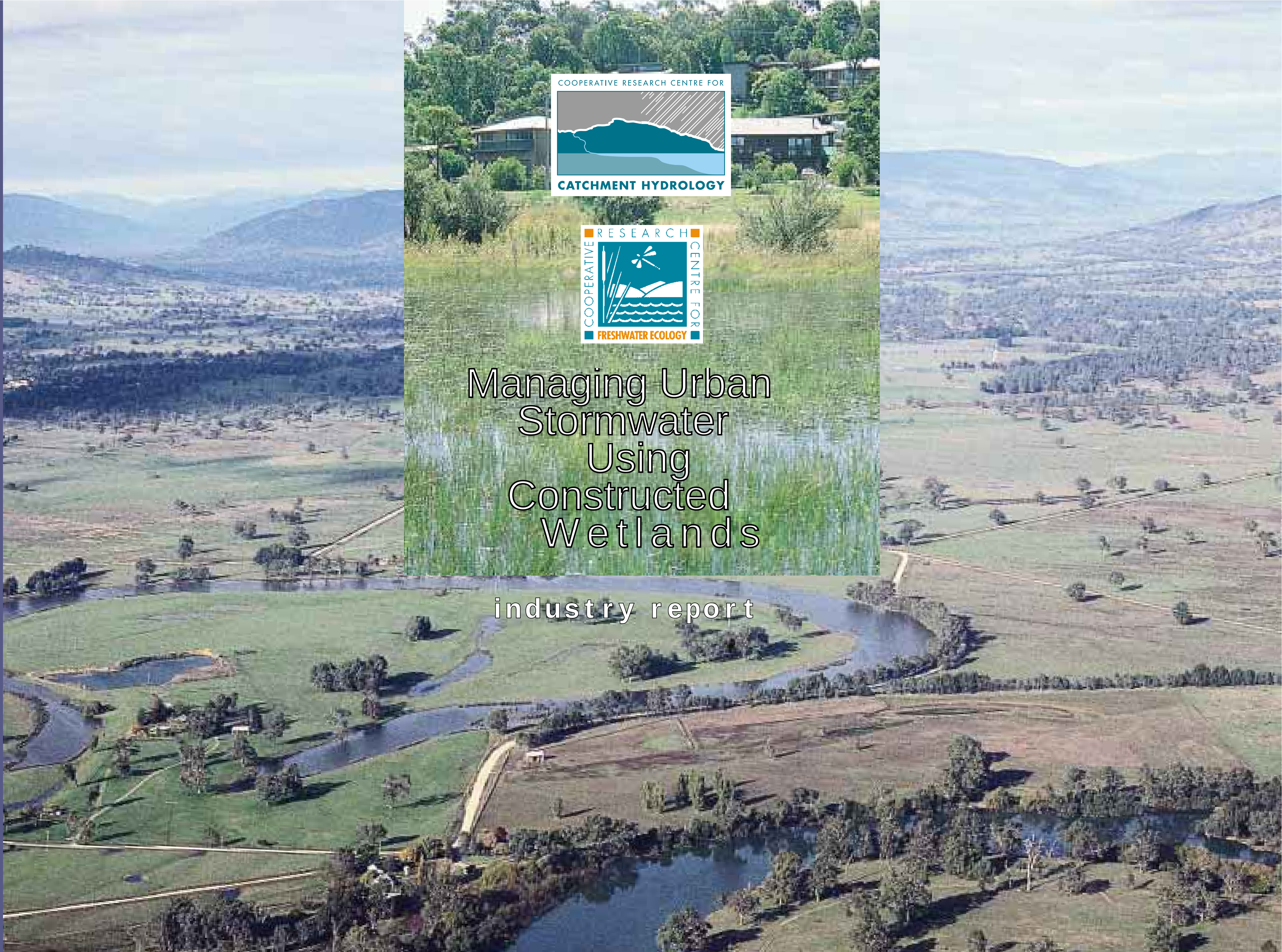

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

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FRESHWATER ECOLOGY

Managing Urban Stormwater Using Constructed Wetlands

industry report

Managing Urban Stormwater Using Constructed Wetlands

by

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Industry Report

Report 98/7

Second Edition

September 1999

Wong, T.
Managing urban stormwater using constructed wetlands

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ISBN 1 876006 36 6

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628.3

Keywords:

Stormwater Management
Urban Design
Wetlands
Ponds
Land Use Planning
Hydrodynamics
Macrophytes
Stormwater Treatment
Modelling (Hydrological)

First published November 1998.
Second edition published September 1999.

Background cover photo: Aerial view of Murray River billabong near Albury, NSW.

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Photographs were provided by:
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- Phillip Scanlon
- Ian Rutherfurd

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Foreword

This Industry Report is one of a series prepared by the Cooperative Research Centre (CRC) for Catchment Hydrology to help provide agencies and consultants in the Australian land and water industry with improved ways of managing catchments.

Through this series of reports and other forms of technology transfer, industry is now able to benefit from the Centre's high-quality, comprehensive research on salinity, forest hydrology, waterway management, urban hydrology and flood hydrology.

This particular Report represents a major collaboration between the CRC for Catchment Hydrology and the CRC for Freshwater Ecology, and presents key findings from a number of wetland research projects. (More detailed explanations and research findings from these projects can be found in a separate series of Research Reports and Working Documents published by the two Centres.) This second edition includes a new section, Appendix A, which answers a number of common questions on the use of constructed wetlands in stormwater management.

The CRC welcomes feedback on the work reported here, and is keen to discuss opportunities for further collaboration with industry to expedite the process of getting research outcomes into practice.

Russell Mein

Director, CRC for Catchment Hydrology

P r e f a c e

This report presents an overview of design and management issues related to the use of constructed wetlands in managing urban stormwater. Stormwater treatment using constructed wetlands involves a combination of physical, chemical and biological processes, and the design of sustainable constructed wetlands must involve the integration of hydrological, hydraulics and botanical design considerations.

This report is also the result of cooperative research between the CRC for Catchment Hydrology and the CRC for Freshwater Ecology, involving a program of field and laboratory studies and computer modelling. The authors of this report are the principal researchers of this program. However, there were many colleagues who assisted in developing and refining our ideas, provided assistance, and contributed to the progress of the research program.

ACKNOWLEDGMENTS

Research studies involving field investigation are expensive, and funding support from various organisations was instrumental to the success of the research. The following organisations and individuals provided significant support for our research:

- Department of Civil Engineering, Monash University (funded instrumentation of the Monash University Research Wetland)
- Faculty of Engineering, Monash University (funded instrumentation of the Monash University Research Wetland)
- Candowie/Lance Creek Catchment Management Group (funded construction of the Monash University Research Wetland and water quality analysis)
- Mr Mort Stuchbery (provided land for the construction of the Monash University Research Wetland)
- Water Studies Centre, Monash University (water quality analysis)
- Dr Julius Fabian, Mr Warwick Bishop and Mr Richard Wootton (development of theoretical work)

Contents

Constructed wetlands – a sustainable natural system for stormwater treatment

Constructed wetlands and ponds – Background to terms used

Wetland is a generic term used to describe 'wet land' – marsh and swamp environments in which emergent macrophytes such as rushes, reeds and sedges are the dominant feature. Swamp environments are typically distinguished by the presence of woody vegetation, and marsh environments by herbaceous vegetation.

Wetlands are characteristically shallow (less than 2 m deep) environments that represent the interface between permanent water bodies and the land environment. They usually have fluctuating water levels, and a regular-to-very-erratic drying cycle. While wetlands may also contain pockets of deeper permanent water, their characteristic feature is the presence of emergent macrophytes, (large aquatic plants whose parts protrude above the waterline). Epiphytes (algae growing on the surface of aquatic macrophytes) are often associated with macrophytes in wetlands.

Pond is a term generally used to describe a small artificial body of open water, such as a dam or small lake. The pond edge may be fringed with emergent macrophytes. While submerged macrophytes may occur throughout the water column, the dominant feature is open water. Compared with wetlands, ponds are usually more permanent, deeper water bodies with narrow, steep edges.

Constructed wetlands may contain marsh, swamp and pond elements. The inlet zone of a constructed wetland may, for instance, resemble a pond, but the dominant feature of the system is the macrophyte zone, containing emergent vegetation that requires or can withstand wetting and drying cycles.

Many definitions of wetland exist in the scientific literature; the term has also been used to describe a broader range of aquatic environments than those suggested here. Environments ranging from intertidal rocky shores to rivers have been referred to as wetlands. Similarly, some parts of the stormwater management industry refer to the whole system of gross pollutant trap, marshland, pond and urban forest as a constructed wetland. While good stormwater solutions may involve integrating many of these features to achieve a range of functions, their combined solution is more than a constructed wetland.

We believe it is more accurate and less confusing, both in general communications and in technical design, if the term wetland is restricted to those environments it best describes – natural or constructed marsh – and swamp-type environments.

Urban wetlands in suburban Melbourne are often incorporated into a system of stormwater and urban design features for flood retardation, landscaping and passive recreation

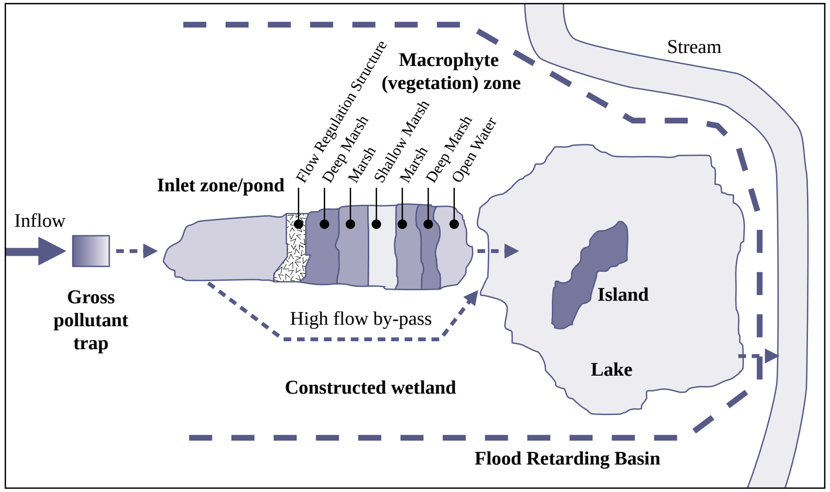


Figure 1: Modular elements in an integrated stormwater management system

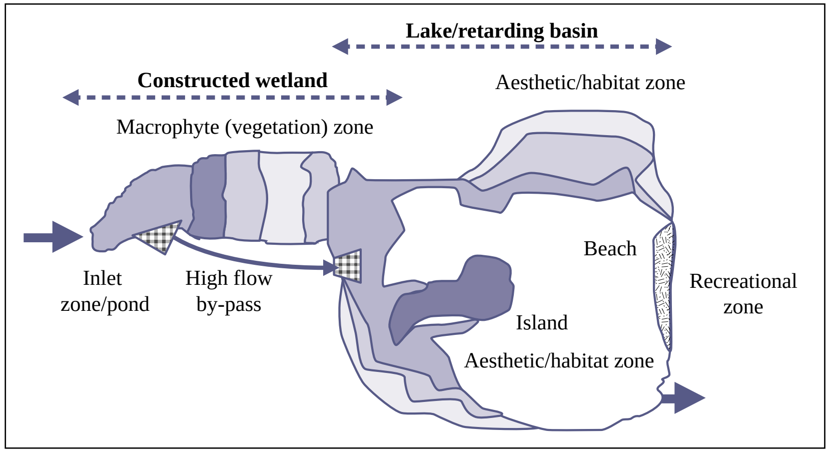


Figure 2: Integration of modular stormwater elements can lead to optimal utilisation of available open space

INTRODUCTION

Growing public awareness of environmental issues has highlighted the importance of urban stormwater management. Urban stormwater contains a range of pollutants, from gross pollutants, to trace metals and nutrients associated with fine sediment, to dissolved pollutants.

Structural and non-structural stormwater management measures often need to be combined to control the hydrology of urban runoff and to remove stormwater pollutants. One group of stormwater management measures that has proved effective in removing stormwater pollutants associated with fine particulates – such as suspended solids, nutrients and toxicants – is constructed wetlands and ponds.

Constructed wetlands also satisfy urban design objectives, such as providing passive recreational and landscape value, wildlife habitat, flood control and control of the physical changes in a stream due to urban development. Catchment managers may integrate urban design elements to promote these objectives. Often the area of land required for such an integrated, urbanised stormwater system is significantly less than the sum of the land areas required to meet individual design objectives.

Early identification of multiple-use priorities is critical for the design process and for the planning of future system maintenance requirements. The management of open space around constructed stormwater wetlands is often directed towards finding an effective balance between pollution abatement and landscape, botanical and habitat functions.

Urban wetlands are becoming part of the urban landscape. This report focuses on issues surrounding the design and management of the constructed wetland component of stormwater management systems.

INTEGRATING CONSTRUCTED WETLANDS WITH STORMWATER MANAGEMENT

Stormwater management is a subset of land use planning and urban design. Both exercises must be coordinated and consider the downstream impact of urban development, with respect to water use and management and aquatic ecosystem conservation. Stormwater management involves the use of many devices and techniques with a range of purposes and benefits, including:

- flood protection and flow control
- water quality improvement
- landscape and recreational amenity
- provision of wildlife habitat

Figure 1 illustrates the modular nature of a typical stormwater management system. While these elements are modular, their sequence within the stormwater management system ensures that the primary function of each is sustainable. For example, stormwater quality treatment elements are often essential to achieve other stormwater management benefits such as landscape aesthetics, recreational amenity and sustainable wildlife habitat. Consequently, some stormwater management benefits may not be achieved without the presence of particular modules in the treatment sequence.

A typical stormwater management system includes:

- Gross pollutant trap (GPT) – to trap artificial and natural litter and coarse particles like gravel and sand.
- Pollution control pond/constructed wetland inlet zone – to trap sand- to silt-sized particles and improve water quality. This module can have some secondary benefits, including landscape aesthetics and flow attenuation.

• Macrophyte zone ie. an area of plants such as rushes, reeds and sedges – to improve water quality through the trapping of fine particles and soluble pollutants. This module can have some secondary benefits, including wildlife habitat and flow attenuation.

• Lake/island – to provide passive recreation, landscape enhancement and wildlife habitat. Depending on the outlet structure, lakes can significantly attenuate flow. Lakes can also provide water quality benefits, but this function can be compromised if the lake attracts large populations of wildlife, which can degrade water quality.

• Flood retarding basin – to protect downstream areas from flooding and to control stream hydrology. This module can provide more open space within the urban landscape. Stormwater treatment modules located in flood retarding basins can benefit from the extra hydrologic control provided by the basin.

In practice, the boundaries of these stormwater management modules need not be as distinct as those shown in Figure 1. Early planning and identifying the uses and their priorities for each module in a stormwater management system allows improved integration of the modules and optimal utilisation of the available open space as shown in Figure 2.

CRC WETLANDS RESEARCH

The Cooperative Research Centres (CRCs) for Catchment Hydrology (CRCCH) and Freshwater Ecology (CRCFE) have been collaborating to develop technically sound design guidelines for constructed wetlands and ponds. This research has included:

• statistical analyses of pollutant-removal performance data from studies of wetlands and ponds in Australia and overseas

• field and laboratory experimental studies

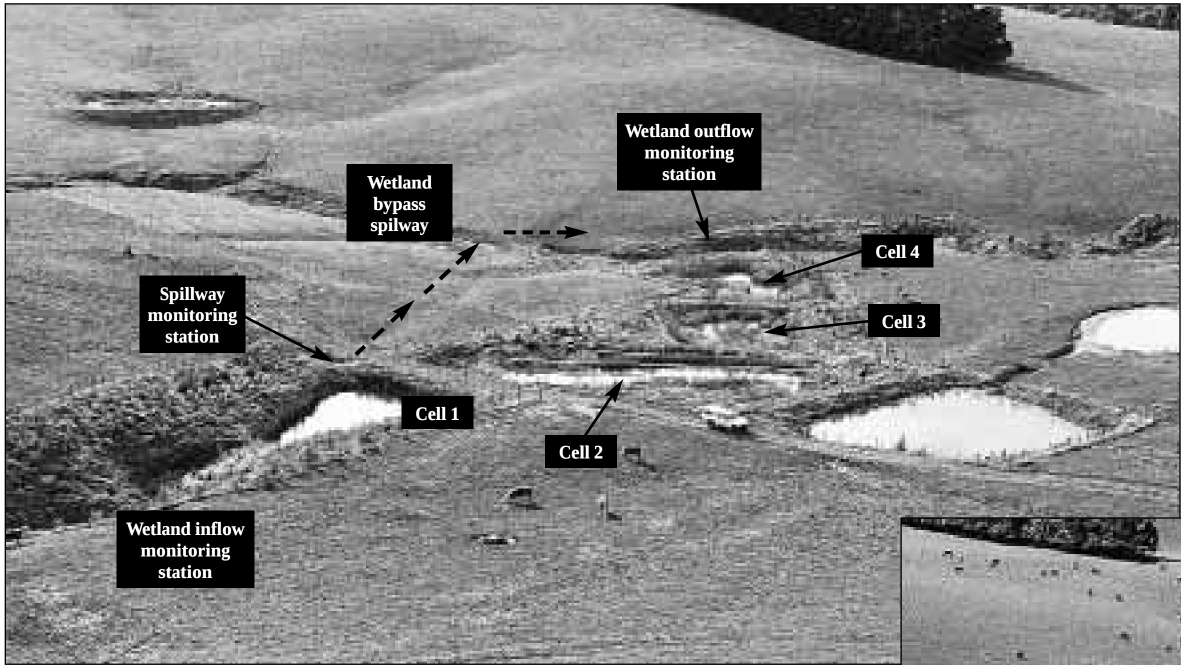
• field monitoring of stormwater wetlands and ponds

• computer simulation of wetland and pond flow hydrodynamics and treatment processes

Statistical analysis of wetland performance

Data was collected on the performance of constructed wetlands and ponds used in stormwater treatment from 76 Australian and overseas sites. Statistical analysis of the effectiveness of these detention systems was undertaken, testing regression equations relating the expected removal of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) to a number of explanatory variables.

Results showed that the effectiveness of a wetland system appeared to be most influenced by the catchment runoff characteristics of the respective site (i.e. the combined effects of climate, catchment size and land use), as well as the design and surface area of the wetland or pond system.

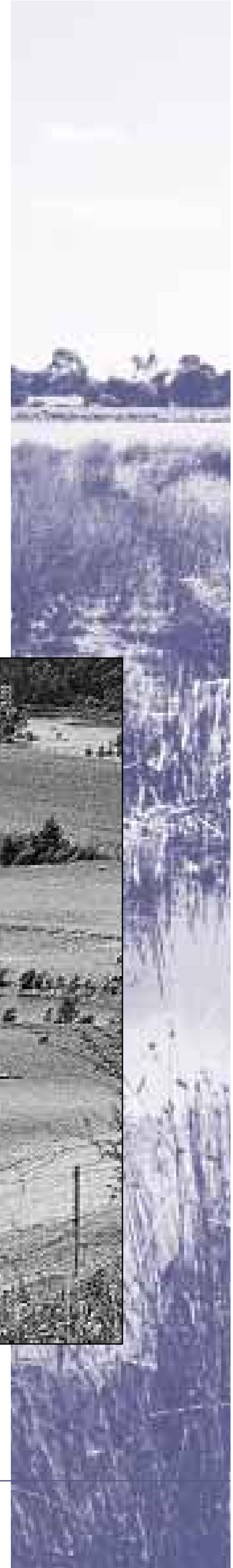


Left: The Monash University Research Wetland in South Gippsland constructed to support field studies of wetland processes (1996)

Below: The Monash University Research wetland is now fully established for wetland research (1998)

Monash University Research Wetland

Over the past four years, CRC researchers have undertaken a number of research projects to understand and define the design processes of constructed stormwater wetlands. These projects included field studies at a research wetland established in South Gippsland, Victoria – known as the Monash University Research Wetland – as well as computer simulations. The research focused on the hydrologic and hydraulic operation of stormwater wetlands, and the influence of vegetation on the deposition of fine particulates within the system.

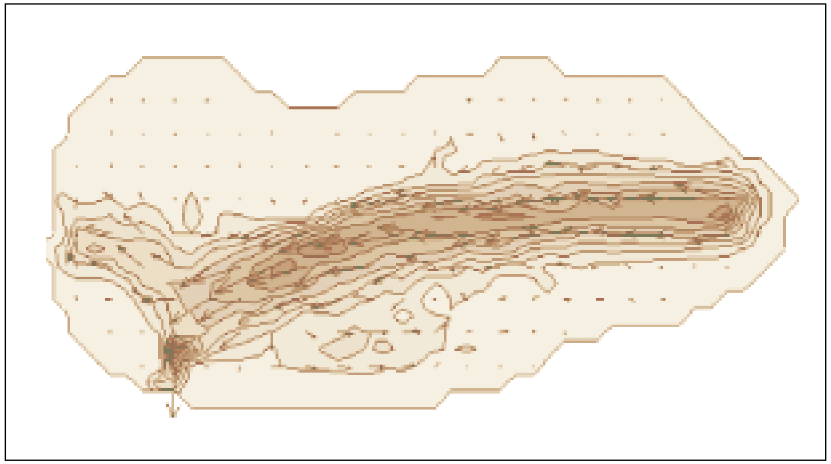


Sediment in the Monash University Research Wetland is cored for analysis of sediment deposition, particle size distribution, and correlation with botanical species and layout

Field tracer study at the Streeton View Pond

Constructed wetland and pond hydrodynamic modelling

CRC researchers have been developing two-dimensional and quasi three-dimensional computer models of flow hydrodynamics in ponds and wetlands. Numerical modelling of flow patterns in ponds and wetlands enables researchers to understand the influence of system morphology and hydraulic structures on the performance of these systems for stormwater pollution control. Numerical models have been calibrated and verified by field tracer studies and two and three-dimensional velocity mapping studies of the Monash University Research Wetland and Streeton Views Pond in Victoria.



Computer simulation of flow hydrodynamic within a constructed wetland provides an insight into the effectiveness of stormwater treatment processes

The Role of Wetland Vegetation

Wetlands can support a range of water quality management objectives. The processes influencing water quality in wetlands resemble those operating in better-known aquatic environments. The wetland's inflow, organic matter and nutrient loads, and hydrologic regime determine the dominance of particular processes in the wetland and their relative importance. Wetland water quality is influenced by a complex array of processes, including:

- biological uptake of nutrients and metals by aquatic vegetation
- formation of chemical complexes of nutrients and metals in the sediments
- coagulation of small particles

Wetland vegetation provides surface areas for filtration and surface adhesion of fine particles

- filtration and surface adhesion of small particles by vegetation
- enhanced sedimentation of smaller particles in vegetation
- direct sedimentation of larger particles
- decomposition of accumulated organic matter
- gas losses through chemical and microbial processes (ammonia, nitrogen, methane, hydrogen sulphide)
- microbial UV disinfection by exposure to sunlight

The three significant types of processes are:

- biological and chemical processes involving soluble materials (e.g. uptake of nutrients by epiphytes, adsorption and desorption of phosphorus onto and from particles, nitrification and denitrification)
- coagulation and filtration of small, colloidal particles (e.g. adhesion of colloids and particles on the surface of aquatic vegetation. These particles are in a size-density range that makes them too small to settle under all but the most quiescent conditions.)
- physical sedimentation of particles (e.g. sedimentation in wetlands due to decreased water velocity. Large plants (macrophytes) such as reeds and rushes enhance this process by further reducing turbulence and water velocity.)

Wetland vegetation creates the physical and biological conditions required for the successful removal of finely graded particles and associated pollutants. The physical conditions created by wetland vegetation that maximise the removal of finely graded particles include uniform flow distribution and flow retardation, leading to increased pollutant contact with plant surfaces. Emergent vegetation minimises wind-generated turbulence. The root system of wetland vegetation binds and stabilises deposited particulates, protecting

them against re-suspension. The root-zone can also modify sediment redox (reduction-oxidisation) conditions, and influence the stability of pollutants trapped in sediments.

Because most pollutants are transported during storm events, physical processes are more important in trapping pollutants at these times. Biological processes become important under low flow conditions, when previously trapped materials are transformed and recycled. Small suspended particles adhere to plant surfaces, which act as filters. Plants also provide a surface on which photosynthetic organisms such as algae can grow. These epiphytic algae remove both fine particles and dissolved pollutants from the water column.

We examined wetland plant surfaces using light- and electron-microscopy, including staining techniques to distinguish between mineral, algal and bacterial particles. Results demonstrated the enhanced sedimentation and particle adhesion functions of plants. Examination of *Schoenoplectus validus (River Club-rush)*, a common species of wetland vegetation, for example, showed particles as small as 0.5-2.5 microns (1 micron is 0.001 of a millimetre) sticking to both the plant surface and the epiphytes.

Table 1 summarises the functions of vegetation during storm-event flow and baseflow conditions in wetlands. Desirable plant characteristics maximise surface area in the water column and provide uniform hydraulic resistance. Contrary to common practice, vegetation should be established perpendicular to the direction of flow to optimise interaction between wetland vegetation and polluted water.

During baseflow	During storm-event flow
Provides surface area for epiphytes • epiphytes take up materials from the water and introduce them to sediments, as cells dislodge from plant surfaces and settle; this is a short-term process occurring over hours to weeks	*Increases hydraulic roughness*
	Promotes uniform flow
Takes up nutrients from the sediments • nutrients in the sediment are transformed into plant biomass; this is a medium-term process occurring over weeks to years	*Enhances sedimentation of particles*
Transforms absorbed materials into less available forms • plant biomass is returned to the sediment for storage as low-level biodegradable macrophyte litter; this is a long-term process occurring over years to decades	*Provides surface area for small-particle adhesion*
Control of surface sediment redox • plant root-zones generally help maintain an oxidised sediment surface layer preventing chemical transformation of settled pollutants	*Protects sediments from erosion*

Table 1: The functions of vegetation for stormwater control in constructed wetlands

An integrated approach to stormwater wetland design

The successful design of constructed wetlands for stormwater management requires the integration of many disciplines over several space and time scales. Figure 3 illustrates the design process, and the major linkages between wetland design elements.

At the catchment scale, climate and terrain interact with land use and drainage design to determine the hydrology and quality of catchment runoff. In urbanised catchments, to protect the aquatic ecosystems of receiving waters, both the quantity and quality of runoff must be managed. Landscape planning and urban design can help create catchment conditions that, in turn, influence catchment hydrology and runoff quality. Consideration of water issues at the urban planning stage can prevent stormwater management problems in mature catchments, and reduce the magnitude and difficulty of runoff treatment.

Hydrologic effectiveness integrates the competing factors that need to be considered to determine wetland volume for a particular application. It allows the trade-off between volume of runoff treated, detention time and wetland volume to be balanced and evaluated. These considerations determine the extent of land required (i.e. wetland volume) for a required level of treatment to protect downstream aquatic ecosystems.

While catchment-scale factors are important in determining wetland volume, local-scale factors are important in determining the effective use of

> ***Hydrologic effectiveness** describes the interaction between runoff capture, detention time and wetland volume.*

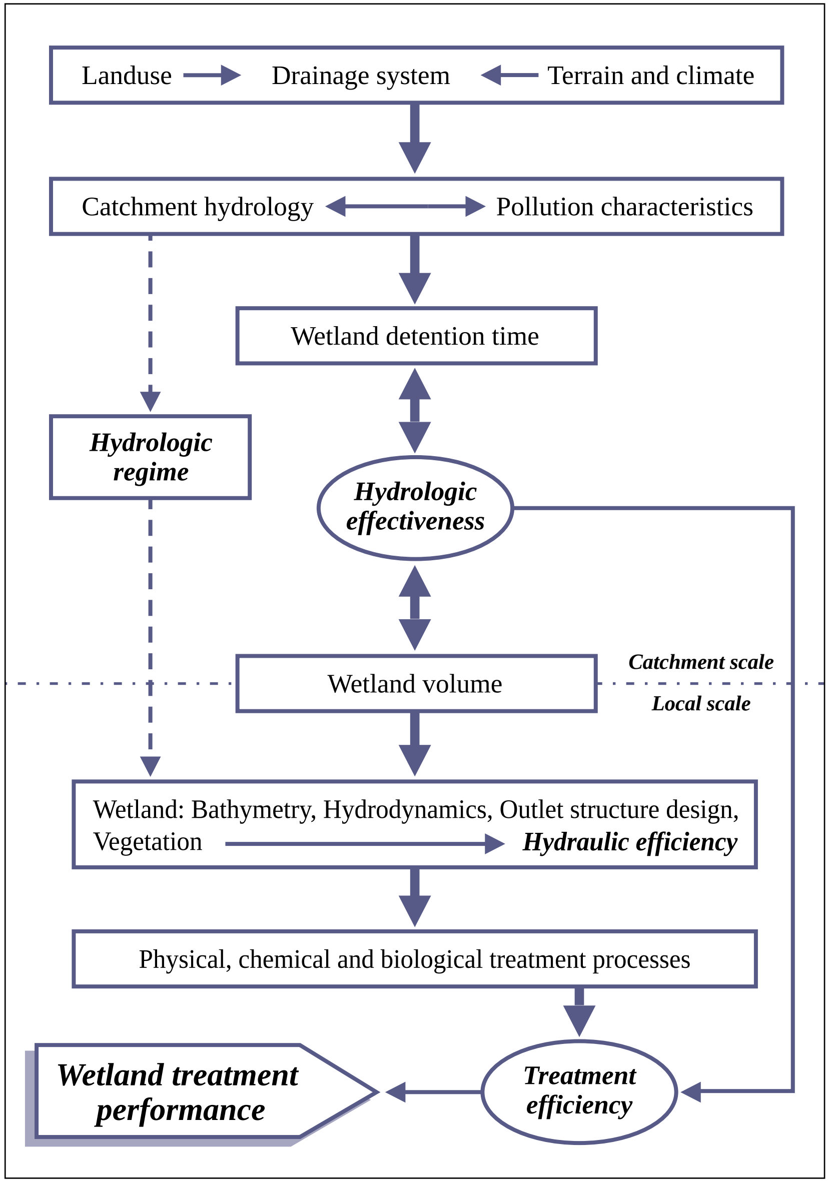


Figure 3: Interaction of wetland design elements

this volume for runoff-treatment purposes. The physical, chemical and biological processes responsible for stormwater treatment are optimised under uniform flow conditions (i.e. the total volume of the basin operating under ideal flow conditions).

Hydraulic efficiency is strongly influenced by basin shape and depth; hydraulic structures such as inlets, outlets and berms; and the type, extent and distribution of wetland vegetation. The interaction between wetland bathymetry (the topography beneath the water surface) and vegetation is the single most important factor influencing wetland hydraulic efficiency.

Wetland plants are adapted to specific wetting and drying cycles. The major factor in determining these **hydrologic regimes** within a wetland is the interaction between catchment hydrology, basin bathymetry and the hydraulic behaviour of the outlet structure. Thus, in order to maximise treatment efficiency, hydraulic efficiency has to be optimised through modification of basin shape and depth and careful placement of hydraulic structures. The designed botanical layout of a wetland can be sustained if the design of outlet structures match the hydrologic requirements of wetland vegetation in both establishment and operational phases.

Hydraulic efficiency *describes the extent to which plug flow conditions are approximated and the proportion of the wetland volume utilised in the movement of inflows through the wetland.*

Hydrologic regime *describes the long-term spatial variation in water depth and period of inundation within a wetland system. The hydrologic regime is the main factor controlling wetland vegetation distribution.*

The treatment performance of a constructed wetland results from the combined effect of the wetland's hydrologic effectiveness and treatment efficiency. The hydrologic effectiveness defines the overall percentage of catchment runoff introduced to the wetland; the wetland treatment efficiency defines the extent to which pollutants introduced into the wetland are removed.

Successful stormwater management requires the following factors to be considered at all space and time scales:

- Catchment planning and local urban design must be integrated to reduce runoff volume and improve its quality.
- The variable nature of catchment runoff must be incorporated into decisions regarding the proportion of runoff to be treated, and the wetland volume required.
- Stormwater treatment processes must be optimised by integrated consideration of wetland ecology and hydraulics.
- The role of the outlet structure in determining the hydrologic regime needs to be considered during establishment, operation and maintenance of the wetland.

CONSTRUCTED WETLAND LAYOUT

A constructed wetland typically comprises both vegetated (macrophyte zone) and open water areas as shown in Figure 4. The inlet zone and the macrophyte zone have different functions. The function of the inlet zone is to maximise detention storage for the settling of coarse- to medium-sized fractions of suspended solids, and to control inflow into the macrophyte zone. This zone is generally deep and normally has only fringing vegetation. It can often be landscaped to provide visual and passive recreational value.

The macrophyte zone is a shallow, relatively tranquil part of the constructed wetland, where particles settle and adhere to vegetation. This zone also provides a framework for the development of biofilms, which are instrumental in the uptake of soluble pollutants, making the macrophyte zone the central component of a constructed wetland. Flow velocities in this zone tend to be less varied, due to the hydrologic control provided by the inlet zone. The macrophyte zone should be allowed to fill and drain regularly in response to the intermittent inflow of stormwater runoff from the catchment.

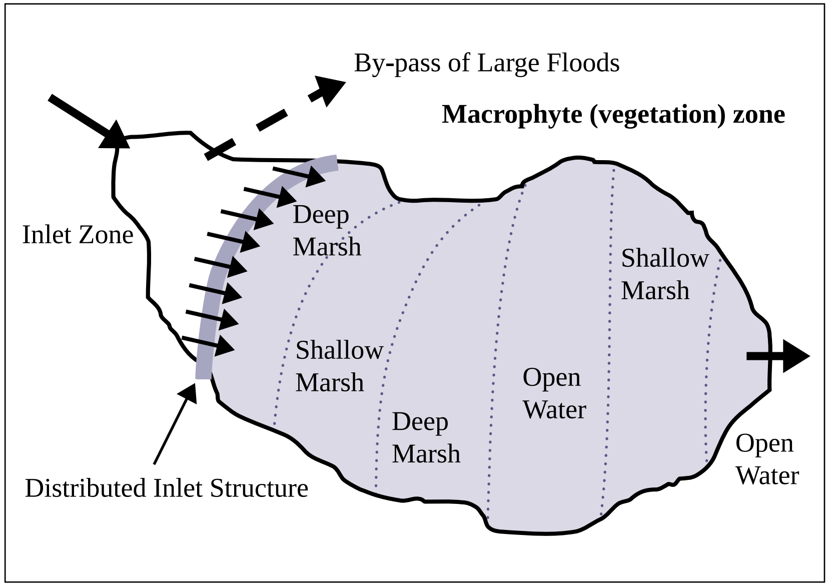


Figure 4: Illustration of a typical constructed wetland system layout

The **wetting and drying cycle**, a feature of natural wetlands, is essential to the sustainable operation of constructed wetlands. The outlet structure in this zone must be designed to provide the detention period required to achieve the desired degree of stormwater treatment. Additional stormwater runoff should be diverted away from the macrophyte zone when it reaches maximum operating level.

Constructed wetland inlet zone with a porous rock embankment to distribute flows evenly across the macrophyte zone. The by-pass weir is located on the far side of the open water area

As a general rule, a constructed wetland should consist of a minimum of two cells – an open water inlet zone and a macrophyte zone. Landscape features may include an ornamental lake that could form part of the inlet zone or be located downstream of the macrophyte zone. Including an ornamental lake in the inlet zone is not generally recommended, due to the potentially poor water quality. As described previously, components in this part of a stormwater management system would normally be located there for treatment purposes, and not for aesthetics or ornamental purposes. However, site and other land use constraints may only allow the placement of an ornamental lake upstream of the constructed wetland. The consequences of such conflicting objectives should be recognised in the design phase.

Wetting and drying cycles

Periodic filling and draining is important in the regulation of natural wetlands. Duration of inundation is also a crucial operational and maintenance feature in constructed wetlands. Wetting and drying is needed for the regulation and maintenance of wetland vegetation,and also significantly influences the organic content and nutrient cycling in sediments.

Drying substantially improves the oxygen supply to sediments and increases the rate and completeness of organic degradation. Consequently, organic sediments and accumulated plant litter (peat) only develop under permanently inundated conditions. The benefit of organic sediments and peat deposits in deep marsh zones is that they represent a long-term storage of biodegradable materials. However, the accumulation of plant litter in shallow zones may interfere with hydraulic performance. A regular drying cycle in shallow marsh zones normally results in the rapid degradation of organic material. Natural shallow marsh and ephemeral zones tend to have low organic content mineral sediments.

Wetting and drying cycles can also influence the storage and availability of nutrients such as phosphorus. While inundation can result in the release of phosphorus from sediments, it is time-dependent and influenced by the organic content of the sediment. Phosphorus release is greatest from organic sediments after a medium period of inundation (e.g. 4-6 weeks) and least from mineral sediments under repeated short-term inundation (less than 7 days). Repeated wetting and drying converts sediment iron oxides and adsorbed phosphorus to progressively less available forms. Consequently, it is important to design for both shallow and ephemeral wetland areas, and to recognise and manage them as long-term phosphorus storage areas.

HYDROLOGIC EFFECTIVENESS

Constructed wetlands are stormwater detention systems. Their behaviour is determined by three factors: detention period, inflow characteristics and storage volume. These factors interact to influence the system's effectiveness in detaining stormwater. The hydrologic effectiveness of a wetland reflects the result of this interaction, and defines the long-term percentage of catchment runoff entering the macrophyte zone.

The hydrologic effectiveness of wetlands of varying size and detention time can be defined by computer simulation of the wetland behaviour using long-term rainfall data. As an example, the results of simulations using rainfall data for wetlands in Melbourne are summarised in Figure 5.

The results show increases in storage volumes or reductions in detention times can lead to improved hydrologic effectiveness. A combination of small detention volume and a long detention period would lead to frequent

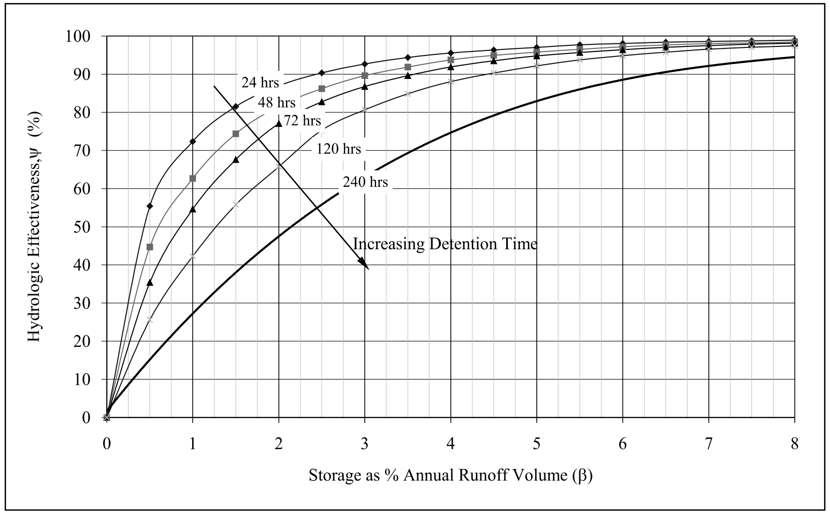


Figure 5: Hydrologic effectiveness curves for wetlands in Melbourne

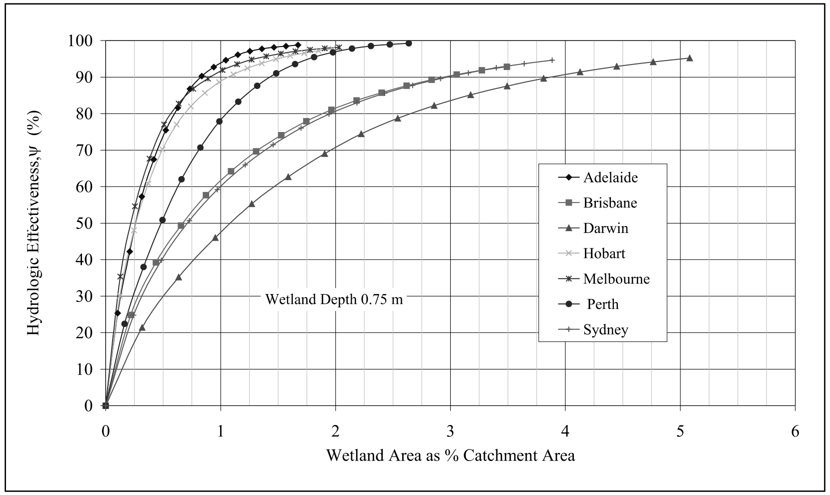


Figure 6: Wetland hydrologic effectiveness vs wetland area for detention period of 72 hours and 30% catchment imperviousness

occurrences of stormwater by-pass, resulting in low hydrologic effectiveness. With inadequate detention storage or excessively long detention periods, there is a higher likelihood of the system being already filled or partly filled from previous storms at the start of a storm event. Clearly, wetland design demands a balance between the available area and the design detention period to achieve the most appropriate hydrologic effectiveness for optimal long-term pollutant-load reduction.

Hydrologic effectiveness curves have been derived for a number of capital cities in Australia using rainfall records. Comparison of these curves indicates that different rainfall regions would require different wetland areas to achieve comparable levels of wetland performance (Figure 6).

The variation around Australia in wetland hydrologic effectiveness for a given detention period and area is due to the climatic variability that occurs not just in mean annual rainfall depth, but also in storm intensity, inter-event dry periods and seasonal rainfall distribution. For instance, the climate of temperate areas such as Melbourne, Adelaide and Hobart is characterised by relatively even distributions of rainfall throughout the year with storms of similar intensity at regular intervals. Thus, wetlands in these areas have high hydrologic effectiveness compared with wetlands of similar size in tropical and sub-tropical areas. The latter are characterised by high seasonal variations of rainfall with a wet season dominated by frequent, intense storms and a dry season with relatively little rainfall.

Influence of the Outlet Structure on Detention Period

In the past, practitioners have assumed that the detention period of runoff entering wetlands is a constant and equivalent to the time difference between the centroids of inflow and outflow hydrographs.

However, recent research has shown that the combined effects of intermittent and unsteady stormwater inflow, antecedent storage conditions within the wetland, and outlet characteristics lead to wetland outflow having been subjected to a range of detention times. Detention periods in wetlands should therefore be considered as a distribution to describe the range of detention times that can occur within the wetland. This distribution, which reflects the influence of the highly variable nature of inflow and antecedent storage conditions, is referred to as the ‘probabilistic residence time distribution’ (PRTD) and varies with outlet type, storage volume and permanent pool volume.

Figures 7, 8, 9 and 10 show the PRTDs derived for four different types of outlet structure from simulations using 100 years of Melbourne rainfall data. The four outlet structures investigated were a riser, a culvert, a weir, and a siphon, each sized to provide a notional mean detention period of 72 hours.

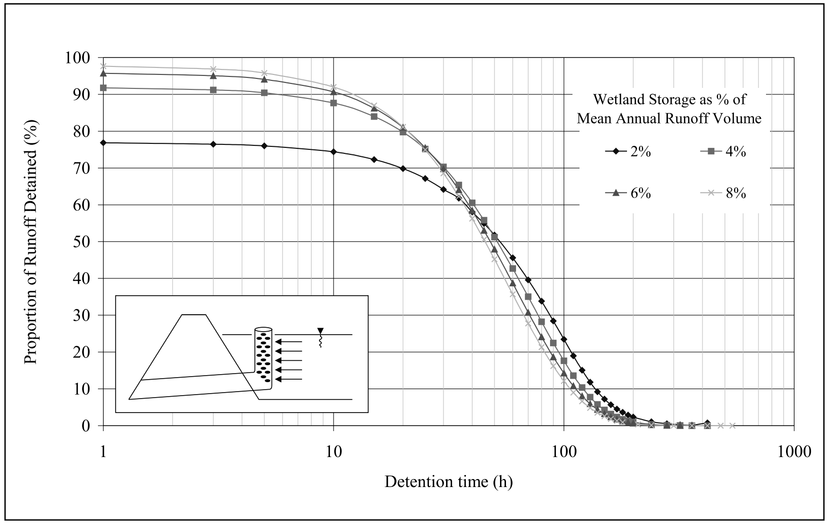


Figure 7: PRTD curves for a riser outlet

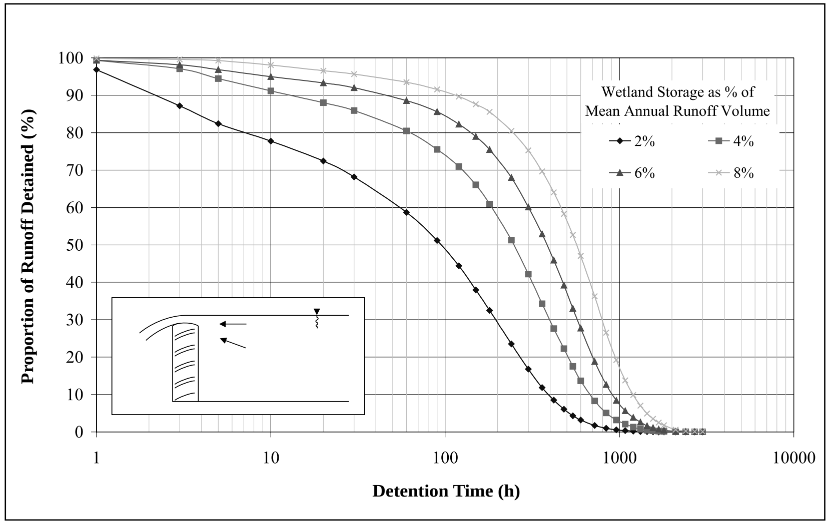


Figure 9: PRTD curves for a weir outlet

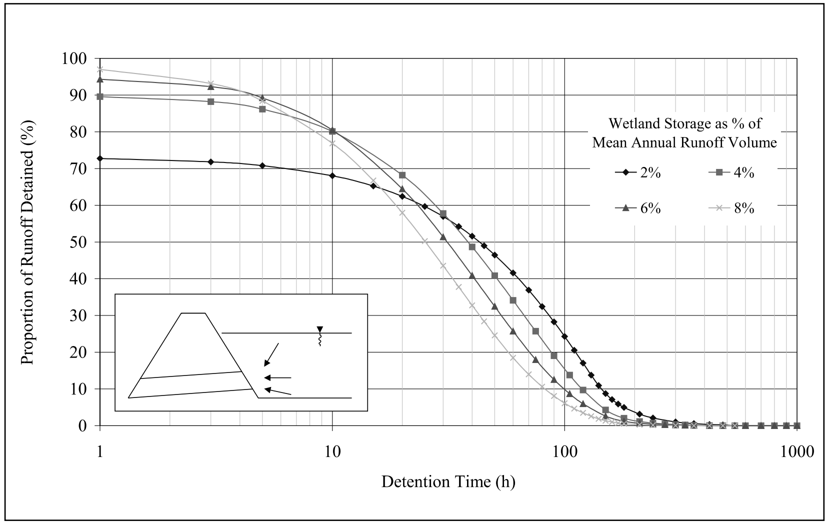


Figure 8: PRTD curves for a culvert outlet

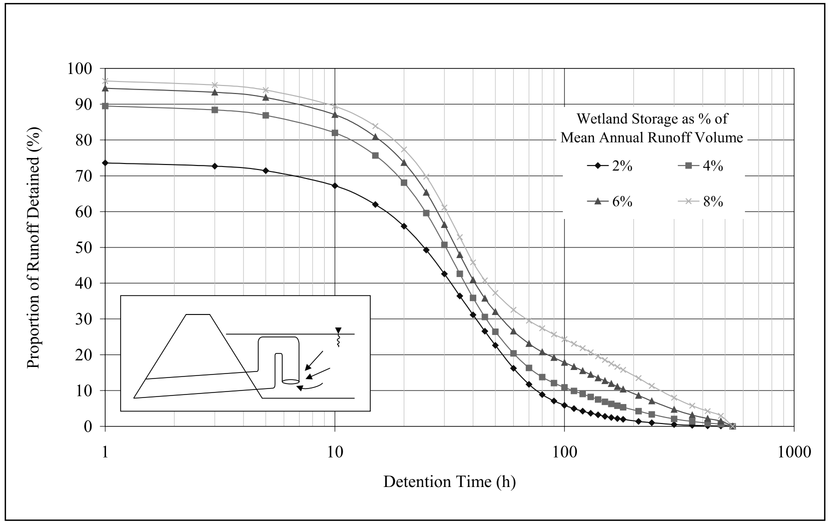


Figure 10: PRTD curves for a siphon outlet

Each curve represents a single storage volume, with the volume expressed as a percentage of the mean annual runoff volume of the catchment investigated. The vertical axis represents the cumulative proportion of flow through each wetland, with the intercept being equivalent to the hydrologic effectiveness, i.e. the overall proportion of catchment runoff subjected to treatment. The results demonstrate that the type of outlet structure significantly influences the wetland's PRTD.

Riser structures, due to the multiple outlet holes, produce the smallest range of detention periods; it is possible, with careful design of the outlet, to achieve a PRTD that resembles a step function, with a near constant detention time over the full depth range. This results in a consistent level of stormwater treatment for all storm events, independent of the event size or the antecedent storage condition of the wetland. This is a desirable design objective for outlet structures.

Culvert outlets produce a slightly wider spread in the PRTD compared with the riser, due to the non-linear stage-discharge characteristics of the outlet. The discharge characteristics of a culvert comprise weir flow and open channel flow at low headwater level and orifice flow when the headwater level is above the obvert (top) of the culvert.

Weir outlets result in a large proportion of the available detention storage being the permanent pool storage. If the volume of the inflow event is less than the permanent pool storage, a significant proportion of the inflow is detained in the permanent pool, and will only leave the wetland when displaced by a subsequent storm inflow event. The period of detention under this condition is directly linked to the dry period preceding the next storm event. If the volume of an inflow event is larger than the permanent pool, a larger proportion of the inflow will leave the wetland during the event. The volume of the inflow of individual events and the inter-event dry period therefore influence the PRTD of wetlands controlled by weir outlets. Weir outlets thus produce the widest variation in detention period.

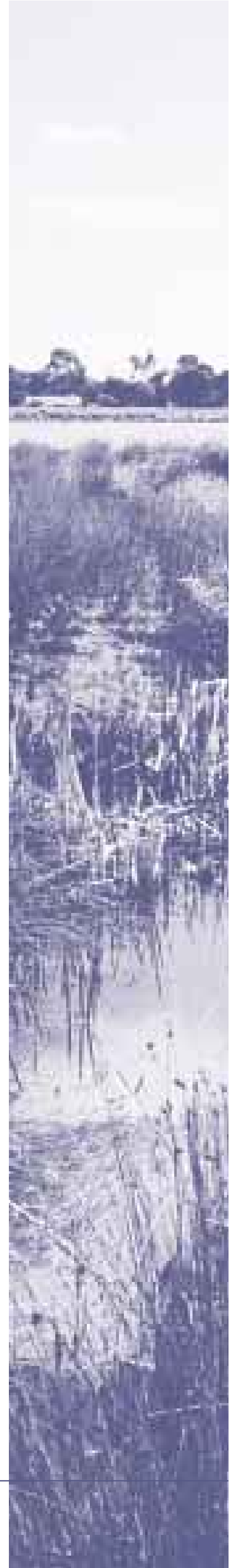
The PRTD curves for siphons have the combined characteristics of both the culvert and the weir. The upper part of the curves resembles that for a culvert, while the tail of the curves reflects the extended period of detention between episodes of siphon operation, and is influenced by the inter-event dry period.

Influence of the Permanent Pool Storage on Detention Period

The permanent pool in a wetland system is formed by the water level below the invert of the lowest wetland outlet. In the case of a wetland controlled by a weir, the permanent pool can make up a large proportion of the total detention storage of a wetland compared to one controlled by a riser.

In systems with a large permanent pool, the outflow following a small runoff event will often consist of runoff stored from previous events. The influence of the inter-event dry period on the detention period of stormwater increases with increasing permanent pool storage. While systems with large permanent pool volumes promote long detention periods, they do not provide the wetting and drying cycles necessary for effective stormwater treatment and promotion of diverse wetland vegetation. Outlets that promote a more variable hydrologic regime are considered to be more desirable. **A balance between these attributes needs to be achieved in design**.

Continuous simulations have been carried out to examine the PRTDs of constructed wetlands in Melbourne for different levels of permanent pool volume in combination with a riser outlet. The results are presented in Figure 11. They indicate that a permanent pool making up 12.5% of the



detention volume can result in the doubling of the detention time compared to that of a wetland without a permanent pool.

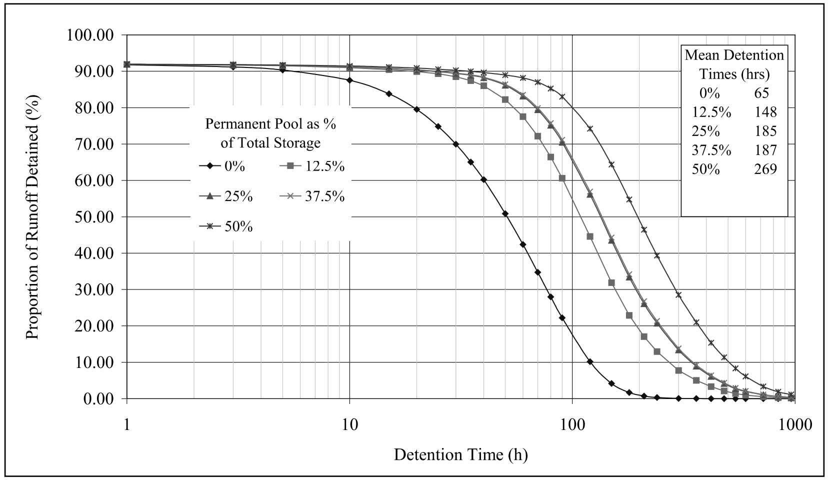


Figure 11: Influence of the permanent pool on PRTD

Sizing the permanent pool storage in wetland design

Research suggests that a good wetland outlet design may consist of a riser with a permanent pool storage of between 10% and 15% of the total storage. This design takes advantage of a longer detention period promoted by the presence of a permanent pool without compromising the hydrologic regime of the wetland.

Selecting The Design Detention Period

The appropriate design detention period for wetlands is dependent on the characteristics of the stormwater pollutant, particularly the ratio of its soluble to particulate form, and the size distribution of the particulate fraction. A conservative approach to the selection of the design detention period for wetlands is to match the settling time of the target particle size for the priority pollutant. This approach is based on the application of sedimentation theory and is traditionally applied to ponds.

The detention period required for effective reduction of suspended solids would normally be shorter than that for total phosphorus owing to the latter having a higher association with the fine particle size fraction. Lawrence and Breen (1998) incorporate this method into a pond model to determine detention periods for suspended solids and total phosphorus for a range of particle sizes. The organic carbon load influences the release of phosphorus from the pond sediments. This process has been incorporated into the calculation of total phosphorus removal in the pond model.

CRC research undertaken has provided evidence of the contribution of wetland macrophytes to increased effectiveness in the removal of stormwater pollutants. The pond design detention period based on matching the settling time of the target particle size could therefore be considered an upper limit of the appropriate design detention period for a vegetated wetland system.

The extent to which a reduction to the pond detention period could be applied to reflect the contribution of wetland macrophytes is a subject of on-going research. In the interim, we envisaged that a possible reduction factor of 0.7 could be applied in a fully vegetated wetland system.

FLOW HYDRODYNAMICS IN A WETLAND

Residence time distribution

The computed PRTD curves are based on the assumption of ideal hydrodynamic flow conditions. They were derived to gain an insight into the influence of stormwater inflow and outlet structure design on the long-term distribution of detention times in a wetland system.

Ideal flow conditions occur when all 'parcels' of water take the same amount of time to pass through the wetland (known as plug flow), and when the entire volume of the wetland is being utilised. Ideal flow conditions never occur in stormwater wetland systems, and it is essential that appropriate steps be taken in the hydraulic design of the wetland to achieve optimum flow conditions.

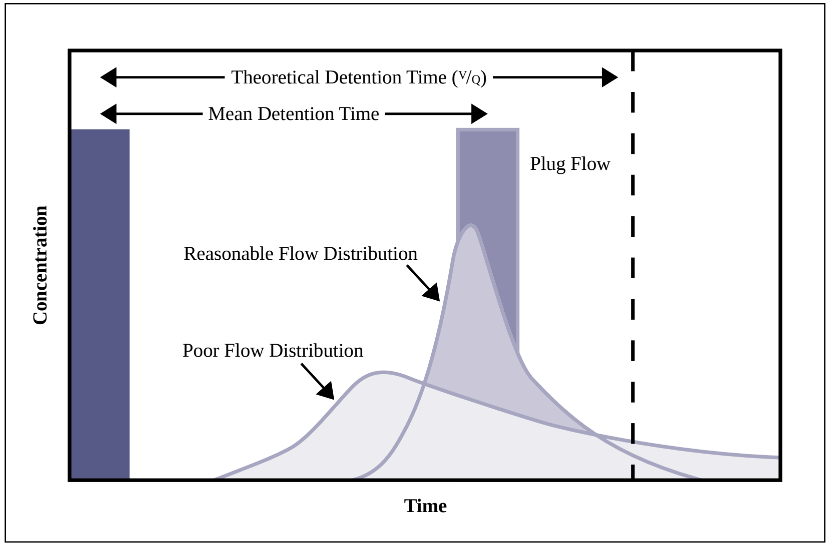


Figure 12: Residence time distributions

The internal configurations of the wetland – such as the shape and form of the basin, the type and location of the inlet and outlet structures, and the botanical layout – have a direct influence on the hydraulic efficiency within the wetland. The characteristics defining the hydraulic efficiency of a wetland system are shown in Figure 12, which illustrates hypothetical tracer responses at the outlet of a wetland for a pulse injection of the tracer at the inlet under steady flow conditions.

These responses are often referred to as the 'residence time distribution' (RTD), and they describe the hydraulic efficiency of the detention system. Plug flow conditions occur when the shape of the tracer concentration at the outflow remains a pulse, but translated in time. The time difference between the inflow and outflow pulses represents the mean detention time. Full utilisation of available wetland storage would result in the mean detention time being equivalent to the volume of the system (V) divided by the outflow rate (Q), i.e. V/Q.

Hydraulic inefficiencies within the wetland due to zones of re-circulation and stagnation reduce the engaged basin volume. Short-circuiting of flows through the wetland results in outflows having a range of detention times. As the hydrodynamic flow conditions depart further from ideal flow and more eddies and stagnant zones form, the range of detention times increases. Wetland features that promote high hydraulic efficiency are summarised in Table 2. These are based on results of two-dimensional hydraulic modelling of hypothetical and real wetlands and a series of velocity readings taken at the Monash University Research Wetland.

Open water areas	
Maximise length-to-width ratio (L:W)	Include meanders or berms if needed to ensure L:W ratio > 3. Avoid having excessively high L:W ratio such that flow velocities are higher than 0.02 m/s, leading to re-suspension of settled particulates.
Spread flow at inlet	• weirs • multiple inlets • submerged berms • islands in front of inlet
Macrophyte areas	
Vegetate across flow path	Either fully vegetate basin, or arrange bands of vegetation across flow path.
Uniform cross-section	Ensure depth across flow path is uniform.

Table 2: Guide to achieving good hydraulic efficiency in wetlands

Influence of basin shape and form and vegetation layout

An investigation of options to improve the hydraulic efficiency of a wetland system was undertaken at the Monash University Research Wetland. A two-dimensional hydraulic model was calibrated against field measurements of flow velocities, and then used to simulate five possible modification options to the existing natural bathymetry (topography beneath the water surface) with non-uniform distribution of vegetation.

The five options simulated were:

1. natural bathymetry with full vegetation
2. banded bathymetry with fringing vegetation
3. labyrinth bathymetry and full vegetation
4. banded bathymetry and full vegetation
5. uniform depth with a wide trapezoidal bathymetry and full vegetation

Figure 13 plots the tracer responses for the simulations with the x-axis normalised to the theoretical detention time of V/Q (i.e. the mean detention time would have a normalised value of one under ideal conditions). The hydraulic efficiency for the existing condition (base case) is very low, typical of systems built on creek lines with a clear preferential flow path along the old creek bed.

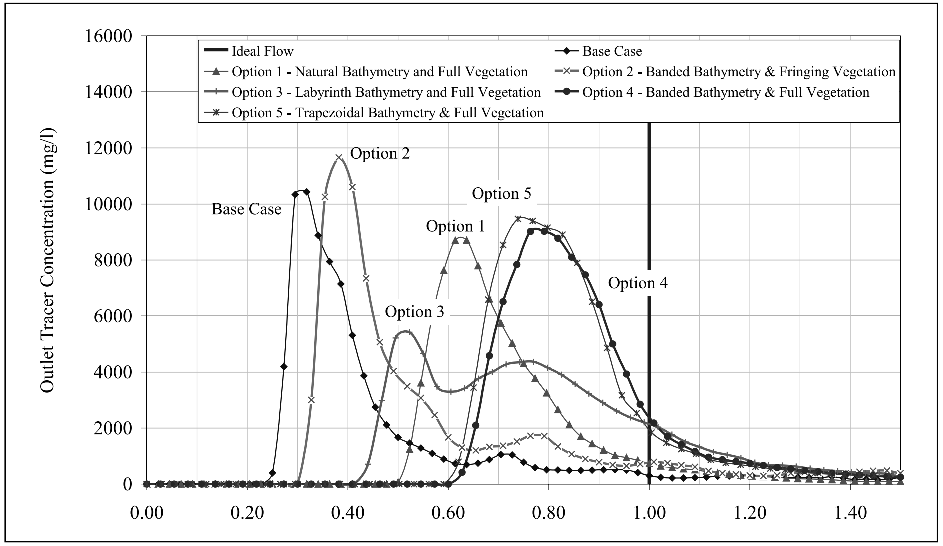


Figure 13: Tracer responses from two-dimensional modelling for five different improvement options for the Monash University Research Wetland

While the shape of the outflow tracer pollutograph indicates a reasonable flow distribution, the mean detention time is significantly shorter than the theoretical detention time (V/Q). This is attributed to the fringing vegetation adding to the already poor flow characteristics of the creek line bathymetry.

Of the improvement options investigated, those involving a change in bathymetry of the wetland and full vegetation gave the best results. A banded bathymetry would repeatedly assist to distribute flow across the width of the wetland. While this bathymetry is desirable, the presence of non-uniform vegetation – such as fringing vegetation – would rapidly re-establish preferential flow paths. Full vegetation would result in a uniform hydraulic roughness across the width of the wetland, leading to more uniform flow patterns. A labyrinth bathymetry, commonly used to create a meandering flow path under low flow conditions, can often lead to poor hydraulic efficiencies when these berms are submerged during higher flow conditions. This is illustrated in Figure 13, which shows the tracer pollutograph exhibiting two peak concentrations, reflecting two preferential flow paths in the system.

Uniform marsh vegetation across the flow path assists in promoting high hydraulic efficiency in wetlands

VEGETATION LAYOUT AND SPECIES SELECTION

Achieving a desirable hydrologic regime for plant growth

The hydraulic characteristics of outlet structures define a wetland's range of water depths and duration of inundation. Water depth and inundation duration are the main factors controlling aquatic plant distribution.

The bathymetry and hydrologic regime of the wetland directly influence the layout of wetland vegetation

Wetland plants have adapted to a wide range of water depth-inundation period conditions, from permanently wet to mostly dry. Individual species have evolved preferences for particular conditions within the water depth-inundation period spectrum. These preferences are responsible for the vegetation zones seen in natural wetlands. The locations within a wetland that are best suited to specific wetland plants are determined by the interaction between basin bathymetry, outlet hydraulics and catchment hydrology – the hydrologic regime.

Contrary to common practice, weirs are not considered suitable for the control of wetland hydrologic regime due to their inability to promote a range of water-level fluctuations in the wetland. Similarly, a single culvert outlet is not considered suitable due to its non-linear stage-discharge relationship.

Figure 14 presents the result of a continuous simulation of the hydrologic regime of a typical Melbourne wetland for a culvert outlet. It clearly shows that there is a significant period of time when water depth is between 0 and 0.2 metres above the permanent pool. This indicates that the system above 0.2 metres 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.

Riser outlets have a number of small holes in a vertical pipe; experience with riser discharge characteristics indicates that a near-constant detention period for the full depth range of the wetland (i.e. a near-constant ratio of storage volume to discharge) can be readily established by appropriate placement of holes along the riser. When water levels are below the top of the riser, the wetland is drained by the smaller holes distributed along the riser. When the water levels are above the top of the riser, water is also discharged via the end of the pipe. The sizing and number of holes required depends on the detention time and drawdown characteristics desired for the storage.

Figure 15 shows the improvements made to the hydrologic regime using a riser as the outlet type. This increases inundation frequency in areas of the wetland above 0.2 m by 26%, providing the opportunity for other vegetation types, such as shallow marsh, to be sustained.

The possible use of a combination of a siphon and an overflow spillway in wetland drainage was also investigated. This system of outlet control was found to be of some advantage, as it operates only when the siphon has been primed, allowing several smaller events to be detained for extended periods as

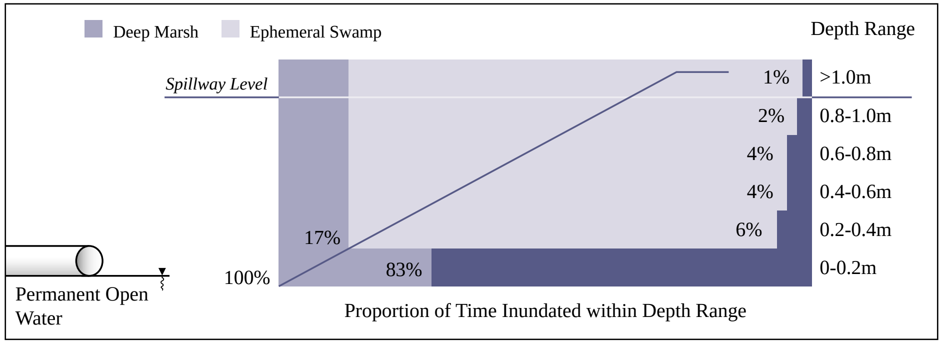


Figure 14: Hydrologic regime for a wetland with a culvert outlet

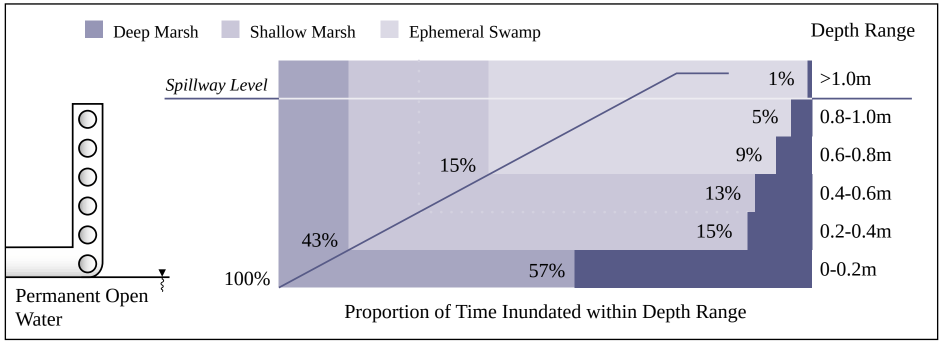


Figure 15: Hydrologic regime for a wetland with a riser outlet

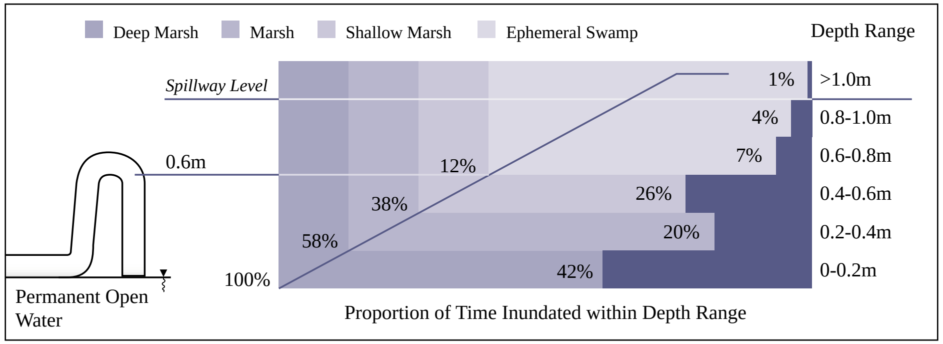


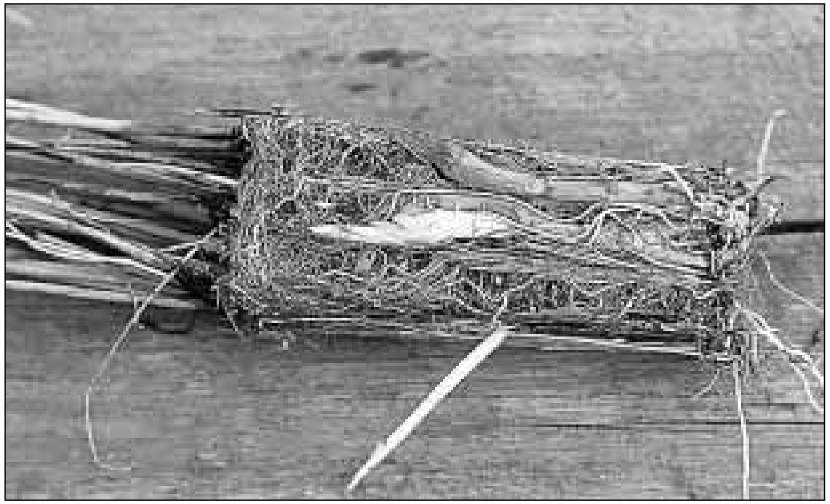
Figure 16: Hydrologic regime for a wetland with a siphon outlet

the water level rises. Once initiated, they operate at near-constant discharge until air entrainment occurs.

Figure 16 shows the improved hydrologic regimes due to the use of a siphon outlet placed at 0.6 m above the permanent pool level. As a result, diverse vegetative zones can be created, ranging from shallow marsh to deep marsh. Both riser and siphon outlets are capable of promoting a diverse botanical layout in the wetland, with the siphon having the added advantage of a longer detention period for the same size wetland and maximum outflow rate.

Desirable plant characteristics

The correct choice of plant species is a balance between selecting species for particular wetland depth ranges, and selecting plants to enhance particular treatment processes. Usually, species with vegetative or rhizomatous growth have desirable characteristics for use in stormwater treatment wetlands. The hydrologic regime will govern the wetland vegetation zones present within the system, determining which species will dominate. Table 3 outlines the typical functional wetland vegetation zones that most stormwater treatment systems contain, showing typical species for south-eastern Australia. Where possible, native plants (native to the area or site) should be selected, as they are more likely to grow well under the prevailing environmental conditions, and have less impact on the flora and fauna of surrounding communities.



Schoenoplectus validus (River Club-rush) – An example of rhizomatous root structure

Phragmites australis (Common Reed), a hardy reed for the inlet zone of a wetland

Wetland zone	Primary role of plants	Examples of plants
Inlet	To distribute flows and bind and protect sediments	*Schoenoplectus validus (River Club-rush)* *Phragmites australis (Common Reed)* *Juncus procerus (rush)*
Shallow marsh: shallow inundated area that regularly dries out	To provide a substratum for algal epiphytes and biofilms to enhance soluble pollutant uptake	*Eleocharis acuta (Common Spike rush)* *Baumea acuta (Pale Twig-rush)* *Baumea ribiginosa (Soft Twig-rush)* *Isolepsis inundata (Swamp Club-rush)*
Marsh: medium-depth inundated area that occasionally dries out	To maximise surface area in the flow path for the adhesion of particles	*Bolboschoenus medianus (Marsh Club-rush)* *Baumea arthrophylla (rush)* *Schoenoplectus pungens (rush)*
Deep marsh: permanent inundated area	To enhance sedimentation of particles	*Schoenoplectus validus (River Club-rush)* *Baumea articulata (Jointed Twig-rush)* *Eleocharis sphacelata (Tall Spike-rush)*
Littoral: transitional area between wet and dry zones, undergoing regular water level fluctuations	To provide an edge buffer zone to protect banks from erosion	*Carex appressa (Tall sedge)* *Carex fascicularis (Tassel sedge)* *Baumea tetragonia (Square Twig-rush)* *Juncus spp (rushes)* *Restio tetraphyllus (Tassel Cord-rush)* *Melaleuca spp (Paperbarks)*
Ephemeral: a dry to water logged area that experiences regular inundation	To maximise surface area in the flow path for the adhesion of particles under event flows	*Carex appressa (Tall sedge)* *Carex tereticaulis (Common sedge)* *Isolepis nodosa (Knobby Club-rush)* *Juncus spp (rushes - eg. amabilis, flavidus, subsecondus)* *Melaleuca spp (Paperbarks)*

Table 3: Role and selection of plants in wetland zones

Eleocharis sphacelata (Tall Spike-rush), a typical deep-marsh vegetation species

Establishment and maintenance of wetland vegetation

Site preparation

The major elements of site preparation are the provision of suitable substratum for growth, and the control of undesirable weed species.

The desirable covering of top soil for successful establishment of wetland vegetation is about 0.2 m. Where species are to be established in undisturbed soils, it is necessary to control any existing vegetation prior to planting. This will reduce competition during the establishment phase. To establish wetland vegetation, it is necessary to have good water-level control. Even large species like *Schoenoplectus validus* establish best in water depths less than 0.2 m. Shallow marsh and ephemeral species may establish best in moist soil. It is therefore necessary to have water-level control over the full range of water depths in the wetland. This allows the best water-level conditions to be selected for each wetland zone, and for the zones to be planted sequentially.

Planting of nursery-grown seedlings often results in the most reliable species establishment for constructed wetlands

Plant establishment

Various methods exist to establish wetland vegetation, including direct seeding, seedlings, transplantation of harvested material and transplanting wetland sediment seedbanks. The recommended strategy for vegetating wetlands is to use nursery-grown seedlings for the planting of broad areas. Direct seeding and transplanting of harvested materials can be used where opportunities arise and site conditions are appropriate. Seedbank material is best suited to rehabilitating degraded wetlands, or where species selection is less critical for constructed wetlands (e.g. for wildlife habitat or aesthetics).

Planting density should be approximately 80% vegetation coverage. This means that plants should occupy 80% of each square metre in the vegetated zones. This reduces the risk of weed invasion. Each planting method has advantages and disadvantages, some of which will be discussed here.

Nursery stock

Nurseries can provide large quantities of even-aged hardened stock easily allowing for a range of planting densities. Depending on the species, nursery propagation time varies from 6 to 18 months; therefore the planning and ordering of the stock must begin early in the wetland system design phase.

Direct seeding

Under some conditions, direct seeding can be a useful establishment technique, as it is a relatively fast and inexpensive way of vegetating large areas of ephemeral or terrestrial habitats. For best results, considerable knowledge about the germination characteristics of the species involved is required. Once the seed is spread, germination and establishment is uncontrolled, and the risk of failure due to flooding, drying, seed predation and fungal attack is high. Direct seeding can be vulnerable to weed invasion if topsoil has not been well prepared.

Transplantation of harvested materials

Transplanting harvested material offers a cost effective method of plant establishment. It requires intensive labour and is most suited to establishing small areas. Species with rhizome material or tussocks are most successfully established using this technique.

A major advantage of this technique is that the transplanted material is mature, and can be planted directly into the wetland. With this method, adjusting the water level to help plants establish is less critical, although many species will establish more successfully in low water conditions.

For large wetland systems, disadvantages include finding potential sites from which to harvest material; high rates of damage to stock, especially if stockpiling is required; the limited species that can be established with this method; and the difficulties in handling large and heavy stock.

Timing of planting

The timing of planting is crucial for successful plant establishment. Plants in most climates in Australia (temperate and sub-tropical) have a distinct growth season. If stock is planted at the start of the growth season (spring) it has an entire growth season to establish before it has to survive the non-growth season (winter). Stock planted out of season has to survive on the reserves developed prior to planting. Depending on the type of stock, these reserves

Planting mature harvested material together with nursery grown seedlings can improve plant establishment

can often be inadequate and the plants fail to survival the non-growth period. Large, active stock may survive unseasonal planting better than smaller, younger material. However if large, mature stock is held too long prior to planting, it may lose vigor and be just as susceptible to poor establishment as immature stock. The key to successful planting is to plan and order stock far enough in advance to ensure appropriate stock is ready at the start of the growth season.

Maintenance

Vegetation and site maintenance require good water-level control. Both weed and target species respond to water level management.

Controlling water level can be a simple and powerful management tool. For example, after a succession of wet years, shallow marsh zones may require a deliberate reduction in water level to maintain vigor and to control invasion

by marsh and deep-marsh species. Similarly, it may be necessary to raise water levels after long, dry periods to control terrestrial weeds in the ephemeral and littoral zones. Without this, vegetation management can be a problem. Issues that require continual attention include vegetation composition, accumulation of organic matter and sediment, variations in hydraulic behaviour, and the development of potential pest habitats.

MANAGING WETLANDS

PREDICTING WETLAND PERFORMANCE

Many guides are currently available for predicting the expected performance of stormwater wetland. These guides range from simple empirical relationships, to detailed wetland system modelling.

A recent analysis of 76 Australian and overseas studies by the CRC for Catchment Hydrology (Duncan, 1998) has resulted in the derivation of a number of empirical relationships. These can be used to calculate initial estimates of the required wetland size to meet pollutant removal targets for total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) These relationships are shown in Figures 17, 18 and 19.

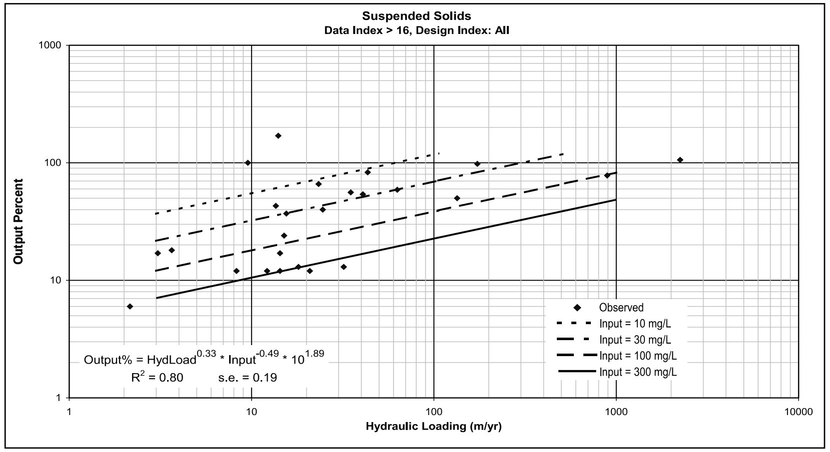


Figure 17: Predicted outflow TSS concentrations as a percentage of inflow concentration from statistical analysis of Australian and overseas data.

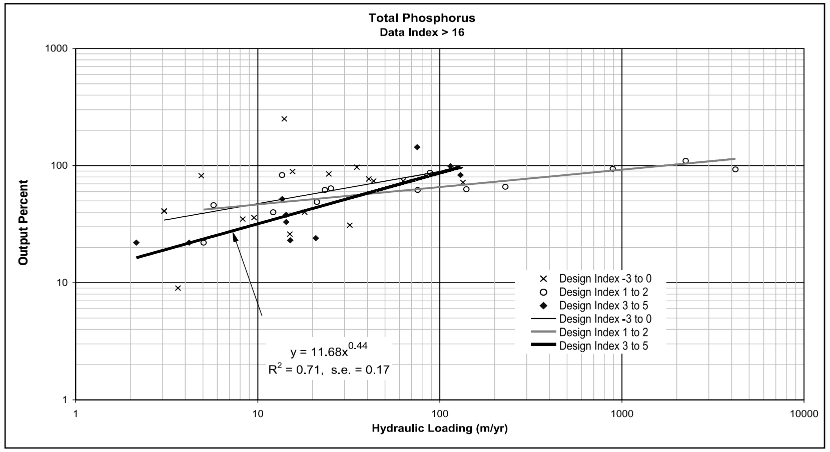


Figure 18: Predicted outflow TP concentrations as percentage of inflow concentration from statistical analysis of Australian and overseas data

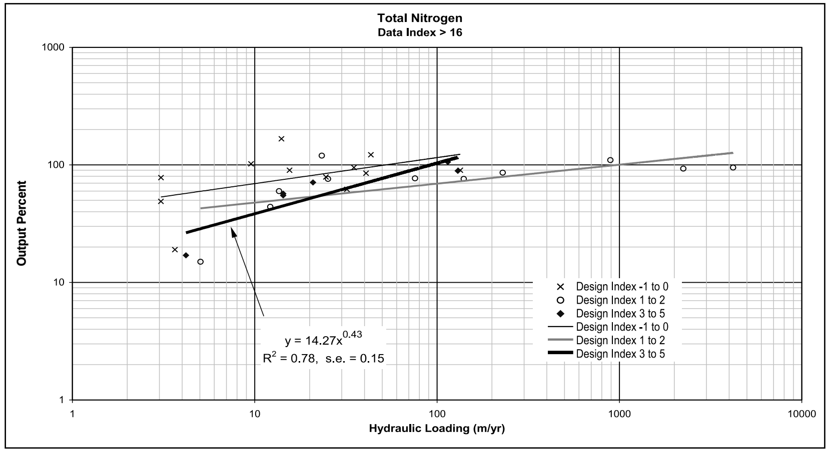


Figure 19: Predicted outflow TN concentrations as percentage of inflow concentration from statistical analysis of Australian and overseas date

The key independent variable in each of the three wetland performance relationships is the mean annual hydraulic loading rate, defined as the ratio of the mean annual runoff to the surface area of the wetland. In the case of TSS, the inflow concentration was also found to be an important independent variable. These relationships partly account for meteorological and hydrological differences between the catchments of the 76 wetlands used in the regression analysis. While the standard errors of these performance curves are large, they nevertheless provide a preliminary basis for determining the wetland size required to meet a pollutant removal target.

A number of other techniques exist for the sizing of wetlands, including curves representing the relationships between hydraulic residence time and pollutant removal for TSS, TP and TN. These curves were derived from field monitoring, but generally do not have sufficient data, and consistency and rigor in monitoring techniques, to allow their wide application.

Lawrence and Breen (1998) have generated typical relationships between TSS and TP removal efficiencies and hydraulic residence times based on coagulation and settling rates of particles. In generating these relationships, characteristic particle size distributions were used to determine the percentage removal of suspended solids. A typical characteristic phosphorus adsorption-particle size fraction relationship was adopted in determining the removal of total phosphorus through suspended solids sedimentation. Adjustments were then made to the total phosphorus removal efficiency for a range of biological and chemical processes such as biofilm uptake and remobilisation of phosphorus from the sediment.

Monitoring wetland performance

Constructed stormwater wetlands are often sized to meet a specific target water quality at the wetland outflow, or a target percentage removal of inflow pollutant concentration. To guide the design of stormwater pollution control wetlands, performance data of constructed stormwater wetlands in Australia and overseas may be used to provide a broad indicator of expected performance of these systems.

A common measure of wetland pollutant removal effectiveness is the percentage reduction in pollutant concentration, or the pollutant 'removal efficiency', RE, which is expressed as:

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

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 can often mask the effects of significant influences of the wetland system operating conditions on the wetland system's effectiveness as a water pollution control facility.

These operating conditions include:

- **background pollutant concentration** levels
- input concentration
- hydraulic loading (ratio of mean discharge to wetland surface area)
- hydraulic residence time of the pollutant phase

Each of the above factors influences the performance of a wetland, as measured by RE, in a non-linear manner. The combined effects of these factors can 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 of these RE values to determine the ‘mean pollutant removal efficiency’, without relating the individual measures to the above factors of the corresponding events is inappropriate, but nevertheless common in practice. In comparing RE values derived for different wetlands, the above four factors must also be incorporated to allow a common basis for comparison.

Background pollutant concentration

The background pollutant level is the pollutant concentration within the wetland caused predominantly by physical mechanisms within the wetland, and which has little relationship with the quality of the inflow to the wetland. For example, the background concentration of TSS can be related to the mechanism of flow turbulence in re-suspending fine solids in the wetland, thus maintaining a ‘background’ level of TSS concentration independent of the quality of the inflow. A recent analysis of water-quality data in a constructed wetland has established clear relationships between the background concentrations of TSS, BOD, COD and TP with the flow rate through the wetland, supporting the notion of a background concentration driven by the physical flow conditions within the wetland system.

SUMMARY

As shown in this report, the proper design of constructed wetlands for treatment of urban stormwater is a multi-disciplinary task. Early planning, identification and prioritising of the various beneficial uses are vital in ensuring a sustainable urban stormwater management and urban design system.

The 'flashy' nature of urban stormwater runoff results in a wide variability in stormwater wetlands operation. This is perhaps the single most important characteristic that differentiates urban stormwater wetlands from natural wetlands and wetlands used in wastewater treatment. Due to this variability, important design criteria for particular wetland features may vary, depending on site-specific characteristics. Research results presented in this report have indicated that many hydrologic, hydraulic and botanical factors interact to influence the operation of constructed stormwater wetlands as a stormwater-quality treatment system.

The key design considerations are:

- Treatment performance of a constructed stormwater wetland results from the combined effect of the wetland's hydrologic effectiveness and treatment efficiency.
- Constructed wetlands are stormwater detention systems. The hydrologic effectiveness of a wetland reflects the interaction of three factors – detention period, inflow characteristics and storage volume – and defines the overall percentage of catchment runoff introduced to the wetland for treatment.
- The treatment efficiency of a wetland depends on the hydraulic efficiency and the botanical design of the wetland.

The recommended features of a constructed wetland are:

- A constructed stormwater wetland should consist of a minimum of two cells – an open water inlet zone and a macrophyte (vegetation) zone, with an associated high-flow by-pass system for the macrophyte zone.
- The macrophyte (vegetation) zone should be allowed to fill and drain regularly in response to the intermittent inflow of stormwater runoff from the catchment.
- The wetland outlet design should consist of a riser, with the lowest outlet hole located to create a permanent pool equal to 10% to 15% of the total storage volume.
- The wetland should have a length-to-width ratio exceeding 3 to 1, unless steps are taken to incorporate such features as flow spreader berms and islands to promote more uniform flow pattern.
- Wetland vegetation and basin depth variation should be banded perpendicular to the flow path.
- The outlet structure should provide for manual control of water level and duration of inundation to facilitate vegetation establishment and management.

The creation of constructed wetlands requires the coordination of civil works and wetland vegetation establishment. While the management of civil works is well understood, site management of the wetland establishment phase is not. Wetland vegetation establishment requires well-prepared planting stock and good site preparation. The provision of well-prepared planting stock includes:

- selection of appropriate local species

• propagation of plant stock, which may require many months

Good site preparation includes:

• provision of suitable top soil

• control of weeds and pests

The interaction of hydrologic, hydraulic and botanical factors directly determines the treatment performance of constructed wetlands for stormwater management. This report highlights the effect of this interaction at both the catchment and local scale. The CRCs for Catchment Hydrology and Freshwater Ecology are preparing a comprehensive guide to integrate these factors into the design of constructed stormwater wetlands.

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GLOSSARY

Antecedent storage condition - The level of water within a wetland prior to the onset of the next inflow event.

Aquatic macrophyte - A large plant capable of living in water or periodically inundated habitats; see macrophytes.

Bathymetry - The topography or the shape of the land below the water surface.

Biofilm - A growth of microscopic organisms (i.e. bacteria and algae) living on any available surfaces (e.g. plant, rock, sediment) in the water body; see ephiphytes.

Constructed wetland - An artificially created system containing pond, marsh and swamp features. The dominant element of the system is the vegetation of the marsh and swamp zones which either requires or can withstand wetting and drying.

Detention time - The time it takes for a "parcel" of water to flow from the inlet of a wetland system to the outlet. Depending on the flow path taken by individual parcels of water, the time may vary significantly within the one system.

Emergent aquatic macrophyte - Large aquatic plants, typically rooted in the sediment, but characterised by sections of the plant (e.g. leaves and stems) which emerge above the water surface.

Ephemeral - A short-lived, transitory event or occurrence often used to describe the life cycle of plants and animals. When used to describe wetlands, ephemeral refers to habitats that are either rarely inundated or only inundated for a very short period of time.

Epiphytes - A plant which lives on the surface of another plant but does not derive water or nourishment from the host; in this document, epiphytes generally refer to algae growing on the surface of aquatic macrophytes; see biofilm.

Flood retarding basin - A temporary flood storage system used to reduce flood peaks.

Flow attenuation - The reduction in peak flow resulting from the temporary storage.

Gross pollutant trap - A structure used to trap large pieces of debris (> 5 mm) transported through the stormwater system.

Hydraulic efficiency - Describes the extent to which uniform flow conditions occur at any wetland cross section.

Hydraulic roughness - Surface roughness of any medium that influences the velocity distribution of flow.

Hydraulics - The science of the conveyance of water through a natural or artificial structure (e.g. wetland, pipe, channel).

Hydrodynamics - The fluctuation or changes in flow behaviour (depth, direction, etc.) within a waterbody resulting from the interaction of hydrologic and hydraulic attributes of the system and surrounding environment.

Hydrologic effectiveness - Describes the interaction between runoff capture, detention time and detention volume within a wetland system.

Hydrologic regime - Describes the long-term spatial variation in the water depths and period of inundation within a wetland system.

Hydrology - The science of the natural occurrence, distribution and movement of water.

Macrophyte - A large plant including macroscopic algae, mosses, ferns and flowering plants; a term commonly used to differentiate large plant from microscopic plants. Sometimes also used to describe aquatic macrophytes; see aquatic macrophytes, emergent aquatic macrophytes, submerged aquatic macrophytes.

Permanent pool - The level of water retained within a basin below the invert of the lowest outlet structure.

Plug flow - Flow conditions where all “parcels” of inflow have the same detention time. In this document this term is also used to describe flow conditions where a constant detention time is achieved, but is less than maximum (Q/V) because of ineffective flow volume, i.e. ‘apparent’ plug flow.

Pond - A small artificial body of open water (i.e. dam or small lake).

Rhizomateous -The pattern of plant growth originating from an underground stem-like root system.

Stochastic - The random variability in the occurrence and magnitude of a parameter (e.g. rainfall, streamflow, etc.)

Submerged aquatic macrophyte - A large plant that predominately grows below the surface of the water.

Wetland - An area transitional between land and water systems, which is either permanently or periodically inundated with shallow water, and either permanently or periodically supports the growth of aquatic macrophytes (e.g. marsh, swamp, fen, bog).

APPENDIX A

FREQUENTLY ASKED QUESTIONS

Since the first publication of this report, Associate Professor Tony Wong (CRC for Catchment Hydrology), Dr Peter Breen (CRC for Freshwater Ecology), and Mr Alf Lester (LFA Pty Ltd - Urban Designer) have presented four industry seminars on Constructed Stormwater Wetlands to over 600 people in Melbourne, Canberra, Sydney and Brisbane. A number of questions were asked during these seminars; this appendix represents a summary of the answers to the seven most common.

1. How do climatic factors and catchment characteristics influence the design and operation of constructed wetlands?

Answer

Climatic factors

Climatic factors affecting the design of a constructed wetland include the mean annual rainfall, seasonal variation of rainfall and the inter-event period.

The inter-relationship between the required size of the wetland to meet a level of treatment (in terms of detention period) and the hydrologic effectiveness are influenced by these climatic factors. For example, Auckland has a slightly higher mean annual rainfall than Brisbane (1330 mm compared with 1150 mm), but a constructed wetland's size in Auckland need only be 40% of that in Brisbane to achieve the same treatment effectiveness. This is because rainfall in Auckland is more evenly distributed throughout the year.

The design of the inlet structure may be influenced by the typical intensity of rainfall events in the catchment. Catchments with higher hydraulic loading of the system may require the inlet zone to provide a higher level of "hydrologic pre-treatment" in the form of flow attenuation for the macrophyte zone.

The design and selection of the outlet structure can often be influenced by the climatic characteristics of the catchment. For example, regions with a distinctive wet and dry season may benefit from a siphon outlet structure which allows for a much longer detention of stormwater inflow during the dry season - this would also promote a more diverse botanical structure in the wetland.

Catchment Characteristics

Catchment characteristics affecting the design of constructed wetlands include the land use, geology and terrain.

Catchment landuse and geology affect the pollutant types and hence the target pollutant characteristics for configuring the constructed wetland, eg. on line vs off line systems, ponds vs wetlands and detention period. The terrain of the site can sometimes preclude the construction of a wetland system, and a pond system (with longer detention periods) may have to be employed.

2. Land developers often view areas of open water (lakes and ponds) as more marketable in land development than areas of aquatic vegetation (wetlands). What issues should be taken into account to arrive at the right balance between these elements in a particular development?

Answer from a technical perspective

Good site analysis and clear runoff treatment objectives are crucial to the appropriate selection of a stormwater treatment and management system.

Well-designed constructed wetland systems contain many of the treatment features of ponds, with some additional treatment mechanisms associated with wetland vegetation. Where space is available and topography is suitable, a constructed wetland system can potentially offer a greater range of treatment processes and improved treatment performance. In steep terrain it may only be practical to utilise ponds. Similarly, in a catchment where the geology results in the production of coarse suspended solids with little associated nutrients, it may not be necessary to utilise the additional treatment mechanisms provided by a constructed wetland system. In catchments where significant quantities of fine sediments and nutrients are generated, it is advisable to employ constructed wetlands if the topography is suitable.

If ponds are employed a number of issues need to be considered:

1. Inlet and outlet structures need to be designed to minimise short-circuiting during periods of in-pond stratification.
2. The likely reduced removal efficiency for fine particles.
3. The organic loading to the system necessary to avoid the development of low sediment redox conditions, which can result in the release of pollutants trapped in the sediments.
4. The likelihood that there will be at least some periods when water quality in the system will conflict with other beneficial uses, such as landscape and aesthetic values.

Where constructed wetland systems are employed the following issues need to be considered:

1. Inlet and outlet structures need to be designed to minimise short-circuiting.
2. Wetland basin design has to be matched to catchment hydrology in order to produce a wetland hydrologic regime that will support and maximise vegetation diversity.
3. The vegetated component of the system needs to be appropriately placed in the treatment train so it is protected from coarse sediments.
4. The design needs to consider specific faunal habitats and conditions, eg. adequate mosquito predator habitat is required, whereas extensive water bird breeding habitat may jeopardize water quality objectives.

Answer from a landscape and urban design perspective

This question can probably be best answered by looking at the planning stage of wetland development. It is critical that the overall form of the wetland is read in its surrounding context, ie. where most people will view the wetland (viewslots) ensure that this view takes in a proportionally larger area of clear water. This gives an impression of a larger expanse of water than might exist. The open water zone can be achieved by creating deep water relatively close to the edge, or by producing a “stepped” edge (shallow narrow shelf then a steep drop-off). Similarly, where most people have access to the waters edge, it may also be appropriate to create a clear water zone, giving a different visual impression of the wetland.

The type and scale of wetland planting also plays a critical role in the end vision. Where water views are desirable, choose plants that do not become too tall, or are submerged/semi-submerged, so that it is possible to look over them to a larger expanse of open water. Wetland planting can also produce marked seasonal changes in the character of the wetland, as some species die down and others proliferate. Hence the expanse of open water may vary throughout the year.

In summary - some helpful hints

Examine carefully the site context of the wetland, taking into consideration where the majority of people will view the wetland from. Manipulate the shape of the wetland where possible to allow for expanses of open water closest to public view and allow for accessibility to a clear water zone eg. boardwalk, jetty, small boat ramp. Carefully select wetland planting types, particularly where it is important to create unobstructed views and take into account seasonal variations.

Recreational and visual values are important when considering the placement of wetland systems within public open space. An enlarged open water zone at the outlet end of the wetland or an additional downstream water body can provide landscape and aesthetic opportunities. Where land and economic constraints allow, these values can be included without being compromised by poor water quality.

3. What are the key maintenance considerations in a constructed wetland system?

Answer

Wetland systems are low maintenance systems, not 'no maintenance' systems. Constructed wetlands are treatment systems designed to facilitate the removal of stormwater pollutants and thereby protect the ecological heath of the receiving waterbody. Partitioning of treatment components in a wetland system allows for maintenance of individual components to be targeted:

Gross pollutant traps (GPTs) are designed to remove natural and gross litter from human activities. (Gross litter is defined as litter greater than 5mm in diameter). Gross pollutant loading in urban catchments can be high and maintenance frequency of GPTs is often in terms of months. The maintenance operation is dependent on the type of trap; the pollutants removed can normally be safely disposed of in landfills. Gross pollutant traps with a permanent pool can cause odour problems, and maintenance frequency may need to be increased. Access for frequent and efficient maintenance operation is an important consideration in siting gross pollutant traps.

Inlet zone/sedimentation basins are designed to allow sedimentation of coarse to medium size particles. Maintenance frequency is between 5 to 10 years, depending on the geology, and level and maturity of development in the catchment. Maintenance involves mechanical excavation of the deposited sediment, so vehicle access is an important design consideration of the inlet zone. Deposited sediment can be disposed of in landfill provided care is taken to ensure that the basin is not over-designed to provide longer than required detention period, ie. longer than desired detention period promotes settling of finer material and associated contaminants (eg. metals). It may also promote the deposition of excessive organic material leading to possible reduced redox potential in the sediment and subsequent release of sediment-bound contaminants.

The macrophyte zone is responsible for the trapping and settling of fine particulates; typical maintenance operation of this zone includes weed control and removal of dominant macrophyte species which may alter the hydrodynamic flow characteristics of the wetland. Water level manipulations may be necessary as a means of controlling excessive dominance of macrophyte species, as well as promoting the rapid degradation of organic matter. The removal frequency of deposited material and vegetation biomass is expected to be between 15 to 25 years. The deposited sediment may need to be disposed of as prescribed waste.

4. Constructed wetlands are often perceived as having public health and safety risks, eg. proximity of children to water, providing habitat for undesirable wildlife (snakes), increasing the risk of disease (toxicants in the waters). How can good design overcome these potential problems?

Answer

Odour problems are often linked to an overload of organic and solid pollutants followed by the process of eutrophication. This can be addressed, to a large extent, by ensuring that the inlet zone is designed to cater for such loads, eg. by incorporating gross pollutant traps in the pre-treatment to reduce the amount of solids entering the system. Where litter from human activities is not an issue, another alternative is to have multiple inlet points which are carefully placed within the system to disperse the load entering the system over a greater area.

Mosquito populations thrive in slow or stagnant water, so it is critical to maintain adequate flow within the wetland system, and design the system so that no stagnant pools occur. Alternatively, wetland systems that rely wholly on subsurface flow do not generate mosquito problems, but may not be perceived as visually attractive to the public. Often, their operation is not suited to the unsteady nature of stormwater inflow.

Native fish species also have a role to play in keeping mosquito populations in check. This reflects the need to encourage biodiversity of flora and fauna within a constructed system, as it will, over time, become more robust and self-sustaining.

There will always be a risk factor where water is in close proximity to children; no matter how deep or shallow it may be - a puddle or Sydney Harbour! Reducing this risk can be achieved by controlling access to the waters edge through the following ways:

- Planting **to** the waters edge to discourage access
- Planting **within** waters edge to discourage access
- Placement of pathways and clearly identifiable points (eg. jetty, ramp or beach) where access is permitted and safe
- Ensure that accessible water zones have clear sight lines from surrounding open space areas
- Adequate signage highlighting safety issues
- Use of shallow edge profile where access to waters edge is encouraged

Snake populations can be kept in check by encouraging biodiversity as discussed above. Otherwise this issue can be controlled, to some extent by maintenance at the appropriate time of year.

5. Uncontrolled mosquitoes are a specific public health and amenity issue with regard to the use of constructed wetlands. How can good design reduce this risk?

Answer

Mosquitoes are a natural component of pond and wetland fauna and the construction of any water body (ponds or wetlands) will create some mosquito habitat. Mosquitoes however are usually not a dominant component of the fauna in freshwater systems and are controlled by natural processes such as predation.

Where mosquitoes have become a dominant component of the fauna in freshwater systems (and are a public health risk) there are usually clear reasons:

- Water quality changes have impacted on predators
- The accumulation of plant litter or the growth of particular plant species has isolated areas of shallow marsh habitat from predators. In many systems this occurs as a result of reducing natural water level fluctuations
- Increased areas of ponded or slow moving water where natural predators eg. other insects, frogs and fish cannot reach

A number of relatively simple design and operational features will limit mosquito populations and reduce public health risks:

- Ensure predators such as other insects, frogs and fish have access to all parts of the water body
- Ensure a proportion of the system is permanently inundated and acts as a refuge for predators
- Ensure the system experiences natural water level fluctuations. This interrupts the breeding cycle of some species and strands the larvae during draw down
- When water fluctuations occur ensure draw down is even so isolated pools are not separated from predators in the main body of water
- Ensure the system receives a distinct wetting and drying cycle to help maintain a desirable vegetation composition, breakdown plant litter and avoid excessive habitat partitioning by plant litter build-up
- Ensure human derived litter (eg. bottles, cans, cartons, etc.) does not accumulate in the system and act as an isolated breeding area
- Provide for artificial control over water level so seasonal adjustments can be made and active intervention undertaken
- Avoid directing low or trickle flows into overland flow paths. Where overflow paths are very flat or will be regularly engaged provide sub-surface drainage
- During both construction and maintenance periods avoid the use of heavy machinery that create wheel ruts, isolated pockets and impede uniform drainage

Mosquito control is relevant to all components of the treatment train from GPT to the recreational lake.

6. What are the management requirements of the vegetated zone? Do the emergent aquatic macrophytes need to be harvested?

Answer

The major long term management strategy for vegetation is to ensure that the different vegetation zones receive an appropriate hydrologic regime. This will allow the target specie(s) for a particular zone to survive naturally and have a competitive advantage over potentially invasive species. A major element of vegetation management is to ensure as natural a hydrologic regime as possible. Most natural hydrologic regimes are variable, characterised by water level fluctuations and wetting and drying cycles. The normal water level of a system has to be able to vary up, but particularly down, in a relatively seasonal way to ensure good vegetation cover and stability. In constructed wetland systems, the design of the outlet structure is critical to achieving variable hydrologic regimes that are well matched to the requirements of vegetation. Weir outlets tend to miminise water level variation, whereas perforated riser outlets and siphons maximise variation and allow some control of the hydrologic regime and the wetland vegetation.

Harvesting of emergent aquatic macrophytes in stormwater treatment systems is not required as a pollutant removal mechanism. The major role of vegetation in pollutant removal during event flows is its role in enhancing sedimentation processes, and providing surface area for the trapping and filtering of fine particles. During low flows, vegetation provides a surface for the growth of biofilms which promotes pollutant uptake and transformation. This is an important stormwater treatment process and consequently, the harvesting of vegetation could potentially decrease the treatment performance.

Over time, some large, deep-water species plantings, may build up a large amount of dead, standing plant material that can limit new growth, and result in a patchy vegetation distribution. Consequently, harvesting may occasionally be required to ensure vigorous and even growth across the flow path. Because of the vital role of vegetation in stormwater treatment systems, it is not advisable to harvest the whole system at one time. Should harvesting be required, the system should be progressively harvested, to ensure uniform hydraulic resistance across the flow path and to encourage vegetation diversity.

7. It is clear that the construction of some stormwater quality control devices and waterbodies within residential development will incur additional costs over and above what might be regarded as the standard order of costs for development. How can such additional costs be justified?

Answer

In part the answer lies in sensitive urban design that adds value to the estate. The allocation of open space, drainage corridors and flow management are now standard planning control and development conditions. There is already a clear requirement in many states to treat the quality of stormwater within the development site; often the use of constructed wetlands forms part of the Water Sensitive Urban Design strategy. The experience gathered from the design and development of a number of estates with significant water quality control devices, including waterbodies and wetlands, shows that these elements add to the character and help brand the estate.

Empirical data drawn from a number of projects indicates that the value of residential land, immediately adjacent to linear open space wetland/lakes, will sell at two to three times the average value received for residential lots within standard sectors of the estate. The increased value of lots adjacent to water elements also has a ‘ripple effect’. Although land values progressively decline with distance from the open space/water elements, there is a substantial added value that accrues to the whole of the estate, rather than only to those lots that line the perimeter of linear open space/wetlands.

Data also indicates that where a strong image has been created, and there has been a high level of ‘possession’ by the incoming community, there is a higher rate of sale than might otherwise be achieved. This higher rate of sale effectively translates into further added value for the estate. A result of this is a faster return on investment, helping to off-set any extra costs of development.

Stormwater management using ponds and wetlands may not be suitable for all developments either due to size or topography constraints. However, development conditions still need to be met and other Water Sensitive Urban Design techniques can normally be applied with little or no additional cost over conventional design.

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