchments. Like all environmental engineering systems, the processes underlying the role of wetlands in water pollution control are multi-disciplinary involving biological and ecological sciences, aquatic chemistry, engineering hydrology and flow hydraulics.

A review of current practices in the utilisation of constructed and natural wetlands for stormwater pollution control found current design guidelines to be ad-hoc. Most design parameters were based on adaptation of experiences from treatment of wastewater. It was not clear in most cases how some of the differences in the hydrologic and pollutant loading characteristics between stormwater and wastewater have been accommodated in the design guidelines.

Urban and agricultural runoff quality control by detention in wetlands has unique challenges that differentiates it from wastewater quality control. A recent review of current design practices for the use of wetlands for urban and agricultural runoff found them to be primarily based on wastewater treatment technology and were generally inadequate in accounting for the inherent variability of stormwater runoff generation and pollutant loading. The variable nature of urban and agricultural runoff characteristics includes:-

- the intermittent nature of runoff;

- the variability of rainfall depth, storm duration and storm pattern;
- the variable rate of pollutant accumulation during the period preceding a storm event; and
- the uneven distribution of pollutants during a storm event, eg. differences in the pollutograph compared to the runoff hydrograph.

All these characteristics contribute to a much higher inflow dynamics to the wetland. Design practices based on assumptions of steady inflows and a prescribed performance (eg. detention time) for an individual probabilistic event are considered to be inappropriate for urban and agricultural runoff treatment. **It is therefore not surprising that insufficient provision of storage volume and unsatisfactory hydrologic and hydrodynamic control are the main causal factors for poor performance of constructed wetlands as water pollution control facilities.**

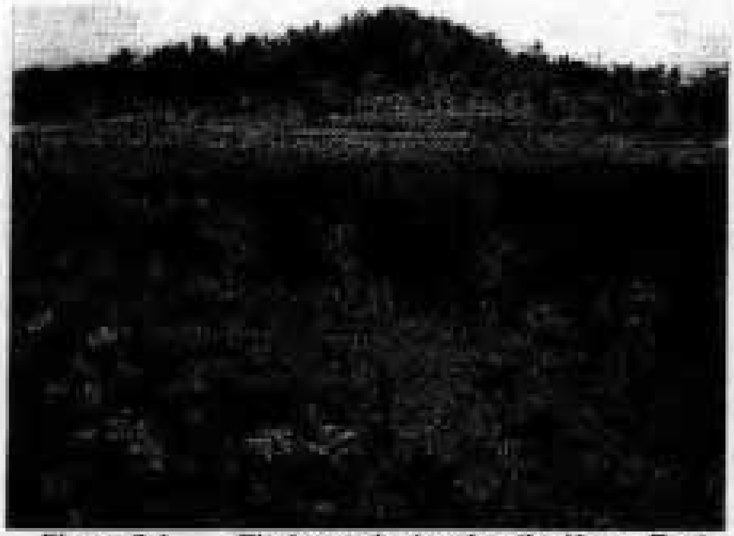

Figure 9.1 Photograph showing the Upper East Wetland in Putrajaya

Recent experiences have indicated a trend towards either the incorporation of existing natural wetlands or the development of wetlands and ponds as landscape features to enhance the landscape amenity of associated urban developments as shown in Figure 9.1. However there is often little thought on how these wetlands can be utilised effectively to serve other beneficial functions associated with improvements to stormwater quality and provision of wildlife habitats. As a result, many of these urban wetlands and ponds are becoming a long term liability to the community. Common problems encountered include:-

- accumulation of litter in some sections of the wetland;
- accumulation of oil and scum at "dead zones" in the wetland;
- infestation of weeds or dominance of certain species of vegetation;
- mosquito problems;
- algal blooms;
- scouring of sediment and banks.

A lot of the above problems can be minimised or avoided by good engineering design principles. Poor wetland hydrodynamics and lack of appreciation of the stormwater treatment chain are often identified as major contributors to wetland management problems. Wong and Geiger (1998) list some of the desirable hydrodynamic characteristics and the design issues requiring attention to promote these characteristics in Table 9.1.

Like all environmental engineering systems, the processes underlying the role of wetlands in water pollution control are multi-disciplinary involving biological and ecological sciences, aquatic chemistry, engineering hydrology and flow hydraulics. **Expert inputs are required in the design of stormwater wetlands and this chapter merely serves to provide broad**

outline of design issues associated with the design of ponds and wetlands for stormwater pollution control.

Table 9.1
Desired Wetland Hydrodynamic Characteristics and Design Elements

Hydrodynamic Characteristics	Design Issues	Remarks
Uniform distribution of flow velocity	Wetland shape, inlet and outlet placement and morphological design of wetland to eliminate short-circuit flow paths and "dead zones".	Poor flow pattern within a wetland will lead to zones of stagnant pools which promotes the accumulation of litter, oil and scum as well as potentially supporting mosquito breeding. Short circuit flow paths of high velocities will lead to the wetland being ineffective in water quality improvement.
Inundation depth, wetness gradient, base flow and hydrologic regime	Selection of wetland size and design of outlet control to ensure compatibility with the hydrology and size of the catchment draining into the wetland.	Regular flow throughput in the wetland would promote flushing of the system thus maintaining a dynamic system and avoiding problems associated with stagnant water, eg. algal blooms, mosquito breeding, oil and scum accumulation etc.
	Morphological and outlet control design to match botanical layout design and the hydrology of the wetland.	Inadequate attention to the inundation depth, wetness gradient of the wetland and the frequency of inundation at various depth range would lead to dominance of certain plant species especially weed species over time, which results in a deviation from the intended botanical layout of the wetland. Recent research findings have indicated that regular wetting and drying of the substrata of the wetland can prevent releases of phosphorus from the sediment deposited in the wetland.
Uniform vertical velocity profile	Selection of plant species and location of inlet and outlet structures to promote uniform velocity profile	Preliminary research findings have indicated that certain plant species have a tendency to promote stratification of flow conditions within a wetland leading to ineffective water pollution control and increase the potential for algal bloom.
Scour protection	Design of inlet structures and erosion protection of banks	Owing to the highly dynamic nature of stormwater inflow, measures are to be taken to "protect" the wetland from erosion during periods of high inflow rates.

9.2 TREATMENT PROCESSES IN CONSTRUCTED STORMWATER WETLANDS

9.2.1 General

Nutrients and other contaminants such as trace metals, BOD and COD are transported in either particulate, colloidal or soluble form. The principal mechanisms by which the various forms of nutrients are removed from the stormwater in wetlands are:-

- sedimentation;
- filtration; and
- chemical and biological adsorption.

Of the above three primary processes, sedimentation and filtration are physical processes and would dominate during storm events while a combination of these and biological and chemical uptake mechanism associated with the adsorption process will occur during dry periods in between storm events.

9.2.2 Sedimentation

The process of sedimentation removes the heavier sediments from the water column. Wetland and wet detention basin dimensions would be such that flow velocities would provide sufficient detention time for the particles to settle to the bottom of the wetland. The specification of the wetland area (A) may be based on the expression by Fair and Geyer (1954) for wastewater sedimentation basin design:

$$R = 1 - \left(1 + \frac{1}{n}\frac{v_s}{Q/A}\right)^{-n} \qquad - \qquad 9.1$$

where R = fraction of initial solids removed
v_s = settling velocity of particles
Q/A = rate of applied flow divided by the surface area of the basin or wetland
n = turbulence or short-circuiting parameter

The above equation is strictly applicable for systems with no permanent pool, and may be re-written as follows (Equation 9.2) to account for the effect of the permanent pool storage. The permanent pool influences the flow velocity in the detention basin but not the required detention period to allow the particle size to settle below the invert of the outlet structure.

$$\mathrm{R} = 1 - \left[1 + \frac{1}{\mathrm{n}} \cdot \frac{\mathrm{v_s}(\mathrm{S_p} + \mathrm{S_e})}{\mathrm{Q} \cdot \mathrm{d}}\right]^{-\mathrm{n}} \qquad - \qquad 9.2$$

where d is the depth range of the extended storage
S_p is the storage volume of the permanent pool
S_e is the storage volume of the extended detention area

Field settling velocities are often significantly lower than laboratory-derived settling velocities. It is often suggested that settling velocities of half the theoretical velocities of sediments should be adopted in sizing sedimentation basins. Table 9.2 list the typical settling velocities of sediments.

Table 9.2
Settling velocities under ideal conditions
(Maryland Department of Environment, 1987)

Classification of Particle size range	Particle diameter (μm)	Settling velocities (mm/s)
Very coarse sand	2000	200
Coarse sand	1000	100
Medium sand	500	53
Fine sand	250	26
Very fine sand	125	11
Coarse silt	62	2.3
Medium silt	31	0.66
Fine silt	16	0.18
Very fine silt	8	0.04
Clay	4	0.011

9.2.3 Filtration

Colloidal substances present in stormwater would take too long to settle and their treatment involves filtering them out of the stormwater by flow through wetland vegetation. The process of collodial agglomeration and adhesion to macrophytes was clearly documented by field studies undertaken by Lloyd (1997) and provided strong evidence of the enhance sedimentation and filtration mechanisms facilitated by wetland macrophytes and organic biomass in the wetland system (see Figure 9.2). The wetland depth and the density and type of vegetation are key wetland design parameters affecting this treatment process. The selection of the appropriate vegetation species would depend on availability and the hydrologic regime (e.g. water level fluctuation) of the wetland. In general, species with fine but dense stem structures are desirable as they provide more efficient "adhesion" sites for colloidal substance than broad leaf vegetation.

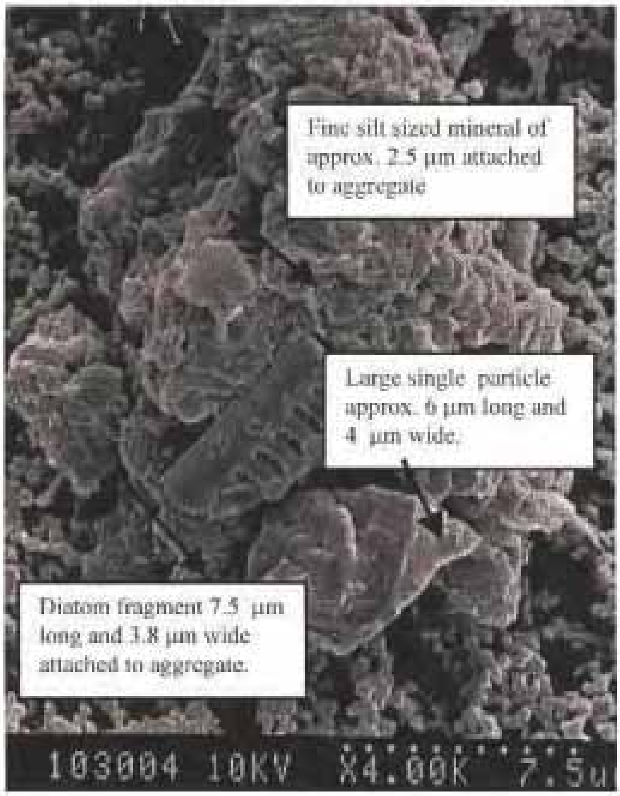

Figure 9.2 **Electron Microscope of an Aggregate showing agglomeration of Inorganic Particles and Organic Fragments**

Nutrients in their soluble form are often adsorbed by the sediment which involve both chemical and biological processes. Nitrification followed by denitrification are the obvious mechanism for the removal of nitrogen. The sediment uptake of soluble phosphorus have been widely acknowledged as a dominant mechanism transforming soluble phosphorus into particulate phosphorus. It is envisaged that the processes involved are a combination of chemical bonding, diffusion into the interstitial water and microbial activities (Chiam et al., 1994).

Soluble phosphorus is the form of phosphorus most readily available for algal growth. The process of sediment adsorption can effectively transform the chemical structure of phosphorus from one of being most bio-available for algal growth to one which is chemically bonded to the sediment. Settling of these nutrient bound sediment is still necessary to prevent its transportation into the deeper receiving waters (e.g. reservoirs or lakes) where anaerobic conditions may cause the release of phosphorus from the sediment. The treatment of soluble nutrients is thus a two-stage process of adsorption and precipitation followed by sedimentation.

9.3 COMPONENTS OF A CONSTRUCTED WETLAND SYSTEM

9.3.1 General

A constructed wetland system generally comprises a combination of vegetated area and open water. Ponds are open water body with fringing vegetation and submerged macrophytes while the vegetated or macrophytes zones (often referred to in most literatures as the wetland) often consist of a shallow permanent pool with extensive emergent macrophytes. These two components have different functions and these are summarised in Table 9.3.

A combination of wetland morphology, available storage, hydrologic and hydraulic controls, and wetland vegetation layout determine the overall performance of the wetland. The proportion area of open water to macrophytes zones will vary depending on the nature of the inflow, particularly the suspended sediment particle size distribution. The storage volume of the wetland system is a key design parameter which, in combination with the hydrologic control, defines the detention period of stormwater in the wetland and the percentage of overall stormwater volume treated by the wetland. Wetland morphology and vegetation layout promotes the appropriate flow pattern within the wetland such that the various treatment processes can be optimised.

The layout of a wetland system will vary depending on the number of objectives served by the wetland system. It is generally advisable to locate at least some part of the open water zone upstream of the macrophytes zone. The location of an open water body upstream of the macrophytes zone is consistent with the desired sequence of treatment provided by the two zones as outlined in Table 9.3. A typical cross section of a wetland system is shown in Figure 9.3.

In most urban design, the open water body forms an important urban feature and often require some degree of protection from stormwater pollution. In such circumstances, the macrophyte zone and a smaller open water inlet zone are placed upstream of these waterbodies as shown in Figure 9.3. In the case of the Putrajaya project, the Putrajaya Lake should be considered the waterbody requiring protection from pollution and thus does not strictly form part of the water quality treatment wetland system.

Table 9.3
Functions of Open Water and Macrophytes Zones

Open Water Zone/Pond	Macrophytes Zone/Wetland
• Settlement of coarse materials – the retardation of flow in the pond area facilitate the sedimentation of solids down to coarse and medium silt. • Traps adsorbed pollutants – silt particles trapped in the pond system may also retain adsorbed pollutants such as trace metals and nutrients. • Provides hydrologic and hydraulic management – pond areas attenuate and distribute inflows to the macrophytes zone within the wetland system. Often, the open water area located upstream of the macrophytes zone is used to divert large discharges away from the macrophytes zone to prevent scouring and remobilisation of settled fined material in the macrophytes zone. • Provision of open water for ultra violet exposure as a means of water disinfection.	• Traps pollutants associated with fine suspended particles by enhance sedimentation and filtration by the vegetation (see Table 9.4). • Removal of dissolved pollutants by chemical and biological adsorption. • Provides aquatic fauna zones – wetlands provide an area for predation by aquatic fauna. • Provision of vegetated zones to facilitate oxygenation of the substrata and maintenance of a positive redox potential in the sediment.

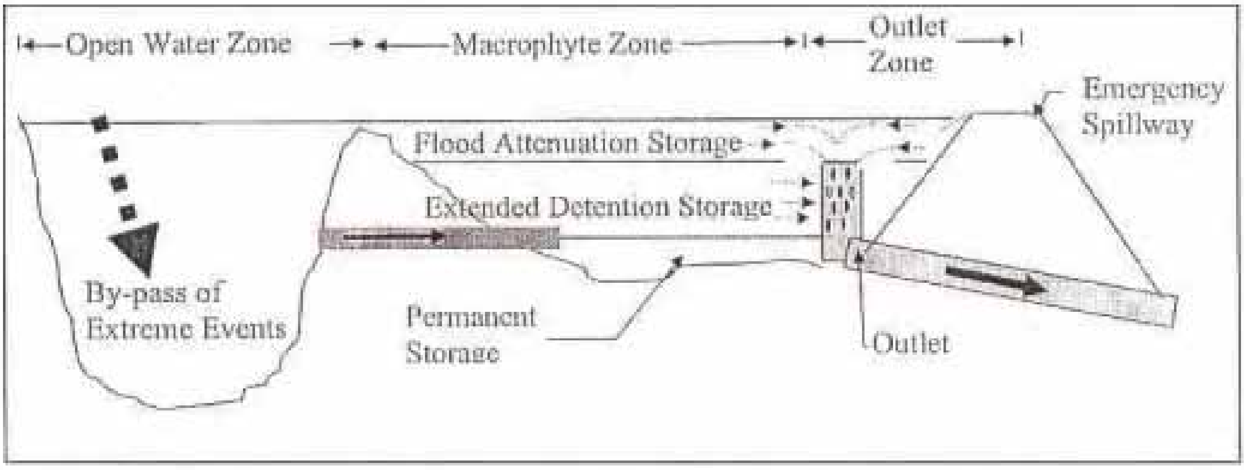

Figure 9.3 Functional Zones in Constructed Wetlands (not to scale)

9.3.2 Open Water Zone/Pond Area

The open water area serves as an inlet zone which serves to intercept incoming flow, dissipate energy, reduce flow velocity and distribute it uniformly over the macrophytes zone. Large flows that would scour and remobilised settled materials in the macrophytes zone would be diverted away at the inlet zone. The protection of the macrophytes zones from scour imposed by excessively high flow velocities is an important design consideration. If topography constraints preclude the provision of a high flow by-pass, the open water zone will need to be designed to attenuate inflow to contain the maximum flow velocity in the macrophytes zone to 2 m/s for the 100 year ARI event. The biofilms attached to the macrophytes will generally be lost under these conditions and some degree of remobilisation of settled material will occur. The macrophytes will, however, provide a degree of armouring to the sediment and thereby minimise the degree of sediment scouring.

The zone also serves to capture heavy sediment and protects vegetation in the storage zone of the constructed wetland from being smothered. This is an important factor in ensuring that maintenance of the wetland area is minimised and that the desilting will be most frequent in the open water zone at approximately once every three to five years, compared to the expected thirty to fifty years in the wetland area.

The use of trash racks and gross pollutant traps in this zone is common to remove litter and other gross solids.

9.3.3 Macrophytes Zone/Wetland Area

This zone is a shallow, relatively tranquil part of the constructed wetland within which particle settling and adhesion to vegetation occurs. The zone can consist of up to three compartments, ie. permanent pool, extended detention storage and flood attenuation storage.

The permanent pool is often made up aquatic vegetation area, sediment storage and open water and represents the permanent habitat for aquatic organisms. The extended detention storage provides the volume required to extend the detention time of smaller size storm events while maintaining sufficient discharge capacity for larger storm events. The flood attenuation zone is the storage between the top of the extended detention storage and the spillway level to provide flood protection of downstream environments.

Figure 9.4 Macrophytes zone in Upper North Wetland utilised to treat effluent entering into the Putrajaya Lake

9.3.4 Outlet Zone

The purpose of this zone is to control the water level in and rate of discharge from the constructed wetland. In addition, the outlet must provide a smooth transition of flow from the extended detention storage, in particular keeping velocities sufficiently low so that re-suspension of settled particles is avoided. Often, the outlet control also defines the hydrologic regime of the constructed wetland, ie. the probabilistic distribution of water levels, and thus has an important influence on the vegetation layout of the wetland.

9.4 ROLE OF WETLAND VEGETATION

It is well documented that wetland vegetation provides a medium for filtration of water, with the macrophytes providing a surface for adhesion of fine particles as shown in Figure 9.5. Apart from the obvious filtration function, wetland vegetation enhances stormwater quality by a number of other physical, chemical and biological processes (Breen 1990). In reviewing the functions of wetland vegetation in urban or rural stormwater treatment, it is useful to consider the treatment functions under the two principal modes of operation outlined by Somes et al. (1996) of baseflow and eventflow as listed in Table 9.3.

Figure 9.5 Wetland Macrophytes in Upper East Wetland in Putrajaya

Under baseflow conditions (ie. periods between runoff events), detention times are at their maximum and wetland vegetation is involved in a range of physical, chemical and biological treatment processes as listed in Table 9.4. Under eventflow conditions, the generally shorter detention times reduce the significance of biological and chemical processes. The wetland vegetation performs the physical functions of distributing and retarding flows and lead to increased inflow contact with plant surface area. These functions increase sedimentation, surface adhesion and filtration of finer particles. As the majority of pollutants are transported during storm events, these physical processes are important in trapping pollutants, which can subsequently be consolidated or transformed by chemical and biological processes during the intervening baseflow periods.

Table 9.4
Functions of Vegetation in Constructed Wetlands for Stormwater Control

During baseflow	During eventflow
Act as substrata for epiphytes (Epiphytes convert soluble nutrients into particulate biomass that can settle out and enter the sediments - this is a short term process occurring over days to weeks)	Promote even distribution of flows
	Promote sedimentation of larger particles
Consolidate nutrients trapped in the sediments into macrophyte biomass (This is a medium-term process occurring over months to years)	Provide surface area for adhesion of smaller Particles
Return particulate biomass as macrophyte litter for storage in the sediments (This is a long term process occurring over years to decades resulting in the development of organic sediment and peats)	Protect sediments from erosion
	Increase system hydraulic roughness

9.5 WETLAND SYSTEM DESIGN ELEMENTS

9.5.1 General

The design of wetlands and wet detention basins for urban and agricultural runoff quality control requires attention to a number of issues. EPA-NSW (1997) lists 12 objectives which are fundamental to wetland design. These objectives are listed as follows:-

1. Location
2. Sizing
3. Pre-treatments
4. Morphology
5. Outlet structures
6. Macrophytes planting
7. Maintenance
8. Loading of organic matter
9. Public safety
10. Multiple uses
11. Groundwater interaction
12. Mosquito control

Wong and Somes (1996) listed three principle components which need to be address when designing wetlands and the above twelve objectives and others may be grouped under the three general headings of:-

- hydrologic effectiveness;
- hydraulic efficiency; and
- facilitation and optimisation of water quality treatment processes.

A systematic design procedure would address these three principal components in the above order on the basis that the first design objective would be to facilitate an optimal rate of capture and detention of stormwater runoff by the wetland, ie. to optimise the *hydrologic* *effectiveness* of the wetland. The second design objective is to ensure that stormwater inflow into the wetland is well distributed throughout the wetland by proper definition of the shape and depth of the wetland. Special flow diversion features using vegetation, wetland morphology design and other hydraulic measures may have to be considered in facilitating the even distribution of flow throughout the wetland. On providing the most appropriate hydrodynamic conditions within the wetland (ie. from Design Objectives 1 & 2) the third design objective is to introduce the necessary biological and chemical (in terms of sediment type where appropriate) features to optimise "treatment" of the stormwater in the wetland.

The hydrologic effectiveness of the wetland is a measure of the available capacity of the wetland to capture and retain runoff for the prescribed period of detention and may be expressed as a percentage of the long-term runoff subjected to this minimum period of detention. Often the prescribed period of detention is dependent on the catchment and pollutant characteristics and the required level of treatment efficiency (as discussed in Section 9.5.2). Furthermore, stormwater inflows are unsteady and intermittent and detention times are expected to vary accordingly. It will be necessary to consult ecologist and relevant government authorities on the appropriate detention period for individual cases. It should however be borne in mind that the issues of detention period, size of the wetland and the hydrologic effectiveness are not mutually exclusive but are interdependent. Defining two of these parameters will fix the third.

The hydraulic efficiency of the wetland is a measure of its ability to distribute the inflow evenly across the wetland and is influenced by the shape of the wetland and its vegetation layout. Inadequate provision of storage volume (low hydrologic effectiveness) and poor hydraulic conditions leading to short-circuiting of flow path are the two most common causes of unsatisfactory wetland performance.

As mentioned earlier, the treatment processes involve the combination of physical, chemical and biological processes being promoted in the wetland through the prescribed detention time, hydrodynamic conditions within the wetland and wetland vegetation. The role of vegetation for runoff treatment is uniquely different with their primary functions being one of promoting sedimentation and facilitation filtration of fine colloidal particles in the inflow to the wetland.

It is evident that the three design components of hydrologic effectiveness, hydraulic efficiency and optimisation of treatment processes are inter-related and the design procedure is, by necessity, iterative.

9.5.2 Current Wetland Design Guidelines

General

Design guidelines for constructed stormwater quality improvement wetlands and wet detention basins are directed at determining the appropriate dimensions and hydrologic regime of the wetland to facilitate the treatment mechanisms described in the previous section. Approaches adopted in current practice in the design of wetlands for stormwater treatment are varied and are found to be generally site specific. In most cases examined, fundamental parameters related to the site conditions such as the inherent hydrologic variability of runoff and the characteristics of the pollutants are not explicitly considered thus limiting the applicability of the design specification to other sites.

Table 9.5 list some of the design guidelines for constructed wetlands recommended from experiences in Australia and overseas. Most of the guidelines were for the specification of wetland storage volume, surface area, depth, detention time and length/width ratio. Most of these parameters are inter-related and they can essentially be reduced to representing the two fundamental criteria of surface area (to facilitate the sedimentation process) and depth (to accommodate vegetation requirements). The combination of these two parameters gives the storage volume which is often expressed in terms of detention time. Other design considerations such as the inlet and outlet conditions and the length/width ratio are directed at ensuring the proper operation of the wetland.

Depth

In most cases the range of depths are governed by the required growing conditions of the local emergent macrophytes for the shallow zone and the submerged macrophytes in the deep zone. All of the design guidelines listed in Table 9.5 recommend at least 25% of the wetland to be less than 1 m deep. The maximum depth recommended is 10 m (ACT Admin. Int. Plan. Auth., 1990) and the minimum is 0.15 m (Livingston, 1988).

Surface Area, Storage Volume and Detention Tine

The specification of the surface area is partly related to the desired removal rate of the sediment particle as expressed in Equation 9.1 or 9.2. The surface area, storage volume and the detention time for a notional design inflow hydrograph are interrelated and thus defining two of these parameters invariably fixes the third as expressed in Equation 9.3.

$$t_d = \frac{A_s \cdot d_m}{Q_{des}} \qquad - \qquad 9.3$$

where t_d is the detention time (s)
A_s is the surface area of the wetland system (m^2)
d_m is the mean depth of the wetland system (m)
Q_{des} is the mean discharge of the design event (m^3/s)

As described in Equation 9.2, the removal rate is dependent on the settling velocity of the sediment particle and the proportion of the storage that form the permanent pool of the wetland system. The settling velocity is in turn dependent on the sediment grading. In addition to this, the removal rate as measured by R in Equation 9.1 or 9.2 is expected to vary markedly from events to events owing to the unsteady inflow (the term Q in the equations) of stormwater. Recommendations for wetland surface area contained in Table 9.5 ranged from 0.5% to 5% of the catchment area.

The storage volume of the wetland defines the detention time of the system for a given inflow rate. This parameter represents the combination of the nominated depth and surface area of the wetland and does not introduce any new criteria to the design. The use of storage volume or detention time as a parameter is essentially a convenient preliminary means of sizing the wetland. Ultimately the range of depth in the wetland is limited to approximately 1.5 m to ensure sustainable macrophytes communities, which therefore fixes the surface area of the wetland.

Table 9.2
Current Design Guidelines for Constructed Wetlands

	Livingston (1988) (Maryland)	Livingston (1988) (Florida)	Water & Rivers Commission WA (1996)	Acer Hosking & Oborn (1992)	Wulliman et al. (1989)	SPCC (1989)	ACT Admin. Int. Plan. Auth. (1990)
Depth	25 % 0.5 - 1 m 25% 0.15-0.3m 50% < 0.15m	Established from existing wetland water levels	Open Water Zone < 4m Macrophyte Zone < 1m	1-1.5m	1m min	25% < 1m rest < 2m	0.75-1m 10m max
Surface Area	3% of catchment area if the specified detention time cannot be achieved			1% of catchment area		0.5 % of catchment area	2-5% of catchment area
Storage Volume	Sufficient to store 1 yr ARI storm for 24 hrs	Sufficient to store 1st 25 mm of runoff	150-250 m^3/ha (sandy catchment) 350-450 m^3/ha (clay catchment)		12.7mm runoff from upstream impervious area		400-500 m^3/ha
Detention Time	24 hrs for 1yr ARI storm	Detention of storage for 120 hrs, with no less than 60 hrs for 50% of the storage	7 days between June and August	10 days for 1yr ARI	12 hrs median 36 hrs total drain time for storage volume		
L:W Ratio	2:1		2-3 : 1	3:1	>3:1		2-3:1
Vegetation Density	Plant at 1 m intervals with additional 40 clumps per acre of each primary species.		Inlet Zone & Macrophyte Zone				

Some storage requirement recommendations are directed at trapping the "first flush" of stormwater runoff, eg. Livingston (1988) reported that the guideline for Florida is for the wetland volume to have sufficient capacity to store the first 25 mm of runoff. Wulliman et al. (1989) suggested a storage volume of 12.7 mm of runoff from impervious areas. Other recommendations for storage provision ranged from 24 hours to 10 days for the 1 year ARI event.

Owing to the highly variable nature of catchment runoff and associated pollutant concentration, a continuous simulation approach should ideally be undertaken in selection the appropriate storage volume for a wetland or sedimentation basin. This would involve some form of storage behaviour analysis of the storage using historical or stochastically generated streamflows (Wong and Somes, 1996). The appropriate storage volume would be selected on the basis of the long-term overall performance rather than a prescribed performance for a given single event.

It is evident that the pollutant detention period will vary according to the system hydrology and the characteristics of the pollutograph in intermittently loaded wetlands. The probability distribution of pollutant detention period can only be studied in detail using a continuous simulation approach. In the absence of a continuous simulation procedure, an alternative means of approximating the representative pollutant detention period needs to be developed. Under unsteady inflow conditions, the inflow hydrograph is often significantly attenuated in wetland with outlet hydraulics controlled by riser structures (ie, vertical pipes with orifices along the length of the pipe) and the outflow hydrograph is characterised by a long duration of near constant rate of outflow. The detention time (t_d) is expressed as the ratio of the storage volume (V) and the discharge (Q), ie.

$$Q_{esr} = \frac{V}{t_d} \qquad 9.4$$

The detention period, t_d, can vary with discharge, the nature of this variation being dependent on the storage-discharge relationship of the basin.

There are currently a number of means with which the required detention time, or wetland area or storage volume can be determined. Section 9.6 outlines three such methods.

Wetland Geometry

Specification of proper wetland geometry (e.g. the length/width ratio) by some practitioners is aimed at reducing short circuiting and promoting optimal flow path. The range of length/width ratios recommended is upwards from 2:1. In essence, pond geometry is not the only option available to achieve optimal flow path. Inlet and outlet devices can be designed to promote even distribution of stormwater and vegetation layout and basin morphology are often much more important considerations (see Section 9.8). Excessively high length/width ratios may result in re-suspension of sediment due to increased flow velocities.

Vegetation Density

Vegetation density is not often mentioned in available guidelines but is an important parameter that can influence the effectiveness of the filtration process. What is recommended is highly subjective. For instance, Livingston (1988) recommends planting with a spacing of 1 m between individual plants with additional forty clumps per acre of each primary species to be planted in areas conducive to growth throughout the rest of the shallow zone.

The effectiveness of the filtration mechanism is dependent on the uniform distribution of the water across the wetland. Sparse vegetation cover in the wetland would result in zones of high velocities between plants where both the filtration and sedimentation mechanisms would be affected.

9.6 PERFORMANCE OF WETLAND SYSTEM

9.6.1 Wetland Effectiveness

As indicated by Lloyd *et al.* (1997), a common measure of wetland effectiveness in pollutant removal is the percentage reduction in pollutant concentration or the pollutant Removal Efficiency, $\Re$. This is simply expressed as follows:-

$$\Re = \left(\frac{c_i - c_o}{c_i} \right) \times 100\% \qquad - \qquad 9.5$$

where c_i and c_o are the inflow and outflow pollutant concentrations respectively.

In the case of unsteady flow and pollutant input conditions, c_i and c_o are often computed as flow weighted mean concentrations. The use of $\Re$ as a measure of wetland effectiveness masks the effects of a number of significant influences of the operating conditions of the wetland system on its effectiveness as a water pollution control facility (Lloyd *et al.*, 1997). These operating conditions include:-

1. background pollutant concentration levels;
2. input concentration;
3. hydraulic loading; and
4. the hydraulic residence time of the pollutant phase.

Each of the above factors are expected to influence the performance of a wetland, as measured by $\Re$, in a non-linear manner. The combined effects of these factors can often account for the vast majority of the variance in $\Re$ values of a given wetland computed for different events and for $\Re$ values computed for different wetlands. In the case of different $\Re$ values corresponding to different events in a given wetland, simply deriving the average these $\Re$ values to determine the "mean pollutant removal effectiveness" without relating the individual measures to the hydraulic loading of the corresponding events is totally inappropriate, but is nevertheless common in practice.

Background pollutant levels are the concentration of the pollutants within the wetland during baseflow conditions and are not attributed to catchment wash off processes during storm events. Background pollutant concentration levels generally reflect the lowest concentration of the pollutant that can be achieved by the wetland. The calculated value of the pollutant removal efficiency, $\Re$, can be very sensitive to the relative difference between the inflow pollutant concentration and the background pollutant concentration. One common mistake in the monitoring of wetland systems is the lack of consideration given to background pollutant concentration levels when computing pollutant efficiencies. For example, if the inflow pollutant concentration is twice the background concentration, ignoring the background concentration in computing $\Re$ can be in error by as much as 100%. Background concentrations are highly varied from one wetland to another and often from one season to another for a given wetland. It is therefore not surprising to observe significant scatter when comparing the computed values of $\Re$ for different wetlands.

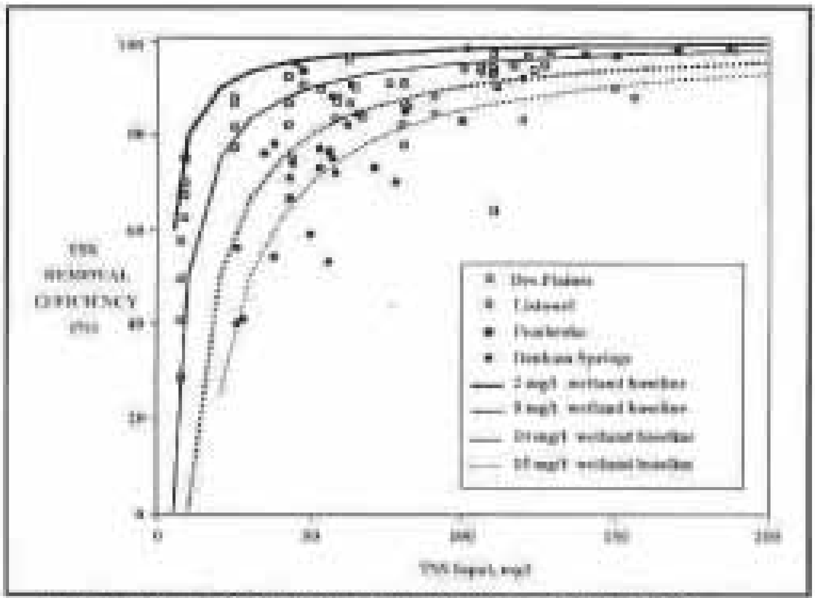

Figure 9.6 TSS removal efficiency as a function of Background Concentration and Input Concentration (Source: Kadlec and Knight, 1996)

It is generally well established, particularly for wastewater wetlands, that the removal efficiency of wetlands is a non-linear function of the inflow pollutant concentration. Duncan (1997) undertook a statistical overview of the effectiveness of urban stormwater treatment by wet detention systems and found suspended solids removal to be a power function of the inflow concentration with the exponent value of 0.6. This finding is consistent with results from analysis of removal efficiencies of wastewater wetlands by Kadlec and Knight (1996) as indicated in Figure 9.6.

9.6.2 Regression of Wetlands and Ponds Performance Data

Duncan (1997) carried out regression analysis of data of wetland and pond performances in pollutant removal. A total of 88 Australian and overseas (mainly United States of America) studies of pollutant removal efficiencies of ponds and wetlands were collected and regressions analysis were carried out to relate the ratio of the outflow to inflow event mean event concentration of the pond/wetland to the following factors:-

- the wetland area to catchment area ratio;
- the inflow pollutant concentration;
- storage volume of the wetland system in relation to the catchment area;
- hydraulic loading rate of the wetland (expressed as the ratio of the estimated average annual runoff volume and the surface area of the system); and
- the average annual hydraulic residence time expressed as the ratio of the pond/wetland volume and the estimated annual runoff volume.

The analysis found the correlation between the pollutant removal efficiency and the hydraulic loading rate to be consistently strong for the three pollutants of TSS, TP and TN investigated. The resulting regression between the log of the hydraulic loading rate and the log of the output pollutant concentration (expressed as a percentage of the inflow concentration) are presented in Figure 9.7. In the case of TSS, the analysis found the inflow concentration to be statistically significant in the regression.

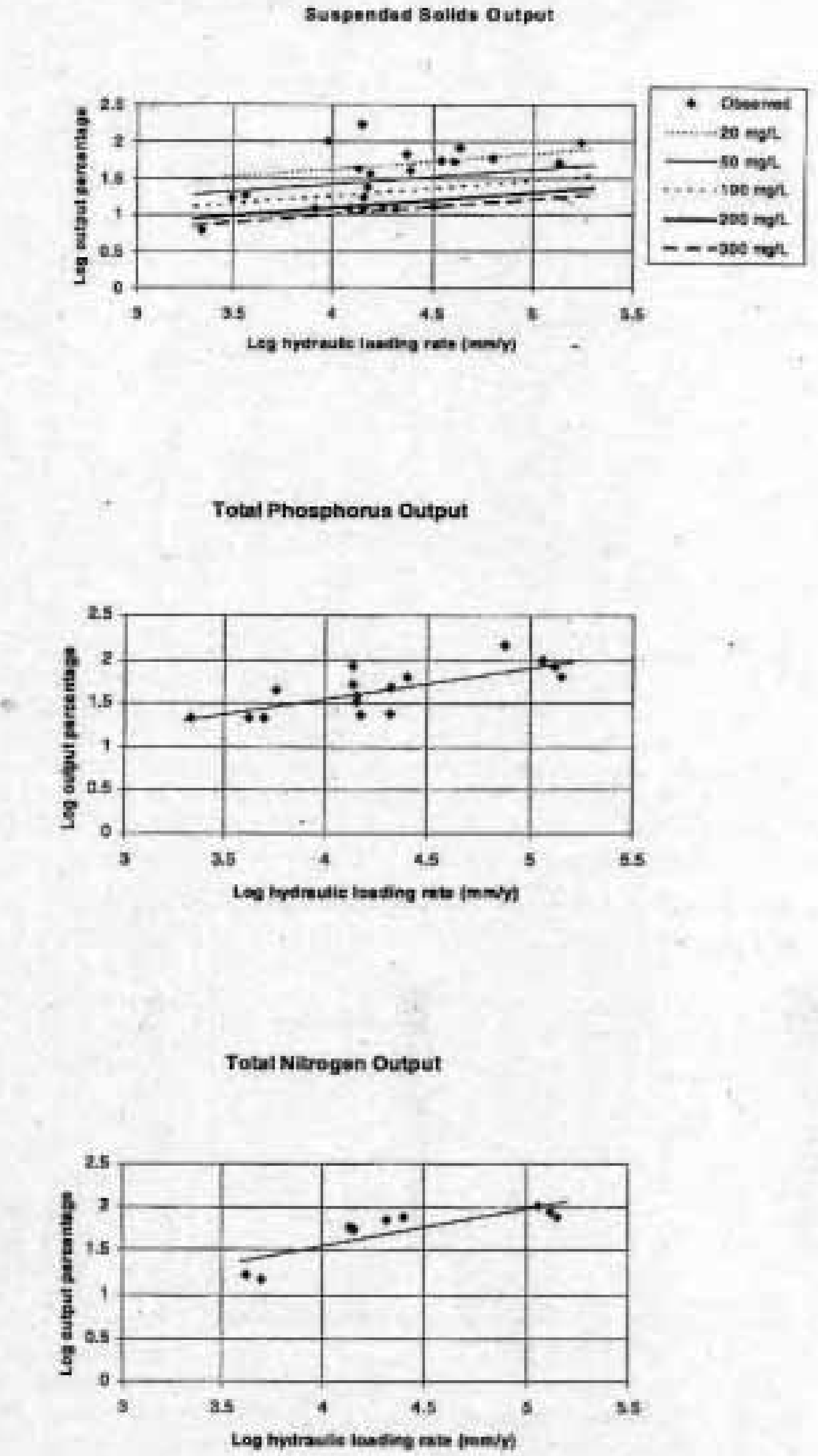

Figure 9.7 Pond/wetland Performance Relationship (Duncan, 1997)

9.6.3 Hydraulic Residence Time Relationship

The ACT Planning Authority (1996) presented empirical relationships relating the pollutant removal efficiencies to residence time in sedimentation and macrophytes zones in ponds and wetlands. These relationships are given in Table 9.3 below.

Table 9.3
Pollutant Removal Relationships used for the Canberra Region
(ACT Planning Authority, 1996)

Pollutant	Sedimentation Regime		Macrophytes Regime	
Suspended Solids	$R = 113.5 + 32.6*\log(T)$	$T < 0.15$	$R = 163.9 + 47.4*\log(T)$ $R = 115.2 + 25.2*\log(T)$	$T \leq 0.0064$ $0.0064 < T < 0.15$
Total Phosphorus	$R = 85.9 + 36.0*\log(T)$	$T < 1.0$	$R = 167.8 + 64.3*\log(T)$ $R = 93.3 + 14.6*\log(T)$	$T \leq 0.03$ $0.03 < T < 1.0$
E.coli			$R = 103.3 + 9.91*\log(T)$	

The hydraulic loading of a wetland is inter-related to the pollutant detention period or the hydraulic residence time within the wetland. The pollutant hydraulic residence time should not be confused with the time lag between the centroids of the inflow and outflow hydrographs. As shown by Fabian and Wong (1997), this time lag does not represent the average detention period of the pollutant and the departure between the hydraulic residence time of the water phase and the pollutant phase is most significant for wetlands with a permanent pool under flow conditions where the volume of the inflow hydrograph is less than the volume of the permanent pool.

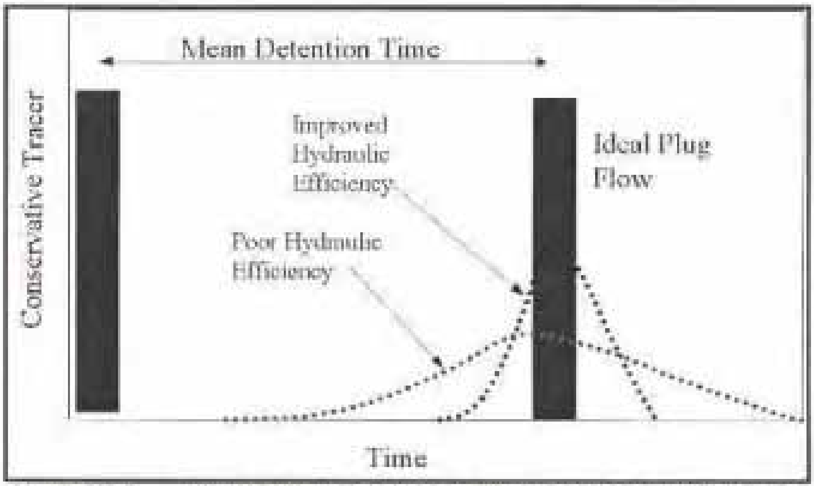

Figure 9.8 **Illustration of the Pollutant Hydraulic Residence Time (HRT) Distribution**

The Hydraulic Residence Time (HRT) in a stormwater treatment wetland varies significantly depending largely on the rainfall characteristics (duration and intensity), the available storage capacity in the wetland at the onset of a rainfall event, and the draw down rate during the event (Wong and Somes, 1995). Kadlec and Knight (1996) describe a distribution function of hydraulic residence time, referred to as the Retention Time Distribution Function (RTD) which is used to describe the degree in which the hydraulic residence time varies. Under plug flow conditions, the HRT is simply a spike with a very small standard deviation about the mean residence time. For fully mixed flows, the HRT takes the form of a exponential function. A natural system lies somewhere in between these two extremes and often takes the form of a skewed probability distribution as illustrated in Figure 9.8.

9.6.4 Decay Rate Relationship

Wetland treatment processes are highly complex and involve a combination of interacting physical, chemical and biological mechanisms. Each of these mechanisms has different optimal operating conditions and long-term outcomes from these processes (ie. effluent water quality) in wastewater systems can be modelled with a two-parameter first order decay function. This function expresses the rate at which pollutant concentration decreases with distance along the wetland as a linear function of the concentration (Kadlec and Knight, 1996). The model assumes steady and plug flow conditions and is typically expressed as follows:-

$$q\frac{dC}{dx} = -k(C - C^*) \qquad - \qquad 9.6$$

where q = hydraulic loading rate (m/y), defined as the ratio of the inflow and the surface area of the system
x = fraction of distance from inlet to outlet
C = concentration of the water quality parameter
C^* = background concentration of the water quality parameter
k = areal rate constant (m/y) which is different for different water quality constituents

Typical values of the areal rate constant and background concentrations for different water quality parameters derived by researchers have been collated and presented by Kadlec and Knight (1996) and reproduced in Table 9.4. There is a lot of uncertainty in the values of the two parameters k and C* listed in Table 9.4. This is a reflection of a combination of intersystem variability attributed to differences in wetland physical and ecological characteristics as well as catchment and pollutant characteristics. Furthermore, the assumptions of plug flow and constant parameter value are also not strictly correct. The influence of such factors as wetland depth, shape of the wetland, inlet and outlet locations, vegetation type and density, soil type, level of mixing within the wetland etc. can be expected to contribute significantly to the variability of the parameters evident in Table 9.4.

In spite of the large variation in the parameter values of k and C*, empirical data of individual wetlands on the spatial distribution of pollutant concentrations have tended to confirm the applicability of the general form of equation 9.5. This would suggest that the inadequacies may not be related to the structure of the model but rather in the proper definition of its parameters to reflect catchment and wetland characteristics. It can be expected that the uncertainty of the parameters would be significantly reduced when local data becomes available for calibration of the model either through a pilot scheme or performance monitoring during the early stages of the operation of the constructed wetland. Regional design guidelines, which progressively incorporate local experiences on the performances of wetlands, can be developed on this basis.

The k values listed in Table 9.4 are areal rate constants and inherently assume independence of depth although the operating depth range of most typical wetlands is not expected to be large. Kadlec and Knight (1996) have adopted a notional mean depth of 0.3 m with a range of between 0.15 m and 0.45 m in their calculations of the hydraulic retention time.

Table 9.4
Rate Constants and Background Concentrations for Key Water Quality Parameters
(Ref. Kadlec & Knight, 1996)

Water Quality Parameter	k (m/y); C*	Remarks
Total Suspended Solids	k = 1000 m/y $C^* = 5.1 + 0.16C_i$	Represents the settling velocity of the particles in the water column. Empirical data gives the range of k to be between 1000 m/y to 10000 m/yr. The relationship for the background concentration of TSS is poorly defined with an R^2 value of 0.23 with 1582 data points.
Biochemical Oxygen Demand	k = 34 m/y $C^* = 3.5 + 0.053C_i$	Average of data from 20 wetlands at 8 systems with a standard deviation of 22. Range is between 8.5 to 93.7. The relationship for the background concentration of BOD has an R^2 of 0.67 based on 33 data points. (avg. = 6.2 for marsh; 1.9 for forested wetlands)
Total Phosphorus	k=12 m/y C* = 0.02 mg/L	Based on 20 emergent marsh systems with a standard deviation of 6.1. General lower limit
Total Nitrogen	k = 22 m/y C* = 1.50 mg/L	Based on 59 wetland systems with rates ranging from 0.56 to 66. General lower limit

Stormwater wetlands are subject to a wide range of hydraulic loading and serve multiple functions. As a consequence, their depth range has tended to be wider than wastewater wetlands. Stormwater wetlands are also different in their operation from stormwater quality control ponds in that the depth range needs to be sufficiently wide to support a variety of wetland vegetation types. Somes et al. (1996), in their discussion in integrating hydrological and botanical design considerations, examines the suitable depth of inundation and frequency of wetting and drying necessary to support a diverse vegetation characteristics within the wetland. Typical depth range examined in that study was up to 1 m above the permanent pool level. Typically the depth of the permanent pool is approximately 0.3 m and simulations by Somes et al. (1996) for Melbourne conditions found water depth to be between 0 and 0.6 m above the permanent pool for 80% of the time owing to the stochasticity of stormwater inflow.

Wong and Geiger (1997) discussed possible effects of unsteady intermittent inflows on the parameters k and C* as follows:-

Pollutants Affected by Physical Treatment Processes

Pollutants that are pre-dominantly affected by sedimentation include TSS and associated attached metals and chemical compounds. Discussion below focuses mainly on TSS but may have relevance to other pollutants that are similarly affected by the sedimentation processes in the wetland.

Rate Constant k_{TSS} - Settling Velocity

With sedimentation processes being the dominant mechanism for removal of TSS, the settling velocity of suspended particles may be used as a measure of the rate constant k. The distribution of particle settling velocities is related to the grading, shape and density of the particles entering the wetland. Settling velocities measured in the laboratory can only be an indicator of the order of magnitude of the parameter k for TSS. Other factors such as resuspension due to non-ideal flow conditions can be expected to significantly reduce the effective settling velocities. Wetland vegetation can have the effect of increasing the magnitude of the rate constant k as demonstrated by Lloyd (1997).

As indicated in Table 9.3, the range of k values is between 1000 m/y and 10000 m/y and they correspond to particle sizes (diameter) of between 7 μm to 20 μm. This size range is typical of the material in the silt fraction, and is appropriate for use in stormwater wetlands.

The following are some brief comments on the likely positive and negative effects on the rate constant as a result of unsteady intermittent inflows:-

- Experience with some data gathered from research projects undertaken by the authors has indicated that the cyclic filling and draining of the wetland can facilitate the adhesion of fine particles on vegetation surfaces leading to a **higher** k_{TSS} value.

- Tracer studies as well as two dimensional hydrodynamic modelling by various researchers have found the flow hydrodynamics within the wetland during its filling and draining stages to be grossly two (or even three) dimensional. The flow of water through densely vegetated sections of the wetland during these phases is envisaged to have a positive effect on trapping suspended solids leading to a **higher** k_{TSS} value than applicable for steady flow systems.

- The vegetation cover reduces the potential for solid resuspension. Data from studies of TSS reduction in ponds and wetlands in Canberra, Australia (ACT Administration Interim Planning Authority, 1990) have shown that a 20% **increase** in TSS removal can be gained by the introduction of macrophytes in a wet detention system.

- The unsteady inflow conditions prevalent in stormwater wetlands would lead to a higher tendency for fine solids to be resuspended in these systems leading to a **lower** k_{TSS} value than applicable to steady flow systems. Solid resuspension is expected to have the highest tendency near the inlet where the inflows have not been subjected to the full effect of storage attenuation. However, proper design of inlet structures as well as vegetation layout can significantly mitigate this condition.

In the interim, it is suggested that the appropriate value of k_{TSS} in stormwater wetland be based on the settling velocity of the 50 percentile sediment grade with adjustments for increased effectiveness for wetlands with high vegetation density to reflect the experience from the Canberra study. This adjustment may be by multiplying k_{TSS} by 1.2 if more than 50% of the wetland area is vegetated with a sliding scale to 1.0 for vegetation density between 50% and zero.

Background Concentration C^*_{TSS}

Background concentration of TSS for a given wetland is a reflection of the characteristics of the substrata of the system and the characteristics of suspended solids generated from the catchment. A single measure using the inflow TSS concentration is insufficient to relate the influence of hydraulic loading, particle size distribution, substrata conditions, biota growth etc on the background TSS concentration. The hydraulic loading and the size grading of the deposited sediment is envisaged to have a direct influence on the amount of solids which can be resuspended and kept in suspension in the water column. The dry period between events also have an influence on the structure of settled particle as well as the development of organic solids.

It is envisaged that background concentrations of TSS will be related to outflow rate as flow velocities within the wetland is considered to be the primary source of energy in the resuspension and maintenance of suspended particles in the water column. It is possible for the relationship between background concentration and flow rate to be derived from the field by regular monitoring of effluent concentrations during low flow conditions. Furthermore, it is possible to conduct simple experiments involving the filling of a wetland (by closure of the outlet structure) and letting the water remain in the wetland for some extended period of time. The wetland is then allowed to drain and TSS concentration determined at a range of outflow rates. These experiments could be carried out for different antecedent conditions related to the duration of the dry period following the last event to account for the effect of this duration on the structure of settled particles and algal growth in the unvegetated areas.

Pollutants Affected by Biological Treatment Processes

A category of pollutants that are influenced by a combination of physical, chemical and biological processes include such pollutants as BOD, COD, TN, TKN, NH_4-N and PO_4. The degree at which one type of process dominates the overall treatment is dependent on various factors related to the characteristics of the pollutant, the chemical and biological state of the wetland etc. It is unlikely that one form of treatment process will completely dominate the system. Discussion below is mainly directed to BOD but may have similar relevance to other pollutants in this category.

Rate Constant k_{BOD}

There is little known about how k_{BOD} can be affected by unsteady intermittent inflows to the wetland. Intuitively, k_{BOD} for stormwater wetlands ought to be **higher** than corresponding values in wastewater wetlands for a number of plausible reasons:-

1. a higher proportion of BOD in particulate form compared to soluble BOD is expected in stormwater runoff and thus a significant amount of BOD reduction may be associated with TSS reduction;

1. the opportunities for the ecosystem to recovery following a period of high BOD loading during the inter-event periods;

1. the unsteady hydrodynamic within the wetland would have a higher DO reaeration potential thus able to satisfy BOD more rapidly.

Background Concentration C^*_{BOD}

Regression analysis of background BOD concentrations by Kadlec and Knight (1996) found a correlation of this parameter with the influent BOD concentration in wastewater wetlands. It is envisaged that intermittent inflow conditions in stormwater wetlands could diminish the dependence of influent BOD concentration and that the background concentration of stormwater wetlands would more reflect the wetland characteristics including its vegetation type(s) and density, and soil type. Kadlec and

Knight (1996) found mean background BOD concentration in marshes to be approximately 6 mg/L and data from a limited number of forested wetlands found significantly lower background BOD concentration. It is envisaged that the background BOD concentration in stormwater wetlands could be **lower** than that observed for marshes.

9.7 HYDROLOGIC EFFECTIVENESS

9.7.1 General

Hydrologic effectiveness of a stormwater detention systems (including constructed wetlands) is a measures first used by Wong and Somes (1995) in quantifying the effects of the interaction between the (i) volume of the detention system; (ii) the hydraulic capacity of the outlet structure of the system; and (iii) the variability of runoff inflow to the system. The use of hydrologic effectiveness as a performance measure (or design criterion) by Wong and Somes (1995) stems from an appreciation that stormwater detention systems are highly dynamic in its hydrological character. The system is subjected to intermittent inflows of stormwater and associated pollutants from surrounding catchments and sizing of detention storages should be based on its long term performance rather than on its performance for a given probabilistic event. As an example, under steady flow conditions, all water entering the detention system will be provide the same period of detention, that defined by the ratio of the effective volume of the system to the steady flow discharge. In an intermittently load system, inflows vary both in magnitude and temporal pattern and special considerations now needs to be given to the effect of storage attenuation, prevention of unacceptably high flow velocities within the wetland and varying periods of detention. The concept of a constant detention period does not apply in stormwater systems.

The effectiveness of stormwater treatment by detention (whether by wetlands or detention basins) is dependent on a number of factors but first and foremost is conditional on the antecedent water level in the detention system as this influence the attenuation of flow entering the wetland system. This consequently influence the detention period of the incoming stormwater and associated pollutants as well as the amount of runoff which will need to be diverted away from the wetland to prevent scouring and remobilisation of deposited particulates. The antecedent water level immediately prior to the occurrence of stormwater inflows to the detention system is dependent on the available detention storage volume, the emptying rate of the detention system and the period between storm events.

9.7.2 Detention Period

The hydrologic effectiveness curves are, in theory, strictly applicable to dry detention systems where the detention periods of inflows are entirely influence by the combined effect of the detention system storage-elevation characteristics and the hydraulic characteristics of the outlet structure. The presence of a permanent pool storage in the detention system will lead to an under-estimation of the likely performance of the detention system. This may be explained by examining the influence of the permanent pool storage on the pollutant detention period.

The pollutant detention time varies in an intermittently loaded wetland and the long term distribution of pollutant detention time is dependent on a number of factors. These include the ratio of the volume of the inflow hydrograph, the shape of the pollutograph in relation to the inflow hydrograph, the storage volume of the permanent pool and the duration of the dry weather period preceding the next storm event. Two general scenarios are possible and they require a different approach towards computing the mean pollutant detention period, ie.

1. if the volumes of the typical inflow hydrographs are generally smaller than the permanent pool volume, a significant portion of the inflow pollutants would be detained in the permanent pool until the occurrence of the next event. Analysis of the sequence of storm events using stochastic simulations will be necessary to computed the combination of storm events and dry periods between events (Wong and Somes, 1995; Somes and Wong, 1997). Under these circumstamces, the wetland system essentially behaves as a pond and the hydrologic effectiveness curves are less relevant to design;

1. if the volume of the permanent pool is small in comparison to the volumes of typical inflow hydrographs, the mean pollutant detention period may be computed by calculating the time difference of the centroids of the inflow and outflow hydrographs, but with the centroid of the outflow hydrograph adjusted for the wetland permanent pool volume deemed to have been discharged at the early stages of the outflow hydrograph. This adjustment would have the effect of shifting the centroid of the outflow hydrograph further away from the centroid of the inflow hydrograph. The influence of the inter-event dry period on the pollutant detention period is generally small and the hydrologic effectiveness curve is most appropriate for design.

9.7.3 Hydrologic Effectiveness Curves

Wong and Somes (1995) undertook continuous simulations of wetland hydrological performance and derived interaction charts for dry detention systems highlighting the inter-relationship between three key parameters, ie.

- the detention period;
- the volume of wetland storage available for detention; and
- the overall percentage of runoff (Hydrologic Effectiveness) which can be expected to be detained at or longer than the desired detention period under intermittent loading conditions.

These three key parameters are interrelated in that for a given size constructed wetland, the Hydrologic Effectiveness varies inversely with the detention period. Figure 9.9 shows the Hydrologic Effectiveness Curves of constructed wetlands derived from continuous simulation with 100 years of rainfall data recorded in Melbourne, Australia. Effectiveness curves shown in Figure 9.9 are unique to the Melbourne region and will be different from one region to another owing to differences in the characteristics in their respective rainfall intensity-frequency-duration relationships, seasonal rainfall distribution, rainfall durations and inter-event dry periods. Wong et al. (1998) presented hydrologic effectiveness curves for all major capital cities in Australia, as typically shown in Figure 9.10 for the 72 hour detention period, to facilitate stormwater wetland design. A similar series of simulations may be carried out for Malaysian conditions using continuous rainfall records. As a guide, the monthly statistics of rainfall conditions for the Australian and New Zealand capital cities are listed in Tables 9.5 to 9.7.

From consideration of the likely seasonal effect on rainfall patterns in Malaysian condition, it is recommended that the hydrologic effectiveness curves for the city of Brisbane is most suited for use in the Putrajaya project in the absence of any other information. Figure 9.11 shows the hydrologic effectiveness curves recommended for use in Malaysian catchments in the interim.

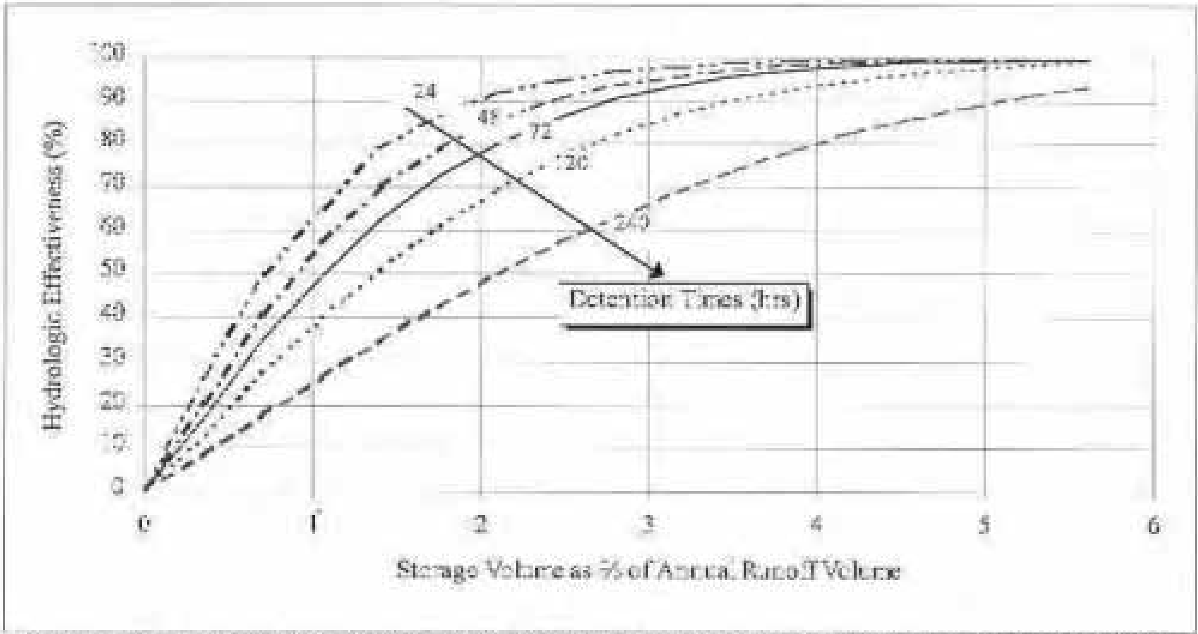

Figure 9.9 Hydrologic Effectiveness of Wetlands in Melbourne (ref. Wong & Somes, 1995)

Taking the hydrologic effectiveness curves for the city of Auckland as an example, comparison of the hydrologic effectiveness against wetland area (as % of the catchment area) amongst the capital cities places the Auckland region in the same group as Perth eventhough the annual rainfall of the Auckland is almost twice that of Perth. If design curves regionalisation were to be based on annual rainfall, the Auckland region would have been grouped with Sydney, Darwin and Brisbane. As shown in Figure 9.12, all of the three cities mentioned were found to exhibit lower hydrologic effectiveness for the same wetland area compared to Auckland. This is due to lower variability in rainfall and shorter inter-event period in the Auckland region compared to these capital cities.

If design curves regionalisation were to be based on the degree of variability of rainfall characteristics over the year, the Auckland region would be grouped with Hobart and Melbourne, but both these cities were found to yield higher hydrologic effectiveness for a given wetland area. This is due to the significantly higher annual rainfall in Auckland compared to these two cities. This highlights the potential problem with current guidelines on wetland area (as % of catchment area) based on overseas data which are used directly for local conditions without adjustments or when adjustments are made only for differences in the mean annual rainfall.

9.7.4 Selection of Probabilistic Design Event

As there is no hydrologic effectiveness curves derived for Malaysian catchment, an alternative to the use of the Brisbane curves suggested in the previous section is the design of stormwater wetlands in Malaysia based on a probabilistic event. The selection of the 1 year ARI event appears to be the most commonly adopted probabilistic event overseas and is recommended. The recommended storm duration to compute the runoff volume is 24 hours.

Table 9.5
Rainfall Statistics – Inter-event Dry Period (hrs)

Cities	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Auckland	59.7	64.2	53.1	42.1	33.6	28.6	29.5	29.2	34.7	37.0	45.8	52.1	40
Adelnide	165.9	189.4	156.5	94.8	61.1	51.16	44.0	44.5	54.9	69.6	94.0	129.0	77
Brisbane	65.4	57.3	58.1	74.5	93.7	111.0	133.9	141.2	126.2	90.9	81.9	72.4	88
Darwin	33.0	32.1	41.4	116.1	130.3	561.1	417.0	240.4	217.4	120.8	62.2	58.7	94
Hobart	72.3	83.3	74.8	60.9	56.2	50.7	47.9	46.9	50.5	47.3	49.0	59.9	57
Melbourne	97.4	107.6	89.6	66.7	55.2	49.5	49.6	45.0	50.6	53.4	65.3	75.3	62
Perth	250.7	238.3	200.5	89.2	58.0	39.9	39.9	53.8	62.2	88.2	142.0	193.2	87
Sydney	70.3	64.7	66.6	69.3	70.2	73.4	91.5	98.5	97.8	77.9	68.9	76.3	75

Table 9.6
Rainfall Statistics – Mean Storm Duration (hrs)

Cities	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Auckland	6.05	7.20	7.15	8.49	9.02	10.00	10.00	10.60	9.35	7.42	7.45	8.72	8.7
Adelaide	9.88	10.42	11.13	11.60	12.72	11.75	11.74	10.84	11.83	10.74	9.67	8.50	11.2
Brisbane	11.68	12.83	13.30	12.40	12.81	14.31	13.56	9.90	9.48	9.37	9.07	8.50	11.0
Darwin	10.88	11.47	9.46	8.10	11.85	15.06	22.8	9.51	11.58	7.48	9.70	7.87	9.5
Hobart	9.47	11.40	11.53	13.06	14.06	17.10	16.93	14.35	12.29	11.91	11.60	11.79	13.1
Melbourne	9.21	9.47	9.44	9.54	10.29	10.56	9.50	8.48	8.50	8.84	9.61	8.95	9.4
Perth	9.6	12.68	14.12	13.72	16.81	17.35	19.76	18.00	14.07	15.11	12.22	10.32	16.1
Sydney	11.05	11.41	12.18	13.80	13.55	16.20	13.38	13.00	11.05	11.35	10.68	11.48	12.4

Table 9.7
Rainfall Statistics – Mean Rainfalls (mm)

Cities	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Auckland	68.2	82.6	93.9	113.6	129.1	144.9	150.0	136.2	112.3	106.8	95.9	99.1	1333
Adelaide	20.0	20.7	24.0	44.3	68.2	71.7	66.5	61.5	51.1	44.5	30.7	26.3	530
Brisbane	159.6	158.3	140.7	92.5	73.7	67.8	56.5	45.9	45.7	73.4	97.0	133.3	1146
Darwin	393.2	329.7	258.3	102.6	14.3	3.0	1.3	1.6	12.8	52.1	124.0	241.8	1535
Hobart	48.3	39.8	45.7	52.9	47.9	54.8	53.8	52.8	51.7	62.8	54.8	58.2	624
Melbourne	49.0	47.7	51.8	58.4	57.2	50.2	48.7	50.6	59.4	67.7	60.2	59.9	661
Perth	7.8	12.1	17.4	50.3	110.8	186.8	170.3	114.3	70.3	49.2	19.4	12.6	821
Sydney	103.0	117.1	133.7	126.6	120.4	131.7	98.2	79.8	69.9	77.5	83.1	79.6	1220

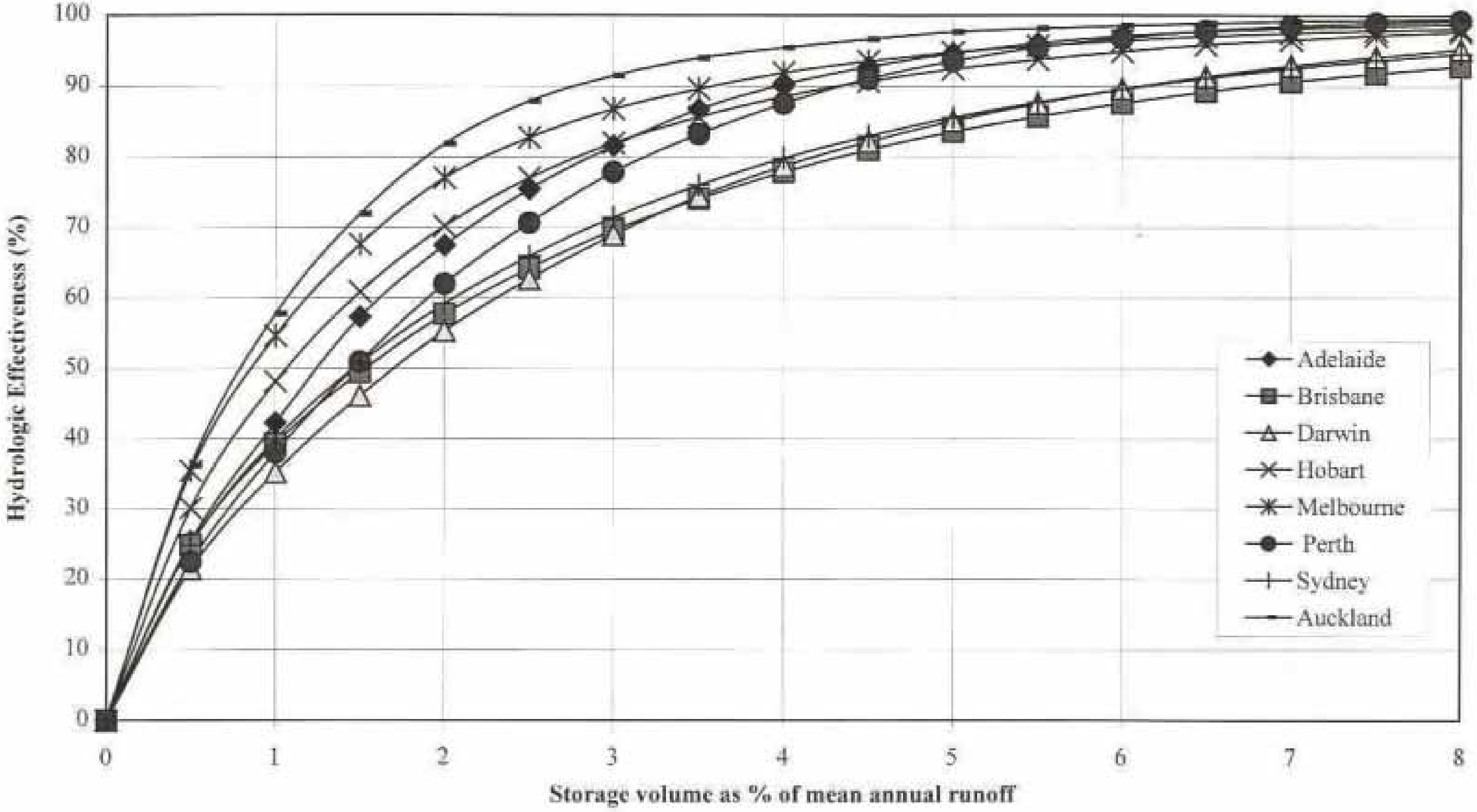

Figure 9.10 Hydrologic Effectiveness (72 hrs detention) - Australian and New Zealand Capital Cities

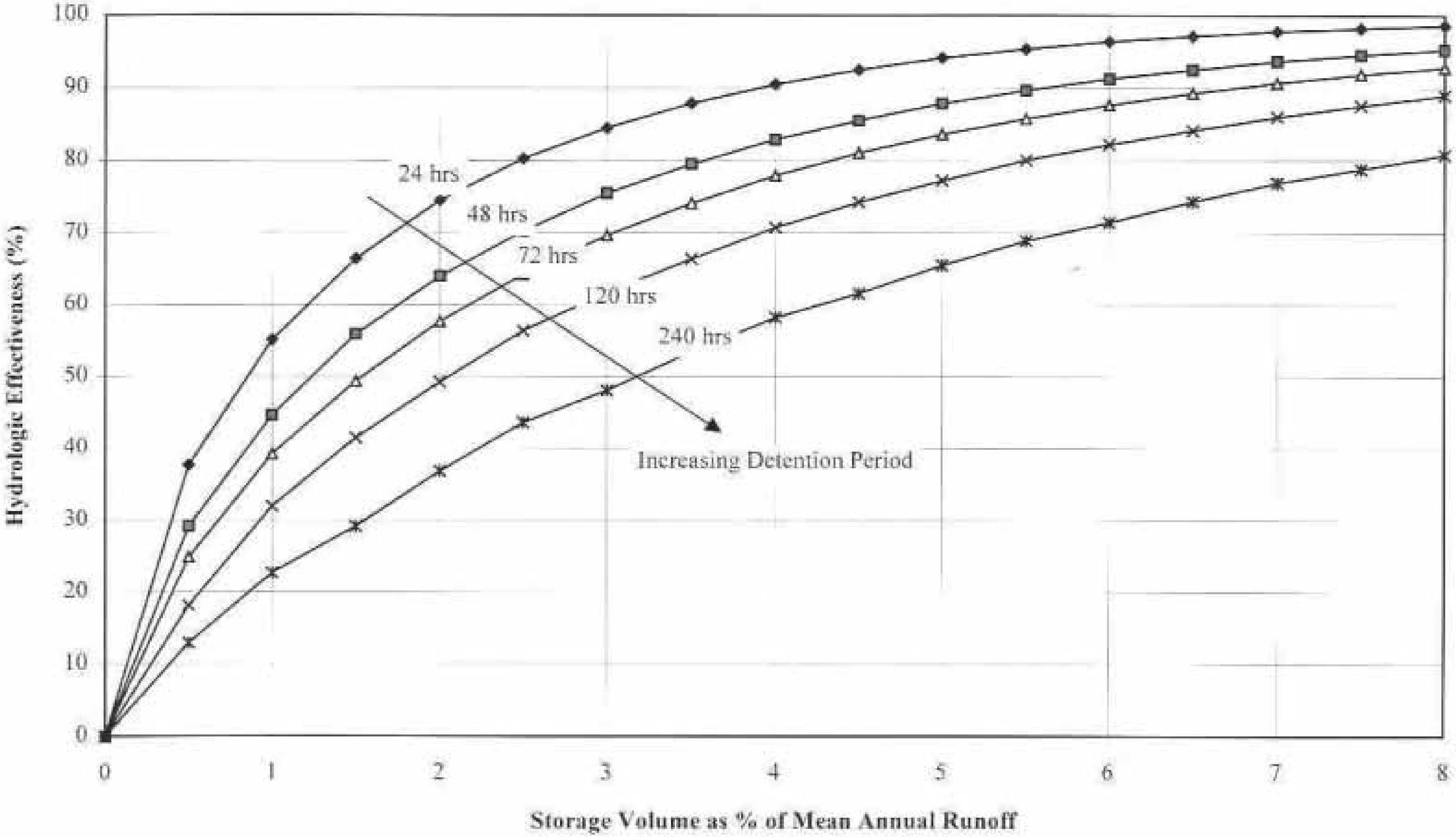

Figure 9.11 Interim Hydrologic Effectiveness Curves for Malaysian Cities

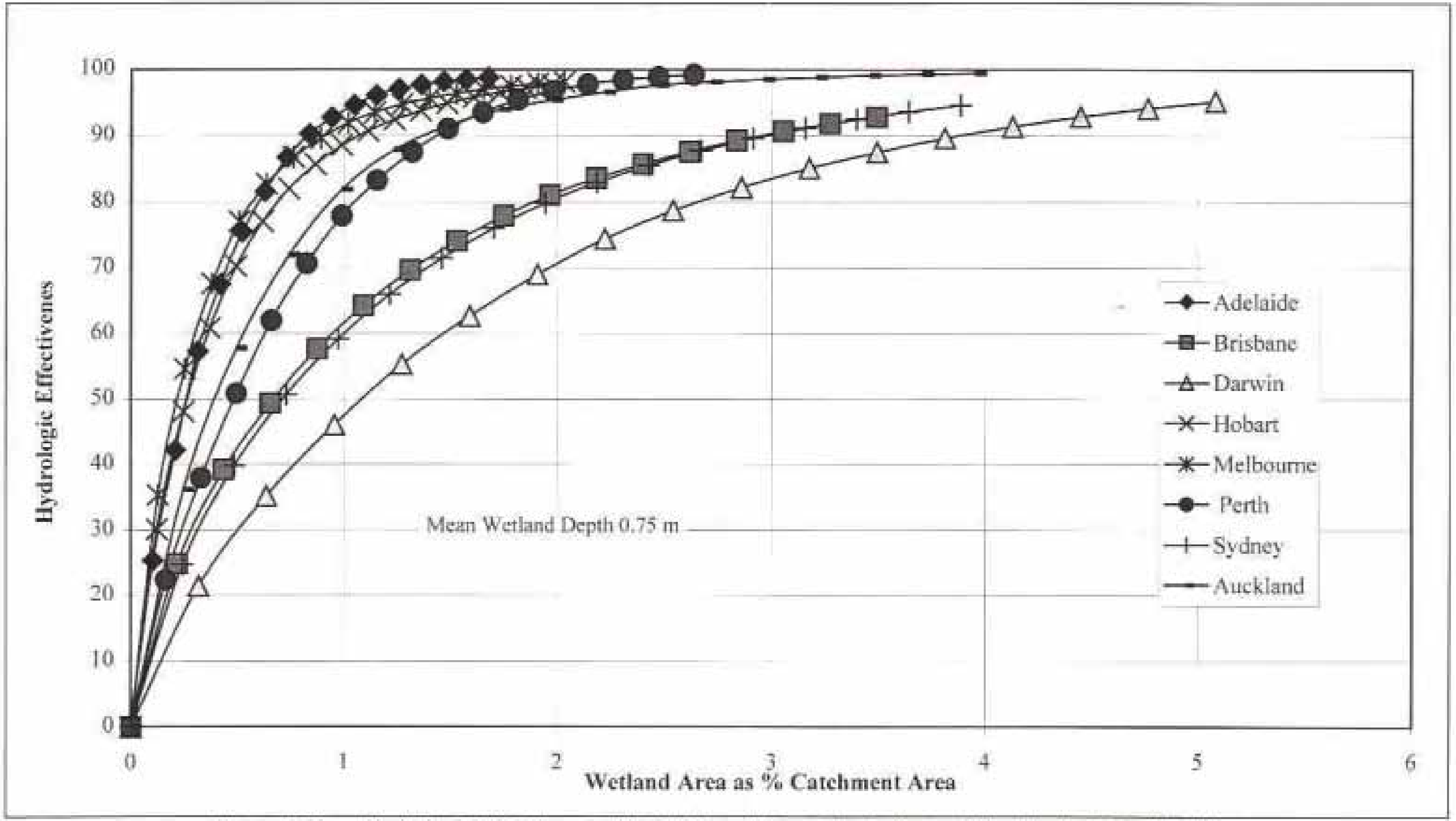

Figure 9.12 Hydrologic Effectiveness Vs Catchment Area - Australian and New Zealand Capital Cities

9.8 HYDRAULIC EFFICIENCY AND OPTIMISING TREATMENT PROCESSES

9.8.1 General

Optimisation of treatment processes involves inputs from ecologist, aquatic chemist, hydrologist and hydraulic engineers. There is a significant amount of on-going research aimed at developing definitive guidelines (such as that currently available for hydrologic effectiveness of constructed wetlands). This section of the guideline document highlights the range of issues requiring consideration to promote hydraulic efficiency and facilitate optimal stormwater treatment processes.

Hydraulic efficiency involves the proper control of flow patterns within the constructed wetland such that flow is uniformly distributed throughout the constructed wetland and thus providing optimal treatment of the inflow.

9.8.2 Control of Flow Distribution

In natural wetlands, vegetation structure can be related to functional processes associated with energy dissipation, flow distribution, sedimentation and filtration. In order to maximise wetland treatment performance in runoff control systems it is necessary to create in these systems the vegetation zones associated with the desired functions. The plants in these zones need to have suitable morphologies in order to enhance the physical processes as well as being ecologically adapted to the water regime. Table 9.8 summarises the characteristics of five typical wetland zones that commonly occur in natural wetlands and which can be incorporated into constructed wetland design. Under ideal conditions it would be better to arrange these wetland zones in series across the notional flow path as shown in Figure 9.13. Topography frequently interferes, and therefore most systems need to be individually designed to accommodate the particular topography of the local drainage system.

The purpose of the hydraulic design is to create a well vegetated flow path, with a high diversity of plant surfaces to enhance particle sedimentation and filtration, while optimising detention time and minimising short-circuiting.

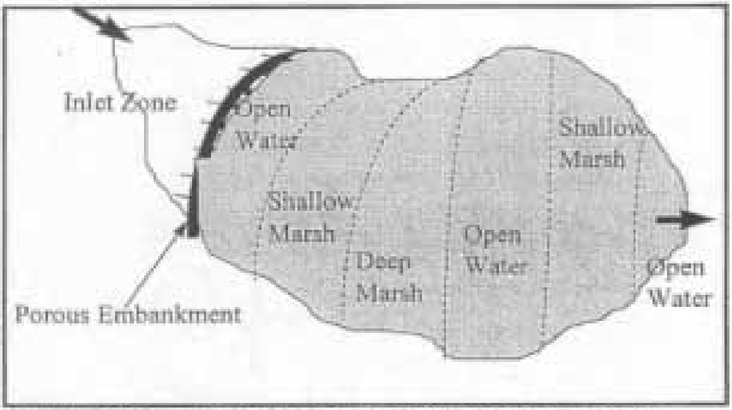

Figure 9.13 **Notional Layout of Vegetation Zones for Optimal Flow Distribution**

9.8.3 Control of Detention Time

Many other designs are also used, the particular type dependent on location and performance requirements (Goldman et al, 1986, Schueler, 1987). When water levels are below the top of the riser the wetland is drained by the smaller orifices distributed along the riser. When the water levels are above the top of the riser, water is also drained via the larger glory hole orifice. The sizing and number of the orifices in the extended detention storage depends on the retention time and drawdown characteristics desired for the storage.

Table 9.8
Wetland zones, species and functional processes (Somes et al., 1996)

Ephemeral Swamp
Typical Ecological Characteristics ***Dominant species***: eg. *Eucalyptus, Melaleuca, Poa, Juncus* ; ***Vegetation***: 2m woodland overstorey, low-high density open-closed canopy, ~0.5m low-high density grassland-rushland groundcover **Typical Physical Characteristics** ***Surface area : volume ratio***: high (when inundated); ***Water depth***: ~0.1-0.2m; ***Natural water regime***: ephemeral (mostly dry, occasional irregular inundation cycle) **Potential Treatment Processes and Mechanisms** ***Solids removal***: sedimentation and filtration (particularly of fine particles); ***Mineralisation***: microbial growth, enhanced by wetting and drying; ***Nutrient uptake and transformation***: microbial and macrophyte growth; ***Nutrient storage***: sediment adsorption
Shallow Marsh
Typical Ecological Characteristics ***Dominant species***: eg. *Eleocharis acuta* (Common Spike-rush) ; ***Vegetation***: 0.3-0.7m, low-medium density open canopy, typically supports epiphytic algae on submerged culms **Typical Physical Characteristics** ***Surface area : volume ratio***: high; ***Water depth***: ~0.1-0.2m; ***Natural water regime***: ephemeral (regular seasonal dry cycle) **Potential Treatment Processes and Mechanisms** ***Aeration***: surface exchange and epiphytic photosynthesis; ***Solids removal***: filtration (surface adhesion); ***Mineralisation***: microbial growth, enhanced by wetting and drying; ***Nutrient uptake and transformation***: microbial, epiphyte and macrophyte growth; ***Nutrient storage***: sediment adsorption
Marsh
Typical Ecological Characteristics ***Dominant species***: eg. *Bolboschoenus medianus* (Marsh Club-rush) ; ***Vegetation***: 0.5-1.5m high, high density closed canopy, high litter production **Typical Physical Characteristics** ***Surface area : volume ratio*** :medium-high; ***Water depth***: ~0.3m; ***Natural water regime***: ephemeral (occasional-regular dry cycle) **Potential Treatment Processes and Mechanisms** ***Solids removal***: sedimentation and filtration; ***Mineralisation***: microbial growth; ***Nutrient uptake and transformation***: microbial and macrophyte growth; ***Nutrient storage***: sediment adsorption and litter accumulation
Deep Marsh
Typical Ecological Characteristics ***Dominant species***: eg. *Schoenoplectus validus* (River Club-rush) ; ***Vegetation***: 1-2m, medium-dense semi-closed canopy, supporting some epiphytic algae, moderate litter production **Typical Physical Characteristics** ***Surface area : volume ratio***: medium; ***Water depth:*** ~0.4-0.6m; ***Natural water regime***: permanent (occasional irregular dry cycle) **Potential Treatment Processes and Mechanisms** ***Solids removal***: sedimentation and filtration; ***Mineralisation***: microbial growth; ***Nutrient uptake and transformation***: microbial, epiphyte and macrophyte growth; ***Nutrient storage***: sediment adsorption and litter accumulation
Open Water
Typical Ecological Characteristics ***Dominant species***: algae (or submerged macrophytes in low nutrient conditions) ; ***Vegetation***: phytoplankton growth resulting in secondary solids production, (macrophyte growth inhibiting mixing and removing solids by sedimentation and filtration) **Typical Physical Characteristics** ***Surface area : volume ratio***: low; ***Water depth***: 1m; ***Natural water regime***: permanent, generally well mixed but may stratify during still conditions, particularly in the warmer months **Potential Treatment Processes and Mechanisms** ***Solids removal***: sedimentation (and filtration); ***Aeration***: wind mixing, algal photosynthesis; ***Sterilisation***: UV exposure***; Nutrient uptake and transformation***: phytoplankton and submerged macrophyte growth; ***Nutrient storage***: sediment adsorption and accumulation

Typically, under a single orifice outlet, the discharge condition is that of weir flow initially until the depth of inundation exceeds the soffit level of the orifice at which point flow condition is that of orifice flow. The form of the storage-discharge relationship is non-linear and thus the detention period-discharge relationship can also be expected to be non-linear. Generally this is an undesirable form of the detention period-discharge relationship as the detention period during low discharges are often low owing to the more efficient discharge characteristics at low levels of inundation. Riser outlets involve a number of small orifices and experience with riser discharge characteristics indicates that near constant detention period for the full depth range of the wetland (ie. a near constant ratio of storage volume to discharge) can be readily established by appropriate placement of orifices along the riser.

9.8.4 Permanent Pool

The extent in which the permanent pool accounts for the detention storage of the wetland storage has a significant influence on the performance of the wetland system. It is well established that systems with a higher amount of its storage being in the permanent pool will provide a longer pollutant detention period. The detention period being a function of the inflow rate, the inflow volume and the period between storm events. There are however a number of disadvantages in maintaining a high proportion of the detention storage as the permanent pool. As illustrated in Figure 9.14, increasing the percentage of the storage associated with the permanent pool will lead to decreasing attenuation capability of the detention storage as well as decreasing vegetation density in the system. With a high percentage of the storage as permanent pool, the wetland system essentially becomes a pond with fringing vegetation.

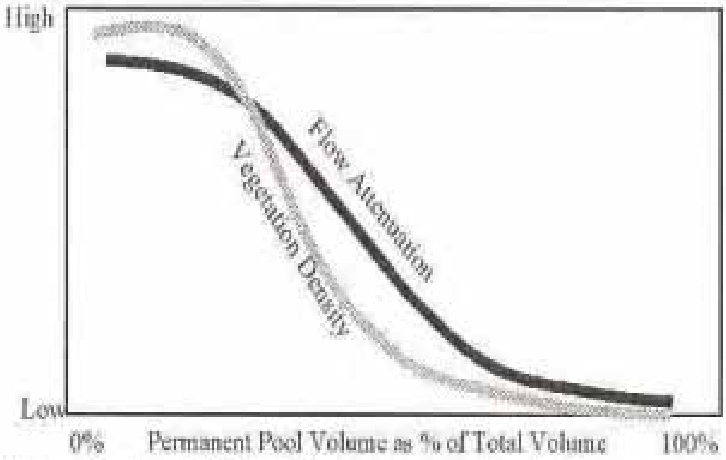

Figure 9.14 **Effect of the permanent pool storage on flow attenuation and vegetation density**

Flow patterns in a system with a large permanent pool system have also been found to be generally less efficient with a highly likelihood of short-circuit flow paths. The resulting HRT distribution function of a pond system often exhibit a lower kurtosis compared to the HRT distribution of a macrphytes zone. This was illustrated by Walker (1996) as shown in Figures 9.15 and 9.16. The two figures show the flow pattern in a wetland during its filling stage and when full. The wetland outlet hydraulics are controlled by a weir structure such that at the filling stage, the inflow was distributed to all areas within the wetland. When full, Walker found that a dominant flow path exist (as shown in Figure 9.16) which is expected to significantly reduce the pollutant detention period.

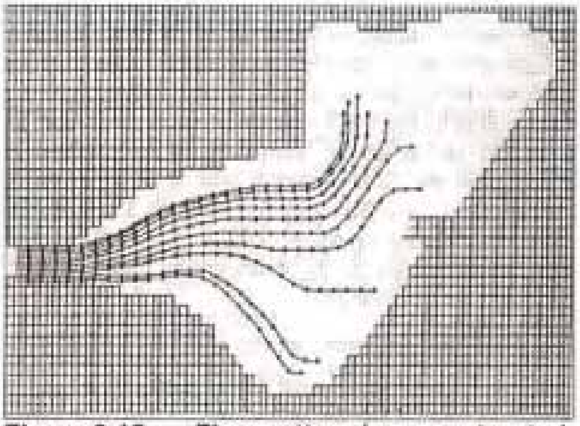

Figure 9.15 Flow pattern in a constructed wetland when filling (Walker, 1996)

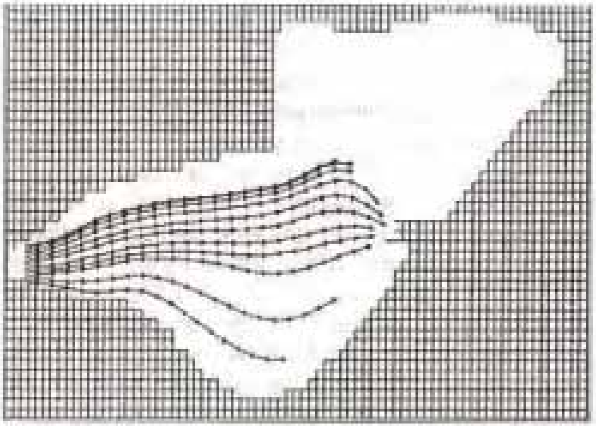

Figure 9.16 Flow pattern in a constructed wetland under full storage conditions (Walker, 1996)

9.8.5 Control of Hydrologic Regime

In relation to the botanical design of the wetland, the probabilistic distribution of water levels influences the sustainability and positioning of different species of plants within wetland vegetation. The probabilistic distribution of water levels is referred to as the hydrologic regime. The interaction between hydrological and botanical issues in designing a constructed wetland for stormwater management needs to be clearly appreciated by designers to ensure a ecologically sustainable wetland system.

The composition and distribution of wetland vegetation is essentially controlled by the wetland morphology and system hydrology. The hydraulic characteristics of the inlet and outlet structures define the range of water depths in the wetland. Water depth is a fundamental factor controlling the distribution of aquatic plants. In correctly designed wetlands vegetation is positioned to maximise treatment processes by taking advantage of the physical characteristics of the plants to control flow and stabilise bottom sediments. Plants have intrinsic preference to grow in conditions ranging from permanently wet to highly ephemeral (Somes et al, 1995). The locations within a wetland that are best suited to specific wetland plants is determined by the hydrologic regime. Individual species differ in their ability to grow in wet conditions, often resulting in a zonation of species along wetness gradients (see Table 9.8).

Weirs are not considered to be suitable as the primary control of the hydrologic regime of wetlands due to its inability to promote a wide range of water level fluctuation in the wetland. Orifice outlets can also lead to poor probabilistic distribution of water levels and consequently may not suitable for sustaining a wide variety of wetland vegetation. This is demonstrated by Somes et al. (1996) in a case study of the hydrologic regime for a typical constructed wetland in Melbourne controlled by an orifice outlet. Figure 9.17 presents the result of that study and clearly shows that there is a significant period of time in which water depth in the constructed wetland is between 0 and 0.2 m. This indicates that the system is highly ephemeral. This hydrologic regime will result in low vegetation diversity with deep marsh species occurring below 0.2 m and ephemeral swamp species above. The sharpness of the boundary between vegetation zones is essentially determined by the slope of the wetness gradient. Vegetation on steep slopes with good drainage will develop distinct boundaries.

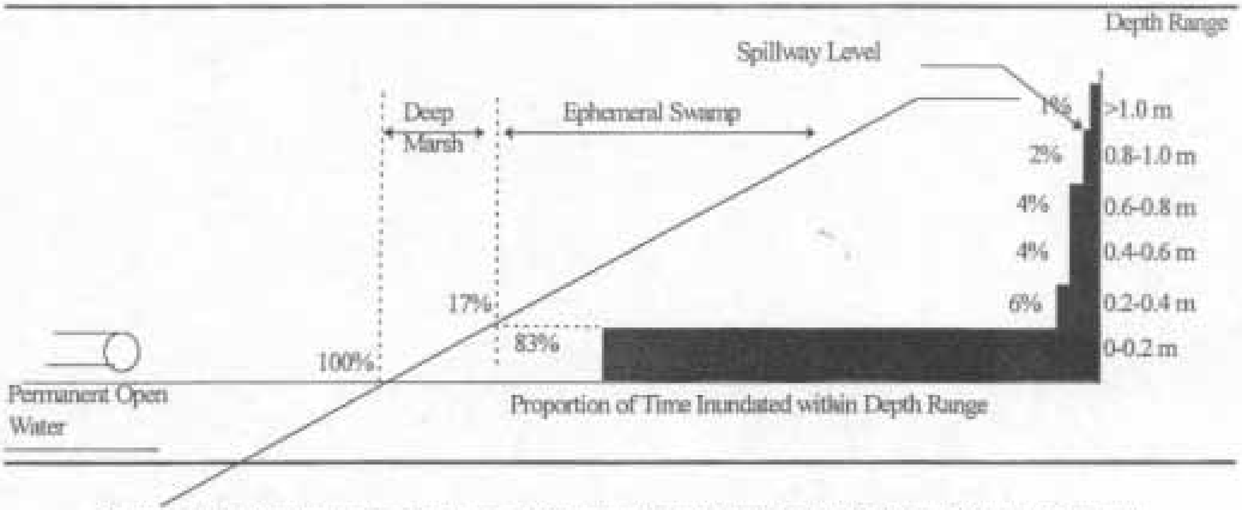

Figure 9.17 Hydrologic Regime of Constructed Wetland with Riser Outlet Control

It is evident that for a given detention period, increasing the wetland size would increase its hydrologic effectiveness but the consequence of this is a corresponding decrease in the even probabilistic distribution of water levels. Similarly, for a given size wetland, a reduction of the wetland's minimum detention period would have the same effect. This may have important implications in sustaining the desired diversity in wetland habitats. For example, a draw down period of 72 hours would provide 93% hydrologic effectiveness (see Figure 9.9) if the wetland volume equals approximately 3% of the average annual runoff volume. Table 9.9 lists the frequency at which water depth in the constructed wetland falls within specified depth range expressed as percentage of the full depth of the wetland.

Table 9.9
Probabilistic Distribution of Water Depth
(Typical Constructed Wetland in Melbourne; Volume = 3% of Mean Annual Runoff)

Depth Range (% of Full Depth)	Prescribed Detention Period				
	24 hours	48 hours	72 hours	120 hours	240 hours
0% - 20%	95%	88%	81%	70%	49%
20% - 40%	2.3%	4.4%	5.9%	7.4%	8.2%
40% - 60%	1.3%	3.1%	5.0%	7.4%	9.4%
60% - 80%	0.77%	2.4%	4.0%	7.2%	12%
80% - 100%	0.38%	1.4%	2.9%	6.5%	17%
Spill	0.25%	0.7%	1.2%	1.5%	4.4%

As evident from Table 9.9, water depth was found to be below 20% of the full depth for 81% of the time for a 72 hours prescribed detention period. It may be more appropriate to adopt a longer prescribed detention period in an attempt to achieve a higher frequency of water depth above 20% of the full depth and compromise for a lower hydrologic effectiveness. If the outlet were to be designed to draw down the wetland over 120 hours, its hydrologic effectiveness would reduce from 93% to 85% (Figure 9.9). This would in-turn reduce the periods at which the wetland would be below 20% of its full depth from 81% to 70% resulting in a more "hydrologically balanced" system. For a 240 hours prescribed detention period, the corresponding hydrologic effectiveness is 70% and the period of time water depth is below 20% of full depth is 49%.

The possible use of a combination of a siphon and glory hole spillway in wetland drainage was investigated by Somes and Wong (1996). This system of outlet control was found to be of some advantage as they operate only once the siphon has been primed, allowing several smaller events to be detained for extended periods as the water level rises. Once initiated they operate at near constant discharge until air entrainment occurs. Figures 9.18 and 9.19 show the improved hydrologic regimes due to the used of a combined siphon and glory hole spillway system.

Compared to the orifice outlet described in Figure 9.17, the hydrologic regime for a system with a siphon outlet placed at 0.4 m (Figure 9.18) shows an increase in the frequency of inundation at water depths in the 0.2 m to 0.4 m range from 6% to 29%. As a result shallow marsh type vegetation could be expected to develop in this zone. While this outlet option has increased vegetation diversity much of the basin remains either wet or dry for much of the time. A further improvement to the hydrologic regime is evident from Figure 9.19 for the case of a siphon outlet placed at 0.6 m.

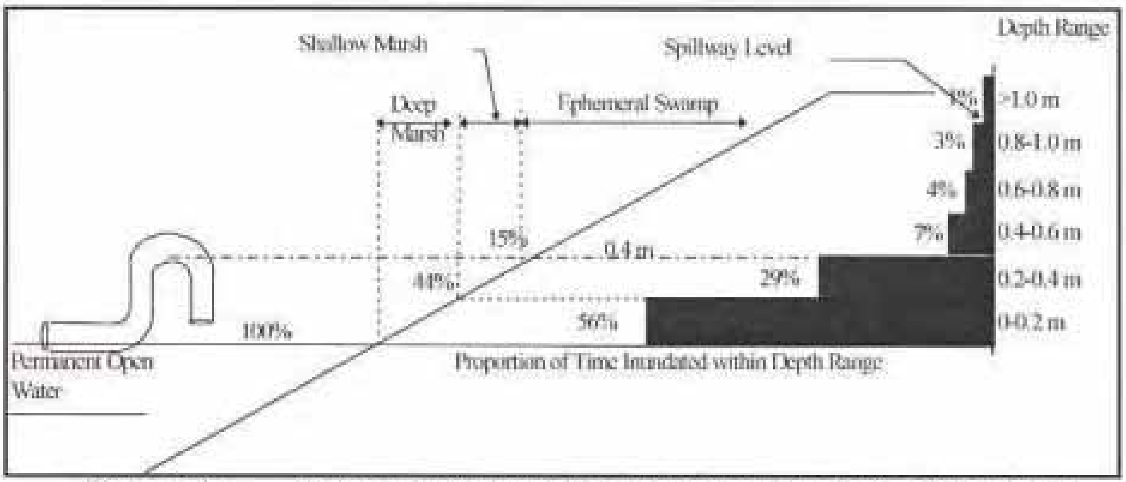

Figure 9.18 Hydrologic Regime of Constructed Wetland with Siphon/Glory Hole Spillway Outlet Control - Siphon at 0.4 m depth

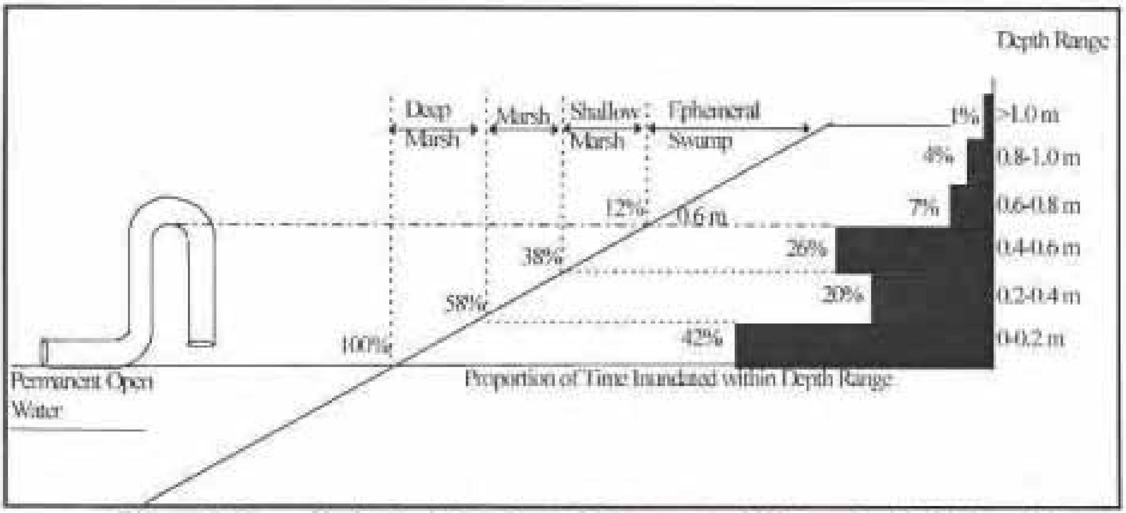

Figure 9.19 Hydrologic Regime of Constructed Wetland with Siphon/Glory Hole Spillway Outlet Control - Siphon at 0.6 m depth