2

Freshwater Wetlands: Ecology, Rehabilitation and Management

2.1 Ecology of urban freshwater wetlands

Dr Liza Miller
Watershed Ecology
6/42 – 46 Waters Road, Cremore
NSW Sydney 2090
Australia

Abstract

Wetlands in urban environments are subject to an array of anthropogenic disturbances leading to wetland degradation or a state of environmental change from what a wetland might be in a natural setting. This is largely because developed landscapes affect wetland condition through impacts emanating from surrounding uplands as well as the immediate area. In particular, urban landscapes influence nutrient and pollutant inputs through water deposition leading to issues such as eutrophication. Nonetheless, urban wetlands are often valued for their amenity as well as their environmental attributes. Recreation activities, including kayaking, sailing, and bird watching, contribute to wetland amenity. The environmental values of a wetland and human activities in and around a wetland pose a challenge for wetland managers. That is, natural processes, such as eutrophication, have to be managed to ensure that recreational activities can be maintained but human health is not adversely affected. As well, opportunities for native flora and fauna need consideration in order to promote wetland values for their recreational use.

This chapter introduces wetland ecology and examines the impact of urban activities on wetland condition. Three Australian case studies are examined; the Dandenong wetland (Victoria), Lake Tuggeranong (Australian Capital Territory), and the Jerrabomberra wetlands (Australian Capital Territory). All three wetlands are constructed, and with the exception of the Dandenong Wetland, multiple uses need to be managed to promote their condition and manage human activities in and around the wetlands.

Introduction

Wetlands in the Catchment

River catchments are areas that funnel water into flowing streams (Coenraads and Koivula 2007). At higher altitudes, there might be thousands of these small streams that join to form larger streams that eventually meet the dominant river (Coenraads and Koivula 2007). Rivers are dynamic systems. Their drainage patterns, channel, meander, alluvial fans and delta constantly change; sometimes quite dramatically after flood events (Coenraads and Koivula 2007).

Wetlands are usually associated with flowing rivers and streams (Coenraads and Koivula 2007). They occur in areas of a catchment where the water table is at or above the land surface for prolonged periods, providing waterlogged conditions for aquatic biota. Wetland character, or the assemblages of flora and fauna that influence wetland patterns and processes, is largely determined by its location in the landscape. That is, whether they are associated with montane or headwater environments, or floodplain or coastal riverine environments.

The shape and extent of a wetland depends on the underlying topography, geology and its location in the landscape over a larger drainage basin. Montane wetlands are typically associated with headwater streams in mountainous regions (Kleeman *et al*. 2008). For instance, the Snowy Mountains has numerous small montane wetlands where snowmelt drains into low-lying areas, keeping them constantly saturated (Kleeman *et al*. 2008). These areas are important as they tend to distribute run-off over prolonged periods and support unique communities of plants and animals (Kleeman *et al.* 2008).

Riverine wetlands typically form in lower reaches of a river catchment where a larger river is characterised by extensive meandering channels that twist and turn through a broad alluvial floodplain. Many loops of these meanders have been cut to form oxbow lakes or billabongs and these, together with extensive marshes, form remnants of a river's past active channel (Coenraads and Koivula 2007). Usually a billabong or oxbow remains isolated from its neighbouring river (Kleeman *et al*. 2008), but during floods the billabong may form part of an active river channel (Kleeman *et al*. 2008). Toward the lower reaches of a catchment, floodplain and coastal wetlands begin to dominate lentic environments. Depending on the characteristics of the local landscape, including the river reaches, the values of a wetland may vary. For instance, a delta-based wetland, through which a river runs, will fulfil more of a water – filter/flow moderator function, while water bodies cut off from an active river channel fulfil more of a role as sheltered habitats or refugia (Kleeman *et al.* 2008).

Wetlands Defined

Irrespective of the wetland type, a wetland is typically an area of land covered by shallow water. A more formal definition is provided in chapter 2.2, as adopted by Ramsar Convention. Wetlands can be natural or artificial, permanent or temporary. The water in them can be still or flowing, and fresh, brackish, or salty (Melbourne Water n.d.). Wetland areas are defined according to their depth, degree and timing of inundation and often the degree of brackishness. Functionally, wetlands can be divided into three zones:

- Inlet zone. The inlet zone is where a river or creek meets the wetland. This zone slows water flows and enables larger sediment particles carried in the water to settle and sink. Aquatic plants may also grow in the edges of this area and as such, are able to withstand fast water flows.
- Macrophyte zone. The macrophyte zone comprises of plants that are wholly or partly inundated. Here plants trap nutrients, heavy metals, suspended solids and organic matter.
- Open water zone. The open water zone provides opportunities for finer particles to settle out of the water column and sunlight to kill pathogenic bacteria. Due to sunlight and high nutrient levels, algal growth occurs from time to time in this zone. Algae trap the dissolved nutrients, which allows them to either enter the food chain or settle to the bottom of the pond.

Wetland Ecology

Hydrology

Wetland hydrology is dealt with in greater details in chapters 2.2 and 3.2 in this eBook. For the benefit of this chapter a brief overview of hydrology is provided here.

Many wetlands fulfil an important role in the landscape. Some wetland functions are (after (Kleeman *et al.* 2008);

- Reduce or moderate river flow and enable sediments to settle;

- Trap sediment and nutrients;
- Provide habitat for fish, birds, vegetation and invertebrates;
- Provide refugia for migratory birdlife; and
- Provide a resource area for recreation and cultural events.

A key factor influencing wetland condition and extent is the hydrology or water regimes that, in turn, influence wetland functions or ecology as mentioned previously. Wetland ecosystem health (including the vegetation) is generally dependent on natural water regimes that may be highly variable. The wetland water regimes include the following features (Boulton and Brock 1999a):

- Timing of water presence. For seasonal wetlands within-year patterns are important while among-year patterns and variability in timing are relevant to temporary wetlands.
- Frequency of wetland filling and drying occurs. These regimes can range from zero (permanent waters) to frequent filling and drying in shallow wetlands many times a year.
- Periods of inundation. Inundation can vary from days to years and vary within and among wetlands. Rates of rise and fall may also be important.
- The area of inundation and depth of water in a wetland.
- Wetland variability. That is, the degree to which these above features change at a range of time scales

In turn the extent and type of native vegetation associated with wetland ecosystems is largely dependent on wetland hydrology. Factors such as width of the fringing vegetation of a wetland and its continuity, overall vegetation diversity, and condition all influence the quality and presence of faunal habitat (Boulton and Brock 1999b). The occurrence and quality of fauna habitat for invertebrates, fish, frogs, reptiles and birds influences their distribution and breeding success over their range. Wetland hydrology and the location of a wetland in its catchment contribute to forming a unique ecosystem that provides food, water, critical habitat, and breeding for a range of plants and animals (Boulton and Brock 1999b).

Wetland Health or Condition

Wetlands are among the most impacted and degraded of all ecological systems. A global overview indicates that massive losses of wetlands have occurred worldwide and that the majority of the remaining wetlands are degraded, or under threat of degradation (Finlayson 2000). The health or condition of wetlands and associated vegetation communities can be negatively impacted by changes in salinity, sedimentation, pollution, removal and destruction of wetland habitat, and altered wetting regimes. These threatening processes can impact on the fauna directly, through direct toxic effects, or indirectly, for example, through the loss of suitable breeding, sheltering and feeding sites and isolation of species' populations due to lack of water connectivity; particularly between floodplain wetlands and their adjacent river system. These impacts and threats can result in declines of aquatic biodiversity from these systems. Activities causing such impacts are believed to be large-scale clearing of native vegetation, use of fertilisers and erosion of agricultural land, and regulation of rivers for water supply and irrigation (Department of Conservation and Environment, and Office of the Environment 1992). Other activities that potentially threaten wetlands are infilling, over-grazing by livestock, introduced species, littering and pollution (Department of Conservation and Environment, and Office of the Environment 1992).

Many naturally occurring wetlands in Australia are modified, through human-induced disturbance such as land use and water management. Variability of water regime is a driving factor influencing the physical, chemical and biological components of Australian wetlands (Boulton and Brock 1999a). For example, in the Murray – Darling Basin, some wetlands have become permanent (e.g. Menindee Lakes) and act as water storages, thus reducing variability in the water regime and resulting in declines in waterbird abundance and diversity (Kingsford *et al.* 2004). Other wetlands are often almost permanently dry or significantly reduced in extent (e.g. Macquarie Marshes and the Lowbidgee). Largely because river regulation and water extraction have reduced flow volumes and flood frequencies, in significant declines in wetland extent, vegetation and waterbirds has occurred over time (Kingsford and Thomas 1995; Kingsford and Johnson 1998; Kingsford and Thomas 2002, 2004; Kingsford and Auld 2005).

Urban Wetlands

Like their rural counterparts, many urban wetlands have undergone substantial changes in their flow regimes. In particular, urban wetlands are often subject to the adverse affects of stormwater runoff. Stormwater comprises of uncontrolled nutrient-rich, sediment-laden wastewater. It can lead to phytoplankton blooms in natural and manmade systems. Such blooms promote the risk of eutrophication and biodiversity decline as well as unsightly conditions and noxious odour. In some naturally occurring wetlands that undergo seasonal flooding and drying regimes, nutrient peaks and phytoplankton blooms are an important part of a floodplain's response to wetting (e.g. Kobayashi *et al.* 2007). However, in an urban environment eutrophication is often indicative of human-induced disturbance through unnaturally high phosphorous and nitrogen concentrations (see Additional Information below). Indeed, wetlands such as Lake Tuggeranong (ACT), phytoplankton blooms are common in the warmer months and represent an increased risk to public health. To protect public health, primary contact such as swimming and boating activities area usually cancelled (SMEC 2012).

The condition of many (remnant) natural wetlands in urban environments is challenged by flood risks, the degree of urbanisation (sealed areas), deteriorating water quality and pressures on the aquatic and terrestrial habitat in and around wetlands. Indeed, the quality of stormwater is typically associated with the proportion of sealed areas over a wetland's catchment area. That is, with increasing sealed areas, such as pavements and roads, adverse water quality inputs are more likely due to increased run-off to a wetland. In many instances, this run-off is unlikely to have undergone any filtration and will comprise of gross pollutants, sediment and suspended solids, nutrients (phosphorous and nitrogen), heavy metals, oils and surfactants (*sensu*) (Integrated Management Information System *et al.* 2003).

In light of increasing urban pressures, many local authorities and agencies work to promote environmental outcomes for wetlands and improved recreational opportunities in and around these waterways. A key component of this multiple use approach is the rehabilitation, creation and/or recreation of wetlands (Griffith 1995). Indeed, constructed wetlands are useful in managing the quantity and quality of stormwater runoff from impervious surfaces in their catchment (Hunter 2003). Such wetlands rely on a combination of hard engineering solutions and ecological processes to manage nutrient loads in a catchment. In addition, these wetlands may also provide opportunities for increased amenity and recreation in and around a wetland as well as refugia for local flora and fauna. For example, Blue Hills Wetland in Penrith (NSW) was developed to manage stormwater flows from the surrounding housing estate. Here Surveyors Creek, originally an intermittent system, was developed to form Blue Hills Wetland. The purpose of the wetland was to manage adverse impacts associated with stormwater flows and provide opportunities for public recreation. The wetland comprises of three artificial lakes connected by Surveyors Creek. The fringing and riparian zones are planted with local and indigenous plant species and provide habitat for a range of local water-dependent fauna (Watershed Ecology 2013). A public path skirts the wetland and storyboards highlight environmental features of the wetland.

Larger stormwater or water quality issues might be addressed through the development of more extensive wetland systems. For example, the Dandenong wetlands as discussed later in this chapter, cover 48 hectares on the Dandenong Creek floodplain and are designed to reduce excessive nutrient inputs to Port Phillip Bay (Evans *et al.* 2010). Other naturally occurring systems, such as the Edithvale – Seaford Wetlands, also filter excess nutrients from their catchments. The Edithvale – Seaford Wetlands are remnants of the Carrum Carrum swamp, which originally stretched over 4000 hectares (Department of Sustainability Environment Water Populations and Communities 2013). These wetlands comprise of a range of permanent, intermittent freshwater and brackish systems and filter and treat water from Boggy Creek, Eel Race Drain and stormwater runoff before flowing into Port Phillip Bay (Frankston City Council n.d.). As well as buffering the adverse effects of human-induced disturbance, 14 ecological vegetation classes are present and 190 bird species are recorded on the wetlands (Frankston City Council n.d.).

Threats to Wetland Condition

Whether urban wetlands were constructed from pre-existing aquatic ecosystems or were naturally occurring prior to urban development, their management represents several challenges with respect to human activities that adversely affect wetland condition. The most significant impacts on wetland condition are changes in the seasonal pattern of water flows over its catchment. Also of importance is the diversion or extraction of water from a wetland and altered run-off characteristics (e.g. stormwater inputs) due to changes in land use (i.e. increasing hard surfaces) in the catchment area of a wetland.

Major changes in wetland ecology include (Kleeman *et al.* 2008);

- Changes in seasonality of flows;
- Reduced frequency and magnitude of floods;
- Permanent inundation or wetlands where seasonal drying and filling were natural processes; and
- Large areas of impounded water with deeper, colder and different water chemistry.

These hydrological changes affect profound shifts in the water chemistry and wetland flora and fauna. Some ecological changes that occur due to permanent inundation are (Ehrenfeld 2000; Kleeman *et al.* 2008);

- Replacement of species adapted to drying and filling by species adapted to permanent flooding;
- Obstruction of fish passage and some water-dependent invertebrates;
- Nutrients are often present in abundant or over abundant amounts; and
- Habitat patches are often small and isolated with connections that are difficult to sustain or establish.

Although the precise response of an urban wetland to a stressor depends on its sensitivity and landscape position, the general trend is a sharp decline in the diversity of the native plant and animal community and an increase in invasive plant species that can tolerate stressed conditions (Wright *et al.* 2006). Research has shown that degraded urban wetlands lose many of their important watershed functions (Wright *et al.* 2006). Upland development increases storm water to wetlands, and downstream crossings create flow constrictions. Together these changes lead to increased ponding, greater water level fluctuation, and/or hydrologic drought in urban wetlands. In addition, urban wetlands receive greater inputs of sediment, nutrients, chlorides, and other pollutants; concentrations in urban storm water that are typically one to two orders of magnitude greater than predevelopment conditions (Schueler 1987).

In turn, compared to wetlands in more natural environments, the biological diversity of species available to form communities, dispersal ability, and mutualistic interactions (e.g. pollination, mycorrhizae) may all be limited or altered (Ehrenfeld 2000). Rare or unusual types of microhabitats, especially bush or wetland habitats, may be limited to non-existent in extent (Ehrenfeld 2000). Both animal behaviour and plant reproductive ecology may also be strongly affected by the size, shape and heterogeneity of habitat patches. Thus, the possible states for the flora and fauna in urban areas are qualitatively different from those of non-urban areas (Ehrenfeld 2000).

Constructed Wetlands

Constructed wetlands are primarily designed to filter stormwater by slowing water velocity, reducing the amount of sediment in the water column and enabling natural wetland functions to help improve the water quality. They are typically built to manage and treat stormwater before it reaches local rivers and streams and mostly urban wetlands. This is because stormwater is often polluted with litter and other contaminants washed from roads, gardens, nature strips and gutters. Constructed wetlands are usually situated next to rivers and creeks that benefit from water quality treatment. They comprise of a shallow depression on the floodplain with structures that enable water to flow in and out of the wetland with suitable vegetation. A series of sedimentation ponds is usually built with flow control structures that direct water into the wetland and ensure that the water is held in the wetland for a specified time period. Aquatic, indigenous plants, such as sedges and rushes, are planted in the 'fringing zone' of the wetland and act as a carbon filter. This vegetation traps plant material (for example, leaves and grass clippings) and organic matter before it enters the wetland. The largest particles in the stormwater settle on the bottom of the wetland ponds and the plant stems adsorb fine particles. Plant uptake and other biological processes occurring naturally in the water remove nitrogen from the stormwater.

Environmental Benefits from Constructed Wetlands

Natural and constructed wetlands are useful in controlling stormwater runoff generated by the impervious nature of urban development. However, the extent to which this can be achieved depends on the wetland characteristics (e.g. total wetland volume, bathymetry) and the amount of pollution entering the wetland (loading rate) and residence time within the wetland (Hunter 2003). The main pollution removal processes include:

- Physical: sedimentation and filtration of heavy and coarse particles;
- Chemical: breakdown of pollutants into chemical compounds and elements through processes such as phosphorous, nitrogen, carbon and sulphur cycles, redox potential and pH; and
- Biological: the consumption of pollutants by aquatic plants and fauna that feed on the nutrients. Associated processes include: photosynthesis, nitrification, denitrification, and fermentation.

The vegetated areas of wetlands are useful for removing pollutants as they promote all three processes (Hunter 2003). However, predicting pollutant removal is problematic and problems, such as eutrophication in urban systems can occur.

The removal rate for pathogens in natural wetlands has not been widely studied, but research on constructed stormwater and wastewater treatment wetlands indicates that they can be extremely effective. Constructed wetlands designed with long retention times, high light penetration, and emergent vegetation achieved higher pathogen removal rates than in natural wetlands (Schueler 1999, cited in Wright *et al.* 2006).

While much more details and elaborate explanation of wetland ecology could be given here; it is perhaps a best idea to cover this aspect through diverse case study scenarios.

Additional Information 1: Physico-chemical processes in a constructed wetland

Swapan Paul, Sydney Olympic Park Authority

The ecological drivers that are mentioned above have consequential effects and there are several ecological processes that may occur in response. Such processes can be independent, interactive, inter-related, mutual, antagonistic, sympathetic, and/or complementary. These processes include:

- Primary production, through water plants, plankton, algae and other plant communities
- Transportation of dissolved organic material, particulate matter, biota, etc.
- Reproductive cues for biota such as for plant propagation, fish spawning, invertebrate breeding, plant seeding, etc.
- Erosion and sedimentation process, involving both physical and chemical phases
- Chemical processes, involving release, recycling and transfer of nutrients, metals, minerals, etc.

There are a number of closely related physico-chemical processes that influence the ecology of a wetland.

Physical processes

In a typical constructed freshwater wetland, changes in the ecology, predominantly involve:

- changes in the shape and depth of the wetland and its bed;
- wetland depth and contour profile;
- water-related changes, such an quality, quantity, velocity, circulation;
- sediment deposition and movement of materials;
- pollutants and contaminants also causing physical damage and interactions of wetland components;
- light penetration related to water transparency, thus influencing chemical and biological activities;
- etc.

Particularly, water temperature directly influences aquatic life. The diversity, population size, richness, fertility, mobility and health are all directly affected by changes in the water temperature of a wetland.

Chemical processes

Chemical processes involve many different elements of chemicals, whether simple or complex/compound. The most familiar among these are the roles of nitrogen (N), phosphorus (P) and metals (sodium, potassium, magnesium, lead, zinc, etc.) and their cycles in a wetland. In this section nitrogen-cycle, phosphorus-cycle, dissolved oxygen, pH, turbidity and conductivity/salinity in a constructed wetland are briefly described.

Nitrogen cycle

Nitrogen plays a key role in determining the flora activities in a wetland. This includes plant growth, vigour, diversity and interactions as well as plankton and algae. Nitrogen can come from soil, air and plant materials; nevertheless, the majority in urban catchments are drawn in from the upper catchment/s by rain and drain. While plants and algae/plankton are very important components of a wetland ecosystem, excess nitrogen or an imbalance in N:P ratio can make a pond ecologically dysfunctional or aesthetically unacceptable. A desirable nitrogen to phosphorus ratio is 20:1.

Bacteria and other micro-organisms play the major functions in transforming various phases of Nitrogen: dissolved Ammonia ($NH^{+}{}_{4}$), nitrite ($NO^{-}{}_{2}$), nitrate ($NO^{-}{}_{3}$) and nitrogen gas (N_2), urea, amino acids and amines. Contents of these various forms of Nitrogen in water can provide a good indication of the dominant nature of the nitrogen-cycle in the water body at the time of water sampling. Water pH and temperature play key roles in N transformation as well as microorganisms and plants. For example, at pH 7, ammonium is the dominant form of nitrogen while at pH 12, ammonia as a dissolved gas is the dominant form. In excessive amounts, ammonia, in this form is considered to be a pollutant.

The nitrification process transfers ammonia to nitrite in aerobic situation and the nitrite is converted to nitrate. Then, de-nitrification occurs, converting nitrate to gaseous nitrogen. This occurs in anaerobic environments, however, organic carbon (decomposed plant/animal materials) is required to complete this chemical reaction. Therefore, the contents of organic matter, that is carbon in water, will have an influence on nitrogen-cycle. In both stages, water pH is important. Although did not recommend a guideline for wetlands, to reflect urban constructed wetlands, the guidelines for freshwater lakes and reservoirs is followed (ANZECC 2000) (Table 1). In freshwater wetlands, nitrogen concentrations above 0.35 mg/L are considered undesirable. The cyclic changes in nitrogen are dependent on the state of life-decay and nitrogen inputs. As mentioned earlier, nitrogen contributes to algal growth and blooms. Nevertheless, it is often plausible that at the peak of algal bloom the contents of nitrogen in water column is at least due to the present consumption by existing algae for the production of its biomass. This, however, in a few days' or weeks' time might be released back in the water column due to algal decay, hence elevating the nitrogen contents in the water column, as shown in Figure 1. Management decisions need to be adjusted on the above bases.

Excess phosphorus can cause an imbalance in N:P ratio in water and trigger algal blooms.

Phosphorus cycle

Phosphorus is an important component in a wetland system, as it is an essential requirement for biological growth. In a freshwater system it originates from a number of sources. Some Phosphorous enters naturally, through the weathering and dissolution of catchment soils. However, most phosphorus inputs are the result of poor land management practises. Development activities potentially speed up soil erosion and sediment export process, which ultimately increases phosphorus load. For example, sewer overflow can export high concentration of P in the form of ammonia and faecal coliforms. Landscaping practices; especially fertiliser run-off and industrial effluent also contribute to excessive phosphorus inputs in a wetland system.

Both the dissolved and particulate forms of phosphorus can be found in a wetland and their forms can interchange with changes in pH, temperature, dissolved oxygen and other factors. A functional wetland system is truly a dynamic system and the state of a chemical in a given time can only reflect or represent the situation at that point in time; not necessarily the remaining life of the wetland. Often, such an

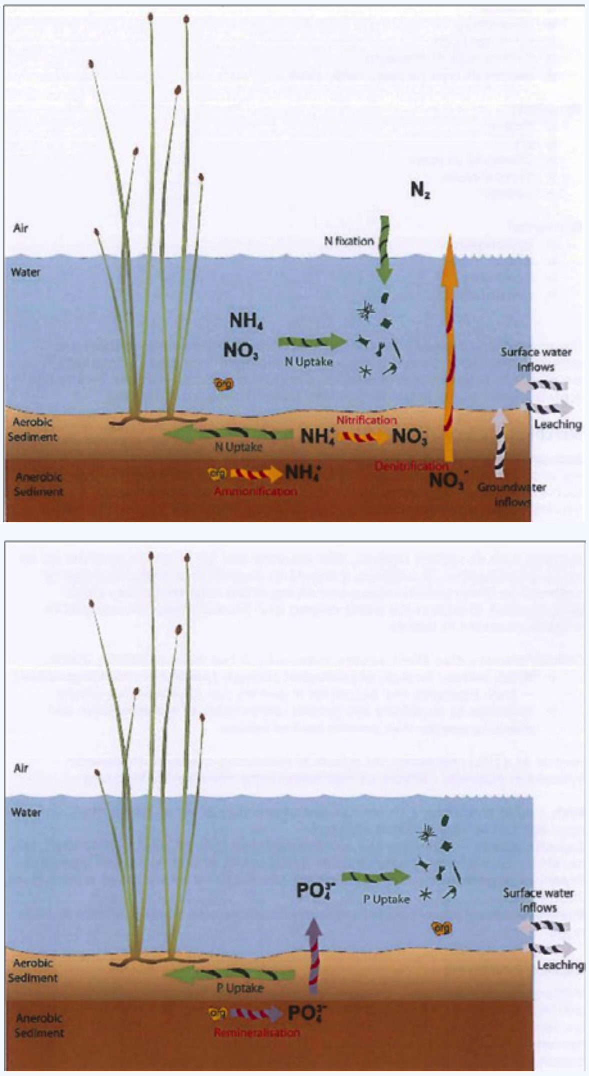

Figure 1. Nitrogen and Phosphorus Cycles in a freshwater wetland. (Source: Wetlands Ecology, workshop notes from Wetlands.Edu, Australian Government, 5-6 December 2009.)

important consideration is not taken into account as part of the decision-making process in wetland management. Monitoring of key chemical parameters provide the best indication of wetland condition and an understanding of the underlying chemical processes that ultimately influence wetland health. Example of relationship between phosphorus and pH may be explained; as in acidic pH (below 7), phosphates of iron, aluminium and manganese can be highly insoluble in water and form precipitates. At pH higher than 6, calcium phosphates can form and precipitate. This means that the availability of dissolved P in water column is highly dependent on other factors, including pH phosphorus availability in dissolved form or in precipitate dictates whether there could be instant flux of nutrients in the water column, or it might be locked in the sediment and gradually be released in the water column. Typically, phosphorus exits wetlands through outflow, by leaching into the subsoil, or by removal of plants and animals.

Constructed wetlands, or wetlands with selective macrophytes and good root biomass (and other biofilms) can quickly adsorb phosphorus from the water column and relieve pressure on management by potentially avoiding an algal bloom, because, as discussed earlier, excess phosphorus can cause an imbalance in N: P ratio in water and quickly trigger algal blooms.

Total phosphorus levels in freshwater are expected to be below 0.01 mg/L. The level of total phosphorus in a water body can be dependent on its internal sources and recycling, but in a typical urban wetland it is largely dependent on the catchment character and the degree and type of human-induced disturbance.

Dissolved Oxygen (DO)

Oxygen is essential for aquatic life. It enters the water column of a wetland through diffusion and aquatic plant communities also produce oxygen into the water column through photosynthesis. The oxygen so generated by water plants through photosynthetic process is then transferred to the root zone by the plants and made available in the sediment zone, thus making the sediment oxygen rich (Brown *et al*. 1998). In the water column, however, oxygen is generated through photosynthetic activities by plankton/algal mass.

Plants and animals take up oxygen during respiration, either during the day or night. Oxygen is also consumed during decomposition, nitrification and most other chemical reactions. Some oxygen may be also lost in the atmosphere. Due to respiratory activities, especially at night when also there is almost no photosynthetic activity, the concentration of DO in the water is generally lowest at dawn.

In constructed freshwater wetlands a healthy DO content is expected to remain not less than 4.0 ppm and not exceed 12.0 ppm. Super saturation of the water column with DO can influence pH content and may cause tissue damage to animals in extreme situations. Fish

Table 1. Water Quality Parameter Guidelines for South-East Australia (ANZECC 2000).

Water Quality Parameters	ANZECC Guideline (Lower Limit)	ANZECC Guideline (Upper Limit)
TP (mg/L or ppm)	0.01	-
TN (mg/L or ppm)	0.35	-
Ammonium (mg/l or ppm)	0.01	-
DO (% saturation)	90	110
DO (mg/L or ppm)	No guidelines but generally believed to be above 4 and below 12	-
pH	6.5	8.0
Salinity (µS/cm)	20	30
Turbidity (NTU)	1	20

kills are often evidence of environmental stress, either due to low dissolved oxygen or super saturation; though the former is more prevailing.

pH

Water pH is a measure of acidity or alkalinity (sodicity) state of water. As indicated above, many essential chemical reactions in a wetland are dependent on its acidic or alkaline nature. Since pH is expressed in terms of the amount of H+ (Hydrogen ions) that are free to combine or bind with another negatively charged element or compound in the water, pH status is indeed a big indicator of water health. Therefore, sudden change in water pH is highly undesirable. This often occurs when industrial effluent is discharged or sediment-rich water released.

Water pH ranges between 0 and 14.0, with the neutral pH being 7.0. Wetland pH is closely associated with calcium concentrations. At pH 7.0, calcium content is 20mg/l and ideally, a wetland pH should be between 6.0 and 8.0.

Acidity or pH can influence most chemical reactions in a wetland, the condition and type of life forms, including fecundity, and population growth rates. Populations of plankton and algal mass can be also highly influenced by water pH; acidic pH often encourages zooplankton and alkaline pH may promote phytoplankton and algae. Wetland managers' management decision is often guided by pH status.

Turbidity

Turbidity is a natural condition is a wetland, which is caused by both internal and external factors. Turbidity is primarily due to the suspended state of fine and/or coarse particles in the water column; their settlement being dependent on a number of factors, however, primarily due to water velocity, depth, temperature and presence/absence of plant communities. Turbidity is a condition in a water body, which is often expressed as a relative measure of water clarity or muddiness status. Unless it is treated or purified water, all waters in a wetland are likely to have some degree of turbidity.

Dead and decomposed life, natural re-suspension of sediment, movement of larger creatures in the wetland can cause internal sources of turbidity. Unfortunately, some introduced species of fish, specifically carp (*Cyprinus carpio*), can make a wetland very turbid by disturbing the bottom sediment through its mumbling habit. On the other hand, external sources include sediment washed from lands with stormwater, pollutants and particles from road-runoff and industries, organic decomposed materials, etc. Among these, the most common is the sediment wash from the catchment.

While some turbidity is a natural phenomenon in a wetland, too much turbidity is a problem for aquatic life-forms in a wetland. Plant communities, including plankton require light penetration for their normal functions, which can be affected by excess turbidity. Excess turbidity can quickly smother submerged vegetation within days. This can trigger a series of biological reactions in a wetland and quickly upset the fine ecological balance in the wetland. Animal life can be severely affected by turbidity in a number of ways, including loss of visual cues affecting feeding and breeding activities, shelter and migration, etc. It is not uncommon to observe mass fish kill due to excessive turbidity. The suite of flora and fauna that are likely to be present in a wetland can be dictated by the level and duration of turbidity in a wetland.

The range of suitable turbidity in a wetland may vary depending on its usage, nevertheless, readings over 20 units (NTU) are undesirable. Excessive turbidity can influence water chemistry in the short- and long-term. Especially, DO, pH and nutrient status in a wetland can vary due to the level of turbidity.

Turbidity can be artificially (chemically) dropped in a water body but the best approach is to let aquatic plants do the job. Emergent plants, submerged plants, biofilms, plankton and bacteria play a key role in the natural flocculation process. The rate at which turbidity-causing particles flocculate/coagulate largely depends on the nature and size of the particles. The finer they are in size the more likely are they to be in colloidal form and take longer to settle. Coarse sand and larger particles naturally should settle faster, however, this depends on water velocity.

Salinity and Conductivity

Salinity being a measure of the presence of salt in the water column, it is closely associated with the state of electrical conductance in the water due to the presence of salt molecules/compounds. Since these two are inter-dependent, they are often measured in either form and then conversions are conducted, with temperature as an additional factor in the conversion because the electrical conductance is directly influenced by water temperature. Although in case of water quality measure, salinity and conductivity may be used interchangeably, elevated saline condition in a freshwater wetland generally gives a much more negative connotation.

Freshwater wetlands often show high levels of salinity in the water. The primary reason for this phenomenon is the soils, local geology, catchment characteristics and maintenance regime.

High salinity or conductivity readings in a freshwater system indicates poor ecological health. The salinity generally affects freshwater wetlands through adverse changes in the electrolyte balance of plant and animal tissue/cell. This can be quickly reflected in stunted growth of plant communities, hence a shift towards those which can tolerate higher salinities is favoured. Likewise, fish and other aquatic life can be directly affected by high conductivity. The ultimate outcome is often a rapid shift in flora-fauna community structure in the wetland.

Conductivity readings vary sharply depending on the type of water. These readings can be easily converted to salinity, which, however, requires water temperature reading as an important determinant.

Other Physico-chemical Cycles

In a constructed wetland other chemical reactions can occur either singly or closely linked to one another. The consequences of these reactions on the aquatic ecosystem can be either favorable or adverse, depending on the ongoing catchment processes influencing wetland condition, local climate, and goals for managing wetland condition.

Since the ecological health of a wetland is largely dependent on its water chemistry and the chemical nature of water can change quite rapidly, it is advisable that careful considerations are given before any chemical treatments of wetlands.

Case Study 1: Dandenong Wetland

Wetland functions are sometimes used to improve waterway health in a catchment. For some agencies, such as Melbourne Water, constructed wetlands are considered to be a useful method for treating stormwater on a regional scale as they remove pollutants effectively through physical, biological and chemical methods (Somes *et al*. 2010). Stormwater wetlands are systems that are dominated by emergent macrophytes and control stormwater run-off to remove pollutants before flowing into nearby rivers and streams (Melbourne Water 2010). These wetlands have two key components:

- Sediment pond; that is, an open water inlet zone that reduces inflow velocity and traps coarse sediment.
- Wetland/Macrophyte Zone. Here the wetland is shallow with extensive emergent vegetation arranged in bands perpendicular to the stormwater inflow. These plants support a complex of algal and bacterial organisms, known as biofilms, that grow on the surface of the plants and assimilate fine sediments and soluble pollutants (nitrogen and phosphorous).

The Melbourne Water Waterways Alliance in Victoria (Australia) designed and constructed a 48 hectare wetland on the Dandenong Creek floodplain (Evans *et al*. 2010) (Figure 1). The Dandenong Wetland is in the Melbourne suburb of Scoresby and bound by Ferntree Gully Road, Wellington Road, Eastlink and Dandenong Creek (Somes *et al*. 2010). The wetland was constructed with the aim of removing excess nitrogen, phosphorous, and sediment from Dandenong Creek before it flowed into Port Phillip Bay (Evans *et al*. 2010). To do this the Dandenong Creek Wetland was constructed with a sediment basin and a series of interconnected wetland 'cells' which enable water to flow through the wetland. As part of the design, a calculation of the treatment capacity was conducted using estimates of water flows and pollutant concentrations using scenario modelling (MUSIC – Model for Urban Stormwater Improvement Conceptualisation). The model, which was developed and is managed by the eWater CRC, is often used to simulate urban stormwater systems at varying

Figure 1. An aerial photograph showing the construction of the Dandenong Wetlands. Eastlink is on the left, Dandenong Creek is on the right (SMEC Australia 2009).

spatial and temporal scales (Somes *et al*. 2010). The purpose of this modelling was to ensure that an appropriate hydrologic treatment regime is established with respect to wetland catchment area and water detention periods (Somes *et al*. 2010). For example, if a wetland has a specified period of 72 hours detention time then it would have a 'wet' hydrologic regime. That is, the wetland would experience extended periods of elevated water levels and the floral diversity would be reduced in 'wet' systems. Therefore it is assumed that treatment effectiveness is reduced over periods of sustained high flows as the reduction in vegetation diversity will reduce the hydraulic efficiency and interrupt treatment processes (Somes *et al*. 2010)

The Dandenong Creek Wetland was designed to treat base and medium flows from the Dandenong Creek. This means that the water levels would be high in the wetland for extended periods when flows within Dandenong Creek were high. To reduce the impact of extended periods of high water levels, the depth of all of the wetland zones was reduced. The largest zone in the wetlands is the shallow marsh zone (Figure 2), which occupies about 45 per cent of the wetland surface. The permanent water in this zone is about 100 millimetres deep and it was possible that these areas may dry out completely during summer. The drying out of the wetland raised two issues:

- The large areas of shallow or dry area would allow weeds to establish; or,
- Plant diversity would be lost, as no habitat would remain.

The weed issue is managed by manually manipulating water levels during the first three years of operation, with the aim of restricting the opportunity for weeds to establish (Somes *et al*. 2010). To provide refuges for plants during extended dry periods, deep pockets were introduced to create diversity to improve the wetland ecology in conjunction with breaking the visual pattern of the planting (Somes *et al*. 2010).

Unlike naturally occurring wetlands, constructed wetlands are often designed and built to fulfil a particular aim. In this instance, the Dandenong Creek wetland was designed to remove excess nutrients and sediments from Dandenong Creek (Evans *et al*. 2010). As a consequence, flora

Figure 2. The marsh zone of the Dandenong Wetlands showing the aquatic plantings (Peter Newall).

and faunal assemblages are likely to remain limited over time. This is because the wetland is carefully managed to meet its environmental requirements and not promote biodiversity or form an ecosystem that contributes to broader landscape processes.

Case Study 2: Lake Tuggeranong

Often the key design intents of a constructed wetland can create overlapping or competing management objectives. An example of this scenario is Lake Tuggeranong. Lake Tuggeranong is located in the ACT about 12.5 kilometres southeast of Capital Hill in Canberra. It is surrounded by urban development, with the Tuggeranong commercial district to the west, and significant residential development to the east. The Lake was created upstream of the confluence between Tuggeranong Creek and the Murrumbidgee River by the construction of a dam in 1987 and was filled in 1990 to coincide with urban development in the district (SMEC 1988).

Lake Tuggeranong was developed to abate the risk of adverse impacts from stormwater inputs to the Murrumbidgee River. The Murrumbidgee River supports aquatic systems and many significant natural and cultural features; including areas of the Southern Tablelands and the Snowy Mountains (SMEC 2012). Lake Tuggeranong was designed to provide pollution protection for the Murrumbidgee River, recreational amenity and a semi-natural habitat feature for the town centre (SMEC 1988; Gray 1997). The lake itself provides both riparian and aquatic habitat for a range of species, and is annually stocked with either with either golden perch (*Macquaria ambigua* (Richardson 1845) (*Percicthyidae*)) or Murray cod (*Maccullochella peelii* (Mitchell 1839) (*Percicthyidae*)), for recreational fishing that also has ecological benefits (ACT Department of Environment Climate Change Energy Water 2009).

The Lake comprises of a large lake with three small weirs (SMEC 1988). One is just below Drakeford Drive (that is, Isabella Pond), another follows a pedestrian crossing between Anketell Street and Drakeford Drive (Figure 1) and another, the largest weir, operates to maintain the impoundment of Lake Tuggeranong and includes a spillway for flows downstream into Tuggeranong Creek at Athllon Drive (Figure 2). The two smaller weirs have full supply levels slightly above the main lake and are designed to protect water quality (SMEC 1988).

Stormwater

Stormwater from the Tuggeranong and Erindale Town Centres flow into Lake Tuggeranong. For Lake Tuggeranong, water quality inputs to Lake Tuggeranong are problematic (ACT Planning and Land Authority 2012). This is because the gross pollutant traps for stormwater in the centre remove gross pollutants but not nutrients and the stormwater infrastructure does not meet current water sensitive urban design (WSUD) guidelines (ACT Planning and Land Authority 2012). Indeed stormwater inputs are typically associated with degraded water quality due to high levels of nutrients and sediments. In the warmer periods, blue-green algal outbreaks can occur and pose an adverse risk to public health. As well, offensive odours are more likely which would decrease the public amenity and use of the Lake.

Managing Water Quality

A key challenge in the management of Lake Tuggeranong is the demand for multiple uses. That is, the demands for effective stormwater management over the catchment area of Lake Tuggeranong need to be met. Yet, opportunities for recreation

Figure 1. The weir between Anketell Street and Drakeford Drive. (Photo: SMEC Australia 2011.)

in and around the lake need effective environmental solutions that maintain and improve amenity, while simultaneously abating the risk of adverse impacts from stormwater inputs to the Murrumbidgee River. To address this challenge, the management of Lake Tuggeranong seeks to provide opportunities for multiple use (*sensu)* (Griffith 1995). That is, address a range of objectives, such as improving water quality, enhancing aquatic and riparian habitat values, and improving recreational opportunities in and around the Lake.

Figure 2. The weir exit to the Murrumbidgee River. (Photo: SMEC Australia 2011.)

To address this issue in urban environments, Water Sensitive Urban Design (WSUD) measures are being considered for improving the water quality and subsequent stormwater inputs (sensu (ACT Planning and Land Authority 2012). Options for maintaining or improving the condition of urban wetlands include:

- Reducing sediment inputs using riparian plantings. Where areas of the riparian zone are prone to erosion, native grasses for example, can help to reduce the sediment inputs to a wetland;
- Increase the habitat value of a wetland by incorporating the principles of urban wetland design as part of its stormwater management;
- For Lake Tuggeranong, for example, opportunities for improving the viability of populations of Murray cod and golden perch in the Lake could be improved by increasing local habitat complexity (SMEC 2012). Examples include:
    - Mature trees could be planted in the riparian zone to provide mottled light for the Murray cod;
    - Mature wood (i.e. seasoned snags) could be placed in the Lake for silver perch; and,
    - Artificial habitat structures implemented as potential habitat for the Murray cod.
- In addition, implementing measures to reducing pest fish species in the Lake, such as carp (*Cyprinus caprio*). This is because reducing carp numbers can significantly reduce competition with native fish species for food (Gehrke *et al*. 2011) and also improve the recreational value for angling communities.

Through careful design, wetland areas can achieve a range of functions from improving water quality to providing additional habitat and increased opportunities (Griffith 1995). Incorporating wetlands for effective stormwater treatment, such as Lake Tuggeranong, can form part of an overall strategy for improving the social and environmental values of urban wetlands. Therefore, multiple benefits can be achieved at local and catchment levels.

Through careful design, wetland areas can achieve a range of functions from improving water quality to providing additional habitat and increased opportunities (Griffith 1995). Incorporating wetlands for effective stormwater treatment, such as Lake Tuggeranong, can form part of an overall strategy for improving the social and environmental values of urban wetlands. Therefore, multiple benefits can be achieved at local and catchment levels.

Case Study 3: Jerrabomberra Wetlands

The Jerrabomberra Wetlands are on the Molongolo River floodplain, about four kilometres east of Canberra Civic Centre in the Australian Capital Territory. They were created by the construction and filling of Lake Burley Griffin and are in the Jerrabomberra Nature Reserve, which is part of Canberra Nature Park (Territory and Municipal Services 2006). The wetlands comprise of permanent and ephemeral, still and flowing waters, and their associated floodplains where the Molongolo River and Jerrabomberra Creek enter Lake Burley Griffin. These wetlands are unusual as they have a high biodiversity value in a largely artificial landscape. The reserve provides habitat for a large number of land and water bird species, including migratory species protected under international agreements (ACT Department of Territory and Municipal Services 2010). Recreational uses are restricted to passive or educational nature reflecting the conservation focus of the Jerrabomberra Wetlands (ACT Planning and Land Authority 2007).

The Jerrabomberra wetlands comprise of old river channels that were flooded during the filling of Lake Burley Griffin to form the wetlands, and pools, channels and streams. Most of the wetland area is formed on an alluvial terrace (Dairy Flat) of the Molonglo River. Traces of former river channels (paleochannels) and levee banks are visible on the surface of the floodplain. These are connected on their western ends by a dredged channel (National Capital Development Commission 1988). Paleochannels are uncommon in the ACT and are significant geomorphological features. The quality of water and many aspects of water flow including quantity, timing, and duration are of fundamental importance to the functioning of ecosystems in this wetland. In turn, the wetland provides hydrological and water quality functions for Lake Burley Griffin. The flooded channels provide a permanent drought refuge for water birds and other water-dependent flora and fauna, as well as seasonal habitat for migratory bird species; particularly when Lake Bathurst and Lake George dry out in drought conditions (Department of Territory and Municipal Services 2010).

The water level in Lake Burley Griffin is normally maintained at Australian Height Datum (AHD) 555.93 metres by balancing inflows to the Lake and abstraction from the Lake. The level of the lake may fall in dry periods and during such periods limits may apply to abstraction from the lake (National Capital Authority 2005). Low flow conditions are not necessarily detrimental to the reserve, as aquatic habitat remains in Jerrabomberra Creek, Molonglo Reach, the Jerrabomberra Backwaters, and drying out of Kellys Swamp exposes important mud flat habitat. Nonetheless, the role of Jerrabomberra Wetlands as a regional 'drought refuge' may be reduced in these circumstances.

Figure 1. The Jerrabomberra Wetlands with a bird hide in the background. (Photo: Janet Hope.)

Habitat Diversity

Much of the aquatic and wetland habitat of the reserve is maintained by the relatively stable water levels through flows from Lake Burley Griffin and groundwater influences and therefore, does not experience the seasonal and episodic fluctuations in water level that are typical of many naturally occurring Australian wetlands. During high flows, water overtops the banks of the Molonglo River and Jerrabomberra Creek to enter the surrounding floodplain and create valuable ephemeral habitat.

Figure 2. The Jerrabomberra Wetlands showing bird nest boxes. (Photo: Roger Williams.)

Birdlife

The presence of permanent, shallow water bodies means that the wetlands are a regionally important drought refuge. In periods when Lake Bathurst and Lake George are dry, large numbers of pelicans, cormorants and coots find shelter in the reserve (Figure 1 and Figure 2). One hundred and seventy bird species have been sighted in the reserve (Canberra Ornithologists Group 1987). Of these, more than 80 species of water bird species are recorded, representing most of the common water bird species in southeastern Australia (ACT Parks and Conservation Service 1994). Of these, 15 to 25 species appear to breed in the Jerrabomberra Nature Reserve. Many other birds not specifically associated with water habitats are also recorded as occurring in the locally planted woodlands and grasslands of the reserve. The wetlands also provide habitat for up to 11 fish species as well as the eastern water rat (*Hydromys chrysogaster*), platypus (*Ornithorhynchus anatinus*) and eastern snake-necked tortoise (*Chelodina longicollis*).

Significance

The Jerrabomberra Wetlands are an important part of the vegetated wildlife corridor along the Molonglo River and broader parkland system of Lake Burley Griffin (Territory and Municipal Services 2006). An important attribute of the wetlands is the 'drought refuge' habitat they provide when large regional wetlands such as Lake Bathurst and Lake George dry up. As noted previously, the Jerrabomberra Wetlands is unusual in that the area has high biodiversity value in a largely artificial landscape. The small size of the reserve, its location amidst a range of urban land uses, the wetland habitats created by and maintained by the presence of a large urban lake, and its vegetation cover of mostly introduced and planted species, mean that it cannot be considered from a biodiversity perspective in the same terms as a more naturally occurring area (ACT Department of Territory and Municipal Services 2010). However, in relation to biodiversity conservation, the following attributes of the reserve are significant:

- Bioregional context: The reserve is one of a number of wetlands in south-eastern NSW. Even though there are now well established permanent populations of many water bird species on Lake Burley Griffin, water birds move between wetlands depending on seasonal conditions and may migrate considerable distances. The reserve is a 'drought refuge' habitat when large regional wetlands dry up and may become more important if some wetlands are drier for longer periods due to climate change.
- Connectivity: Wetland habitats at Jerrabomberra have a complementary relationship with the waters of Lake Burley Griffin, and the Molonglo River and Jerrabomberra Creek.
- Habitat diversity: The Jerrabomberra Wetlands are characterised by: aquatic and wetland habitats related to waters of

Lake Burley Griffin (e.g. open water, reed bed, mudflat, and riparian vegetation); exotic grasslands (Dairy Flat grazing land, marshland and wet grassland); landscape plantings (including the woodland south of Jerrabomberra Creek); and shrub cover near Kellys Swamp.

- The reserve contains areas of drowned grassland, mudflat, shallow water, and marshland. These types of habitat are not widespread in the ACT. In the Jerrabomberra Wetlands, these habitats vary in size or are ephemeral depending on seasonal conditions.
- Weeds: The mainly exotic vegetation of the reserve contains many ACT declared weeds and other problem weed species. Despite their exotic origin, these plants provide habitat for local fauna.

Despite being a constructed wetland, the Jerrabomberra wetlands are locally and regionally significant. The wetlands become drought refugia when other systems, such as Lake George, dry out. They also provide breeding habitat for migratory bird species protected under international agreements (ACT Department of Territory and Municipal Services 2010) as well as other water-dependent fauna (e.g. Figure 1 and Figure 2). Nonetheless, as urbanization increases in the Jerrabomberra Creek catchment, sedimentation and the effects of high volume flows may become more frequent through increased intensity of stormwater flows. Here a balance must be sought between maintaining the high environmental values of the Jerrabomberra wetlands and increasing urban pressures.

Conclusions

Urban wetlands, whether constructed or natural, provide ecological services and may be of particular importance to both people and wildlife because of their location in the landscape. Management of urban wetlands must start with an understanding and assessment of the particular conditions imposed by the urban environment and the goal(s) of wetland use. These conditions can be identified and incorporated into management objectives that promote wetland function and their use in the landscape.

Acknowledgements

The author thanks the Australian Society for Limnology for assisting in gathering photographs for this chapter. In particular she thanks Peter Newall, John Patten and Bob Evans.

References

ACT Department of Environment Climate Change Energy Water (2009). Fish stocking plan for the Australian Capital Territory. Environment, Canberra ACT 2600.

ACT Department of Territory and Municipal Services (2010). Jerrabomberra Wetlands Nature Reserve. Plan of Management 2010. Conservation Planning and Research, Land Management and Planning Division, Department of Territory and Municipal Services, ACT Government, Canberra ACT 2601.

ACT Parks and Conservation Service (1994). Jerrabomberra Wetlands Nature Reserve Plan of Management. ACT Parks and Conservation Service, Canberra.

ACT Planning and Land Authority (2007). East Lake Urban Renewal Draft Planning Report. ACT Government, Canberra.

ACT Planning and Land Authority (2012). Tuggeranong town centre ideas - Tuggeranong and Erindale Master Plans 2010 - 2012. Canberra ACT 2601.

Australian New Zealand Environment and Conservation Council the Resource Management Council of Australia and New Zealand (ANZECC) (2000). Australian and New Zealand Guidelines for Fresh and Marine Water Quality: Volume 2 - Aquatic Ecosystems - Rationale and Background Information. In 'Australian and New Zealand Environment and Conservation Council and the Resource Management Council of Australia and New Zealand'. (Ed.) Canberra ACT 2601.

Boulton, A., and Brock, M. (1999a). 'Australian Freshwater Ecology: Processes and Management.' (Gleneagles Publishing:South Australia.)

Boulton, A., and Brock, M. (1999b). 'Australian Freshwater Ecology: Processes and Management.' (Gleneagles Publishing: South Australia.)

Brown, M., Beharrel, M., and Bowling, L. (1998). Chemical, Physical and Biological Process in Constructed Wetlands. The Constructed Wetlands Manual Vol 1. NSW Department of Land and Water Conservation.

Canberra Ornithologists Group (1987). Avifauna of the Molonglo River Corridor. Unpublished Report to the National Capital Development Commission. Canberra Ornithologists Group, Canberra.

Coenraads, R. R., and Koivula, J. I. (2007). 'Geologia - The Origins of the Earth.' (Penguin Books, Camberwell: Victoria.)

Department of Conservation and Environment and Office of the Environment (1992). 'An assessment of Victoria's wetlands.' (Department of Conservation and Environment, Office of the Environment, Melbourne.)

Department of Sustainability Environment Water Populations and Communities (2013). Wetlands Australia. National Wetlands Update February 2013 - Issue No 22.

Department of Territory and Municipal Services (2010). Jerrabomberra Wetlands Nature Reserve. Revised Draft Plan of Management. Australian Capital Territory, Canberra.

Ehrenfeld, J. G. 2000. Evaluating wetlands within an urban context. Urban Ecosystems 4:69 - 85.

Evans, R., Smithers, R., and Le Plastrier, B. (2010). 'Innovative Approaches to Wetland Design at Dandenong Creek Wetland.' (SMEC Australia Pty Ltd: Melbourne, VIC.)

Finlayson, C. (2000). Loss and degration of Australian wetlands. LAW ASIA Conference. Environmental Law Issues in the Asia - Pacific Region.

Frankston City Council (n.d.). Seaford Wetlands Reserve. In 'Frankston City Council'. (Ed). Available at http://www.frankston.vic.gov.au/library/scripts/objectifyMedia.aspx?file=pdf/269/91.pdf&.

Gehrke, P., Clarke, M., Matveev, V., St Pierre, S., and Palmer, A. (2011). Carp control improves the health of aquatic ecosystems. *Water* **35**, 91–95.

Gray, J. (1997). Statements on the Historical and Cultural Background of Selected Urban Parks in Canberra - Volume 2. Canberra Urban Parks and Places, Canberra.

Griffith, E. (1995). Multiple use of urban waterways: a local government perspective of wetland rehabilitation and re-creation. *Wetlands (Australia)* **15**, 26–36.

Hunter, G. (2003). Wetlands for Stormwater Management: water, vegetation and mosquitos - a recipe for concern. In 'Waterplants in Australia. A Field Guide'. (Eds G. Sainty and S. Jacobs.) pp. 395–405. (Sainty and Associates Pty Ltd: Potts Point, NSW.)

Integrated Management Information System, Masson, W. T., Sinclair, K. M., and Watson, H. (2003). M5 South West Environmental Impacts. Prepared for Interlink Roads.

Kingsford, R., and Auld, K. (2005). Waterbird breeding and environmental flow management in the Macquarie Marshes, arid Australia. *Rivers Research and Applications* **21**, 187–200.

Kingsford, R., Brandis, K., Thomas, R., Crighton, P., Knowles, E., *et al*. (2004). Classifying landform at broad spatial scales: the distribution and conservation of wetlands in NSW, Australia. *Marine and Freshwater Research* **55**, 17–31.

Kingsford, R., and Johnson, W. (1998). Impact of water diversions on colonially nesting waterbirds in the Macquarie Marshes in arid Australia. *Colonial Waterbirds* **21**, 159–170.

Kingsford, R., and Thomas, R. (1995). The Macquarie Marshes and its waterbirds in arid Australia: A 50-year history of decline. *Environmental Management* **19**, 867–878.

Kingsford, R., and Thomas, R. (2002). Use of satellite image analysis to track wetland loss on the Murrumbidgee River floodplain in arid Australia, 1975-1998. *Water Science and Technology* **45**, 45–53.

Kingsford, R., and Thomas, R. (2004). Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. *Environmental Management* **34**, 383–396.

Kleeman, G., Epps, R., Hamper, D., Lloyd, C., Rugendyke, B., *et al*. (2008). 'A Geography of Global Interactions.' (Reed International Books: Port Melbourne, Victoria.)

Kobayashi, T., Shiel, R., and Segers, H. (2007). First record of the rotifer Lecane shieli Segers & Sanoamuang, 1994 from Australia. *Australian Zoologist* **34**, 181–183.

Melbourne Water (2010). Constructed Wetlands Guidelines, Technical Report, Melbourne Water, ISBN 978- 921603-39-6.

National Capital Authority (2005). Lake Burley Griffin Abstraction Plan. Commonwealth Government, Canberra.

National Capital Development Commission (1988). Sites of Significance in the ACT. Volume 2. Inner Canberra. Technical Paper No. 56. National Capital Development Commission, Canberra.

Schueler, T. (1999). Adequate Treatment Volume Critical in Virginia Stormwater Wetland. In 'The Practice of Watershed Protection'. (Center for Watershed Protection: Ellicott City, MD.)

SMEC (1988). Tuggeranong Dam Design Report Volume 1 Part 1 for the National Capital Development Commission. Cooma NSW.

SMEC Australia Pty Ltd. (2012). Greenway Master Plan Aquatic Impact Assessment. Land Development Agency, 243 Northbourne Avenue, Lyneham ACT 2602.

Somes, N., Bermingham, M., and Smithers, R. (2010). Dandenong Valley Wetlands an Integrated team Delivering Outstanding Environmental Outcome. Stormwater 2010 - National Conference of the Stormwater Industry Association, Star City Hotel, Sydney Australia.

Territory and Municipal Services (2006). Jerrabomberra Wetlands Nature Reserve Draft Plan of Management. ACT Government, Canberra.

Watershed Ecology (2013). Aquatic Ecology Monitoring Program in the Penrith Local Government Area. For Penrith City Council. Cremorne NSW 2090.

Wright, T., Tomlinson, J., Schueler, T., Cappiella, K., Kitchell, A., *et al*. (2006). Direct and Indirect Impacts of Urbanization on Wetland Quality. Wetlands & Watersheds Article #1. Office of Wetlands, Oceans and Watersheds U.S. Environmental Protection Agency Washington, DC.