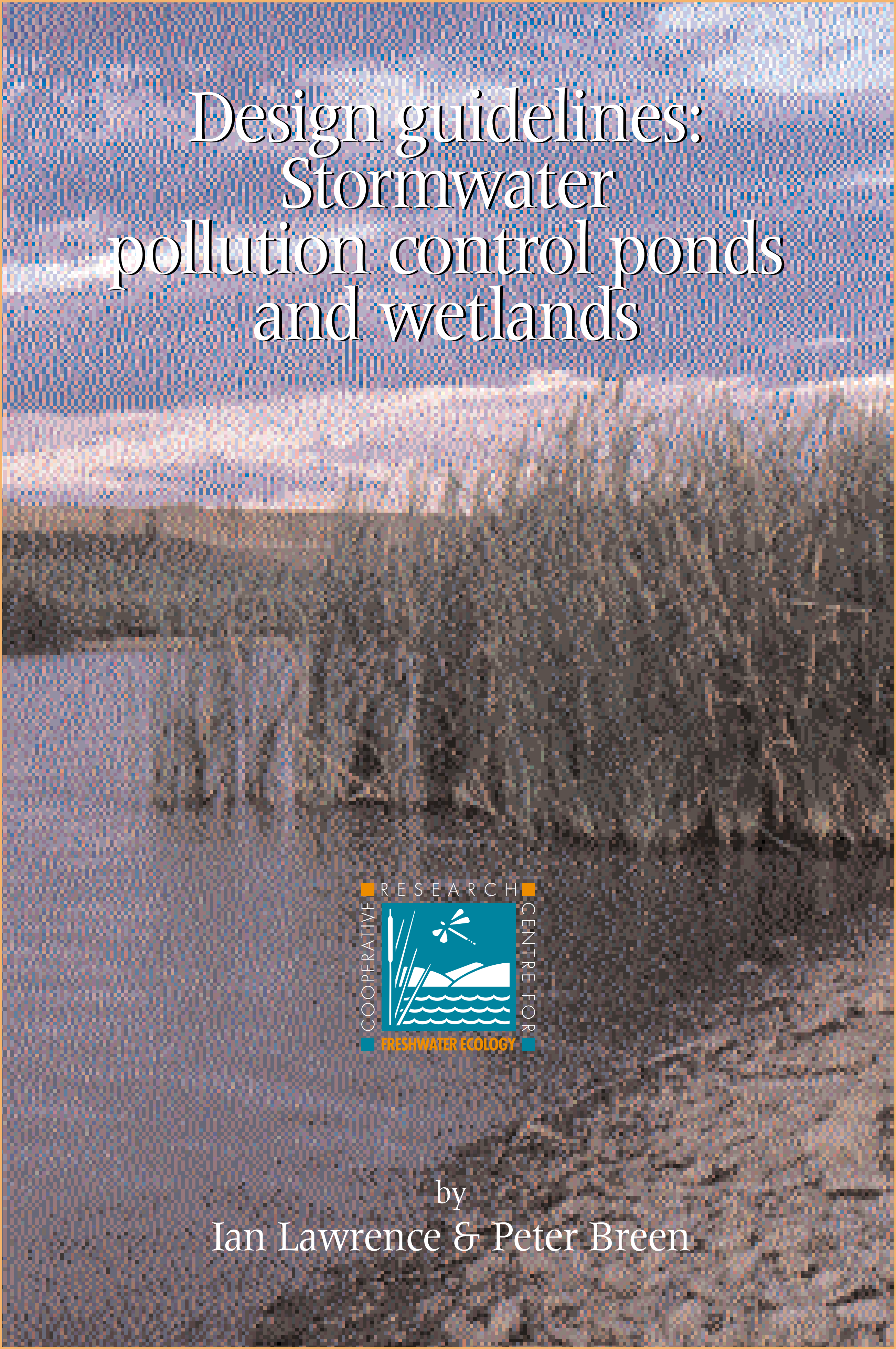
COOPERATIVE RESEARCH CENTRE FOR FRESHWATER ECOLOGY

DESIGN GUIDELINES: STORMWATER POLLUTION CONTROL PONDS & WETLANDS



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by

Ian Lawrence & Peter Breen

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The Cooperative Research Centre for Freshwater Ecology was established under the Australian Government's Cooperative Research Centres Program in 1993.

This CRC exists to improve the condition of Australia's inland waters. It provides ecological understanding to improve inland waters through collaborative research, education and resource management.
It is a collaborative venture between:

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July 1998

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Foreword

As a highly urbanised society, and the continent experiencing the greatest variability in rainfall, it is perhaps not surprising that urban stormwater has become one of the major environmental concerns in Australia. Urban communities are becoming increasingly concerned about the loss of open space and waterway values, and the degradation of large waterways.

As the water industry comes under greater performance scrutiny, there is an increased concern to ensure that the best available information is used in guiding decisions on urban stormwater management and the protection of the environmental values of downstream receiving waters.

The information contained in these Guidelines builds on research undertaken jointly by the CRC for Freshwater Ecology (CRCFE) and CRC for Catchment Hydrology (CRCCH) in the areas of stormwater pollution discharges, and pollutant interception in stormwater control ponds and wetlands. The material significantly advances our understanding of pollutant transport and transformation pathways, and our ability to select appropriate treatment facilities.

These Guidelines and the enclosed water quality models represent a valuable source of information for state and local government agencies, managers, consultants and the general public concerned with stormwater management and the protection of urban waterways.

Dr John Langford
Chairman CRC for Freshwater Ecology
Director of Water Services
Association of Australia

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Glossary of terms

Abiotic	Environmental features, such as those of soils or climate, that do not derive directly from the presence of organisms.
Adsorption	The taking up of one substance on the surface of another.
Advective forces	Gravitational forces moving water and its constituents longitudinally downstream.
Aerobic, oxic	An environment in which there is free oxygen.
Allochthonous	Plant and animal growth sustained by external inputs of nutrients.
Anaerobic, anoxic	An environment devoid of oxygen.
Attenuation	The temporary storage (detention or retardation) of stormwater to reduce the peak discharge rate of the storm runoff. Commonly used to alleviate flooding of downstream areas.
Autochthonous	Plant and animal growth sustained by internal recycling of nutrients.
Base flow	Regular flow of water when there has not been rain, which is usually due to seepage from the groundwater.
Benthic	Pertaining to the bed or substratum of a lake or pond.
Biofilm	A gelatinous sheath of algae and polysaccharides which adsorbs colloids and nutrients.
Biological uptake	Take-up of gas or fluid through cell membrane.
Biomass	The living weight of plants or animals.
Bioturbation	The physical disturbance of sediments by burrowing animals.
BMP	Best Management Practices or treatment measures most appropriate and practical for reducing the target pollutants.
BOD	Biochemical oxygen demand of bacterial breakdown of organic matter.
Chlorophyll	The green pigments in plants. Used as a measure of algal biomass.
COAG	Council of Australian Governments.

Coagulation	The aggregation of dispersed colloids into larger particles.
Colloids	Fine particles of typically 0.1 µm to 1 nm in diameter.
Constructed ponds	Small water bodies having a depth generally >2 m and containing zones of open water and zones of macrophytes.
Constructed wetlands	Small water bodies having a depth of <2 m and characterised by extensive macrophyte growth.
Continuously Stirred Tank Reactor (CSTR)	A simple means of describing mixing and the mass balance of pollutants within ponds and wetlands during rapidly changing storm discharge conditions.
Critical pollutants	Pollutants of primary concern because of their impacts on water quality and biota.
CSA	Cross sectional area.
Denitrification	The reduction of nitrate or nitrite to ammonia or nitrogen gas, in the absence of oxygen.
Detention basin	A basin designed to temporarily detain storm or flood waters, to attenuate peak discharge to acceptable levels.
Diffusion	Forces (eddy and molecular diffusion) promoting the mixing of water constituents throughout the water body.
	Relatively slow movement of a mass of gas or liquid into a solvent.
DO	The concentration of dissolved oxygen in water.
Dry weather flow	Base or low flow between storm discharge events.
EMC	Equivalent mean concentration: the mass of pollutant discharged in a storm event divided by the volume of water discharged in the event.
Epilimnion	The mixed surface layer of stratified lakes or ponds.
Ephemeral	Systems which exhibit flow or presence of water only periodically
Epipelon	Algal community living in or on the surface of sediments in shallow waters where light penetrates.
Epiphytes	Algae attached to the surfaces of other plants.
Eutrophication	Enrichment of water with nutrients, causing abundant plant growth.
Event	A rainfall or discharge condition which is significantly different (>10 times) from the day to day background levels.
Eh (redox potential)	The value of the redox electrolyte potential, expressed in volts, using an electrochemical cell.
Flow attenuation	(see Attenuation).
Flux	Rate of movement of a mass or quantum of heat.
Grassed swales	Shallow grassed channels, designed to intercept and drain surface runoff.
Greenfield development	Broadacre subdivision on land previously used for agriculture or native vegetation.
Gross pollutant trap (GPT)	A trap designed to reduce flow sufficiently to enable sedimentation of the medium silt and larger suspended solids fraction, and to intercept (by screening) trash and debris entrained by stormwater.
Groundwater	Water found beneath the ground surface, in the soil and in rock aquifers.
Heterotrophs	Bacteria and other organisms dependent on organic carbon as food source.
Hypolimnion	The layer of water below the thermocline in stratified water bodies.
Infiltration or percolation trenches	Trenches filled with permeable material (gravel) and placed to intercept stormwater and direct it to permeable soil or groundwater zones.

Interflow	Water that enters and flows through the surface soil layers, emerging, relatively quickly, further downslope.
Ionic composition	The composition and concentration of anions and cations in water.
Leachate	Water that has passed through, and contains soluble material removed from, the sediment or soil.
Macrophytes	Large aquatic plants, either emergent or submerged.
Nitrification	Process by which bacteria convert nitrogen compounds into nitrate in the soil.
Off-line	Not in the direct flow path of the stormwater drainage system.
On-line	In the direct flow path of the stormwater drainage system.
Overtopping	High discharge rates which exceed outlet pipe or primary spillway capacity, and flow over the top of the embankment or weir bounding the pond or wetland.
Oxic	(see Aerobic).
Oxidation	Chemical addition of oxygen, removal of the hydrogen ion or loss of electrons.
Oxycline	The plane of maximum rate of oxygen concentration decrease in respect to sediment depth.
Particulate	Particle.
Perennial	Systems which maintain continuous flow or presence of water.
Planktonic algae	Algae suspended in water.
Podzolic soils	Soils with distinct layers (horizons) down the profile.
Redox level	A measure of the electron activity or oxidising–reducing conditions
Reduction	Chemical removal of oxygen, addition of hydrogen ions, or addition of electrons, by a reducing agent.
Retention time	The time that inflowing water is retained in a pond or wetland before discharge.
Sedimentation	Process of particles settling out of the water column onto the sediment below.
Short circuiting	A situation where a discharge to a pond or wetland follows a direct route to the outlet, without fully mixing across the pond or wetland water storage.
SPMs	Suspended particulate material.
SS	Suspended solids.
Stratification	The density separation of layers of water vertically, as a result of differences in temperature or salinity.
Thermocline	The plane of maximum rate of temperature drop with respect to depth.
Throughflow	Water that flows down to the watertable and enters the groundwater.
TN	Total nitrogen.
TOC	Total organic carbon.
TP	Total phosphorus.
Treatment train	A series of treatment processes designed to collectively meet a prescribed water quality objective.
Vegetated waterways	A natural or constructed channel, in which surfaces comprise natural grass, shrubs and aquatic plants rather than concrete lining.

List of units and symbols

Units

g	gram weight
ha	area in hectares
kg	kilogram weight
km^2	area in square kilometres
ML	megalitres
mg/L	milligram per litre
m^3/s or m^3/day	cubic metres per second or per day
mm	millimetres
mg/L	microgram per litre

Symbols

A	area in hectares or km^2
BOD	biological/biochemical oxygen demand
C	coefficient of runoff
C_{infl}	concentration of pollutant in inflow to pond or wetland
C_{pd}	concentration of pollutant in pond or wetland
C_{pd}	concentration of pollutant in pond or wetland following inflow period
C_{sp}	coefficient of discharge over spillway
c_p	friction coefficient of pipe
csa	cross sectional area
c_w	specific heat of water
D	diameter of pipe
d	particle diameter
d	pond, wetland or spillway water depth
Eh	redox potential
g	acceleration due to gravity
H	diurnally averaged solar heat flux
L	length of spillway
MAF	mean annual flow
MAP	mean annual precipitation

Symbols

n	number of dry-weather flow days following event
nM	Mannings coefficient of friction
P	rainfall in mm
pH	index of the concentration of the hydrogen ion in solution: a measure of acidity
Q	discharge in ML/d of m^3/s
R	runoff depth in mm
R_{Rey}	Reynolds number
r	hydraulic radius
r_b	daily adsorption rate of biofilm
S	stratification parameter (non-dimensional)
SS	suspended solids
s	hydraulic gradient
T	temperature °C
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
t_{retent}	retention time in days
u	diurnally averaged wind speed
V	volume of runoff in kL
V_{pd}	volume of pond or wetland in ML
v	velocity in m/s
W	oxygen transfer rate $g/m^2/day$
w	width of pond or wetland
α	coefficient of thermal expansion of water
β	temperature correction coefficient
γ	specific weight of water
γ_s	specific weight of particle
ρ	density of water
η	settling efficiency
ν	kinematic viscosity in m^2/s

1. Introduction

Urban stormwater has become one of the major environmental concerns in Australia during the 1980s and 90s. This is partly because urban areas continue to grow, placing urban catchments under greater stress. As a result, urban communities are concerned about the loss of open space and waterway values and there is a perception that large waterways are continually being degraded, in spite of substantial public investment in the upgrading of wastewater treatment facilities.

Federal, state and local governments have decided that one means of addressing these concerns is to institute legislative and administrative requirements to establish stormwater pollution control measures.

Constructed ponds and wetlands are now widely recognised as effective treatment facilities for controlling pollution, for restoring stream values within urban areas, for their recreational and aesthetic qualities, and for conserving flora and fauna. Ponds and wetlands are particularly attractive with their assured ability to substantially reduce (by 50% to 80%) the discharge of stormwater pollutants, provided they are properly designed and sited.

At the outset of the CRC for Freshwater Ecology (CRCFE), the urban water industry said it had a major need for better information to guide the selection and design of stormwater management measures. At that time, published information and models were generally empirically based: it was not clear if they could be applied to catchments having different climatic, hydrological and soil characteristics. It was plain that there was a need for an approach that could be adapted with confidence to local conditions all over Australia, from the tropics to Tasmania.

As well, there was growing awareness of the complexity of pollutant movement through the landscape. It seemed necessary to move away from simplistic, empirically based models, to an approach based on a better understanding of the dominant processes—physical, chemical and biological—that determine the transport, transformation and fate of pollutants.

Research undertaken by the CRCFE in response to these information needs has identified a number of different pathways for the transport, transformation and transfer of stormwater pollutants. This finding has major implications for the selection and design of treatment measures, particularly for constructed ponds and wetlands.

These guidelines summarise the research findings to provide useful background information for stormwater managers all over Australia. Building on this understanding, they show the user how to select and design stormwater treatment ponds and wetlands.

The guidelines* describe how a range of ponding treatment zones and plant treatment zones can best intercept pollutants, and they discuss the selection and arrangement of treatment zones that respond best to specific pollutant forms and discharge

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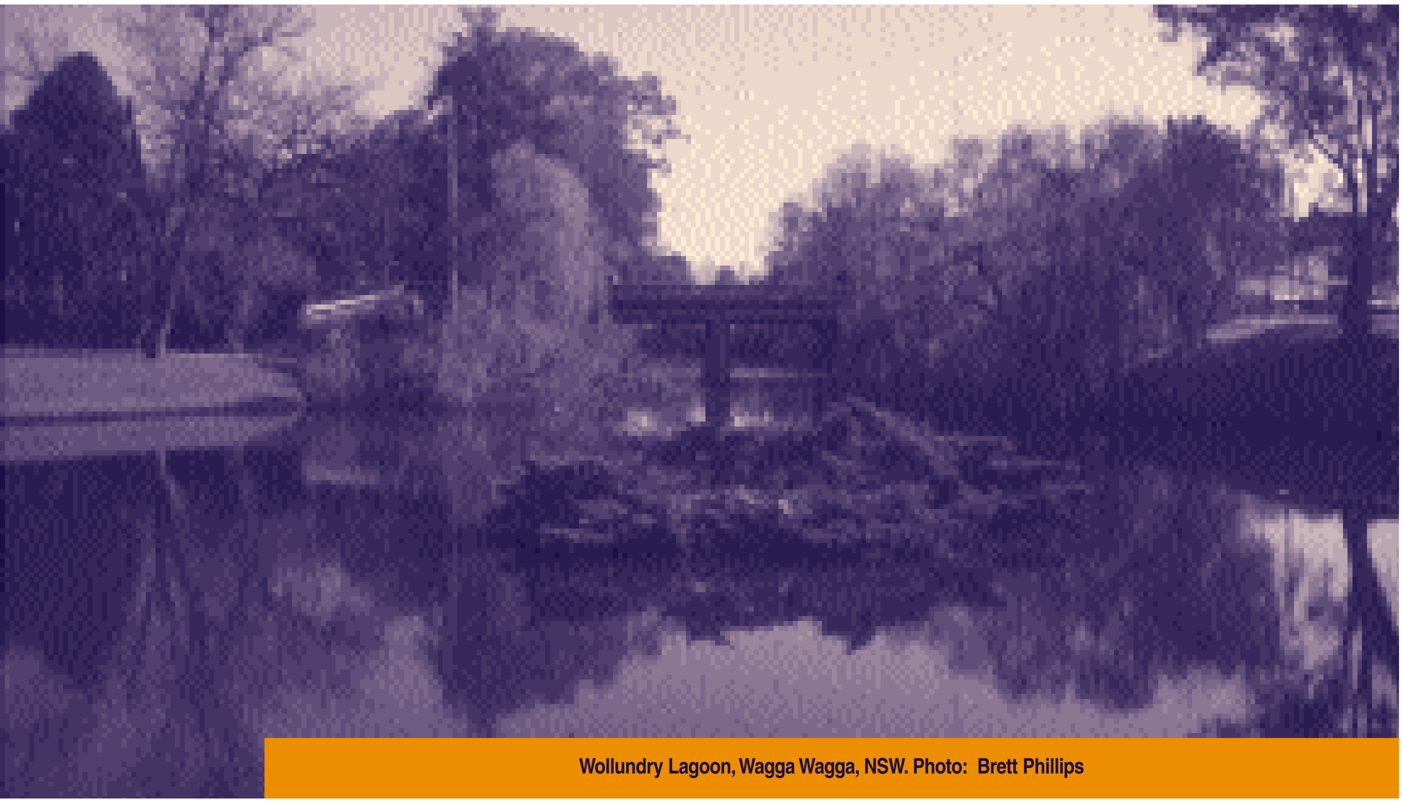
* This version of the guidelines will be refined and updated as knowledge advances



Wollundry Lagoon, Wagga Wagga, NSW. Photo: Brett Phillips

conditions. They guide the choice of management measures appropriate to a catchment and its local climate, hydrology and water quality composition; and they provide decision support tools that help the manager, regulator or consultant decide which measures to use.

Report structure

First, the guidelines outline the legislative and administrative framework of urban stormwater management, and define the meanings of the terms ponds and wetlands as used for that purpose.

Chapter 2 considers the catchment context of urban stormwater: the hydrology, the discharges of pollutants, which pollutants are critical, and by how much they must be reduced to protect downstream waterways. The chapter outlines the techniques for estimating the volumes of stormwater runoff and exported pollutants that can be expected. It shows how to select treatment measures that will be appropriate to deal with the runoff and pollutant exports that characterise a catchment—measures which suit the relevant objectives for critical pollutants and their reduction.

Chapter 3 describes the pollutant pathways and the processes of transformation and transfer, and then provides guidance for deciding on the appropriate size and design of the pond or wetland.

Five case studies in these two chapters demonstrate practical use of the guidelines formulae, in Victoria, Queensland and ACT.

Chapter 4 considers the ecology, safety and aesthetics of pond or wetland design, while Chapter 5 outlines the operation and maintenance issues.

Graphs and simple formulae are given in the text so the reader can determine the size of pond or wetland that is required for various conditions of runoff. Appendices A, B and C give details and background material: A describes the assessment of water quality and pond or wetland performance via monitoring; B gives techniques for determining local in-pond interception curves and particle size grading. Appendix C gives instructions for using a series of computer models (the Pond and Wetland Water Quality Models) that assist the manager, regulator or consultant to determine the most cost-effective design to meet the objectives for environmental protection or restoration.

1.1 Policy and administrative context

Over the last decade, the Council of Australian Governments (COAG), consisting of federal, state and local government representatives, has devised a range of environmental policies that have implications for the manner in which stormwater is managed.

The National Strategy for Ecologically Sustainable Development (COAG 1992a) requires Australians to use and manage land and water in ways that are consistent with maintaining ecological processes now and into the future.

The Intergovernmental Agreement on the Environment (COAG 1992b) requires Australians to protect the biological diversity of the environment and conserve rare and endangered species. The Agreement also defines and initiates a national 'State of the Environment' reporting framework. State of the Environment assessment is used as the basis for measuring performance against the objectives for ecologically sustainable development (ESD) and biodiversity. Assessment based on the composition and diversity of biota has become the basis for measuring the 'health' of streams.

The Australian and New Zealand Environment and Consultative Committee (ANZECC), in association with the Agricultural and Resources Management Committee of Australia and New Zealand (ARMCANZ) adopted The National Water Quality Management Strategy: Policies and Principles (ANZECC 1994) as the basis for integrated management of land and water resources in Australia.

The Strategy expects managers to apply a management process which:

- integrates land and water management in total catchment-based management;
- considers a comprehensive range of social, environmental and economic benefits and costs;
- maximises stakeholder involvement in the development and implementation of the plan.

The COAG Water Reform Policy (COAG 1994) (the Neal Report) requires that the National Water Quality Management Strategy be fully implemented, as an integral part of the Water Reform Policy.

CRCFE researcher Richard Norris sampling macroinvertebrates in a Canberra lake with Landcare coordinator, Mary Ormay. Macroinvertebrates provide valuable information about the condition of our waterways.

State, territory and local governments have responded to these initiatives by establishing urban catchment boards, trusts and committees and administrative procedures. These require managers to adopt integrated strategies for their catchments, addressing the management of stormwater flows and pollution in a comprehensive manner.

The National Water Quality Management Strategy identifies the Australian Water Quality Guidelines (ANZECC 1992) (AWQG, revision in preparation) as the reference document that specifies the environmental designations for freshwaters, and defines water quality guidelines for securing their protection.

An early draft of the revised Guidelines proposes that managers:

- adopt risk-based assessment of potential hazards or impacts;
- adopt issue-based assessment, focusing on major factors that impair water quality;
- develop guidelines, based on reference ecosystems;
- recognise the load-based nature of many systems, and in particular, urban systems;
- recognise modified (urban) systems as a management category.

Ponds are dominated by areas of clear water. A pond in Canberra. Photo: Ian Lawrence

There is a wide range of possible measures that can be used to limit and ameliorate stormwater pollution, to respond to pollution reduction requirements, including:

- raising community awareness of the effects of the use and disposal of household chemicals, garden fertilisers, pesticides and herbicides;
- taking every opportunity for on-site reuse of stormwater and household grey-water;
- adopting on-site infiltration and retention measures; and
- constructing interception devices such as gross pollutant traps, ponds and wetlands in drainage corridors.

1.2 Ponds and wetlands and what they do

In general, 'wetlands' is a generic term used to describe marsh and swamp environments, in which emergent and submerged plants are the dominant feature. `Pond' is a term generally used to describe small water bodies having areas of clear water and emergent macrophytes around their edges.

In some respects, this terminology is simplistic in that aquatic plant zones are a critical component of ponds, just as water ponding is a critical part of wetlands. However, treatment facilities tend to be either predominantly open water systems (termed ponds) with associated macrophyte zones in the discharge transitional zone and littoral zones, or predominantly macrophyte systems (termed wetlands) with some pondage to adsorb variations in flow. The choice of the one or the other reflects the distinctive differences in pollutant forms and loading conditions that they suit.

Previously, the sole focus of pond and wetland design was the reduction in the mass of pollutants (suspended solids, nutrients, organic and heavy metal toxicants) exported from catchments.

It is now appreciated that the form of these potential pollutants is as critical as the quantity. A pond or wetland that transforms even a portion of its intercepted nutrients, metals and organic molecules into forms that are more bioavailable (dissolved), as a result of sediment reduction processes, may seriously undermine an otherwise benign pollutant export condition. Pond and wetland sediments must remain effective as sinks for pollutants in the long term.

The health of downstream water bodies can be seriously endangered if treatment facilities are installed that are too small or incorrectly placed—this only worsens the pollution downstream. It is very important to design a treatment facility (or sequence of treatment facilities) to match its catchment, and to base the design on the very best local information that can be gathered.

2. Selection of catchment management measures

The need to design a new pond or wetland, or to assess existing ones, usually arises from concerns about the existing or potential future impacts of urban runoff on downstream waters.

This chapter considers how urbanisation modifies the movement of water and its constituents through the landscape, and the implications of these changes for downstream water quality and ecology. The chapter introduces the concepts of critical pollutants and pollution reduction targets: that is, the reduction in pollutant exports required to protect or restore downstream water quality.

The chapter outlines techniques for estimating how much stormwater runoff and pollutant export can be expected. It helps managers select treatment measures that will be appropriate to deal with the expected quantities of water and pollutants that will achieve the desired retention of critical pollutants.

2.1 Catchment context

Runoff and its constituents are determined by the terrain, soils, vegetation, drainage morphology and rainfall of a catchment. Vegetation intercepts rainfall, enhances infiltration and soil moisture storage capacity, and depletes the store of soil moisture through evapotranspiration. As water percolates through the soil, it dissolves and transports the minerals of the soil, discharging ultimately to natural drainage channels. Where soil moisture stores become saturated, or intensive rainfall occurs, overland flow may result. The overland flow may dislodge and transport particles of soil and organic material from the surface, ultimately discharging this material to natural drainage channels.

The urbanisation of catchments entails clearing vegetation, modifying drainage systems, imposing substantial areas of impervious surfaces (roofs, paving, roadways), and human activities involving the application of nutrients, hydrocarbons, pesticides and metals (see Fig. 2.1 *Urban Water and Pollutant Cycle*). As a result, the volume of runoff typically increases threefold for urban catchments as compared to their pre-urban (grazing) runoff conditions, while the rate of runoff typically increases sevenfold. Associated with these changes are significant increases in the capacity of runoff to mobilise and transport particulate material such as soil, metals, and organic substances. This increased mobilisation and transport capacity typically increases the export of pollutants by seven to 10 times compared to pre-urban grazing conditions (see Table 2.2).

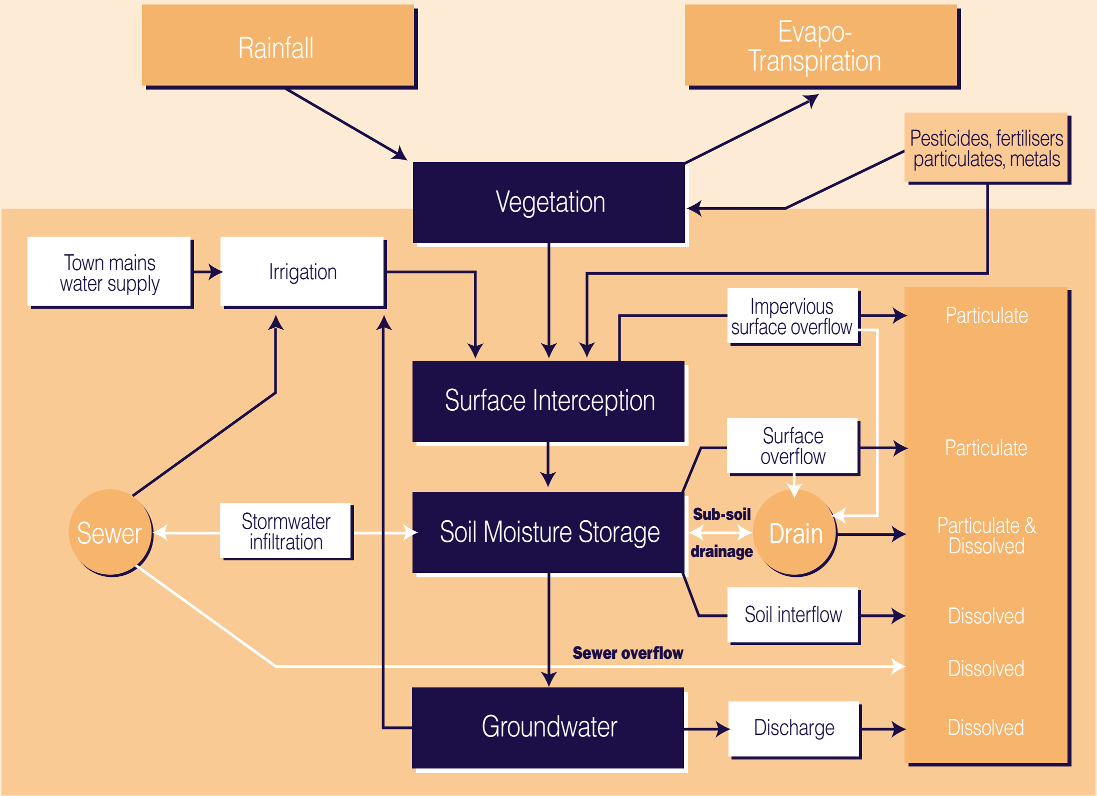


Figure 2.1. **Urban water and pollutant cycle**

2.2 Critical pollutants and receiving water reduction targets

The policies and administrative procedures outlined in Chapter 1.1 require that a catchment management plan be developed as the basis for integrated and systematic management.

The plan identifies downstream water bodies, environmental values and land or water uses that may be impacted by pollutants from the catchment. It determines an overall catchment 'pollutant reduction target'. This is based on an estimate of sustainable loads of critical pollutants, and comparison with current or projected catchment exports. The catchment management plan should also assign parts of the overall target to the various land use sectors that contribute to the cumulative loading on the threatened downstream water bodies. For example, the urban land use sector may be required to secure a 70% reduction in suspended solids (SS) and total phosphorus (TP) and a 60% reduction in total nitrogen (TN) as its contribution to the catchment pollution reduction targets. For techniques and procedures for determining catchment critical pollutants and reduction targets, see the ANZECC/ARMCANZ (1996) Draft Guidelines for Urban Stormwater Management.

Critical pollutants associated with urban stormwater discharges are most commonly sediment, fine suspended solids, substances with high biochemical oxygen demand (BOD), nutrients, bacteria, trash and debris, and toxicants (heavy metals, pesticides). See Appendix A.

The major urban pollutants of concern are summarised in Table 2.1.

Table 2.1. **Classes of urban pollutants and their potential impacts on receiving waters**

Impact on environmental values	**Pollutant**
Nuisance plant growth (including algae)	Nutrients, particularly phosphorus and nitrogen
Oxygen depletion of waters Hydrocarbons (chemical oxygen demand)	Organic materials (biological oxygen demand)
Light modifying substances	Suspended solids (soil particles, organic material)
Toxicants impacting on the physiology of plants and animals	Heavy metals (chromium, copper, lead, zinc), pesticides
Pathogens, potentially impacting on human health	Faecal bacteria, viruses

2.3 Estimating stormwater and pollution discharges

Ideally, typical discharges of stormwater and pollutants from a catchment are estimated from data measured in that catchment, by stream gauging and water quality monitoring. Appendix A describes how to set up monitoring programs.

If, however, managers/designers do not have access to locally measured data, they must assess likely values as best they can, using predictive models such as those given in this section, and their own judgement.

To incorporate the local hydrology into the design for a system to retain stormwater pollution, the manager can use:

- historical flow records for local waterways, or a synthesis of runoff rates and volumes from local historical rainfall data. Analysis should be based on a range of climatic conditions, for example over an extended period of rainfall or a run of wet, average and dry years.
- a histogram of rainfall/flow event frequencies and volumes derived from local historical flow records or rainfall data. This can then be used to assess the probability that pollutants will be retained during events.

For effective pollution retention, all rainfall events with up to 1-in-3 or 1-in-5 year expected recurrence must be included when assessing cumulative retention of pollutants. The approach for designing stormwater pollution control measures therefore differs significantly from that for flood protection and drainage—for those, the designer is concerned with a single ‘design’ event that is expected to recur at a specified frequency.

Increased levels of nutrients, particularly phosphorus and nitrogen, entering waterways can increase nuisance plant growth such as algae. Photo: Karen Markwort

Impact of high sedimentation on macrophytes.
Photo: Brett Phillips

Catchment storm runoff estimates

(i) Rational Method

$$Q = {}^{1}/_{360} \times C \times I \times A; \qquad V = 10 \times C \times P \times A;$$

where
Q is peak discharge rate in m^3/s,
V is the total volume of runoff for the event in kL,
C is runoff coefficient for terrain, soil type and land use,
I is rainfall intensity (mm/hr) for a storm duration equal to the time of concentration, and for the design event frequency,
A is catchment area (ha),
t is the time of concentration of flow or duration of rainfall event in hours,
P is the rainfall in mm/day.

typical C values:

Forest	0.1–0.3
Pasture	0.2–0.6
Urban	0.5–0.7

(Source: IEA 1987)

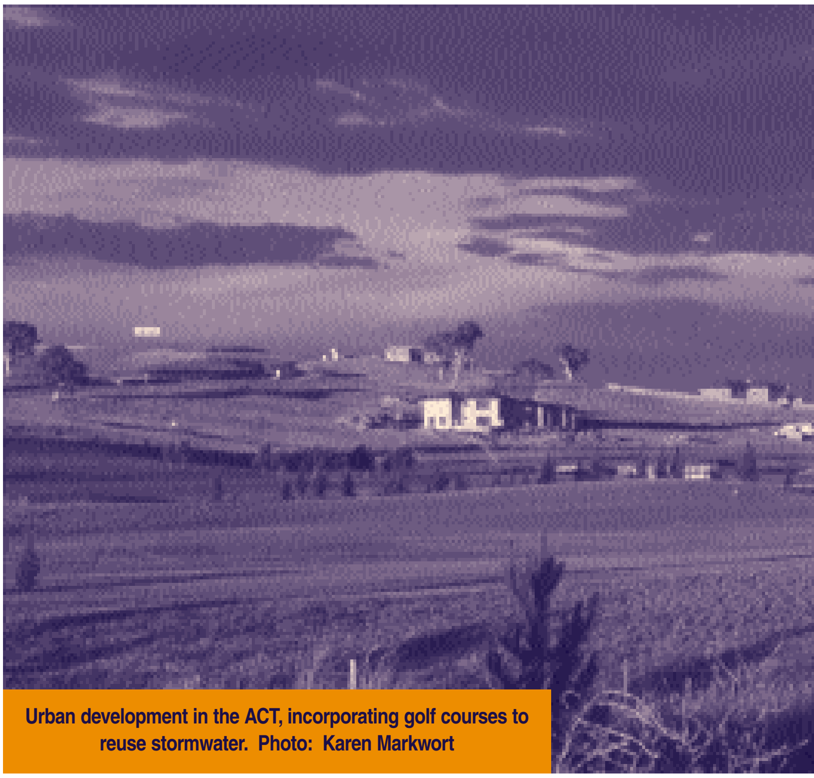
(ii) In the Australian Water Balance Model (AWBM) (Boughton 1993), the estimates of runoff are based on excess soil water storage, not on infiltration capacity. The AWBM provides techniques for calibrating catchments, and estimating discharges for a range of land uses and rainfall records. The model is available in software form, and is easily calibrated for local catchments with minimal stream flow data. It tracks the physical processes of rainfall interception, infiltration, water accumulation in soil (moisture) storages, and storage loss to through-flow, interflow and evapotranspiration.

If monitored data are available for the catchment, models based on science and understanding (rather than empirical) and calibrated against the collected data, can extend the estimates of runoff and pollutant loads. Using these models, managers can assess, say, a longer rainfall sequence, or 'critical' periods, and a range of scenarios of catchment land use and management. The CRC for Freshwater Ecology, together with the CRC for Catchment Hydrology, is developing more of these generically based export models.

Where local data are not available, empirical models exist with which the designer can estimate catchment runoff and pollutant loads. While these estimates may be indicative for catchments, they should be validated against data from local monitoring and analysis of pollutant export.

The AWBM is an alternative to, and more rigorous than, the Rational Method for estimating event discharge volume, especially where significant pervious areas are involved.

The CRC for Catchment Hydrology has published statistically-based reviews of pollutant exports for a range of urban components (Chiew et al. 1997; Chiew & McMahon 1997, 1998; Chiew 1998; Duncan 1997; Mudgway et al. 1997).



Urban development in the ACT, incorporating golf courses to reuse stormwater. Photo: Karen Markwort

Table 2.2. **Pollutants exported (kg/km²) in storm events and over 12 months.**

Pollutant	**Land Use/Vegetation categories**		
	Native vegetation	**Rural grazing**	**Urban**
Storm event exports			
Sediment	$200R^{1.1}$	$400R^{1.1}$	$1000R^{1.4}$
Suspended solids	8R	20R	200R
Total phosphorus	$0.05R^{0.57}$	$0.12R^{0.57}$	$0.4R^{0.8}$
Total nitrogen	$0.15R^{1.6}$	$0.3R^{1.6}$	$3R^{0.84}$
Faecal coliforms	$30–100x10^{9}R^{0.9}$	$300–1500x10^{9}R^{0.9}$	$400–1000x10^{9}R^{0.9}$
Mean annual exports			
Sediment	3000–7000	$10x10^{3}–30x10^{3}$	$50x10^{3}–100x10^{3}$
Suspended solids	100–500	500–1500	$10x10^{3}–30x10^{3}$
Total phosphorus	5–10	20–50	70–100
Total nitrogen	50–300	100–1000	400–1500
Faecal coliforms	$1x10^{12}–4x10^{12}$	$10x10^{12}–50x10^{12}$	$50x10^{12}–100x10^{12}$
Biol. oxyg demand	300–1000	1000–5000	3000–5000

R is runoff in mm/event

Source: Lawrence & Goyen 1987 (based on ACT annual rainfall (550–750 mm) and podzolic soils).

Case Study 1. Estimated catchment storm runoff to decide the size of a pollution control pond in Isabella Plains, Canberra

Analysis of histograms of daily rainfall for the period 1977–96 yields the following data,
using **V** = 10 x C x P x A
where **V** is volume of runoff in kL,
C is the runoff coefficient,
P is the daily rainfall in mm,
A is the area in ha.

The selection of appropriate C values is based on local practice, or is guided by values in Australian Rainfall and Runoff (IEA 1987).

The runoff volume–frequency relationship provides the basis for estimating catchment pollutant exports for a range of probability or risk levels.

Rainfall exceedance frequency	**Rainfall (mm/day) (P)**	**Estimation of runoff/day**	
		Runoff coefficient (C)	**Runoff (V) (ML/100ha or mm depth)**
1 in 5 yr	86	0.5	43
2 in 5 yr	56	0.45	25
4 in 5 yr	49	0.4	20
8 in 5 yr	44	0.35	15
16 in 5 yr	36	0.3	11
32 in 5 yr	27	0.3	8
64 in 5 yr	19	0.25	5
128 in 5 yr	8	0.2	1.6
256 in 5 yr	4	0.2	0.8

2.4 Treatment train selection

Ponds or wetlands are normally installed as part of a wider range of actions or sequence of treatment facilities aimed at managing a catchment’s pollutants. These installations are most effective when primary treatment is provided upstream, as is also the case in wastewater treatment. Any measures that retard runoff and control pollutants at source will enhance the pond or wetland’s overall retention of pollutants. And having separate treatment components for stormwater is highly efficient and practical, just as it is for treating wastewater.

In the case of urban waterways, management may undertake the following actions:

1. at-source minimisation and controls, such as householder education, buffer strips or infiltration trenches to catch and minimise pollutants when they are first discharged;
2. in-stream interception by
    - gross pollutant traps to intercept the larger size particles and trash,
    - vegetated waterways and ponds to intercept the finer suspended particles and attenuate peak flows,
    - wetlands to intercept the fine colloidal and dissolved pollutants.

An arrangement of different treatment measures is termed the treatment train. When designing each component of the sequence, the stormwater

Case Study 2. **Catchment stormwater export of pollutants for Stranger Pond, Canberra**

Building on the previous example for Canberra urban discharges, the CRCFE calculated the pollutant load for each of the rainfall events identified. We assumed that for a 100 ha catchment, 80% of the catchment is residential, with 20% as open space or hill reserves.

Urban TP export per event = $0.4R^{0.8}$ per km^2; open space/hill reserve export = $0.05R^{0.57}$ per km^2, where R is runoff in mm/day.

Pond or wetland performance over a range of event sizes and exceedance frequencies can be analysed using the exports identified in the table below. The table illustrates the marginal benefits of increasing event capture beyond a 1 in 3 year to 1 in 5 year exceedance frequency.

Rainfall exceedance frequency	**Rainfall (mm/event)**	**TP export (kg)**				**Clumulative export as % of total**
		Urban (80 ha)	**Open space (20 ha)**	**Total/event**	**Total in 5 year period**	
1 in 5 yr	43	6.48	0.09	6.57	6.57	100
2 in 5	25	4.20	0.06	4.26	4.26	96
4 in 5	20	3.52	0.06	3.58	7.16	94
8 in 5	15	2.80	0.05	2.85	11.40	90
16 in 5	11	2.18	0.04	2.22	17.75	84
32 in 5	8	1.69	0.03	1.72	27.52	74
64 in 5	5	1.16	0.02	1.18	37.75	58
128 in 5	1.6	0.47	0.01	0.48	30.72	37
256 in 5	0.8	0.27	0.01	0.28	35.84	20
Total for 5 yrs					178.97	

manager needs to be aware of the effects of other management actions upstream that modify flows, pollutant characteristics and pollutant loads.

Many best management practice (BMP) controls for stormwater pollutants in the past have failed because they did not use enough components in their treatment train. Table 2.3 shows how efficiently various treatment components remove various pollutants.

Figure 2.2 *Treatment train options*, outlines the possible arrangements of gross pollutant traps (GPTs), ponds and wetlands, and on-line and off-line options. The appropriate arrangement will be the one that is best for the dominant forms of pollutants and the associated hydrological conditions, and that matches the required pollutant reduction or interception levels. It must make the most of the opportunities and constraints peculiar to the available pond/wetland site, and be cost effective.

The choice of pond or wetland, or pond and wetland, is guided, in the first instance, by an understanding of the hydrological characteristics and pollutant form. There are three distinct pollutant transformation and interception pathways, depending on the catchment hydrology and pollutant form, as follows:

i) *elevated storm discharges, high in suspended solids.* The dominant pollutant pathway in this case is the rapid adsorption of nutrients, metals, and organic molecules onto the surfaces of the suspended particulates, and the sedimentation of the particulates (and their adsorbed pollutants).

Stranger Pond, ACT, the site of considerable experimental work by the CRC for Freshwater Ecology. Photo: Ian Lawrence.

Table 2.3. **Representative capacities of treatment train components for removing pollutants and attenuating flows.** (Source: Lawrence et al. 1996.)

Best management practise	**Pollutant removal**							**Flow attenuation**	
	Trash	**Solids**	**P**	**N**	**BOD**	**Metals**	**Bact**	**Peak**	**Vol**
Percolation trenches/pits	■	■	■	□	■	●	■	□ - ■	□■
Grassed swales	NA	□	□	□	□	☆	□	☆-□	☆
Grassed buffer zones	NA	☆	☆	☆	☆	☆	☆	☆-□	☆
Pervious pavements	■	☆	○	■	○	■	□	☆	☆-□
Infiltration basins	■	■	■	□	■	○	■	□ - ■	□■
Vegetated waterways	NA	□	□	☆	□	☆	□	☆-□	☆
Inlet controls/trapsl	●	□	☆	☆	□	☆	☆	NA	NA
Detention basins	NA	●	■	□	■	○	●	□ - ○	☆ (wet, dry)
Retention ponds/wetlands	NA	○	■ - ○	□ - ■	□ - ■	○	■ - ●	□ - ■	☆
Aeration	NA	NA	NA	NA	●	NA	NA	NA	NA
Street sweeping	○	□ - ■	☆	☆	☆	☆	☆	NA	NA

Key: Removal efficiency

● 80 – 100% ○ 60 – 80% ■ 40 – 60% □ 20 – 40% ☆ 0 – 20% NA = not applicable

Notes: Levels of pollutant removal will be subject to the level of provision of BMP volume or surface areas relative to catchment runoff. In the case of catchments having silty clay or clay soils, higher levels of BMP volume or surface areas relative to catchment runoff will be required to achieve these levels of removal.

Level of flow attenuation in the case of Retention Ponds and Detention Basins is a function of storm frequency, storage provision and spillway design. The efficiency of pollutant removal by street sweeping depends on the equipment used and the frequency of sweeping.

As a general rule, the higher the concentration of in-flowing pollutants the greater the degree of removal.

The primary task in this case is to capture as much of the storm pollutants as possible during the storm event, and to maximise the retention time post event to maximise the sedimentation of the captured pollutants.

The treatment arrangement best suited to these requirements is the on-line pond.

ii) *attenuated storm discharges, with moderate suspended particle levels, predominantly in fine colloidal or organic form.* The dominant pathways in this case are a mix of adsorption of particles onto plant and sediment surfaces, and coagulation and sedimentation of fine particles.

The primary task in this case is to maximise the surface contact time, in order to maximise adsorption, and to calm flows as much as possible.

Figure 2.2. **Treatment train options**

The treatment arrangement best suited to these requirements is an on-line hybrid wetland and pond system.

iii) *base flows low in suspended particulates and high in dissolved nutrients and fine organic colloids*. The dominant pathways in this case are the adsorption of organic colloids on the surfaces of biofilms (see Box 5, page 32) attached to plants and to the sediments, and the biological uptake of dissolved nutrients by algae (epiphytes) attached to the surfaces of plants.

The primary tasks in this case are to limit flow velocities to minimise the loss of biofilm, and to maximise the surface contact time, by providing the substrates (macrophytes and sediment zones) conducive to biofilm growth.

The treatment arrangement best suited to these requirements is an off-line shallow wetland.

The ephemeral wetland, the incorporation of flow retardation into the pond design, and integrated approaches, are three alternatives to the treatment arrangements outlined above. Ephemeral wetlands suit situations where catchment runoff is intermittent as in semi-arid areas. Integrated approaches, and the incorporating flow retardation into pond design, achieve high levels of pollutant reduction, or target a range of pollutants. The decision tree at Figure 2.3 illustrates these systems. Details of the interception processes are given in Chapter 3.

It is essential to install gross pollutant traps upstream, so the ponds and wetlands below them can be effective. If no GPTs are installed, large deposits of sediment and the influx of large quantities of organic material will impair the growth of macrophytes in the pond or wetland. As well, there will be unsightly trash in the pond or wetland. The design of the GPT should follow local guidelines, usually available from the relevant local government authority.

The pollutant load (see Table 2.2 for example) and the catchment's hydrological characteristics primarily determine which transport, transformation and transfer pathways dominate in a pollution-control facility. To be effective, the selected treatment measures must match the local dominant pollutant transport, transformation and transfer processes. (See Section 3.2 for more discussion of the treatment train.)

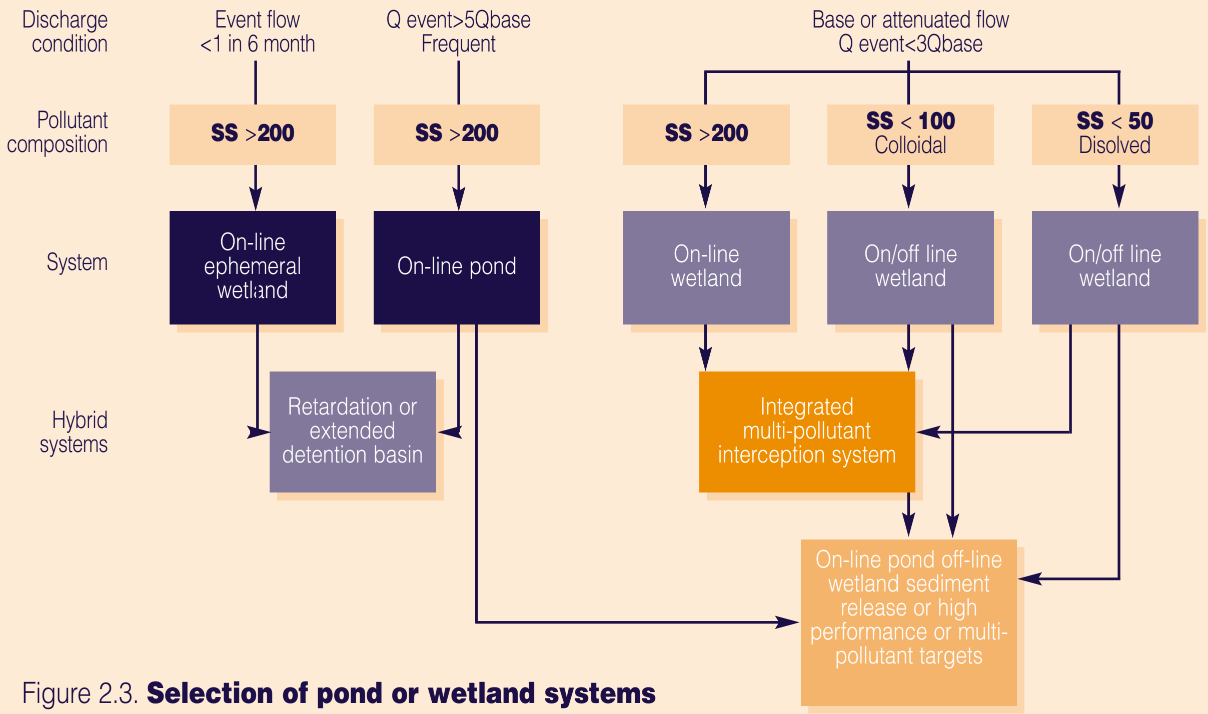


Figure 2.3. **Selection of pond or wetland systems**

2.5 Siting facilities

When siting treatment facilities the designer is guided by three factors:

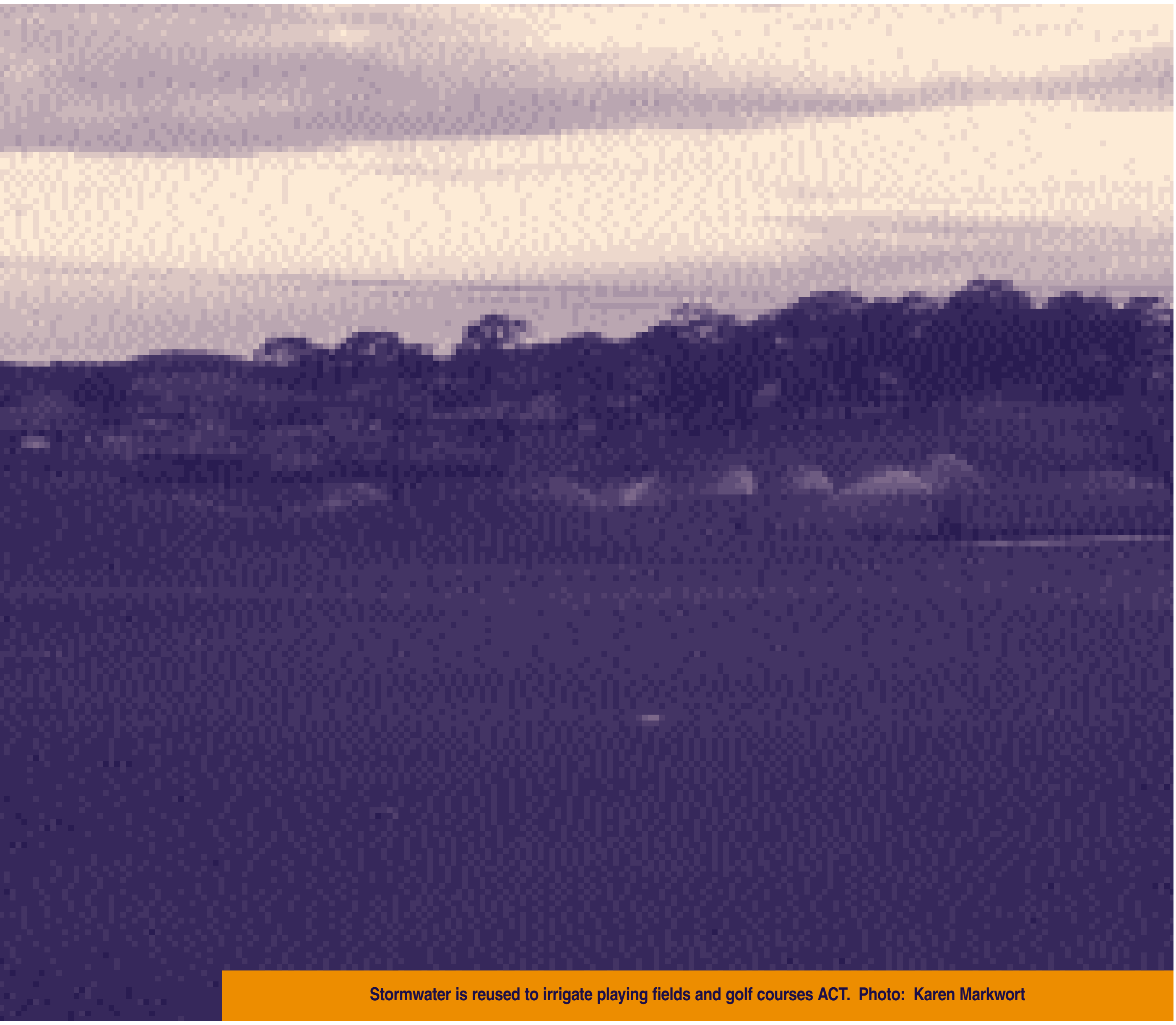
- cost-effectiveness;
- the potential locations, and their spatial and hydraulic opportunities and constraints;
- the accommodation of other objectives.

As a general principle, a single pond (and associated GPT), sited so that it captures all of the urban runoff, provides the most cost effective solution with respect to construction costs (economies of scale) and maintenance (especially GPT cleaning). However, for wetlands, downstream sites are often inappropriate because they suffer from concentrated flow. It is preferable to locate wetlands on, or adjacent to, branch drains.

The type of urban development in which a facility is to be sited largely determines the space and hydraulic conditions available for it. There are four major types of urban development, each with significantly different opportunities and constraints with respect to accommodating stormwater treatment measures:

- greenfield development, where treatment measures can be fully integrated as a condition of urban development, and where space or hydraulic head issues are much less likely to constrain their site or size;
- established urban areas with open space associated with drainage corridors, which provide some opportunities for retrofitting of stormwater management measures;
- established urban areas with limited open areas associated with drainage, which often have little space available and often constrain the facility's hydraulic conditions. This situation may require highly engineered solutions, or greater reliance on 'at-source' type management measures.
- established urban areas undergoing urban renewal or redevelopment, which provide an opportunity in terms of both space and funding, to retrofit stormwater management measures.

Where space permits, it may be preferable to integrate the sedimentation of fine particulate



Stormwater is reused to irrigate playing fields and golf courses ACT. Photo: Karen Markwort

materials and biofilm absorption of colloidal and dissolved nutrient processes into a single system, with separate upstream interception of coarse sediment. On the other hand, as noted above, in the case of limited space, it will be more efficient to separate the biofilm absorption process and locate it off-stream.

Where management groups cannot install an appropriately sized pond, because there is not enough land available or there are hydraulic constraints, they often adopt a linear system of smaller ponds to collectively make up the required volume. Unfortunately, this arrangement does not work effectively. The top pond is usually too small for the incoming loads of organic material; as a consequence there is substantial remobilisation of nutrients from sediments following storm events, but the downstream ponds are inappropriate to intercept a discharge high in algae and colloidal material. It is better, in these cases, to site a pond on each of the major tributaries to the primary waterway, and to designate the primary waterway a ‘control zone’ in stormwater discharge terms (see Figure 2.4).

Case Study 3. **Example of pond arrangement**

The CRCFE was asked to select a design arrangement for a Brisbane stormwater pollution control pond or wetland.

The flow and pollutant characteristics comprised

- discharges dominated by frequent events,
- suspended solids >100 mg/L during events,
- a requirement for a TP reduction of 60% to 70%.

Reference to the decision tree in Fig. 3.2, indicated that an on-line pond was the appropriate treatment system.

In addition, the pond was expected to enhance the landscape. Therefore its design had to ensure a low risk (<1 in 5 years) of algal blooms.

In analysing the pond size requirements, the CRCFE assessed the potential for sediment phosphorus release and associated algal growth, for the range of storm loadings identified. Case study 5 illustrates the technique for analysing sediment phosphorus release. If the analysis indicated a potential for more frequent algal blooms, then either the areas of the pond would need to be increased, or pollutant export reduction treatments should be added upstream, or a wetland facility (for recycled pond water) should be added to the pond arrangement.

2.6 Groundwater considerations

It is essential that the designer understands the association between local groundwater and the pond or wetland.

Where wetlands are sustained by groundwater inflows or levels, the surface flows may be only a minor component of the overall system. In the case of ponds, groundwater may constitute a significant input pathway both for water and for pollutants. Conversely, the designer will need to assess whether the retention of pollutants discharged into the pond or wetland by surface waters will contaminate the local groundwater as well as the downstream surface waters.

Groundwater gradients may also modify pond or wetland water quality processes by increasing the hydraulic gradient across the sediment pore water zone, significantly increasing the diffusion of remobilised pollutants into the water column as compared to molecular diffusion processes. A clay lining may limit losses of ponded waters to groundwater, or the movement of groundwater into a pond or wetland.

Siting ephemeral wetlands over groundwater recharge zones offers an effective means for disposing of large volumes of stormwater. However, before stormwater is discharged to these zones, the designer should ensure that the treatment train removes suspended particulates (which otherwise might seal the porous infiltration zones) and pollutants which could impair the beneficial uses (water supply abstraction, environmental flows) of the groundwater elsewhere.

Groundwater inflow is more akin to the base or dry weather flow conditions than the event based conditions, both in the amount of inflow and in its content of pollutants (low in suspended solids, high in dissolved or colloidal forms).

2.7 Other objectives

Normally, pond or wetland designs can accommodate a number of functions (multi-purpose), which include:

- flood management—the storage capacity to temporarily retain flow associated with peak storm flows, thereby limiting peak flows downstream to design levels;
- landscape and recreation values—open water and wetland features in the urban landscape;
- water supply–regulation of flow and water quality improvement necessary to provide a source of water supply for irrigation or other purposes;
- conservation ecology—habitats restored or created for the conservation of particular species.

A multi-purpose facility can substantially enhance economic and social as well as environmental objectives.

Flood retardation can be provided by temporarily flooding the pond or wetland. In ponds, the 'extended retention' time can enhance sedimentation processes and interception. This arrangement is usually secured by the construction of an embankment higher than required for the permanent pond or wetland water body, restricting the outlet or spillway discharge capacity.

For landscape and recreation values, the management team should establish and maintain the facility as a water feature which is pleasing to the eye. The design should exclude the trash and debris normally discharged in stormwater runoff, and keep the facility free from scums and odours (algal blooms, oxygen depletion). In this respect, the 'treatment facility' becomes a 'receiving water'. The designer should pay close attention to the design of GPTs and to ensuring that the area of pond or wetland is enough to limit the loading of organic material per square metre to levels that minimise remobilisation.

If the ponds will supply irrigation water, the concentrations of suspended solids and algae must meet the water supply guidelines. There may be a compromise in this situation between pond vegetation—landscape values and pond drawdown during extended dry periods. The designer can address this in a number of ways:

- by controlling the abstraction of pond water so that the drawdown limits are not exceeded; and/or
- by installing an off-line wetland to deal with any remobilisation from the pond, thereby reducing the importance of the pond's macrophytes and drawdown limit.

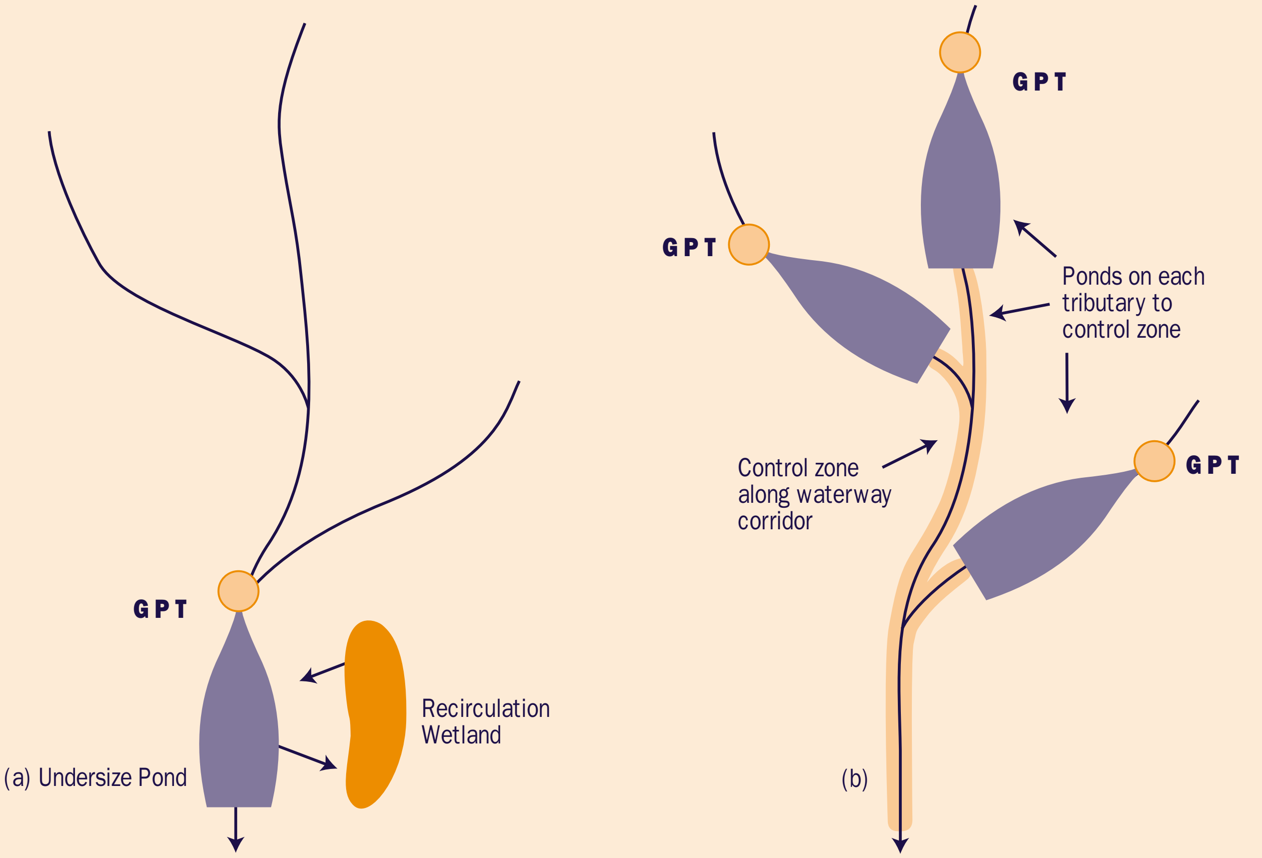


Figure 2.4. **Treatment train options for constrained sites**

3. Principles guiding the design of the facilities

This section focuses mainly on the design of ponds or wetlands so that they fulfil their pollution interception function.

The optimum pond or wetland size (volume, area), shape, depth, edge treatment and planting design, will depend on:

- the characteristics of pollutants and flows discharged to the proposed pond or wetland location;
- the critical pollutant or pollutants and reduction target;
- the treatment train context;
- the siting constraints and opportunities; and
- the pond or wetland pollutant interception and remobilisation processes.

Figure 3.1 *Pond water quality processes* illustrates the dominant pollutant interception pathways.

3.1 Pond or wetland size

This section builds on the format outlined in Figure 2.3 *Selection of pond or wetland system*, while Figure 3.2 *Determination of pond or wetland size* consolidates the factors into a decision tree guiding the size analysis.

For more detailed design purposes, Appendix C describes the pond and wetland water quality models, a series of computer models that integrates the various processes into a fully interactive time-based simulation of discharge, retention, adsorption and sedimentation and sediment remobilisation processes.

3.1.1 Size to suit frequent event-based discharges

Capture of pollutants during events

In the case of event-based discharges, the pond or wetland volume must be large enough to capture the portion of the event pollutants that will meet the pollution reduction target. The success of this capture will depend on the ratio of the pond or wetland volume to the volume of storm discharge.

Figure 3.3 *Graph of pollutant retention*, provides a basis for calculating the required volume; it shows that retention is better the smaller the event discharge is relative to pond volume. These curves have been computed on the basis of complete mixing during the event, with application of a ‘Continuous Stirred Tank Reactor’-based model to calculate the mass balance. Field validation indicates that only in cases of extremely coarse particulate material, extended

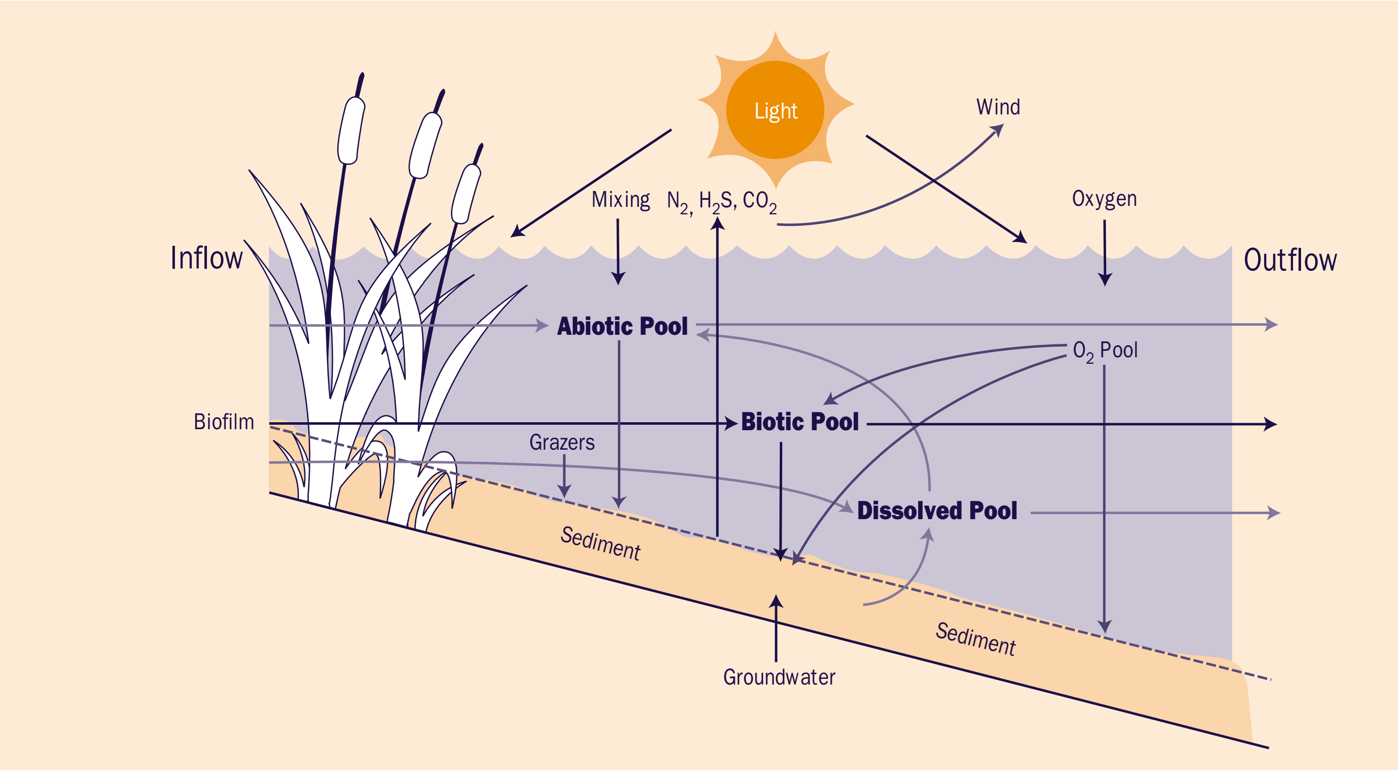


Figure 3.1. **Pond water quality processes**

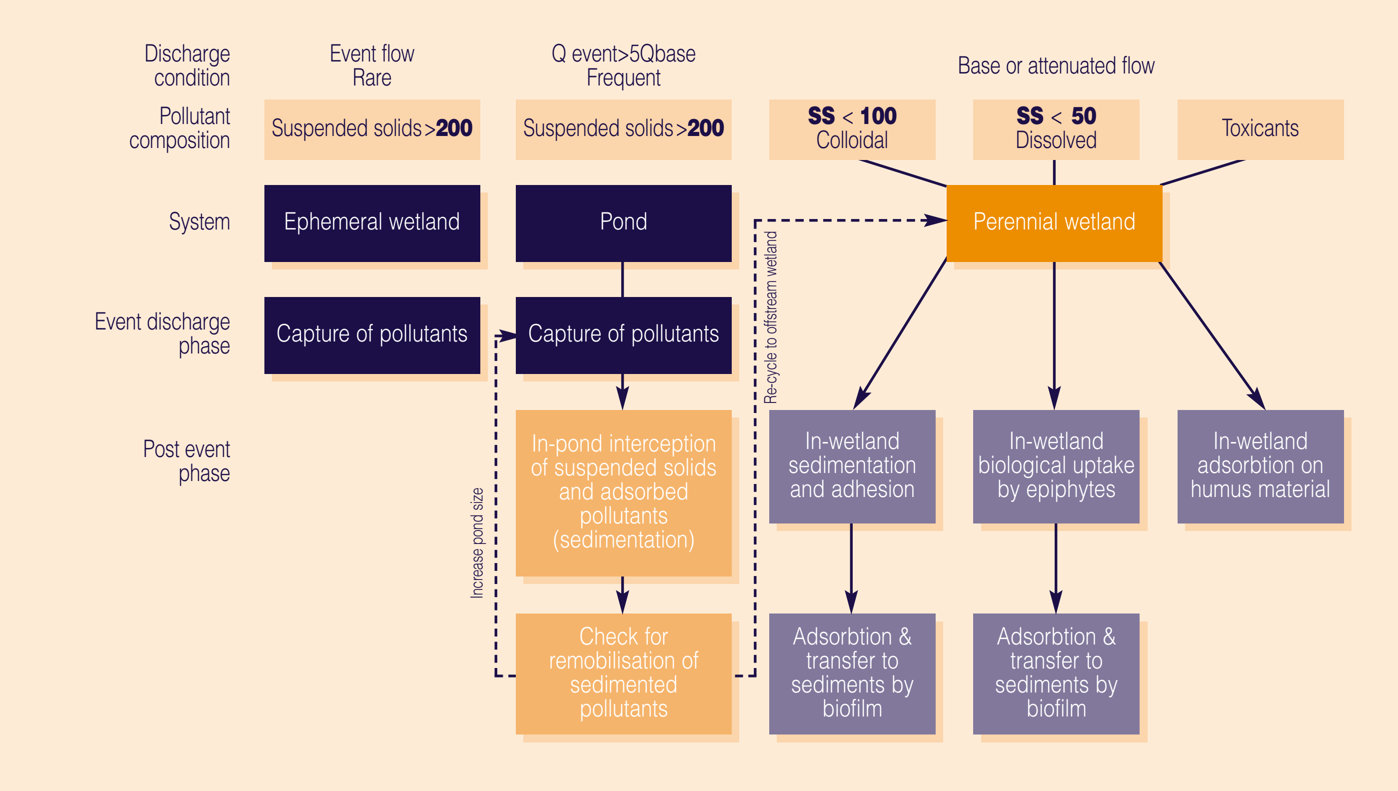


Figure 3.2. **Determining pond or wetland size**

Table 3.1. **Grading of suspended solids**

Sieve size (µm)	Coarse grading		Medium grading		Fine grading	
	Cumulative retention (%)	Individual retention (%)	Cumulative retention (%)	Individual retention (%)	Cumulative retention (%)	Individual retention (%)
476	0	0	0	0	0	0
212	20	20	8	8	0	0
150	30	10	15	7	5	5
63	40	10	30	15	10	5
32	70	30	55	25	20	10
20	80	10	68	13	30	10
2	95	15	85	17	70	40
< 2	100	5	100	15	100	30

period (days) of inflow event, or resuspension (extreme situation) of previously sedimented material is there any deviation from the 'event fully mixed' assumption.

In the graph, C_{infl} is the concentration of pollutants in inflow to the pond or wetland, and C_{pd} is the assumed concentration immediately before the event. This value can be checked in the in-pond interception analysis outlined next.

Interception of captured pollutants in ponds

The in-pond transfer of pollutants from the water column to the sediments, in the period after the event, depends on settling rates (grading of particles) and the length of the 'dry-weather' flow period (that is, the period between events).

Figures 3.4 and 3.5 provide a basis for calculating the in-pond interception of suspended solids (SS) and total phosphorus (TP) respectively, as a function of time and particle size grading (coarse, medium or fine). The curves are based on the coagulation and settling rates of fine particles in the case of SS, and on the adsorption of nutrients (such as TP) and metals onto their surfaces (which varies with particle size) and their removal via the SS sedimentation.

The particle grades used in Figures 3.4 and 3.5 are defined in Table 3.1. Appendix B gives details of the algorithms, grading, specific gravities (SGs) and settling

1: Pollutant dispersion or mixing

A continuously stirred tank reactor (CSTR) is a useful metaphor and model for the receiving water (pool, pond, wetland) for stormwater discharge, and the mixing processes that happen in it. The model describes the water and constituent mass balance and diffusion processes that drive the mixing of a pollutant in a discharge with the pollutant in the receiving water.

Assuming mass balance of flow and constituents,

$$Q_1C_{in^1}+V_{pd}C_{pd} = Q_1C_{pd}+V_{pd}C_{pd^1}$$

$$C_{pd^1} = C_{pd}+Q_1/V(C_{in^1}-C_{pd})$$

$$Q_2C_{in^2}+V_{pd}C_{pd^1} = Q_2C_{pd^1}+V_{pd}C_{pd^2}$$

$$C_{pd^2} = C_{pd^1}+Q_2/V_{pd}(C_{in^2}-C_{pd^1})$$

$$= C_{pd}+Q_1/V_{pd}(C_{in^1}-C_{pd}) + Q_2/V_{pd}(C_{in^2}-C_{pd}) - Q_1Q_2/(V_{pd})^2(C_{in^1}-C_{pd})$$

where	Q_n	is the inflow during period n,
	C_{in}	is the pollutant concentration during inflow period n,
	V_{pd}	is the volume of the pond or wetland in ML,
	C_{pd}	is the pollutant concentration of pond water at the start of period 1,
	C_{pd^1}	is the pollutant concentration of pond water at the end of period 1 or start of period 2,
	C_{pd^2}	is the pollutant concentration of pond water at the end of period 2.

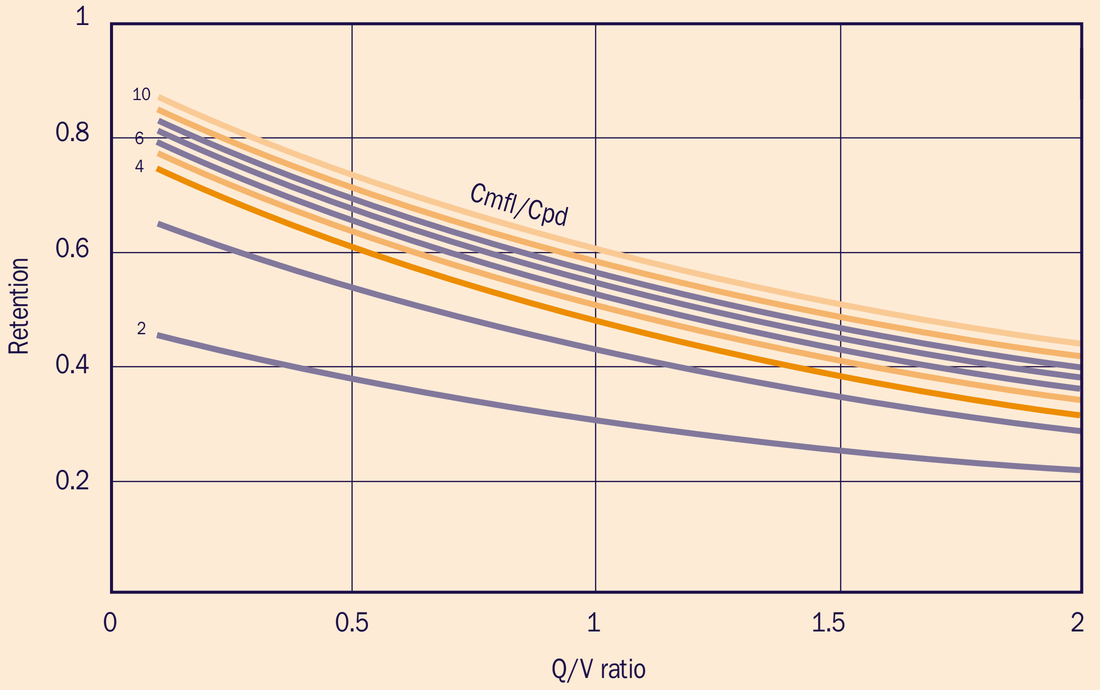


Figure 3.3. **Pollutant retention**

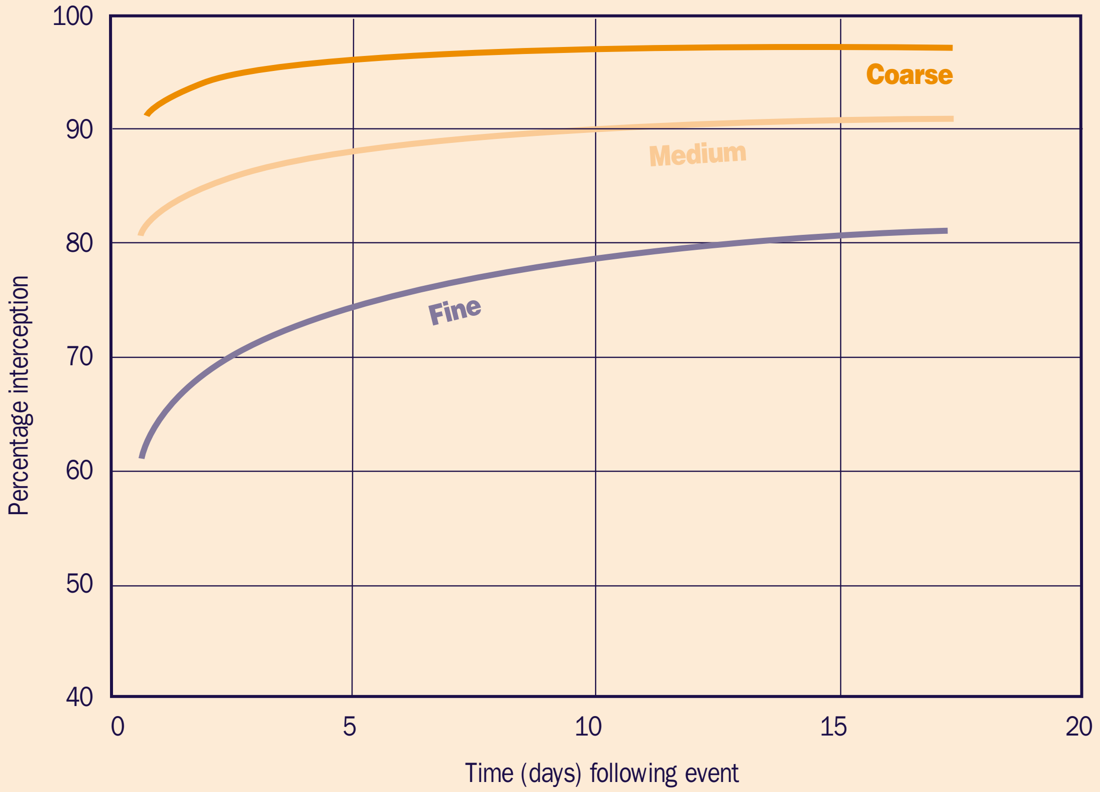


Figure 3.4. **In-pond SS interception**

efficiency values for computing the interception curves. Where local particle size distributions differ from those in Table 3.1, designers can compute interception curves to suit their local material.

Colloids

Colloids (particles <5 µm in size) have significant electrical charge which can keep them in stable suspension in the water column. Consequently, their sedimentation primarily depends on their coagulation behaviour, which in turn is influenced by their surface charge (mineralogy), the crowding (density) of particles, the agitation necessary to create collisions between particles, and the ionic composition (valency and electrolyte concentration) of the liquid within which the colloids are suspended. Their settling velocity then depends on the size of the coagulated particle (floc) that they form and its apparent specific weight (typically 1.1 to 1.3).

Biological processes, such as the clustering of microbes around the colloids and the consumption of colloids by zooplankton, are also involved in colloid coagulation and settling, and may be dominant in some situations.

Coagulation and settling therefore vary with time, with the ionic composition of the water (valency and concentration), with the density of particles, and with the size of floc. Turbulent eddies will break up the aggregates of material, impairing sedimentation. There are no simple generic models to calculate interception of this particle fraction.

If the designer decides that the <2 µm fraction is important, laboratory studies of coagulation and settling analysis will determine coagulation and settling rates and their implications for the ultimate

Case Study 4. **Calculating the pond volume**

Using the Brisbane pond example analysed in Section 2.5, the CRCFE assessed the required pond size by first estimating a probable best size and assessing its performance for each of the events listed. We then refined the initial estimate until the targeted pollution retention matched the estimated pond performance.

Similarly, we estimated a C_{infl}/C_{pd} ratio from experience of local conditions, and then tested it using the in-pond interception curves.

For the 200 ha catchment and a 60% interception of TP, the first estimate of best pond size was 100 ML with a C_{infl}/C_{pd} of 6.

Runoff	Discharge (ML/event)	TP load kg	Q_{infl}/Q_{pd}	C_{infl}/C_{pd}	retention factor	TP retention per event	Cumulative retention TP kg	Cumulative retention as %
1 in 5 yr	400	88x1=88	4.0	6	0.3	26.4	26.4	61.3
2 in 5	300	60x1=60	3.0	6	0.37	22.2	22.2	59.5
4 in 5	250	55x2=110	2.5	6	0.39	21.5	42.9	58.0
8 in 5	180	45x4=180	1.8	6	0.43	19.4	77.4	55.2
16 in 5	130	26x8=208	1.3	6	0.55	14.3	114.4	50.0
32 in 5	85	20x16=320	0.85	6	0.65	13.0	208.0	42.5
64 in 5	30.	9x32=288	0.3	6	0.75	6.8	216.0	28.7
128 in 5	10	4x64=256	0.02	6	0.85	3.4	217.6	14.4
total 5 yrs		1510					924.9	

The table shows the 100 ML initial estimate best meets the TP reduction of 60%.

Then we checked the estimated C_{infl}/C_{pd} ratio must be checked. For soils of this catchment, the suspended solids or sediment grading falls in the medium range on the graph (Figs 3.4, 3.5). The statistical average number of dry weather flow days following events is 22, giving an in-pond interception rate of 0.85, or C_{infl}/C_{pd} of 1/0.15 x C_{infl} = 6.7.

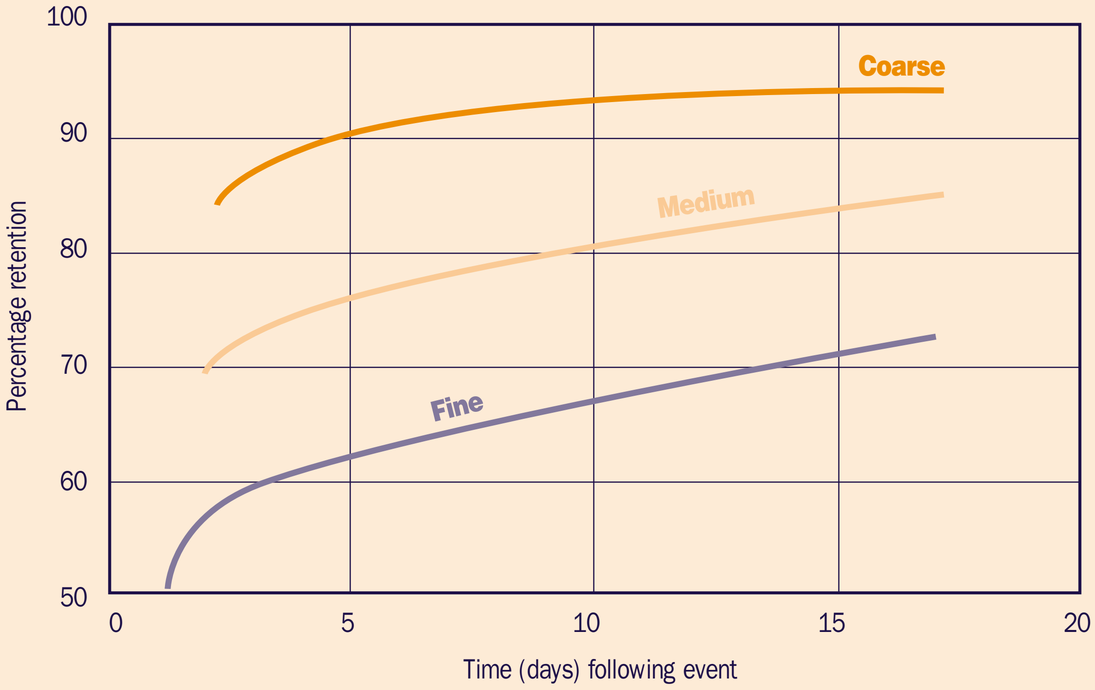


Figure 3.5. **In-pond TP interception**

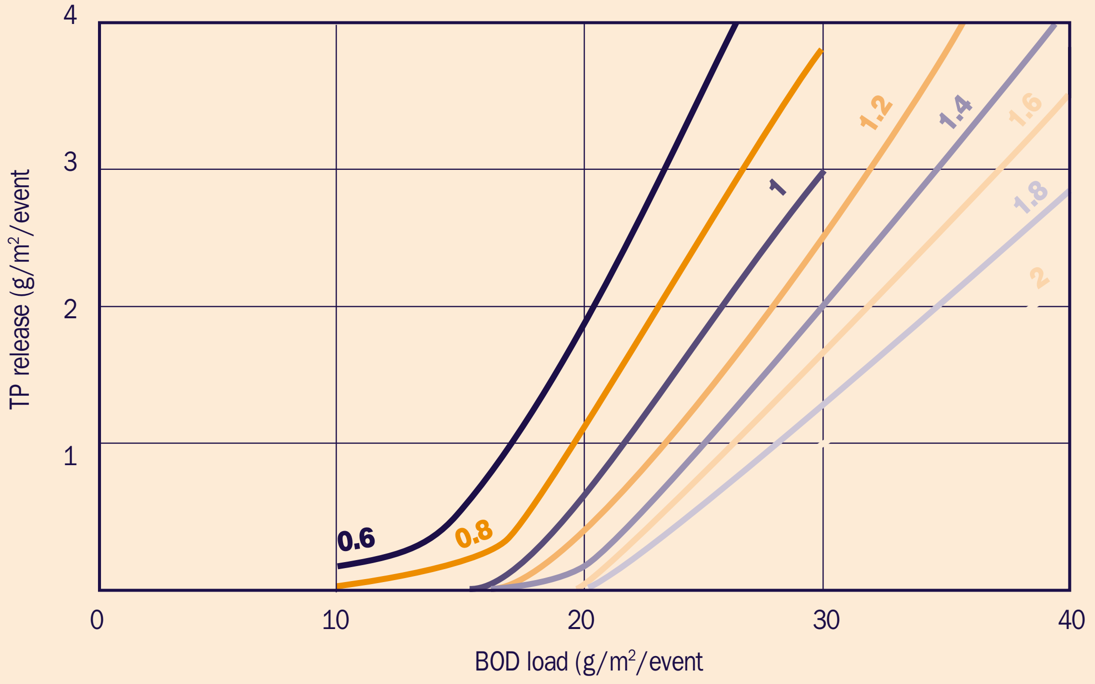
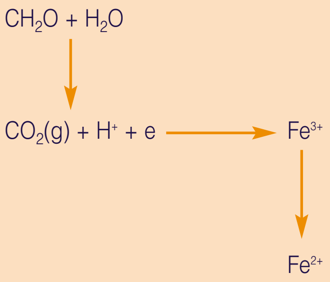


Figure 3.6. **Sediment TP release vs BOD load**

2: Reduction of sediments

Reduction refers to the chemical reactions in which a reducing agent (organic carbon, hydrogen sulphur dioxide, sulphide, hydrogen) acts on a substance to reduce its positive charge (gain electrons), or strip its oxygen.

Example: Reduction of Fe^{3}+ to Fe^{2}+ by organic matter



Reduction processes are described as chemical equilibria, and they are commonly mediated by microbial processes.

The chemical reduction of sediments is biologically mediated by heterotrophic bacteria which use the organic carbon material discharged in storm events as their energy source. As the microbial populations grow, they consume oxygen, first stripping the dissolved oxygen (DO) from the water column, and then using up the oxygen in nitrates and nitrites. This chemical reduction of nitrate and nitrite yields ammonia (NH_3), or nitrogen gas (N_2) under high reducing conditions (denitrification).

When organic carbon remains unused after all sources of oxygen have been exhausted, the microbial populations continue to grow but now they reduce insoluble ferric iron (Fe^{3}+) to soluble ferrous iron (Fe^{2}+), and sulfate (SO_4^{2-}) to hydrogen sulfide (H_2S).

Iron, along with manganese, in natural waters is a key part of the formation of $FePO_4$ (solid) and iron hydroxides, to which a range of heavy metals become fixed or attached in complexes. If the ferric iron becomes ferrous under highly reducing conditions, the phosphorus and metals are released. The reduction of sulfate releases sulfide, which is one of the preferential anions (together with the ammonium cation) for complexing the released metals in a bioavailable form.

Once the supply of organic carbon runs out, the microbially mediated reduction conditions cease and the waters and sediments become reoxygenated by plants, algae and oxygen transfer through the water column, as usual.

These processes are illustrated in Fig. 3.7 *Sediment storage, remobilisation and transformation processes*.

The BOD (here the term refers to organic carbon that is available to microbes) of different sources of organic material can vary by an order of magnitude, according to their molecular form. Organic matter in sewage effluent, for example, has a high availability per gm of total carbon, while organic matter in eucalyptus leaves or macrophytes has a low availability. These differences are illustrated in Fig. 3.8 *Bioavailable carbon content of common organic materials*.

By working step-by-step through the net BOD loading (BOD load minus the oxygen transfer through the water column and/or through the macrophyte rhizomes) on a daily basis, the redox levels and associated mobilisation of sediment constituents can be calculated.

Reoxidation, which is simply the reverse process, occurs when the daily oxygen inflow (from algae, water column mixing and macrophytes) exceeds the daily BOD loading.

choice of control system, size and design. This is a situation where the use of ephemeral wetlands, with their high adhesion capacity, may be most appropriate.

Successful interception

Settled particles become incorporated into the sediments. Monitoring of ponds indicates that even under conditions of intense discharge, there is little if any resuspension of the abiotic material (not derived from organisms). In the case of biotic material with low SG (<1.2), the particles are more likely to be resuspended and washed out if they are subjected to water moving at >0.05–0.1 m/s. Therefore, pollution control treatments that are based on biofilm processes are best located off-line. Designers can calculate the overall interception by pond or wetland as the percentage retention of storm discharge per event multiplied by the dry-weather flow interception percentage, in-pond or in-wetland.

Transformation and remobilisation of sedimented pollutants

While calculating the pond size, the designer must check for release of sedimented material back into the pond or wetland as a result of elevated reducing conditions (stimulated by the decomposition of organic material deposited by events).

The sedimentation of organic material discharged by a storm event leads to rapid growth of the benthic microbes that normally feed on decomposing organic material at the bottom of the pond or wetland. Their growth depletes oxygen in the water column and

Case Study 5. **Estimating pollutant remobilisation from sediments**

The CRCFE assessed the performance of Blackburn Lake, Melbourne, during 1997, including monitoring discharges and pollutant loads and lake water quality over 12 months. The task was to estimate the potential sediment phosphorus mobilisation compared to the monitored BOD loads, assuming a moderate efficiency of BOD distribution (70% of the load spread over 50% of the area).

The lake surface area is 6 ha, and the lake is subject to severe stratification in post event periods (adopt an aeration rate of 0.6 g/m²/d).

Runoff exceedence	**Discharge (ML/event)**	**TP load (kg/event)**	**TP retained (kg/event)**	**BOD retained(kg)**	**BOD load(g/m²)**	**TP release (g/m²)**	**TP release (kg)**
1 in 1 yr	138	17.46	7.2	360	9	0.04	6
2 in 1	99	15.16	6.0	300	7.5	0	0
4 in 1	50	8.03	4.18	210	5.3	0	0
8 in 1	35	5.12	2.27	115	2.9	0	0
16 in 1 yr	5	0.96	0.68	35	0.8	0	0
Cumulative total		77	36				6.0

Notes: phosphorus (P) retention = 37/77 = 47%.
BOD load = BOD retained (kg) x 1.4/(Area (ha) x 10) g/m² = 360 kg x 1.4/(6 x 10) = 8.4 g/m²/day
$P_{release}$ (refer to graph for 0.6 g/m²/day aeration curve for BOD load of 8.4 g/m²/d) = 0.04 g/m²/day.
Total P release = 0.04 x 50% x 6 ha x $10^4/10^3$ = 1.2 kg.

We conclude that the annual phosphorus retention performance is reduced from 47% to 45%. Therefore, the sediment remobilisation is of minor importance in terms of lake pollutant interception performance, but could be significant for the larger storm events in terms of stimulating algal biomass.

sediments, with the potential to create anaerobic conditions. If organic material remains after the oxygen has all been used up, further microbial growth leads to the transformation of a number of pollutants (such as nitrate, ferric iron, sulfate) and their release (as ammonium ions, nitrogen, phosphate, hydrogen sulfide) back into the water column in soluble or gaseous forms. Soluble forms are highly available for uptake by biota; gaseous forms are lost to the atmosphere.

This release can significantly offset the interception performance of the pond. It is more likely to occur in ponds that are too small for their purpose or in which the BOD load is not well distributed across the pond area, or in ponds that can suffer stratification.

Stratification enhances the likelihood that reducing conditions will occur. Research indicates that turbid pools, ponds and lakes are highly susceptible to thermal stratification under typical summer conditions throughout temperate areas. Stratification (formation of layers of different density and/or temperature) blocks the transfer of oxygen from the water surface to the sediments to replace the oxygen used up by BOD during the decomposition of organic material.

Figure 3.6 *Sediment release of TP vs BOD load* summarises the results of pond analyses for typical sediments in pollution control ponds at a range of BOD loadings and aeration rates.

The designer calculates a BOD loading (g/m^2) by multiplying estimates of pollutant distribution efficiency by the event load per unit area (derived from an analysis of the BOD loading per storm event and its retention by the pond). When pollutant distribution efficiency is termed `moderate' it means that about 70% of the load is distributed over 50% of area (multiply by 1.4); `poor efficiency' occurs when 60% of load is distributed over 33% of area (multiply by 1.8).

For local pond mixing–stratification conditions, the designer adopts an aeration rate, and reads off the TP release in g/m^2/event. Multiplying this value by 50% or 33% of the pond area gives a total release value.

If releases are likely to occur, the designer has two options:

i) increase the size of the pond calculated in the first two steps to offset the loss by remobilisation; or

3: Oxygen diffusion and water column stratification

Oxygen movement, from the water surface through the water column, is important for replacing the oxygen depleted by decomposition processes in the sediments. Oxygen transfer by molecular diffusion processes alone is extremely limited. The rates of oxygen transfer by eddy currents and mixing are 1 to 3 orders greater than molecular diffusion rates.

When solar radiation is high and waters are very turbid and winds are light or absent, lakes and ponds are extremely prone to thermal stratification. Under these conditions, the turbid surface waters become warmer than the shaded bottom waters. Now the warmer surface water is lighter than the cooler bottom waters, preventing any mixing through the full depth of lake or pond waters. This is effectively a physical barrier to the transfer of oxygen through the water column to the sediments. Consequently, bottom waters typically become deoxygenated as their oxygen is consumed by benthic microbial growth.

Figure 3.9 *Mixing conditions for ponds* illustrates the implications of these processes for a pond of 2 m depth and solar radiation conditions typical of SE Australia. While in theory this implies almost complete cessation of oxygen movement through the water column, there is however diurnal movement in the thermocline level as a result of air temperature variation between day and night temperatures, resulting in cooling of surface waters overnight. As the thermocline moves up each evening, a portion of the DO in the epilimnion is transferred to the hypolimnion (see also Fig. 3.10).

The overall pond or wetland daily aeration is a combination of eddy diffusion due to wind, eddy diffusion due to flow, and diurnal thermocline transfer where stratification conditions prevail.

$$W = 0.8 + 0.3u^{1.64} + 4v^{0.5}/d^{0.5} \times (C_{sat} - C_{pd})$$

where W is the oxygen transfer rate in g/m^2/d,
u is the diurnally averaged wind velocity in m/s,
v is the average flow velocity through the pond or wetland = Q/csa of pond,
C_{sat} is the oxygen saturation concentration for the prevailing water temperature,
C_{pd} is the concentration of oxygen in pond water.

Photosynthesis by algae is also important for maintaining the oxygen balances within lakes and ponds. The process is incorporated in sewage treatment, for example, where residual organic material is oxidised in maturation or oxidation ponds.

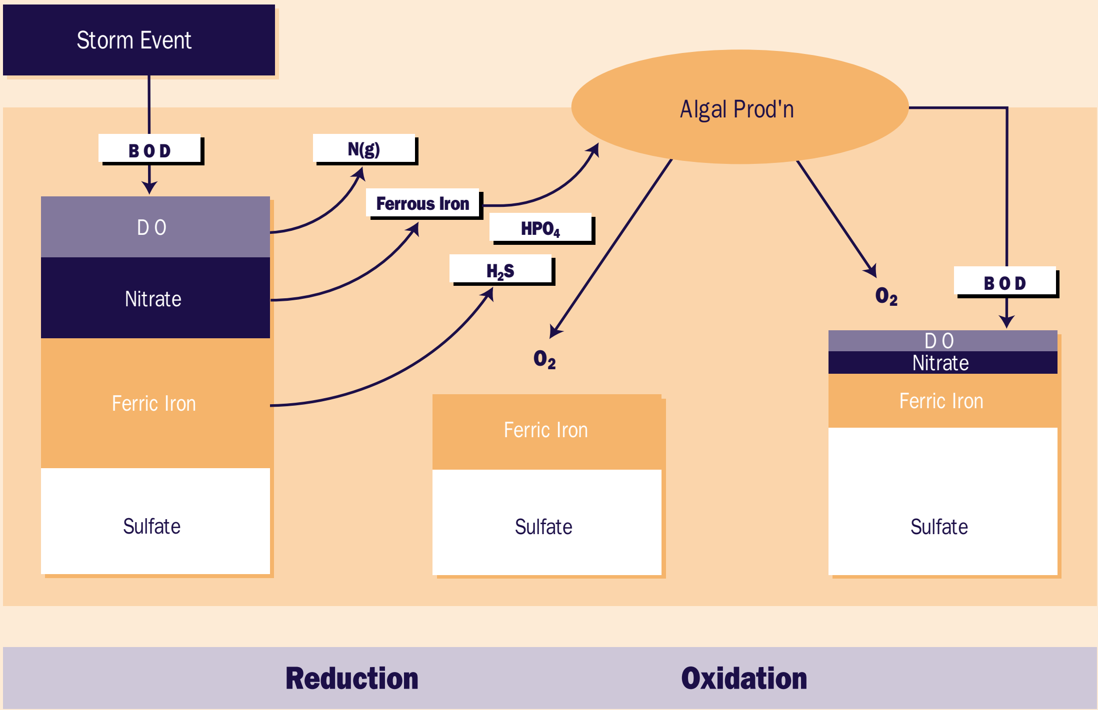


Figure 3.7. **Sediment storage, transformation and remobilisation of pollutants**

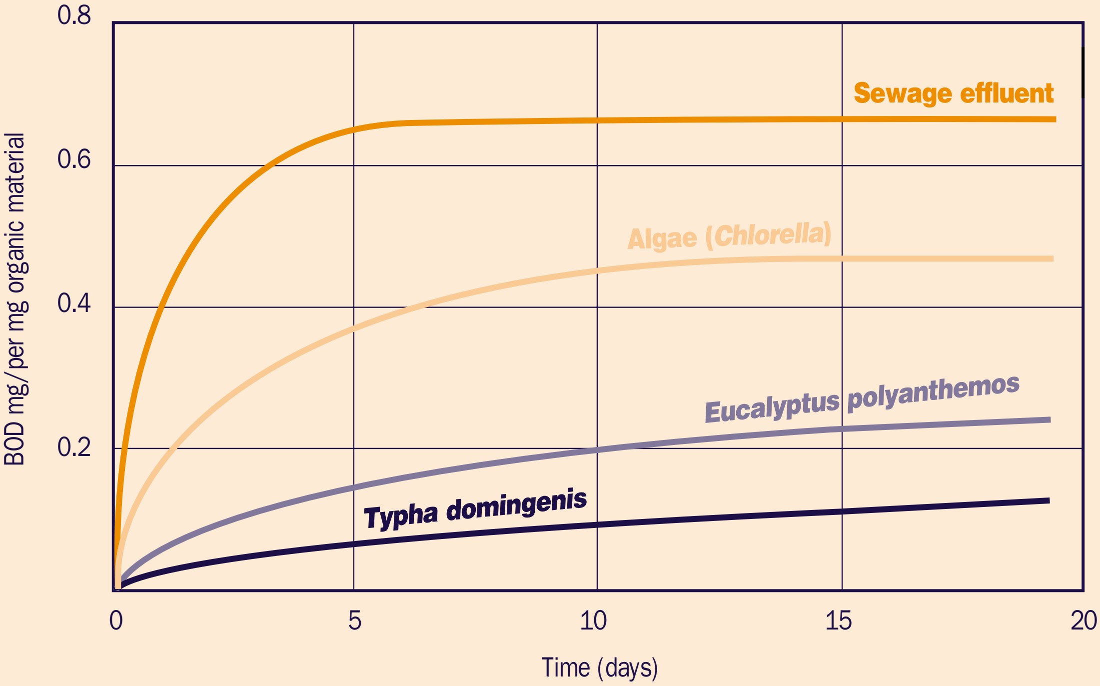


Figure 3.8. **Bioavailable carbon content of common organic materials**

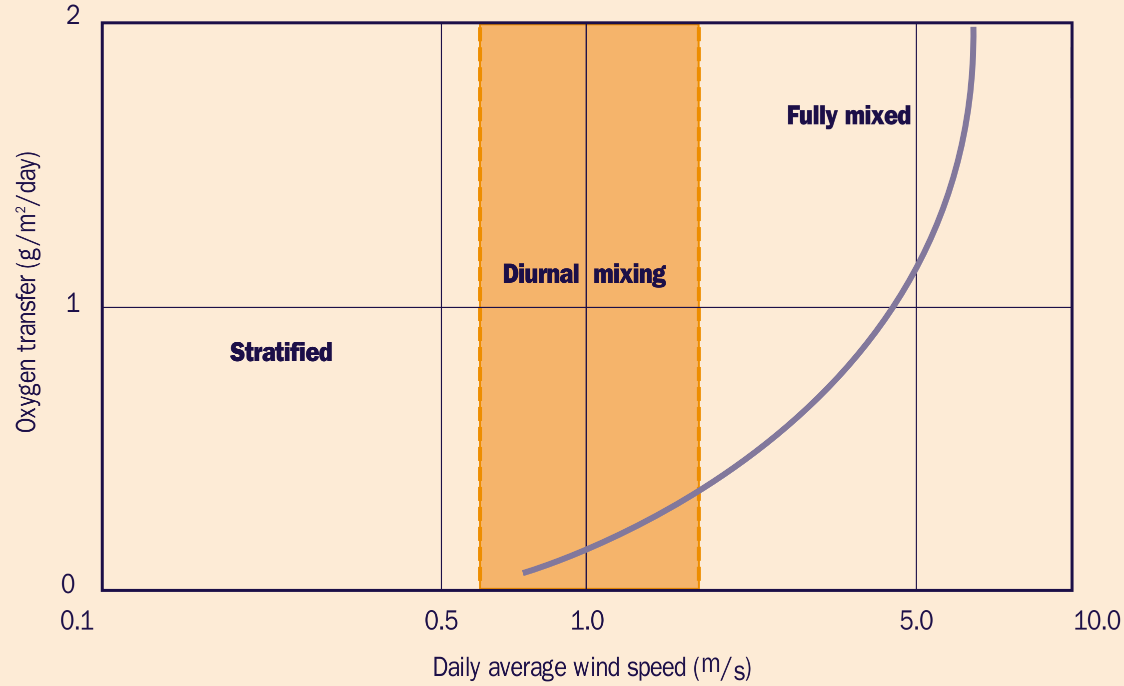


Figure 3.9. **Mixing conditions for ponds**
(for pond of 2 m depth and diurnal solar heat flux of 400 watts/ m^2)

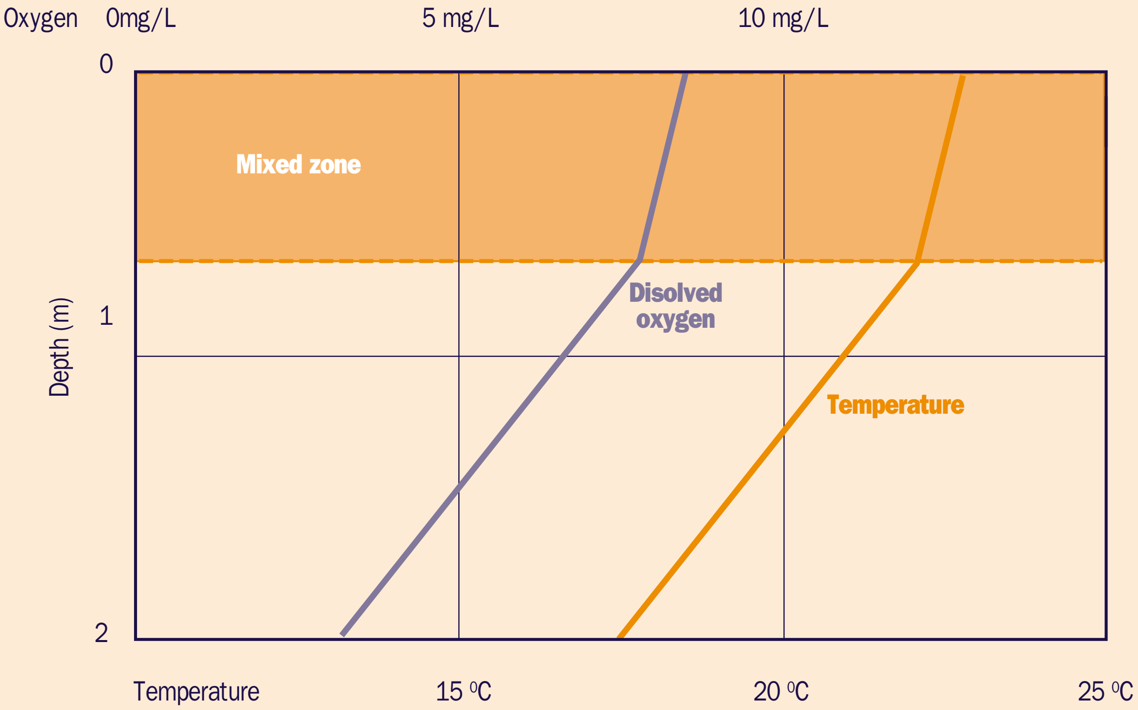


Figure 3.10. **Profile of pond temperature and disolved oxygen** (Stranger Pond, Canberra)

ii) aim to reduce the degree of remobilisation by
   - reducing the event BOD loading, by catchment management;
   - increasing the area of the pond and/or improving pollutant distribution efficiency to reduce the BOD loading rate (g/m^2);
   - extend the planting of macrophytes across the pond where viable, to directly oxygenate their rhizosphere sediment zones;
   - introduce a recycling or mixing mechanism to limit or stop stratification occurring during the post event periods which are so critical for pollution control;
   - cycle pond water in the post event period through an off-line wetland, to take up the released nutrients and organic compounds.

3.1.2 Size to suit base flow or attenuated flows high in suspended solids

In-pond or in-wetland interception of pollutants

During slow influx of water rich in suspended solids, from base flow or storm flows that have been substantially attenuated, the dominant pathway for capturing pollutants still involves their adsorption onto the surfaces of suspended solids (SS), and the sedimentation of the SS. In this case, the designer can estimate the retention time needed for the waters by reading the value directly from Figures 3.3 or 3.4 for the desired pollutant interception target and local grading of SS. The required pond or wetland volume is then given by retention time (days) multiplied by the daily flow.

$$V_{pd} = t_{retent} \text{ x } Q \text{ ,}$$

where V_{pd} is the volume of the pond or wetland in megalitres, Q is the daily discharge of runoff to the pond or wetland, t_{retent} is the retention time in days.

Role of vegetation in particle interception

Research indicate that vegetation has direct and indirect roles in removing particles in wetlands. Direct removal may occur if small particles in the water column adhere to macrophyte and epiphyte surfaces. Indirect removal may include enhanced sedimentation in macrophyte stands.

While wetlands are well known for retaining sediment (eg. Novitski 1978), the particular role of vegetation is not well documented. Both Bowmer et al. (1994) and Wrigley et al. (1991) found the presence of plants in the flowpath to be a major factor in the reduction of turbidity in irrigation drains and water supply systems respectively. Lloyd (1997) found that 1.5 kg/m^3 of *Paspalum distichum* had trapped 4.3 kg/m^3 of sediment. Vegetated zones were also found to have trapped and retained a much higher proportion of clay size particles than non-vegetated open water zones.

To harness these processes the design must:
- ensure uniform flow conditions,
- maximise vegetation in the flowpath,
- ensure uniform vegetation distribution across the flowpath.

The designer protects these fragile adhesion forces and biofilm by excluding high discharges from wetland systems, or, in the case of on-line ponds, by locating the ‘adhesion and uptake macrophyte zones’ around the perimeter of ponds.

The treatment train design also should limit the loading of dissolved nutrients reaching the wetland, or else the wetland should cover an area large enough to take in typical catchment loadings while sustaining viable macrophyte systems.

Transformation and remobilisation of sedimented pollutants

To prevent the transformation and remobilisation of sedimented pollutants into the water column of the pond or wetland as a result of elevated reducing conditions (decomposition of organic material deposited by events), refer to the relevant subsection in 3.1.1.

3.1.3 Size to suit base flow or attenuated flows with colloidal or dissolved pollutants

In-wetland interception of pollutants

Well-designed perennial wetlands intercept dissolved and colloidal forms of nutrients associated with attenuated or base flow. The benthic biofilm adsorbs

4: Adhesion of particles on vegetation surfaces

Particle adhesion onto plant surfaces is not well documented or quantified. Breen (1992) observed particle coatings on vegetation in flood retarding basins, and proposed particle adhesion onto plant surfaces as a potential treatment mechanism in stormwater management systems, particularly for particles too small to be removed via sedimentation. Lloyd (1997) provided photographic evidence of particle removal on the surfaces of several emergent macrophytes.

Where systems undergo significant water level fluctuations during event flows, particles can adhere to all parts of the plants, including those parts usually above the normal water level. Lloyd (1997) examined the submerged surface of *Schoenplectus validus* and found particles as small as 0.5-2.5 μmm sticking both to epiphytes and to clear plant surfaces.

Walker (1995) discussed the size distribution of particles in the Sturt River, SA, and the relationship between particle size and average settling velocities. In the Sturt River, 76% of the suspended particles were <15 μm. Walker pointed out that to remove particles of this size by simple sedimentation requires very low velocities (about 0.00013 m/s). Velocities this low are not found during event runoff when the particulate load is highest. This highlights the potential importance of particle adhesion onto plant surfaces as a removal mechanism. While Lloyd (1997) showed that the processes occur, research is still required to establish their quantitative importance.

Adhesion of particles onto vegetative surfaces is particularly relevant to ephemeral wetland types.

colloidal nutrients and transfers them to the sediments, while dissolved nutrients are primarily taken up by the benthic and epiphytic algae. Adhesion of fine particles onto vegetative surfaces may also play an important role in wetland interception.

The macrophyte substrate and biofilm treatment zones and the macrophyte humus accumulation—adsorption treatment zones are essential for successful treatment of these forms of pollutants. The designer normally accommodates these treatment zones in a perennial wetland design.

Where there is a risk of occasional high discharge events, the designer should locate the wetland off-line. Alternatively, (i) the designer can decide that the events are too infrequent to contribute significantly to the long term pollutant loading, or (ii) the designer can apply separate pond-type techniques for intercepting the event pollutants (refer to Subsection 3.1.5).

Biofilm adsorption of colloids

Size (in this case, area) is simply determined on the following basis:

for base flow:

$$A = 100 \times Q \times C_{infl} \times reduction/r_b$$

for attenuated storm flow:

$$A = 100 \times Q \times C_{infl} \times reduction/(r_b \times t_{retent})$$

where:

A	is wetland area (ha),
Q	is volume (ML) of event discharge fully captured by wetland,
C_{infl}	is inflow concentration of target pollutant (mg/L),
reduction	is the % level of reduction (interception) required,
r_b	is the daily adsorption rate of the target pollutant by biofilm,
t_{retent}	is the retention time (days) or average time between storm events.

Vegetation may remove particles in wetlands both directly and indirectly. Photo: Ian Lawrence

In view of the susceptibility of biofilm to scouring by storm events, in the case of wetland design, it is necessary to design the wetland to limit velocities to <0.05 m/s.

$$v_{max} = Q_{max}/(w \text{ x } d)$$

where v_{max} is maximum velocity in m/s, A is pond area in m^2, d is the average depth in m, w is the width, Q_{max} is the peak flow in m^3/s.

Table 3.2 **Range of biofilm nutrient uptake rates**

Nutrient	**Uptake rate (g/m²/day of contact time)**	
	Event-based System	**Base Flow-based system**
Organic C	0.2 to 1.2	0.5 to 2.5
Kjeldahl N	0.05 to 0.2	0.07 to 0.4
Total P	0.005 to 0.02	0.01 to 0.05

5: Biofilms

Biofilms are made up of a consortium of bacteria, fungi and algae embedded in a polysaccharide matrix.

The polysaccharide matrix has three important functions: it acts as an absorption and retention system for organic and inorganic colloids and nutrients; it retains eco-enzymes that act on particulate and dissolved organic material very near to cells; and it forms a potential external energy reserve (see Fig. 3.11 *Biofilm structure and processes*).

The breakdown of molecules by hydrolytic enzymes is the critical process that determines the rate of decomposition of organic materials: in this process, large organic molecules disintegrate to a size which bacteria are capable of assimilating (Lock 1994).

Macrophytes continually supply organic material to the biofilm in their root zone. This supply maintains the concentrations of enzymes that hydrolyse polymeric material in the near-plant biofilm. In bare sediment areas, the enzyme concentrations in biofilm are much lower. Macrophytes are important also because they transfer oxygen to the sediment via their rhizomes.

There are few reports of the rates at which carbon or nutrients are taken up by biofilm in freshwater ponds, wetlands and lakes. Take-up rates for dissolved organic material are reported as ranging from 3 to 1000 mg/m²/hr for river epipelon layers. In wastewater biofilm systems (trickling filters, maturation ponds), on the other hand, take-up rates range from 60 to 400 mg/m²/hr

Uptake of dissolved nutrients by epiphytes

Algae play an important role in ponds and wetlands because they absorb dissolved nutrients and also reoxygenate the waters. Conversely, if flushed out of the pond or wetland to downstream waters, algae can represent a significant load of BOD and a potential source of nutrients. These guidelines encourage the establishment of epiphytic and benthic forms of algae (which remain attached to, or associated with, the facility under normal circumstances) rather than planktonic algae (which float and can readily move on downstream). Habitats conducive to epiphytic and benthic algae are those where macrophytes grow well, providing a stable substrate.

Dissolved nutrients are primarily taken up by the epiphytic and benthic algae. Published rates of nutrient absorption by epiphytic algae in wetlands indicate:

TN 0.05 to 0.25 g/m²/d of wetland,
TP 0.01 to 0.1 g/m²/d of wetland.

3.1.4 Size to suit rare event-based discharges

Ephemeral wetlands

When storm runoff is infrequent, or in areas naturally subject to periodic flooding, ephemeral wetlands may be appropriate to control pollutants. In ephemeral wetlands the pollutants are intercepted mainly by adhesion to vegetative surfaces and sedimentation (enhanced by evaporation, evapotranspiration and leakage of the ponded water into the groundwater).

As in other wetlands, microbial and vegetative processes incorporate sedimented materials into the soil forming the bed of the wetland. As the ephemeral wetlands and their sediments dry out, the sediments' aeration (oxygen supply) improves, increasing the rate of decomposition of organic material and assisting the long-term management of nutrients (Breen & Craigie 1997).

The wetting and drying cycle is central to the sedimentary processes in ephemeral wetlands. Flooding reduces the oxygen diffusion rate in the sediments by a factor of 10^4, altering a number of redox reactions and changing the pathways of biological metabolism from

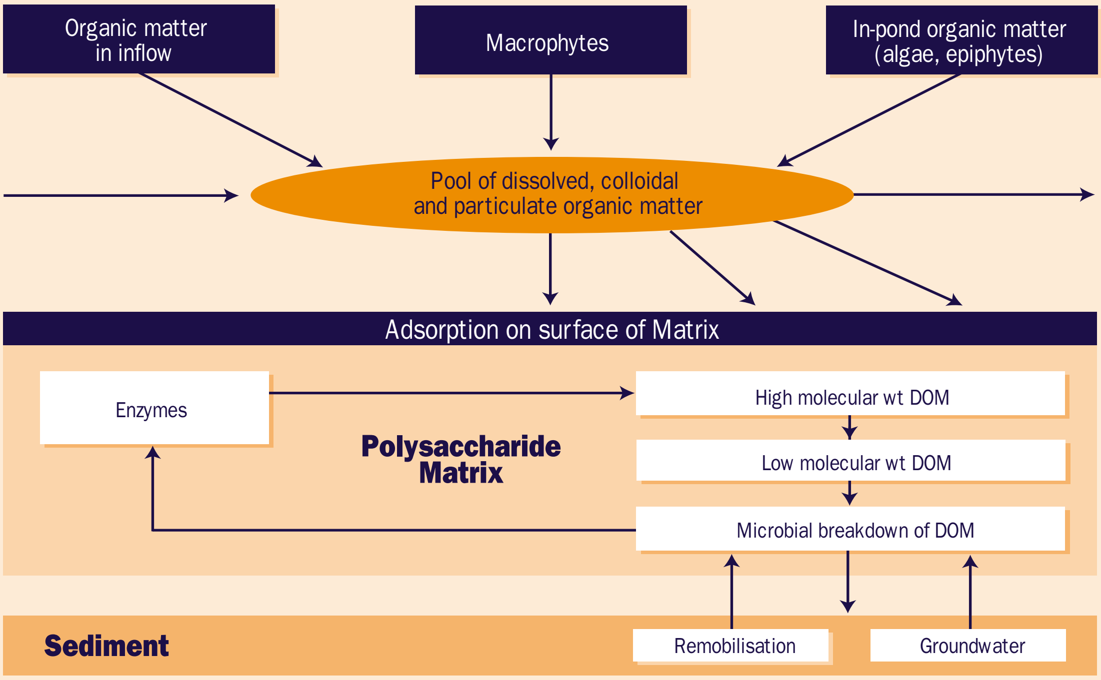


Figure 3.11. **Biofilm structure and processes**

aerobic to anaerobic. Major differences relevant to the wetting and drying of stormwater management systems are discussed in the Information box: Ephemeral wetland sediment rewetting processes.

There is little published research upon which to base a quantitative model for determining a wetland size that will comprehensively intercept the pollutants captured during the storm event. Size in this case is essentially related to the volume required to capture the required proportion of event pollutants. Since ephemeral wetlands have a long retention time, researchers assume that most of the pollutants captured from an event are retained within the ephemeral wetland system.

3.1.5 Sizes for composite designs

Sections 3.1.1 to 3.1.4 have discussed the major types of treatment processes and the discharge conditions and pollutant forms related to them. Often the designer will be confronted with intermediate conditions. The three major groups of composite or treatment train arrangements recommended for dealing with these intermediate conditions comprise:

- use of ephemeral wetlands in association with ponds or perennial wetlands, to provide retardation or extended detention basins;
- integration of the adsorption of organic colloids and uptake of dissolved nutrients into a pond type system;
- recycling of pond water through a separate (off-line) wetland during post event (remobilisation) conditions.

Use of ephemeral wetland zones in pond or wetland design

The specific value of ephemeral zones is that they tend to have greater species diversity than permanently inundated systems. Many of the ephemeral rushes and sedges tend to be smaller than their deep water relatives and have more stems per unit area. This increases the surface area of plants in the flow path and potentially improves a system's particle removal performance.

Shallow ephemeral zones also help to improve overall system performance by acting as hydraulic controls. Shallow ephemeral zones force flows to spread out and help prevent short circuiting (where flows move almost directly to the outlet, without fully mixing across the pond or wetland water storage). The greater diversity of species that can grow in ephemeral zones also enhances the look of a wetland.

Depending on the particular wetland design, ephemeral zones are typically only 100–150 mm deep at normal water level. In temperate areas such as in southeastern Australia, this would result in the ephemeral zone being inundated through winter to late spring, then undergoing wetting and drying phases from late spring to early autumn. During this period the system might alternate between wet and dry about every two weeks. In tropical areas of Australia, the ephemeral zones will be inundated during heavy rainfall periods during the wet season and undergo drying over the dry season.

While inundation after a dry period may be long enough to result in release of nutrients via the pathways discussed above, it seems that in soils which have regular wetting and drying phases, this release is minimal. In general, the benefits of ephemeral zones outweigh the risks of nutrient release on inundation. However it is clear that soils, basin morphology and inundation depth and frequency need to be carefully matched. Depending on design and location, systems containing ephemeral zones may require a low-flow bypass to ensure they have an adequate dry phase.

Integration of treatment processes in one facility

The integration of organic colloid and dissolved pollutant treatment processes with SS treatment processes involves a number of compromises, but may offer several advantages at sites which do not restrict the potential size (area) of the facility.

Elevated SS are generally found in rapid surface runoff and storm event discharges. In a treatment facility (pond or wetland) under these conditions, the large volume of fast-moving water and reduced light normally place at risk the fragile epiphytes and biofilm systems that are fundamental to treatment of colloids and dissolved pollutants. The risks are not so high for events that are small relative to the volume of pond or wetland, or, conversely, for ponds or wetlands that are large relative to the size of the event.

The designer must be guided by the frequency of the storm events and their peak discharge rates when determining the risk that velocities > 0.05 to 0.1 m/s will wash out the epiphytes and biofilm. Infrequent (one event per year) wash-out may be acceptable, provided the epiphytes and biofilm reestablish over time

Dry Creek, Adelaide. While obviously dry, these constructed ephemeral wetlands still support lush vegetation. Photo: Brett Phillips

6: Ephemeral wetland sediment rewetting processes

Many of the changes observed in sediment processes during wetting and drying cycles occur as a result of the significant differences between aerobic and anaerobic decomposition processes.

Decomposition under oxic (aerobic) conditions or during drying phases occurs through the action of a range of organisms including invertebrates, fungi and bacteria. Aerobic decomposition is an efficient process resulting in near complete and rapid degradation of organic material, high energy yields and high assimilation rates.

Decomposition under anaerobic conditions during the wet phase occurs almost entirely through the action of anaerobic bacteria. Fermentation is the major anaerobic decomposition pathway and it results in slow, incomplete degradation of organic matter, low energy yields and low assimilation rates.

The main end products of organic decomposition in well drained soil are carbon dioxide gas (CO_2), nitrate (NO_3^-), sulfate (SO_4^{2-}), and a small amount of resistant residues (soil humus). In submerged soils the end products are CO_2, hydrogen gas (H_2), methane gas (CH_4), ammonium ion (NH_4^+), hydrogen sulfide gas (H_2S), amines, mercaptans and a large proportion of partially humidified residues (peat) (Ponnamperuma 1972, 1984). The organic or peat soils of many permanently inundated wetlands are evidence of the incomplete decomposition process.

Ephemeral wetlands that undergo a regular wetting and drying cycle tend to accumulate much less organic matter and have mineral soils. The breakdown of readily degradable organic matter, as indicated by the rising concentration of CO_2 in the flood water, tends to peak after 1–2 weeks and then slowly decline (Ponnamperuma 1972, 1984). Reductions in redox potential (Eh) on flooding also reflect the breakdown of readily degradable organic matter. Reduction in Eh can occur rapidly, within 1–2 days, but most soils take more than a week to reach a minimum. The fastest reduction occurs in soils high in organic matter (Ponnamperuma 1972, 1984).

The initial conversion of organic nitrogen (N) to mineral nitrogen in flooded soils tends to stop at ammonia because subsequent transformations such as nitrification are limited by oxygen availability. Although denitrification is more rapid under aerobic conditions, more ammonia tends to be produced under anaerobic conditions because there is less uptake and transformation of the ammonium ion under these conditions. While some soils can release significant quantities of ammonia in the first weeks after inundation (200 mg/kg), peak ammonia concentrations in the flood water generally occur after 4 weeks of inundation (Ponnamperuma 1972, 1984). Soil properties strongly influence the amount of ammonia released after flooding, with soils rich in organic matter and N releasing the most (Ponnamperuma 1972, 1984). Although intermittent wetting and drying increases ammonia production by enhancing the decomposition of organic matter it also increases N loss and immobilisation by reducing the amount of organic material available for decomposition and increasing nitrification and denitrification.

Phosphorus (P) becomes more available when a soil is submerged, although the release is not as marked as in sediments after the onset of lake stratification, and it is highly dependent on the soil properties (Ponnamperuma 1972, 1984). While some soils can release P rapidly and increase flood water P concentrations to 2 mg/L after only 1 week of inundation, for most soils peak concentrations of P in flood waters do not occur until after 4–6 weeks of inundation. The increases in P on flooding and the peak P values are highest in the sandy calcareous soils low in iron, moderate in the sandy acid soils low in iron, small in the nearly neutral clays, and least in the acid ferruginous clays (Ponnamperuma 1972, 1984). Qui & McComb (1994) also found much more P released from organic soils than from mineral soils after drying and rewetting. These fluctuations between the forms of P in the sediments on inundation largely correspond to the reduction and oxidation of iron.

Patrick & Mikkolsen (1971) showed that sediment P behaves differently under permanent and intermittent inundation. Although the general availability of P increases during flooding and decreases during dry periods, the P fixation is more extensive and less reversible under intermittent conditions than under either continuous flooded or continuously moist conditions.

Experience from irrigated agriculture has shown that soluble phosphate added to soil is rapidly converted to an unavailable form when soil undergoes alternating flooding drying. Baldwin (1996) found that lake sediments that have dried and have been oxidised have lower P adsorption capacity than those that remain inundated, and that sediments from above the oxycline have lower P adsorption capacity than those from below.

(recovery of treatment capacity), and provided there is only limited wash-out of previously retained pollutants.

Recycling of pond water through an off-line wetland

As an alternative to the integrated approach outlined above, the designer can arrange to recycle pond water through an adjacent wetland facility (or physically separated embayment of the pond) during the post event phase. This gives much better control over the two processes, and has the added benefit of introducing a mechanical mixing and destratification process which will limit the potential for remobilisation of pond pollutants.

This option is also particularly effective where a high (>70%) pollutant reduction target has been set.

3.2 Treatment train context

Section 2.2 introduced the concept of ponds and wetlands as part of a treatment train.

Just as for wastewater treatment, a treatment train involves components designed to intercept specific pollutants. Omission of any one step has significant effects on the efficiency and viability of subsequent steps. Table 3.3 summarises the target pollutants for each of the treatment units, and the implications of omitting any component.

Failure to regularly maintain treatment components such as GPTs will have the same impact as failure to install the components. For wastewater treatment, the first task is to separate the target pollutants (sludge), while the second task is to remove the separated sludge before there is time for the trapped pollutants to remobilise and leak back

Table 3.3. **Target pollutants and appropriate treatment units and their impact on downstream efficiency and viability**

Pollutant	**Treatment unit**	**Implicats: without treatment unit**
Coarse sediment	Gross pollutant trap (GPT)	Loss of pond or wetland volume, loss of interception capacity. Frequent de-silting of pond or wetland required. Loss of aquatic plants, loss of interception capacity. Smothering of benthic organisms in pond sediments, loss of oxidation capacity of sediments, increased remobilisation, loss of interception capacity.
Coarse organic material	GPT	Significant increase in organic loading on pond or wetland, increased remobilisation of sedimented pollutants, loss of interception capacity.
Trash	GPT	Unsightly downstream pond or wetland. Potential for mosquito nuisance.
Medium to fine suspended particles.	Pond	Reduced light underwater in wetland, reduced biofilm and epiphyte uptake of nutrients, reduced macrophyte biomass, loss in interception capacity. Smothering of biofilm and benthic organisms in wetland, lower uptake of pollutants by biofilm and reduced oxidation of sediments, loss in interception capacity.
Colloidal particles and dissolved nutrients	Wetland	Stimulus of algal growth in downstream waters if these pollutants are a significant part of the pollutant load.

Vehicle, pedestrian or cycle paths are often incorporated into embankment designs. Photo: CRCFE

into the effluent stream. The same principles apply to the stormwater treatment train. In the case of sediments in stormwater pollution control ponds and wetlands, provided that the organic loading is not excessive, it is possible to maintain the sedimented material in a condition where leakage back into the effluent stream is minimised.

In the discharge from most storms, a large proportion (80% to 90%) of total sediment is >80 µm in size, so it is operationally more economical, and socially and ecologically less disruptive, to intercept these medium to coarse sediment fractions in a dedicated GPT upstream of the wetland or pond. This reduces the desilting requirements of the pond or wetland from a complete clean-out once in 5 to 10 years, to a small task once every 30 years.

When the organic material trapped in GPTs is removed at regular intervals, the organic loading on the sediments of downstream ponds and wetlands is substantially decreased, enhancing their interception efficiency and viability.

Care must be taken to site GPTs sufficiently high above the pond's or wetland's normal operating water levels that they can be drained by gravity for clean-out purposes.

3.3 Depth

Normally, depth is determined by the volume needed to meet the pollutant retention target.

As well, in selecting the best depth, the designer needs to take into account the type of treatment process proposed. In the case of wetlands which rely on absorption by macrophytes and associated epiphytes for pollutant control, depth must generally be limited to <600 mm for urban stormwater treatment systems. Where open water is required to promote wind mixing and aeration, depths >700 mm will be required, to limit macrophyte establishment. Depths should not exceed 2.5–3.0 m, because there is increased risk of temperature stratification beyond these depths.

3.4 Shape

If ponds or wetlands are long relative to their width, and incorporate islands or baffles across possible lines of short circuiting, water should circulate throughout the pond or wetland, without further intervention (see Fig. 3.12 *Pond shape*). Length-to-width ratios ranging from 3 to 5 are reported as ensuring efficient distribution of flow.

A gross pollutant trap in Kambah, ACT, collects coarse debris before it can make its way into urban ponds. Photo: Ian Lawrence

The designer should avoid including embayments or extended inlets, unless designing them as independent ponds or wetlands with their own inlets. Embayments or extended inlets may create zones of poorly mixed backwaters, subject to water quality degradation.

In cases where the inlet is near the outlet, or where a deep channel connects the inlet and outlet, the storm event discharge may bypass much of the pond's or wetland's volume (short circuiting) thereby substantially reducing the pond's or wetland's effective volume, and its overall retention efficiency.

The use of lake and pond circulation assessment models such as NESSIE (Anderssen et al. 1989, Mooney and Anderssen 1990) can help with the design of pond shapes and with the placement of baffles or islands to achieve optimum mixing.

3.5 Shoreline profile (cross section)

The shoreline profile needs to meet a number of design requirements, including:

- free draining slopes that cannot hold isolated pockets of water (with potential for mosquito nuisance in situations where predators, such as fish, are excluded);
- slopes capable of withstanding wave action without serious erosion, compatible with local soils, local wave height (which is controlled by wind fetch and strength) and local edge vegetation;
- gentle slopes, free of sudden drops which might present a safety hazard to children wading into the pond or wetland.

Suitable grading requirements are illustrated in Fig. 3.13 *Edge treatment*.

3.6 Soil substratum

When wetlands are especially constructed for surface water management, the sediment types brought in or already *in situ* must meet five objectives:

- minimal use of soils high in organic material, nutrients, metals or toxicants, which are likely to impose a high BOD loading on the pond or wetland upon initial filling, potentially leading to mobilisation of nutrients, metals and toxicants and their release into the water column;

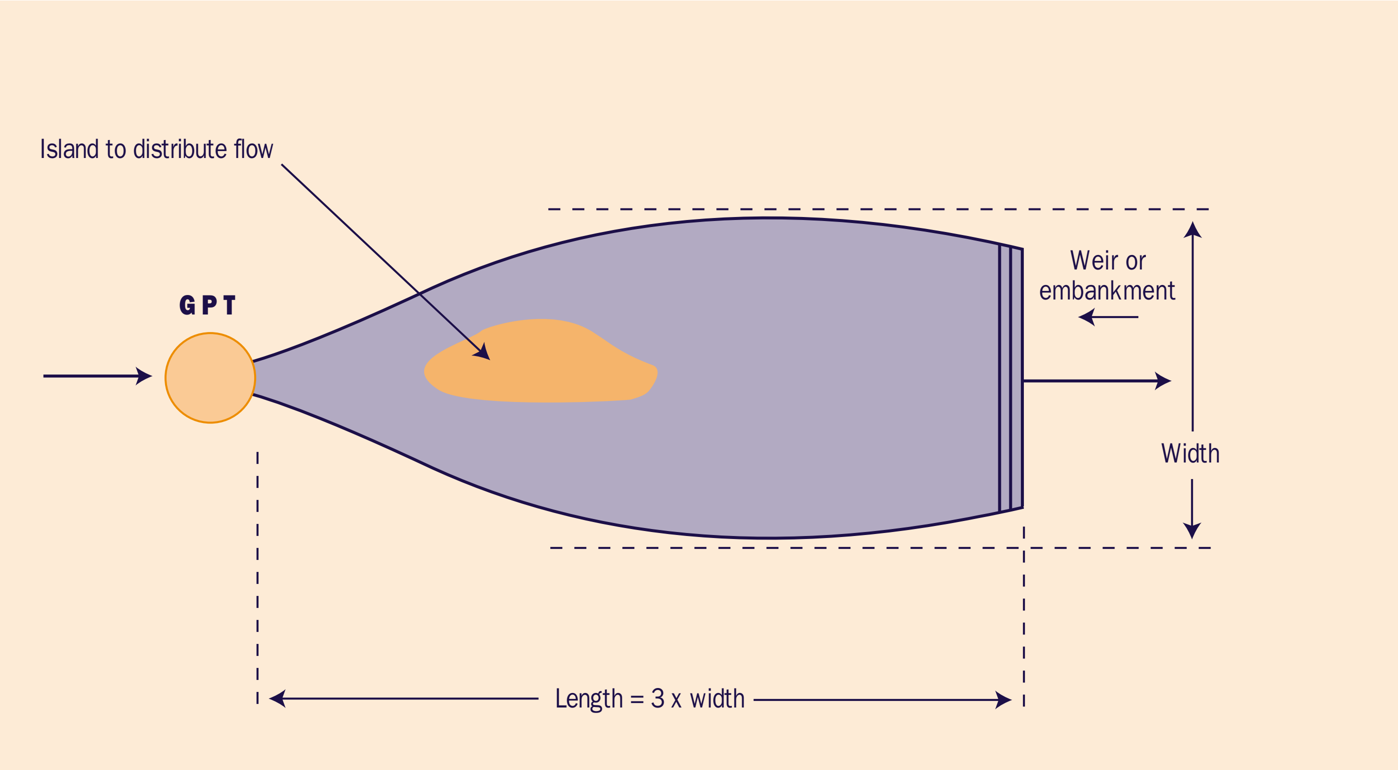


Figure 3.12. **Shape of ponds and wetlands**

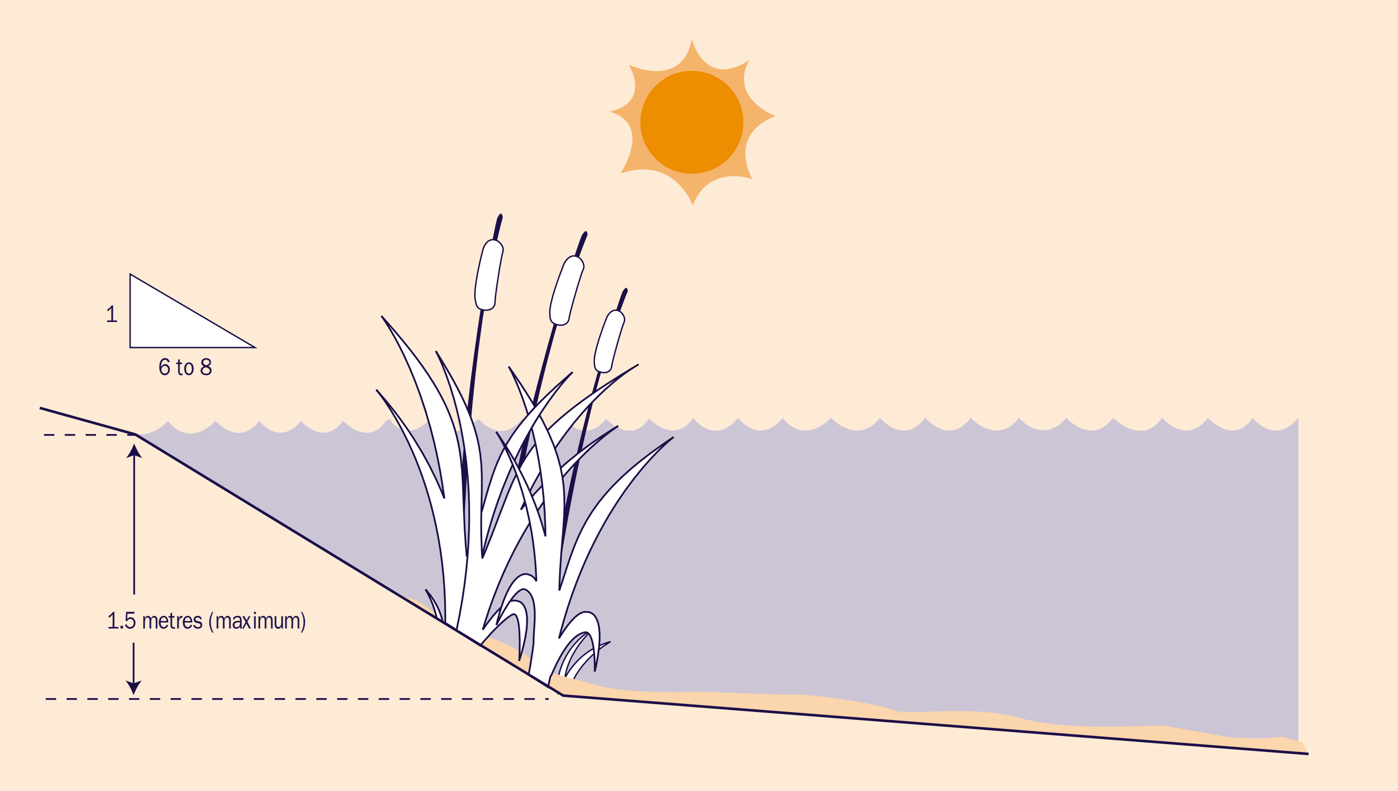


Figure 3.13. **Edge treatment**

- a substrate conducive to a healthy growth of macrophytes within areas designated for them (optimum condition being a loamy soil having a medium organic content, and a depth of 200 mm);
- a range of soil particle size and mineralogy which has a large capacity to adsorb nutrients (high concentration of clays, iron, aluminium);
- minimal cost;
- a limit to minimise seepage into groundwater where ponds or wetlands are located on pervious subsoils.

The final selection of soil will be a compromise between these factors.

Where there are concerns that ponded water will be lost through porous subsoils, or pollute the groundwater, it may be necessary to line the bed of the pond or wetland. Lining techniques commonly involve the use of geofabric and clay to form an impermeable layer.

3.7 Selecting plants and design of planting

The choice of plants and the way they are arranged must reflect the type of pond or wetland adopted (which affects the functions of the plants) and the shape and depth of the pond or wetland.

As noted in previous sections, the major functions of the plants are:

- to assist in the even distribution and calming of flows, to enhance sedimentation in the case of fine suspended particulate systems;
- to maintain transfer of oxygen to sediments in systems where there is a potential for thermal stratification (i.e. at depths >0.5 m in very turbid systems during periods with high solar radiation and low wind);
- to provide a substrate for algal and microbial biofilm biomass, necessary to absorb fine colloidal and dissolved nutrients and toxicants for wetland systems.

Most wetland plants have an optimum position along the wet/dry gradient. From analysis of natural ponds and wetlands, researchers have identified three major categories of water environment:

- ***shallow ephemeral zones*** typically occupied by a diverse range of vegetation;
- ***shallow perennial zones*** occupied by fewer species but a more dense cover;
- ***deep perennial zones*** occupied by a diverse range of plants as a result of variable light regimes and submerged species.

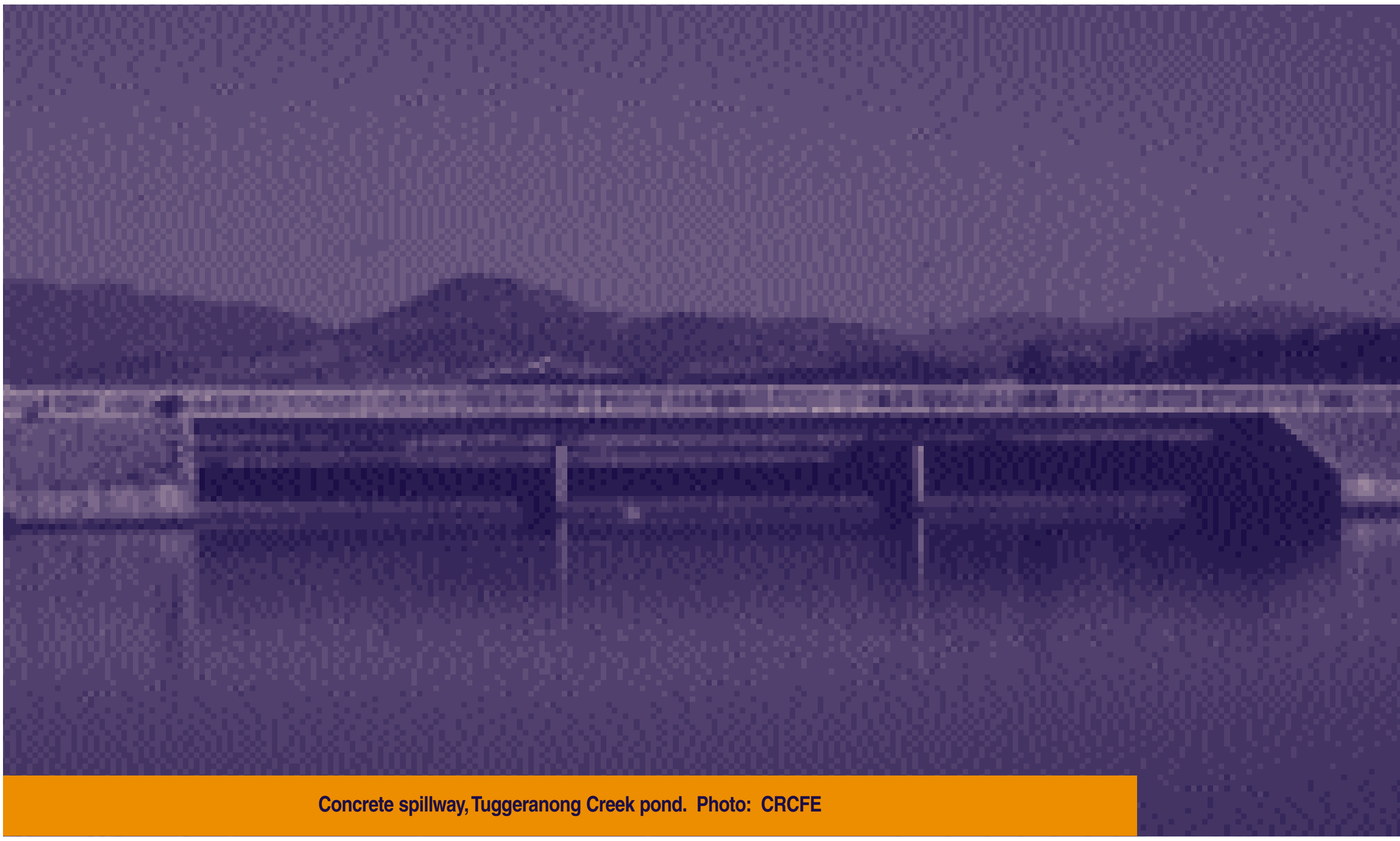
Short-circuiting is probably the single most important factor to guard against in wetland design. Vegetation zones in most natural drainage lines develop parallel to the flowpath and cause a gradient of hydraulic resistance across the flowpath that can result in hydraulic short-circuiting.

Where possible, it is important to design vegetation zones that are perpendicular to the flowpath and have a uniform cross-section. In flat terrain where the basin of the wetland will generally have to be formed by earthworks, the designer can generally meet this requirement. However in steeper terrain, site constraints often limit this approach. In steep locations, the treatment units should be ponds, not wetlands.

The designer should ensure that as much vegetation as possible grows in the flowpath, by designing ponds whose water levels fluctuate significantly during runoff events. This reduces the area of the permanent pool of a pond, but maximises the area within the storage basin that can be vegetated.

To do this, the designer gives the pond an outlet structure that allows water levels to rise significantly during event flows (up to 1 m), but also lets the pond drain slowly enough to irrigate and support the littoral and ephemeral vegetation in the basin above the permanent pool level. However, the pond must also drain fast enough to ensure adequate storage for the next runoff event. Somes et al. (1996) propose a possible design approach, in which the selection of plants and design of planting is matched to the system function, flow regimes, water depth/light regimes, and hydraulics.

In general, areas suitable for establishing macrophytes can have water depths of no more than 0.1 m to 0.8 m. In addition, the designer must specify the nature of the sediment (or substrate) into which macrophytes are to be planted. Sandy loam soil is the best for macrophyte propagation. It is also important to keep zones of high velocity (>2m/s) or



Concrete spillway, Tuggeranong Creek pond. Photo: CRCFE

high sedimentation rates away from macrophytes so they are not damaged and killed.

The macrophyte species can be those common to the area and suitable for the conditions proposed for the pond or wetland. Refer to Table 3.5.

3.8 Embankment design

Normally, the design incorporates embankments, constructed to impound the water forming the pond or wetland. For urban water pollution control ponds or wetlands, they normally comprise roller-compacted earth embankments. Soil for the embankments is selected so as to form an impermeable barrier to water seepage (clays) and provide the stability necessary to withstand the hydraulic pressure of water expected during the design storm event conditions.

Typically, embankments use a sandy clay, placed and compacted in layers, to form upstream and downstream slopes of 1:3, and a crest of 2 m (or greater) width. Geo-technical surveys assess the suitability of local soils for embankment construction, and how the foundations should be treated. The designer may also let an embankment provide a vehicle, cycle, pedestrian and/or sewer crossing.

In cases where a natural rock stream bed and banks occur, or where a large spillway capacity is required, it may be cheaper to form a simple concrete or mortared rock overflow weir. Where it is proposed to discharge storm flows over the embankment, the designer must pay special attention to armouring the compacted soil against scouring. This may require the installation of geo-fabric and grass vegetation, or the installation of geo-fabric and a crushed rock layer.

3.9 Spillway selection and design

Spillways are required to accommodate the design flood. They protect the earth embankment from being washed away by the flood. If the embankments are >10 m in height and hold 20 ML storage, or are >5 m in height and hold 50 ML storage, they are designated ‘high hazard dams’, and must be referred to the state’s or territory’s dam safety officer for assessment. The Australian National

Greenfields development in the ACT…developing the suburbs in Tuggeranong Valley during the 1980s. Pollution control ponds and urban lakes are a feature of recently developed suburbs. Photo: Ian Lawrence.

Committee on Large Dams (ANCOLD) requires that the design flood frequency be 1 in 10,000 years where there are urban areas within a failure flood zone downstream.

These are possible spillway designs:

- a large concrete pipe rise and conduit through one of the abutments (Morning Glory Spillway),
- a concrete weir and drop chute, within either the embankment or one of the abutments,
- a grassed chute located on one of the abutments, graded so as to withstand occasional flows without erosion,
- overtopping of low (<3 m) embankments that are grassed and geo-fabric stabilised.

A common solution to the high cost of concrete spillway structures is to build a small concrete construction as the primary spillway (to accommodate flows up to the 1 in 100 years return frequency storm event), and a grass-stabilised earth channel as the secondary spillway (to accommodate flows in excess of the primary spillway capacity, up to the design flood discharge).

Refer to Australian Rainfall and Runoff (1987) from the Institution of Engineers Australia, or to McMahon, Finlayson, Srikanthan & Haines (1992) for guidance on estimation of flood flows.

Spillway capacity design

Broad crested weir

$Q = C_{sp} \times L \times d^{1.5}$

where C_{sp} is the coefficient of discharge (1.7),
L is length of weir (m),
d is depth of water over weir crest (m),
Q is discharge in m^3/s.

Earth or rock side channel

Mannings formula: $v = {}^{1}/_{nM} \times r^{0.67} \times s^{0.5}$; $Q = v \times csa$

where r is hydraulic radius = $^{(depth \times breadth)}/_{(breadth + 2 \times depth)}$,
v is velocity (m/s),
n_M is Mannings friction coefficient (0.02 for smooth grassed channel,
0.03 for rough rock channel),
s is the hydraulic gradient,
Q is the discharge in m^3/s,
csa is the cross sectional area of flow (m^2).

Conduit (partially filled section)**: Rectangular section**

Mannings formula $v\ (m/s) =$
${}^{1}/_{nM} \times r^{0.67} \times s^{0.5}$; $Q\ (m^3/s) = v \times csa$

where v is velocity in m/s,
nM is Mannings friction coefficient (0.012 for smooth pipe), s is the hydraulic gradient,
Q is the discharge in m3/s,

Outlets may be necessary to maintain base flows or to drain wetlands and ponds if required. Gungahlin, ACT. Photo: Karen Markwort

csa is the cross sectional area of flow (m^2),
r is hydraulic radius = $^{(depth \times breadth)}/_{(breadth + 2 \times depth)}$.

Conduit (partially filled section)**: Circular section**
Mannings formula v (m/s) =
$^1/_{nM} \times r^{0.67} \times s^{0.5}$; Q ($m^3$/s) = v x csa
where v is velocity in m/s,
nM is Mannings friction coefficient (0.012 for smooth pipe),
s is the hydraulic gradient,
Q is the discharge in m^3/s,
csa is the cross sectional area of flow (m^2).

Gross pollutant trash rack.

Table 3.4 **Relative depths, areas and hydraulic radii**

Depth water/pipe diamiter	**csa flow/csa pipe**	**hdr radius flow/radius pipe**
0.8	0.86	1.22
0.6	0.63	1.11
0.4	0.37	0.86

3.10 Outlet arrangements

Outlets may be necessary to maintain base flows downstream, or to make it possible to drain the pond or wetland if it needs to be emptied. Outlet arrangements commonly comprise a small diameter pipe through an abutment or into a spillway structure, with a gate or valve on the inlet or outlet to control flow rates.

Outlet Pipe capacity (pipe full–under pressure):
Hazen Williams formula: $Q = 2.8C_p \times D^{2.63} \times s^{0.54}$;
where Q = discharge in m^3/s,
C_p is Hazen-Williams Coefficient (140 for steel/concrete pipe),
D is diameter of pipe (m),
s is hydraulic gradient = water head/length.

Table 3.5 **Role and selection of macrophytes**

Treatment zones and functions	**Roles of plants**	**Other values**	**Selection of plants**
Discharge transitional zone: depositional fan from inlet to deeper parts of pond/wetland.	To calm and distribute flows; to armour and bind sedimented material; to aerate plant root zones of sediments.	Important ecological zone; distinctive zone in landscape terms.	Plants capable of sustaining periods of elevated flows and variable water levels: *Schoenoplectus validus, Typha orientalis, Phragmites australis, Juncus usitatus.*
Pondage zones: deeper and more open zones of ponds/wetlands.	To provide substrate for adhesion of particles and establishment of epiphytic algae; to directly aerate plant root zones of sediments.	Habitat for larger aquatic animals and birds; landscape qualities.	Larger plants capable of sustaining greater depths: *Typha orientalis, Schoenoplectus alidus, Baumea articulata, Eleocharis sphacelata.*
Substrate and biofilm zones: zones generally <0.5 m, promoting extensive growth of macrophytes as substrate and habitat for biofilms.	To provide substrate for establishment of epiphytic algae; to maintain open conditions for benthic algal and biofilm growth.	Important ecological zone; patches of emergent plants contribute to landscape values.	Mix of narrow leaved plants, and wide leaved plants for substrate: *Eleocharis acuta, Baumea ribiginosa, Schoenoplectus validus, Baumea articulata.*
Humus–adsorption zones: zones generally <0.5 m promoting growth of macrophytes and accumulation of humus to adsorb toxicants.	To accumulate plant stems and humus material, as low bioavailable C sinks, and for adsorption of toxicants, sulphur.	Important ecological zone; patches of emergent plants contribute to landscape values.	High biomass generating plants: *Typha orientalis, Phragmites australis, Baumea articulata, Cyperus lucidus, Eleocharis.*
Littoral and riparian zones: edge zones designed to capture wind blown algae and protect banks against erosion; riparian plants as buffer zone.	To protect banks against erosion; to provide an edge buffer zone.	Habitat for aquatic animals; landscape qualities; barrier to human intrusion and a safety measure for children.	In littoral zone, plants capable of sustaining varying water levels: *Baumea* spp., *Bolboschoenus* spp., *Juncus* spp., *Iolepis* spp., *Cyperus* spp. In riparian zone, *Melaleuca* spp., *Carex appressa, C. fasicularis.*
Ephemeral zones: zones that are periodically inundated, retardation basins, edge zones, semi-arid area wetlands.	To be a substrate for adhesion of fine particles; to transform sedimented material and integrate it into sediments.	Distinctive landscape character; significant ecological zone.	Plants capable of sustaining periodic indundation: *Carex* spp. (e.g. *appressa, guadichaudiana*), *Eleocharis acuta, Juncus* spp. (e.g. *amabilis, flavidus, subsecondus*), *Poa* spp. (e.g. *labillardieri*).

Photos : Judy Frankenberg

4. Design principles for ecology, safety, aesthetics

Apart from their pollution control function, ponds and wetlands may have to be designed to conserve ecological niches or aquatic habitats, retard flood flows, and provide areas that are aesthetically pleasing and useful for recreation.

4.1 In-pond/wetland water quality and ecology

Urban ponds and wetlands are often perceived as having a high conservation value, in view of their very productive emergent plant zones, diverse range of aquatic birds, and fish. If these facilities are expected to conserve ecological niches and aquatic habitats, the designer must identify suitable target species or groups or habitats to be conserved, and understand the water quality and habitat type appropriate to the conservation target.

Pond and wetland ecosystems comprise:

- the primary producers (large rooted plants, floating plants (macrophytes, algae), attached algae), using nutrients and light fluxes;
- the secondary producers (fungi, bacteria), using decaying organic material;
- the grazers (Cladocera, copepods);
- the higher animals (fish and mammals, birds);
- the fluxes of water and its constituents (nutrients, organic material, suspended solids, pollutants);
- the adsorption of nutrients, metals and organic compounds onto suspended particles, and their sedimentation;
- the transformation and transfer of constituents between water column, sediments, atmosphere and biological compartments.

Operation under a range of water levels will enhance species diversity and growth of some plants. Conversely, maintenance of permanent water and levels will favour dominance by the more competitive plants such as *Typha.*

The design of ponds or wetlands inevitably represents a compromise between their roles in conserving and promoting biodiversity and their roles in intercepting pollutants and enhancing the landscape.

Managers of urban wetlands need to control predation by domestic pets on native fauna. One technique often used is to construct an island within the pond or wetland, to act as a refuge for native fauna.

A major concern with ponds is the potential for unsightly algal blooms, especially where the ponds are required to meet aesthetic performance criteria in addition to their pollutant interception function (see *Case study 4*). The high turbidity of ponds, and their propensity for thermal stratification during periods of high solar radiation and low wind, suit the

Urban wetlands provide homes for wildlife.,
Print: Brett Phillips

blue-green algae. Frequent loading from storm events and the possibility of wash-out prevent grazers from being a significant factor in limiting algal biomass in this case.

Conversely, in the rather turbid conditions, both light and nutrients (TP) limit the potential algal biomass. The most dangerous situation occurs when P and N are remobilised following an event, at a time of stratified or poorly mixed conditions. The potential algal biomass is estimated by:

Algal biomass (chlorophyll-a) = $\Delta P \times 0.5 \times 1/d \times 0.7$ mg/L or $y_o^{0.3n}/1000$ mg/L whichever is the smaller,

where ΔP is the release of P from the sediments (g/m²),
0.5 indicates remobilisation across 50% of the pond area,
d is the average depth of the pond (m),
0.7 is the chlorophyll-to-TP ratio,
y_o is the initial chlorophyll-*a* value (µg/L),
n is the probable extent of dry weather flow days following the event,
0.3 is the increase in initial algal level/day for a doubling time of 5 days.

4.2 Flood detention

The designer can combine flood detention functions with pond and wetland systems in two ways:

- by retrofitting ponds or wetlands into existing dry retardation basins;
- by incorporating a pond or wetland into the design of retardation basins (multi-purpose based design).

Since a dry retardation basin typically occupies a large area, it is possible for managers/designers to design and operate it as an ephemeral wetland system (Breen, Mag & Seymour 1994). This safeguards the basin storage capacity in the event of the maximum design storm, while providing a basis for significant interception and removal of stormwater pollutants.

Retardation basins are generally designed to reduce peak flows associated with events likely to recur from once in five or 10 years to once a century. Conversely, as discussed above, stormwater pollution control measures generally are designed to capture the smaller storms (up to a recurrence interval of once every three to five years). Pollutant loads discharged by these events typically represent 85% to 95% of the long term total.

Consequently, retardation basins present convenient existing stormwater control systems into which to retrofit ponds or wetlands with minimal impact on current land uses, minimal cost and only minor loss in retardation capacity. The designer implements this retrofit by modifying the inflow arrangements so that discharges are routed via the pond/wetland instead of via the pipes that bypass the retardation basin for minor flows.

When new ponds or wetlands are proposed, these are excellent opportunities for incorporating retardation functions into the design (making it multi-purpose), often with significant economic as well as environmental benefits. However, the period of plant inundation associated with the extended retention must not impair plant viability (maximum period for inundation is 14 days).

In designing multi-purpose systems, again, the designer must first decide on the size/frequency of events to be routed through the pond or wetland.

Then, the designer determines a storage volume capacity additional to that at the normal operating level of the pond/wetland, on the basis of flow reduction requirements downstream. This arrangement provides enhanced pollutant interception capacity, as a result of the extended retention of larger storm events. The designer must pay careful attention to the size of the pond or wetland, and to the selection and design of the spillway.

4.3 Recreation and aesthetic functions

Urban ponds and wetlands represent important open space and recreation facilities in urban areas, greatly valued by local communities.

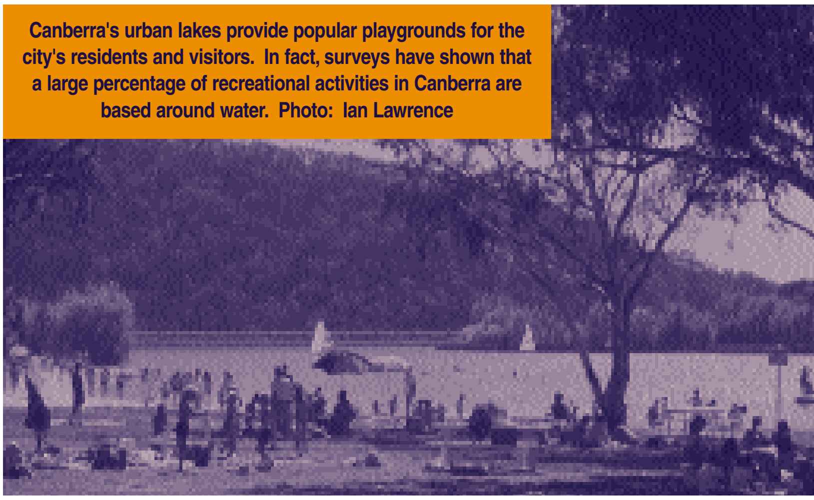
If the ponds and wetlands are primarily for stormwater management, recreation will normally be limited to secondary uses such as fishing and boating, and to passive recreation activities. The designer will need to accommodate water quality and habitat requirements for fish and for aesthetic values (freedom from trash, scums, odours) in the design of the pond or wetland.

From an aesthetic viewpoint, it is important to select and design plants to enhance the visual quality of the facilities. The designer should consider the alignment and treatment of edges to add interest, with the use of small embayments to create interpretative areas.

In ponds and wetlands, the designer can develop a range of terrestrial, ephemeral and perennial zone plant landscape interactions, while flowing and still water offer a range of waterscape opportunities.

4.4 Health and safety issues

When stormwater facilities are being constructed, the owner is responsible for ensuring that they are not a risk to public health or safety.


Canberra's urban lakes provide popular playgrounds for the city's residents and visitors. In fact, surveys have shown that a large percentage of recreational activities in Canberra are based around water. Photo: Ian Lawrence

One major public health concern is the potential that ponds or wetlands will create habitats where mosquitoes can breed close to urban areas, particularly in view of the increase of such mosquito borne diseases as encephalitis (Ross River, Barmah Forest, Gan Gan). While Australia is free of endemic malaria, there is nevertheless a fear of malaria outbreaks associated with the development of ponds and wetlands.

Accordingly, the design of ponds and wetlands should minimise the risk that mosquitoes will breed there. Control strategies comprise a range of measures, including:

- interception of trash (containers, etc) which mosquito predators may not be able to enter;
- shaping of ponds and wetlands to avoid the creation of stagnant (unmixed) areas;
- treatment and shaping of pond or wetland edges to avoid the trapping of water (exclusion of predators) with rise and fall of pond or wetland water levels;
- varying pond or wetland levels in order to ‘beach’ mosquito larvae, and so break their growth cycle;

Gentle grading of edges should be included in urban ponds and wetland design, where possible, to minimise safety hazards. Photo: Karen Markwort

- selection and management of aquatic plants so as to minimise habitats favoured for mosquito breeding;
- provision of fish movement channels or ladders past barriers, to enhance movement and growth of mosquito predators;
- use of pesticides only as a last resort.

Lake and pond mixing models, such as NESSIE (Anderssen et al. 1989, Mooney and Anderssen 1990), will assist the designer in shaping ponds and placing baffles or islands to minimise the potential for creating backwater zones.

In ephemeral wetlands, the management of mosquito nuisance becomes more difficult. Management techniques include the construction of rill drains, enabling drainage of expansive flat areas, and the siting of wetlands far away from residential areas.

Ponds or wetlands can be attractive to small children and therefore can present safety hazards. The designer has a responsibility to avoid the creation of safety traps, such as:

- sudden drops into deep water;
- sudden occurrence of high velocity flows or increases in pond or wetland water level, placing children at risk of drowning;
- raised structures that children can fall off;
- easy access to outlet structures where water has high entry velocities during storms.

Strategies for dealing with these potential hazards include:

- gentle grading of the edges and beds of ponds and wetlands to avoid the creation of sudden drops or underwater 'holes';
- encouraging the growth of emergent macrophytes around the edges of ponds and wetlands, to discourage children from entering these facilities;
- the selection and design of inlet and outlet structures that minimise flow velocities;
- the installation of fences, booms or other barriers where it is not otherwise feasible to ensure 100% safety;
- the installation of signs to warn the public of possible hazards and their need to exercise care;
- the mounting of education programs, particularly targeting pre and primary school children.

Managers/designers are reluctant to fence ponds and wetlands to exclude the public, particularly in view of their landscape and open space values. Indeed, in many cases, there are active programs to use the facilities to raise community awareness of water quality and ecology.

5. Operation and maintenance

5.1 General maintenance

As with any constructed facility or open space asset, ponds and wetlands require ongoing operation and maintenance: litter management, aquatic plant management, fish management, sediment dredging, mechanical aeration/mixing, and so on.

Structures, such as GPTs, embankments, inlets, outlets, spillways, and culverts must be routinely inspected for serviceability, safety, and cleaning and removal of trapped debris and sediment. Safety measures such as fences, booms and warning notices must also be routinely inspected to ensure that they are in good order. Similarly, shorelines should be inspected regularly to ensure that they are stable, that shoreline vegetation is managed, and that litter is collected and removed regularly.

Aquatic plants should be inspected periodically to control pest species and to promote the desired mix of plants for conservation and landscape purposes. Generally the cost per hectare of maintaining aquatic plants is considerably less than the cost of grass cutting associated with parks. Following droughts and drying of ponds or wetlands, some replanting may be necessary to enhance aquatic plant reestablishment.

Periodically, it may be necessary to remove the accumulated sediment in discharge areas, or, over time, from wider areas of the pond or wetland. This sediment removal will only be needed once in every 20 or 30 years if there is a GPT to intercept the coarser sediments.

The stocking of lakes with fish for recreational purposes has been a popular management approach over the last century. In the interests of conservation, there may be a case for initially stocking ponds and wetlands with the native fish species normally associated with this type of habitat.

In situations where ponds or wetlands are subject to nutrient and/or organic loading beyond normal design guideline levels, there may be a case for installing a mechanical aerator and mixer. Use of this equipment can lessen the onset of reducing conditions following storm events, or enhance circulation within the facility between extreme events.

5.2 Plant development and management

Site preparation

The major elements of site preparation for planting are the provision of a suitable substratum for growth and

Structures such as gross pollutant traps need to be cleaned regularly if the pond and wetland are to perform their functions. Photo: Ian Lawrence

the control of weeds and non-target plants. The successful establishment of wetland plants requires an adequate covering and depth of top soil (approx 0.2 m).

Where plants are going to be introduced into undisturbed soils it will be necessary to control existing vegetation prior to planting, to reduce competition during the establishment phase of wetland planting. Where existing vegetation is completely terrestrial it may be satisfactory to simply slash and inundate to obtain a clear planting site. Where aquatic or semi-aquatic vegetation occurs, it may be necessary to use herbicides to obtain a clear planting site. It may take several months in these situations to achieve good weed control.

Supply of stock

A substantial quantity of plant stock is necessary for a large wetland project and its supply requires careful forward planning. Planting density is a major factor determining wetland planting success. The greater the plant density, the less the competition from weeds and the faster the system becomes fully operational. Consequently, it is important to choose a propagation technique that will deliver the necessary quantity of plants in the best possible condition.

Temporary pond for trapping sediment during construction.

(i) Nursery stock

Australian nurseries can grow very large numbers of even-aged, good quality seedlings, that can be planted at any desired density under reasonably controlled conditions. In nurseries, seedlings can be grown to a pre-determined height and maturity to maximise planting success in a particular water depth.

Nursery production of high volumes of seedlings however requires the necessary nursery space, collection of the required seed from natural stands of vegetation, and the necessary nursery propagation time (which varies from species to species and would take between 6 to 12 months. Nursery establishment time, plant evaluation and seed collection could take at least 12 to 18 months.

(ii) Direct seeding

Under some conditions, direct seeding can be a useful plant establishment technique. It has the advantage of being relatively fast and low cost. However for best results it requires very careful site preparation, very fine water level control, and considerable knowledge about the field behaviour and germination characteristics of the species involved. Direct seeding is a relatively uncontrolled process with a high risk of failure due to a whole range of natural processes (e.g. flooding, drying, seed preparation, fungal attack).

(iii) Transplanting harvested material

For many wetland plants transplanting of rhizome material or tussocks can be a very successful technique. It has the advantages that the transplanted material is usually mature and well established, the material is typically moved with its substratum so disturbance to the root zone is minimised, and the material can often be planted directly into the species' normal water level. These advantages can often lead to a more predictable planting pattern and potentially to a faster finished product. However, there are a number of disadvantages of this technique, including:

- the logistics of collecting and transporting large mass of material;
- mechanical handling which can easily damage stock and reduce planting success;
- limitations of the available species;
- environmental damage to donor sites.

Planting

Planting methods are normally determined by the type of planting stock and local terrain and site conditions. However the key to success with any method is minimal damage to the stock during planting. As a result, sensitive planting procedures typically rely on considerable manual labour. Manual techniques can be very sensitive to nursery grown tube stock and result in good planting success rates. Mechanical techniques are available.

Water level control

Most large emergent aquatic plants reproduce asexually by clonal growth in the normal water level range of their habitats. Successful recruitment by seed germination is often an unusual event that occurs only during dry periods or periods of low water level. Consequently to establish macrophytes by direct seeding, or by transplanting nursery seedlings or by event transplanting of clonal material it is usually necessary to reduce water levels and have good control over water level fluctuations during the establishment phase.

Even the largest macrophytes typically require water depths of less than 0.2 m for their establishment. Some ephemeral species that occur in shallow marshes or fringing zones may establish best in moist soil with no free standing water. To ensure optimum plant establishment and subsequent flexibility for maintenance it is necessary to have reasonably fine control over water level over the entire depth range.

Maintenance

(i) Establishment maintenance

During the establishment phase, managers should monitor plant growth and growing conditions frequently and regularly. It is during this period that macrophytes are most vulnerable to impacts and damage. Regular monitoring during this phase allows managers to respond rapidly to any problems and minimise the extent of adverse effects. Water level, weed invasion, and animal damage need particular attention.

(ii) On-going maintenance

During on-going maintenance, the manager gives attention to all the issues that were important during the establishment phase as well as to a range of factors associated with the long-term stability and functioning of the system. These include:

- vegetation composition and structure;
- accumulation of dead and dying plant biomass above-ground;
- accumulation of sediment;
- variations between wetland cells in their hydraulic behaviour;
- development of potential pest habitat.

Macrophyte harvesting/cutting

Except where macrophytes conflict with other pond or wetland objectives such as access to the water's edge, there is now a body of literature reporting that it is inappropriate to cut or harvest macrophytes. Any improvement in nutrient uptake from sediments as a result of harvesting is extremely marginal, while the cutting process introduces the risk of remobilising sediment nutrients, or of exposing rhizome stems and consequent leakage of nutrients.

Mechanical cutters and harvesting systems are commercially available.

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Appendix A

Pond or wetland performance assessment

A.1. Information required

For urban stormwater management ponds and wetlands, information is usually needed on one or more of the following points:

- the types and amounts of catchment runoff and pollutant exports that can be expected from each of the catchment's land uses and management practice (pressures);
- the pollutants that are critical to the environmental values of the receiving waters, and the pollutant loads the receiving waters can carry without environmental damage. What are the dominant water quality and ecological responses of the receiving waters to catchment discharges?
- how well ponds or wetlands perform in limiting catchment discharge of pollutants and in meeting licence requirements;
- pond or wetland water quality and ecology, necessary to determine operations and maintenance actions.

If there is a need to design a new pond or wetland, or assess an existing one, it is usually to achieve some predetermined reduction in catchment pollutant exports, or to meet a pre-determined discharge concentration.

The nature of pollutant discharges and the performance of ponds or wetlands varies from event to event, so any assessment of the long term performance of existing ponds or wetlands has to be made over a range of events.

There are several ways to assess pond or wetland performance.

One simple and low cost approach is to sample the pond or wetland sediments (repository for 95–99% of intercepted pollutants), and analyse their content of accumulated pollutants. This provides an indication of the facility's retention capacity, particularly for the sediments themselves, TP and metals, knowing the period over which sediment has been collected (since the construction of the pond or wetland), and the level of pollutant discharges to the pond or wetland over that period. This technique is not useful for TN or BOD, because these are lost to the atmosphere or mineralised, respectively.

Another approach is to monitor inflows and discharges to a pond or wetland for sufficient events (normally 6 to 10) to develop a statistically significant relation between event volume and pollutant interception. The relation can then be used, in association with long term rainfall or runoff data, to estimate the long term pollutant retention performance of the pond or wetland.

Surveys and monitoring of in-pond water quality and biota will provide valuable qualitative information about the performance of the pond or wetland and its various components.

A.2. Major environmental issues (critical pollutants)

The National Water Quality Management Strategy requires that environmental issues and management strategies be considered in the light of a whole catchment. Issues should be assessed using the 'designation of environmental values — identification of water quality guidelines' approach set out in the Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC 1992).

This approach provides a comprehensive framework within which to consider, systematically, the environmental issues relevant to the catchment or region. Issues comprise:

- loss of aquatic ecological quality as a result of loss of habitats, changes in streamflow regimes, and/or discharge of pollutants;
- effects on the recreational and aesthetic values of waters, as a result of the impacts of pollutant discharges on the quality and ecology of recreation waters;
- impacts on the purity and reliability of drinking water supply, as a result the effects of pollutant discharges on the quality and ecology of the source of the water;
- impacts on agriculture or aquaculture productivity, as a result of the effects of pollutant discharges on the quality and ecology of the source of irrigation or pond water.

The environmental issues may be further described by the dominant processes causing the loss of the environmental values, namely:

- eutrophication (stimulation of excessive plant growth, or changes in composition, as a result of discharges of nutrients);
- organic pollution (oxygen depletion, faecal contamination);
- toxic pollution (heavy metals, pesticides, herbicides impacting directly on aquatic biota);
- temperature changes (heat transfer, or discharge of bottom (cold) waters from dams);
- light modification (impacts on productivity and plant composition of waters as a result of discharge of suspended solids).

Once the major environmental issues and related impact processes are understood, it is possible to identify the critical pollutants that need to be targeted to manage the catchment. Typically this is done through water quality monitoring programs.

A.3. Design of monitoring program

The design of a monitoring network and sampling program should be appropriate to the nature of the receiving water, the environmental concerns and critical pollutants and biota to be monitored, and the major sources of critical pollutants across the catchment. The system to be monitored can be classed by its variability, as:

- a steady state or gradually varying system, such as sustained point source discharges to a steady flow stream;
- a rapidly varying system or non-linear lumped systems, such as non-point (event) based runoff and pollutant export systems.

The kinds of information required depend on the environmental concerns that are to be resolved:

- in the case of characterisation of pressures and responses, monitoring of loads or pollutant mass balances;
- in the case of performance assessment, the monitoring of before-and-after quality, paired catchment based monitoring, or in-pond or wetland sediment surveys.

For ponds that have a storage volume big enough at least for the 1 in 6 months event, a statistically valid assessment of interception performance can be made by monitoring inflows and outflows on an event basis. This is much more difficult for on-line wetlands because of the small interception increment per event and variability in flows and pollutant loads. An alternative approach is to survey the sediments periodically to calculate increases in stored pollutants and their relation to storm events over the period since the last survey.

The critical pollutants to be monitored, associated with each of the dominant processes, comprise:

- for eutrophication – chlorophyll-*a*, cell numbers, algal composition, sea grass areas/densities, TP, TN, NO_x, NH_4, organic N, pH, DO, BOD, TOC, suspended solids, Fe;
- for organic pollution – BOD, TOC, TP, TN, NH_4, algae, DO, faecal coliforms;
- for toxic pollution – heavy metals, pesticides, macroinvertebrates;
- for light modification – suspended solids, Secchi disk depth, chlorophyll-*a*, algal composition.

A.4. Selecting monitoring sites

Monitoring sites will be located in representative catchments or those catchments whose discharges are critically important to the receiving waters; existing facilities must be assessed *in situ*.

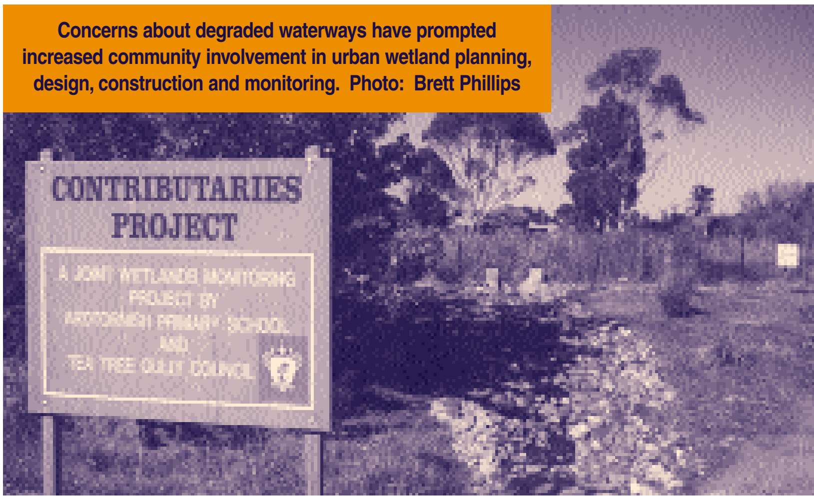
The location within each nominated sub-catchment is chosen so that it:

- is relatively uniform in cross section, alignment and grades, and free of backwater effects, for reliable gauging of flows;
- has well mixed flow, providing a reliable basis for extracting representative samples;
- is secure from damage by flood or vandalism;
- ideally, has easy access to power and telephone services.

Normally, the flow gauge and auto-sampler are located within the same installation, together with meteorological instruments (pluviometer, thermometer (dry and wet bulb), wind direction and speed). If the rainfall varies significantly across the catchment, additional pluviometers may be needed.

A.5. Design of sampling program

The sampling should be frequent enough to reflect the variability characteristics of the system, the information category (level of statistical confidence) needed, and the interpretation tools or models.



Concerns about degraded waterways have prompted increased community involvement in urban wetland planning, design, construction and monitoring. Photo: Brett Phillips

The're should be sufficient samples to provide the desired level of significance/confidence. Normally, an initial pilot study is required to assess the variability of the flow and quality of the systems, so that a statistically valid but more efficient sampling program can be designed.

Event based systems

For urban catchments, sampling should be at intervals of 10 to 20 minutes during storm runoff events, depending on the catchment hydrological characteristics. At least 6 to 10 events normally need to be monitored to establish a statistically significant data set.

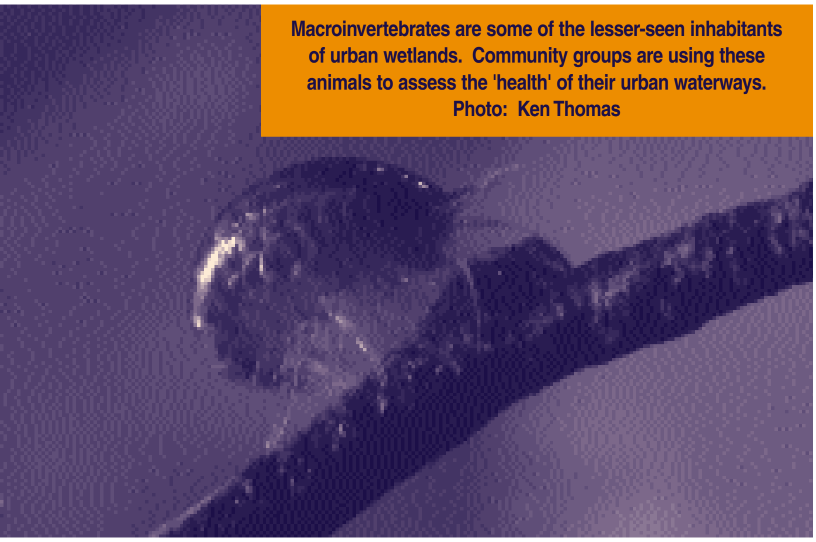
The auto-sampler is normally set to activate on the rising arm of hydrograph, at a level indicative of a significant storm event in the catchment, but not so high that an important part of the pollutograph is missed. Subsequent sampling can either be on a fixed time basis (normal) or according to changes in the hydrograph stage height.

Gradually varying flow based systems

In this case, there are two sampling options: regular calendar-based sampling, and flow percentile-based sampling.

Routine calendar-based sampling builds up a substantial data set over time, providing a historical profile of in-stream water quality ranges. There is, however, a risk that this approach may not yield a true indication of quality, when the major discharge occurs in infrequent flood events.

The flow percentile-based sampling recognises that flow is the primary determinant of water



Macroinvertebrates are some of the lesser-seen inhabitants of urban wetlands. Community groups are using these animals to assess the 'health' of their urban waterways. Photo: Ken Thomas

quality, and that by designing the sampling to cover a representative range of flow conditions (percentiles), a much more statistically significant result can be achieved for substantially less cost.

A.6. Assessing sampling instrumentation requirements

Where it is necessary to monitor events, experience has shown that there is no other option but to locate automatic sampling and/or solid state probe instruments at the monitoring location.

Commercially available auto-samplers are generally reliable, robust, flexible in terms of their settings, and supported by good technical backup.

Progress in the development of solid state probes and micro-scale sampler and *in situ* instruments is reaching the point where these types of instruments are beginning to displace the labour intensive auto-samplers. However, there are still a number of critical pollutants that are not covered by these instruments.

A.7. Developing a quality control program

All monitoring programs require a program to ensure that monitored data are of a defined quality in terms of their relevance, accuracy and precision. The program must address sampling, sample collection and transfer to laboratory, sample storage, sample pre-treatment, analysis, and data entry procedures.

A.8. Role of biological monitoring

Use of biological monitoring is seen as a cost effective first step for assessing the water quality and ecology of regional waters. A more detailed physico-chemical and flow monitoring program can then be developed.

Biological assessment is valuable because:

- biota such as macroinvertebrates provide excellent indicators of a range of physical, chemical and biological conditions over time;
- the ecology of streams (environmental objective) is being measured directly, rather than through physical or chemical water quality surrogates;
- it is more cost effective than physico-chemical approaches in assessing the 'health' of streams, and in identifying areas of pollution.

Biological assessment has these limitations:

- knowledge and skills are required in identifying taxa;
- it does not provide the information necessary to quantify the sustainable loads in respect to catchment land use and management practices.

There are a number of possible approaches to biological monitoring. Where a species is identified that can, by its status, indicate protection of or threat to aquatic ecology, monitoring may focus specifically on populations and the ecology of that species.

There has been substantial development in biological assessment of river health techniques in recent years, with national commitment to the River Health Assessment Program. This Program has resulted in the development of a national river health assessment model (AUSRIVAS), supported by monitoring and validation assessment across all states and territories.

The underlying approach adopted when biologically assessing river health is comparison of the type and diversity of biota surveyed at a test site, with that at a healthy site (reference site) which has channel morphology (shape), substrate (riffles, pools, edges) and flow conditions similar to the test site.

Through the application of the AUSRIVAS model, personnel are guided to adopt standard sampling and sorting protocols and keys, so that there is confidence in the findings. Diagnostic tools are available to relate absence or dominance of particular taxa to possible pollutants.

Appendix B

Computation of in-pond sedimentation rates for local waters

These guidelines provide graphs of in-pond or wetland interception of pollutants as a function of time and a range of suspended particle gradings (Section 3.1.1). There may be occasions when local suspended particle gradings differ significantly from the range provided here. This Appendix shows how to calculate interception curves for local grading of suspended particle.

B.1. Particle settling velocity

The settling velocity of particles is given by:

Rubey's Equation for

$R_{Rey} > 0.1$ (particle $d > 0.08$ mm)

$v = 1/d \times [\sqrt{(10.79d^3 + 36\nu^2)} - 6\nu]$;

Stoke's Law for

$R_{Rey} < 0.1$ (particle $d < 0.08$ mm)

$v = gd^2/18\nu \times 1/\gamma \times [\gamma_s - \gamma]$

for R_{Rey} (Reynolds No.) $(vd/\nu) < 0.1$,

where v is particle settling velocity (m/s)

d is diameter of particle (mm)

g is acceleration due to gravity (9.81 m/s)

ν is the kinematic viscosity in m^2/s

γ is the specific weight of fluid

γ_s is the specific weight of the particle

(Source: Vanoni 1977)

Table B.1 **Kinematic viscosity & specific weight**

Temp °C	Kinematic ν $m^2/s \times 10^{-6}$	Specific Weight γ
10	1.31	0.9997
15	1.14	0.9991
20	1.01	0.9982
25	0.89	0.9971
30	0.80	0.9957

The specific weight of quartz (one of the most common minerals) is 2.65. In the case of particles < 0.08 mm, the specific weight reduces, as a reflection of the increased weathering of finer particles, the increased percentage of biotic materials, and aggregates of finer particles with associated trapped voids.

There is also a loss of sedimentation efficiency associated with small eddies and currents induced by flow, wind and thermal gradients, with non-spherical particles, and with short circuiting of the available storage capacity. These efficiency losses become more critical in relation to the finer particles. These factors are illustrated in the following table.

Table B.2 **Specific weight and sedimentation efficiency as a function of particle size**

Particle size (mm)		Specific wt	Sedimentation efficiency* %
10.5	coarse sand	2.6	100
0.25	medium sand	2.5	100
0.17	fine sand	2.5	90
0.09	v.fine sand	2.5	90
0.05	silt	2.3	90
0.015	silt	2.0	80
0.005	silt	1.7	70
0.0007	clay & organic	1.1	60

Notes: * excluding losses due to short circuiting

Drawing on an analysis of local suspended solids or sediment gradings, it is possible to compute a local 'suspended solids – time' retention curve, for use in deciding on the sizes of ponds locally.

B.2. Retention of settling particles

Retention for individual size range (Hazen 1904)

Retention = $1 - y/y_o = 1 - 1/[(1 + 0.5v_sA/Q)^{0.5}]$

where y is the concentration at 24 hrs
y_o is the concentration at time 0
v_s is the particle settling velocity m/d
A is the pond or wetland surface area (m^2)
Q is the dry weather flow rate post event (m^3/d)

Cumulative retention = $\sum$[Fraction (%) x $(1 - y/y_o)$]

B.3. Interception of other pollutants

Urban stormwater discharges are rich in fine particulates. The particulates have a substantial capacity to adsorb dissolved pollutants, with the adsorption occurring within seconds to minutes of contact. A substantial proportion of the particulates, together with their adsorbed pollutants, settle out under the quiescent conditions characteristic of ponds. Consequently, the degree of removal of the adsorbed pollutants will depend on the location of the pollutants with respect to particle size, and the sedimentation of the particulates in respect to each particle size fraction.

The CRCFE is currently analysing a range of particulates to determine what percentage of the pollutants is adsorbed across the particle size grading, for a range of soils (mineralogies and gradings) and pollutants.

Based on analyses to date, the following correlations have been established:

$$TP = 0.7d^{-0.2}$$

$$TN = 11d^{-0.2}$$

where TP, TN are in µg per gm of suspended particulate material, and
d is particulate material diameter in µm.

These relationships, in association with the particle size grading for local sediments, and sedimentation rates, enable interception curves to be computed for a range of other pollutants for local conditions.

Figure B1 *Adsorption of Phosphorus* illustrates the distribution of total adsorbed P as a function of particle size, for samples from urban and rural streams. It draws on published data for a range of sites: Sydney sandstone at Heathcote St (CRCFE 1997a), Canberra sedimentary (CRCFE 1997b), Adelaide Sedimentary in the Patawalonga catchment (pH Environment 1995), and the Darling River (Oliver et al. 1993).

The retention of each pollutant is calculated as the product of the % of pollutant on each particle size fraction, and the percentage of the particle size fraction intercepted for the sedimentation period. By summing the % retained across the full range of particle size fractions intercepted for the sedimentation period, the total retention can be calculated.

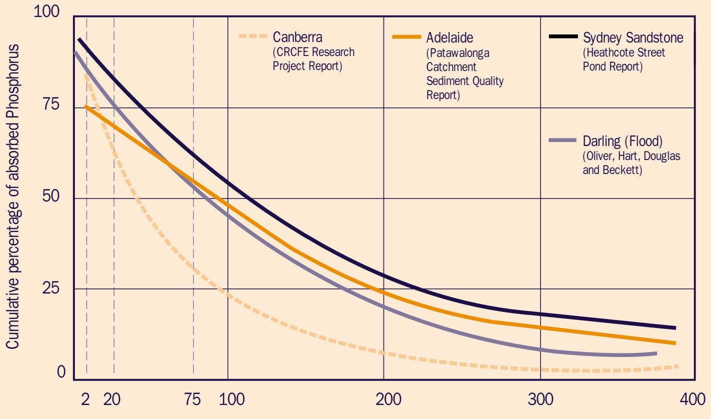


Figure B.1. **Adsorption of phosphorus**

Appendix C

Pond and wetland quality models

C.1. Process-based versus empirical models

In the past, pollution interception predictive models have been empirical, based on limited monitoring of the performance of a few existing ponds. The value of this type of model is limited: the actual local hydrology, catchment, soil, land use and pollutant profiles may be very different to those underpinning the empirical values. In addition, the empirical models provide little guidance about the dominant in-pond processes determining the overall pond performance, and hence limited information on the means of enhancing pond design and operation.

As a result of the research undertaken by the CRC for Freshwater Ecology, it is now possible to describe the dominant pollutant interception processes and water quality responses of ponds or wetlands, for a range of inflow and pollutant conditions. The research indicates that ponds and wetlands comprise a number of compartments, with transfers of water quality constituents between compartments as a result of physical, chemical, biological and microbial processes.

In modelling terms, the transfers or transformations of pollutants can be described by physical, chemical, biological and microbial equilibria and rates (thermodynamics). However, reactions within other compartments determine the factors that drive these transfers. Consequently, all of the compartments have to be analysed conjointly.

A Continuously Stirred Tank Reactor (CSTR) approach makes it possible to track the changes in mass associated with inflows to and discharges from the pond or wetland water column. (see Box 1, page 21). The model also computes losses and gains over time (transfers between the water column and sediment compartments, between the water column and the algal compartments, and between the water column and the atmosphere). A simple computational method is adequate to quantitatively approximate these transfers when the time steps are small.

The model computations happen in a spreadsheet, with a daily time increment for inflows, discharges, and internal mixing, transformations and transfers. The spreadsheet computations are easy for users to access; and they provide information to the designer/manager about in-pond and sediment changes over time (qualitative information on dominant processes). Further, they permit the user to switch on/off various components and pathways as the structure of the dominant physical, chemical

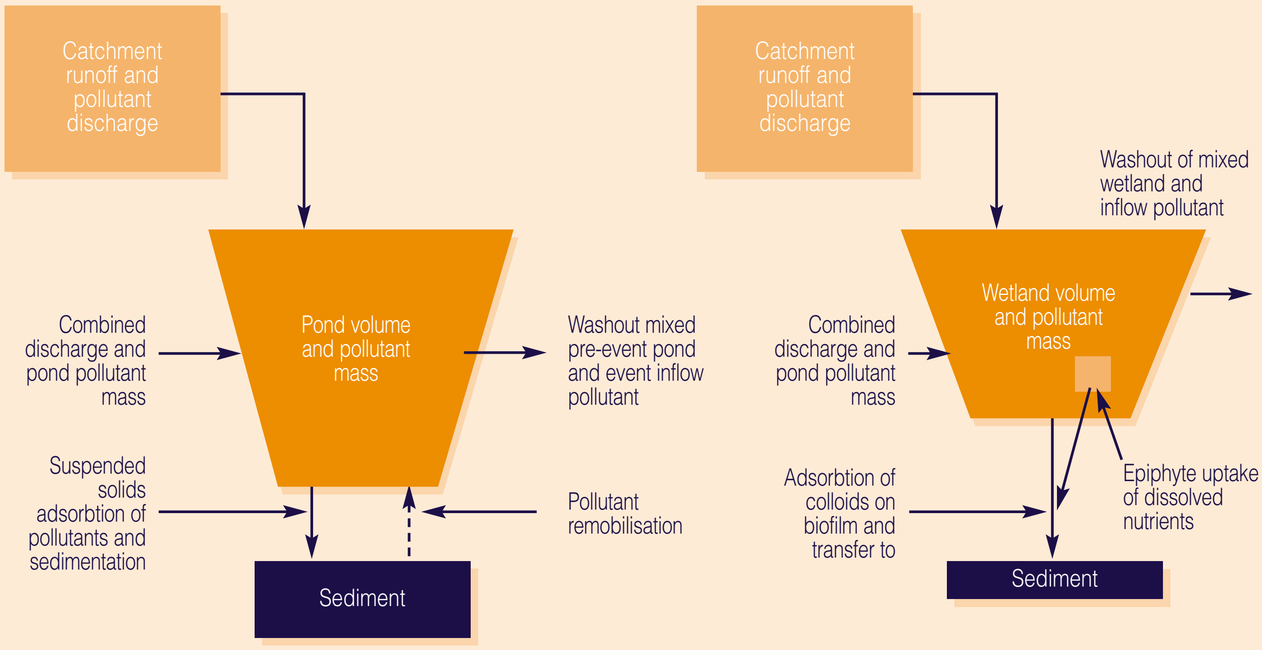


Figure C.1 **Major components of pond and wetland pollutant washout, retention, interception and remobilisation processes.**

and biological processes change over time, or under different mixing or biological oxygen demand (BOD) loading regimes; and they can be adapted if the model develops, or simplified to suit local conditions.

C.2. Computational strategy

As outlined in Figure C1, the Pond and Wetland Models comprise a number of sub-models or component processes, as follows:

Initialisation (Worksheet A)

An initialisation step precedes the running of the sub-models. It consists of the physical description of the pond or wetland to be analysed (volume, area, depth), the initial in-pond or in-wetland water quality, and, in the case of ponds, the suspended solids characteristics (particle size grading, adsorption of pollutants), and the sediment redox properties (composition by weight).

Pond model	**Wetland model**
Catchment runoff and pollutant mass balance–washout sub-model	Catchment runoff and pollutant mass balance–washout sub-model
Adsorption of nutrients, metals and organic materials onto suspended solids and their sedimentation sub-model	Dissolved nutrient uptake by epiphytes attached to macrophytes sub-model
Sediment reduction and oxidation sub-model (remobilisation of pollutants)	Adsorption of organic colloids (inflow and epiphytes) on the biofilm, and their transfer to the sediments sub-model
Mixing (aeration) sub-model	
Algal uptake of remobilised nutrients sub-model	

Water and constituents budgets sub-model (Worksheet B)

As noted above, daily budgets track the changes in mass of constituents of the inflows to, and discharges from, the pond or wetland water column, assuming a Continuously Stirred Tank Reactor (CSTR) system. In the CSTR system, water in the pond (or epilimnion in the case of a stratified system) is assumed fully mixed during the course of the day.

The model also computes losses and gains on a daily basis (transfers between the water column and sediment compartments, between the water column and the algal compartments, and between the water column and the atmosphere).

In the case of the ponds,

- the algal sub-model computes the uptake of nutrients by algae in response to release from the sediments (link to the sediment redox sub-model).

In the case of the wetlands,

- the epiphyte algal sub-model directly computes the epiphyte uptake of dissolved nutrients in the inflow;
- the biofilm sub-model directly computes the biofilm uptake of organic colloidal material from inflows and epiphyte detritus.

The user is required to enter daily inflows and water quality for the local pond or wetland to be assessed. (a macro is to be developed in future to read dB4 or spreadsheet flow and water quality data files directly). The models can run for any period, from a 'design storm' condition, to simulation of pond responses for several years of streamflow and water quality data. Thirty days following a storm event is considered a minimum (where good starting conditions are available), in order to track sediment and algal responses to the storm event.

Adsorption and sedimentation sub-model (Worksheet C)

In urban stormwater pollution control ponds, the bulk of exports (95%) occur during storm events, with runoff characterised by extremely high levels of suspended solids. The research indicates that these fine suspended solids have an extremely high adsorption capability for nutrients, metals, organic materials and bacteria. Consequently, the first and dominant pond response to a runoff event is the adsorption of the bulk of nutrients, metals, organic materials and bacteria onto the surfaces of suspended solids, and the physical settling of the fine suspended material. The rate of settling of suspended particles depends on particle size and pond eddy diffusion conditions, with the coarser (medium silt and larger) particles settling within a time span of a few hours to 2 days, and the bulk of the finer material settling within 10 to 20 days.

The sedimentation sub-model computes the proportions of adsorbed materials attached to the various sizes of suspended solid particles, and the daily loss from the water column of each particle size by settling.

d) Sediment reduction and oxidation sub-model (Worksheet D)

In ponds, typically, stormwater runoff is rich in organic material washed off catchment surfaces. As the organic material settles to the sediments, it can impose a significant biological oxygen demand (BOD) on sediments (the result of rapid heterotrophic bacterial growth in response to the new source of organic carbon).

Following the storm event, the pond water column may be well mixed with significant transfer of oxygen from the atmosphere to the water body to the sediments, offsetting the depression of oxygen created by the bacterial growth. Conversely, under conditions of low base flows following the event and high solar radiation, the pond may quickly stratify thermally, creating a physical barrier to oxygen transfer from the atmosphere to the sediments.

It is particularly under these stratified or poor mixing conditions that the sediments of ponds may undergo significant reduction of oxygen and cations and anions, leading to the release of nutrients, organic compounds and metals in a highly bio-available (soluble) form back into the water column.

Based on the daily sedimentation of organic matter (BOD) from the sedimentation sub-model, the sediment redox sub-model computes the net daily BOD (after depletion of the daily oxygen transfer), and the sequential depletion of oxygen (O_2) and nitrate (NO_3^-), followed by the reduction of ferric iron Fe(III) and sulfate (SO_4^{2-}). The model includes the bottom water column layer (assumed to be the lower 1/3rd of the water column depth in the case of ponds).

As the reduction process proceeds, ultimately either all of the organic carbon is consumed, with cessation of microbial (BOD) growth, or aeration rates increase to levels exceeding the BOD rate. Under either of these conditions, re-oxidation of the sediments will begin, leading to:

- the oxidation of ferrous iron, Fe(II), to Fe(III), and associated reaction with and precipitation of phosphate (PO_4–P);
- the oxidation of hydrogen sulfide (H_2S) to SO_4^{2-} ;
- the oxidation of ammonium ion (NH_4^+) to NO_3^- ;
- more dissolved oxygen (DO) in the water column.

The sub-model computes the daily release of nutrients associated with these transformations, and the oxidation of Fe(II) and SO_4^{2-} and their precipitation back to the sediments. These releases and precipitation transfers are linked back to the Water and Constituents Budget sub-model via a molecular diffusion equation.

Algal growth sub-model (Worksheet D)

An algal growth sub-model is also included in the sediment redox computation.

As outlined above, the research has indicated substantial adsorption of nutrients by fine suspended solids discharged to ponds during storm events, and their removal from the water column by physical sedimentation.

If sediments undergo chemical reduction, they may release nutrients (NH_4^+ and PO_4–P) back into the water column in a highly bio-available form. For example, under the dry weather flow conditions following the event, when the bulk of the fine suspended solids (source of adsorption) have been sedimented, the nutrients released into the lower, oxygen-depleted waters are in a highly bio-available form for algal uptake.

The algal model assumes that sediment release of nutrients is the dominant nutrient pathway sustaining algal growth, and that growth will be a reflection of either the daily release of P, or the doubling rate coefficient, whichever is the smaller. The model assumes an algal decay (lysis) rate of 10% of the algal biomass/day. This loss is linked to the BOD computation through its contribution to the net BOD. The algal growth model also computes the daily photosynthesis O_2 generation, which is linked to the computation of DO in the Water and Constituent Budgets sub-model.

f) Mixing (oxygen transfer) sub-model (Worksheet E)

In ponds, the mixing (oxygen transfer) sub-model has four components:

- the physical mixing of the water column and associated uptake of oxygen at the water surface and its transfer through the column to the sediments (depends on wind strength and duration);
- the physical mixing of the water column by inflow (advective – eddy diffusion forces);
- the sediment oxygen demand plus daily sediment microbial BOD demand associated with microbial use of (growth on) the sedimented organic material;
- the direct transfer of O_2 through macrophyte stems to their rhizome root zones.

Currently, the mixing sub-model sets sediment aeration rates on the basis of (i) local meteorological (wind) conditions for the local pond site, (ii) the volume of inflow relative to pond volume (velocity), and (iii) the computation of direct O_2 transfer by macrophytes.

At this stage, the sub-model does no accounting of the O_2 production by algal photosynthesis, because this happens in the upper layer, and is not available to the sediments under poor mixing conditions.

C.3. Running the model

a) Copy disk to own system

The enclosed disk contains simple spreadsheet-based (Microsoft Excel 95/97) models, based on daily input of inflows and pollutant concentrations, for calculating pond or wetland interception and water quality responses. The disk is in 'read only' format. Accordingly, the files *Pmod2* and *Wetmod2* need to be loaded into your system, so that they can then be run. These copies can then be modified to reflect suspended solids and sediment conditions for local catchments, and local pond physical dimensions.

b) Data entry for local pond or wetland conditions

Initialisation (Worksheet A)

Replace italicised values with local values for physical dimensions, suspended solids' characteristics, sediment composition, and starting water quality conditions.

Water and constituent budgets sub-model (Worksheet B)

Enter local inflow and water quality data. These may be derived from actual stream gauging and water quality sampling at the inlet to the pond, or from estimates based on local pluviometers, catchment area and land use, and rainfall runoff and pollutant export models.

Microsoft Excel automatically re-calculates the spreadsheet values as new values are entered.

c) Application of models

The two major applications of the models are (i) to decide on a size and design of pond and wetland, in response to targeted pollutants and interception levels; (ii) to assess existing pond or wetland performance.

Size and design of ponds and wetlands

The choice of size and design of ponds or wetlands is normally guided by the critical pollutant reduction requirement, or discharge equivalent mean concentration (EMC) necessary for protection of the designated environmental and use values of downstream waters. Where ponds also provide local urban open space landscape values, or are close to residential areas, the water quality in the pond itself may also be an issue.

Worksheet E computes the percentage interception of the range of defined pollutants, and the discharge EMC for the period of analysis. The worksheet also analyses the mean and maximum chlorophyll-a values in ponds, for the period of analysis. Normal in-pond water quality objectives for stormwater pollution control ponds would be:

summer mean chlorophyll-*a*	<10 µg/L
maximum chlorophyll-*a*	<30 µg/L

By running the model for historical daily streamflow and water quality, and a range of pond sizes, depths, volumes and macrophyte zones, the designer can form a picture of the relationship between these variables and the pond interception and in-pond water quality performance. This information then provides the basis, together with other flood routing, landscape, physical constraints and cost considerations, for selecting the best pond size and design.

Assessment of existing pond or wetland performance

Since weather conditions vary, the hydraulic retention time and pollutant interception performance of ponds will vary over time. Consequently, any assessment needs to remove this variability so that performance can be measured against a standard baseline. Application of the Pond Water Quality Model makes this standardised comparison possible.

First, the designer/manager compares monitored in-pond or wetland (and discharge) water quality with estimates, made by the model, of water quality for the same period.

If the monitored and estimated values are not statistically different at a 10% level of probability, the designer/manager can adopt this existing model as the basis for computing performance for standard base (design) conditions.

If the monitored and estimated values differ statistically at a 10% level, the designer/manager can modify the existing model coefficients to better reflect local processes and rates, as follows:

- modify adsorption/sedimentation sub-model rates (comparison of losses within first 5 days following events);
- modify sediment redox releases (comparison of sediment leakage for period 5 to 15 days following event)
  - compare assumed mixing (aeration) conditions for model versus conditions actually experienced; adjust mixing sub-model as necessary;
  - compare sediment reduction and nutrient release conditions for model versus monitored values; adjust sediment redox sub-model as necessary;
- modify algal growth sub-model (compare algal biomass model estimates versus monitored values for period 5 to 20 days following event); adjust algal growth sub-model as necessary.

The designer/manager can then apply the recalibrated or validated model to either historical rainfall or runoff records for the site, or to event—return frequency data, to provide an estimate of pond or wetland performance based on the reference or standardised performance event conditions. The result can then be compared to the criteria for pollutant interception performance.

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McGregor Way pond, an ephemeral wetland system, Cedar Creek, Brisbane. Note the dominance of aquatic plants - submerged and emergent. Photo: Brett Phillips

Cooperative Research Centre for Freshwater Ecology

World Wide Web Home Page: http://lake.canberra.edu.au/crcfe/crchome.html

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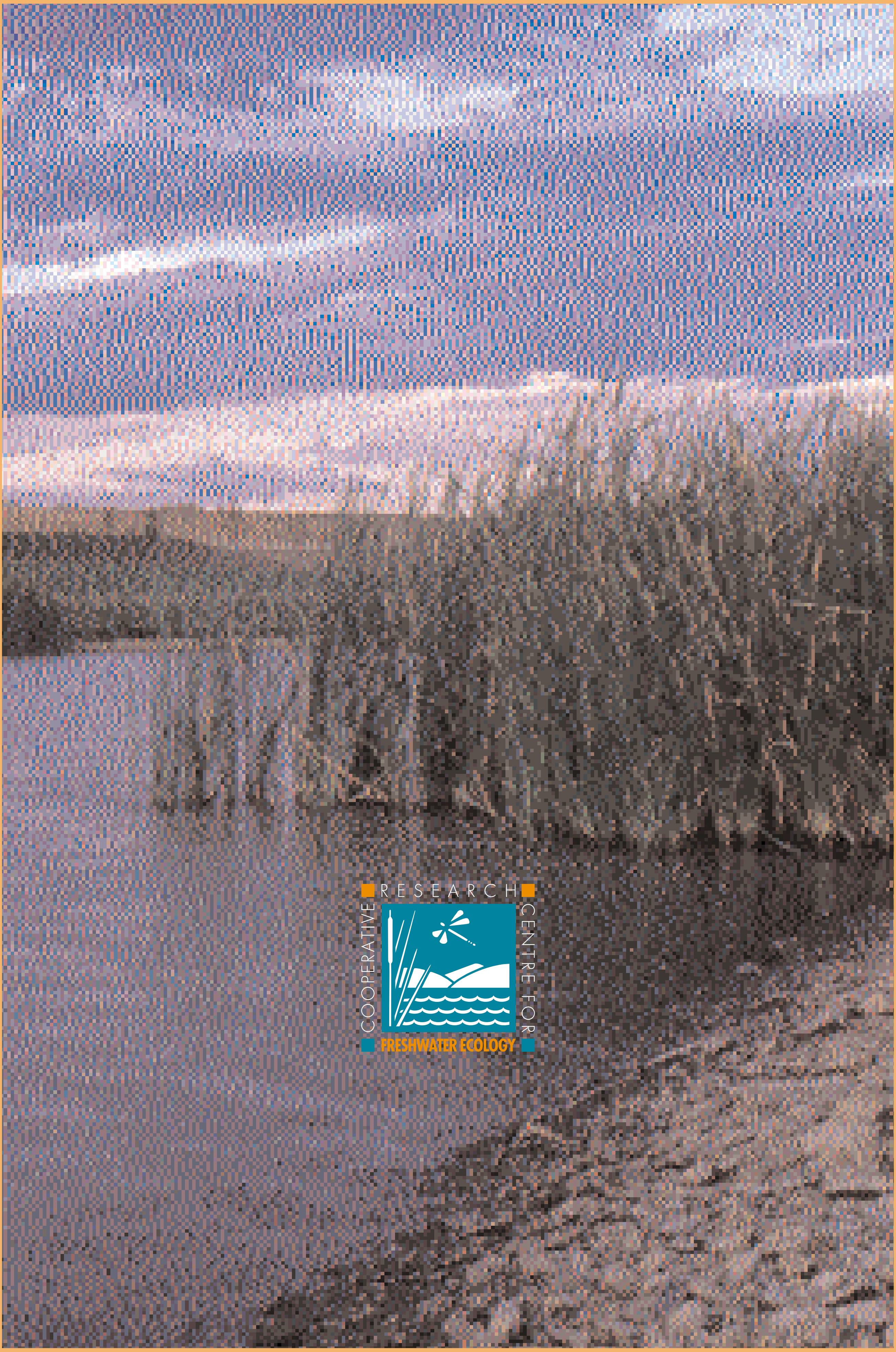

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