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WATER QUALITY AUSTRALIA

Characterising the relationship between water quality and water quantity

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Executive summary

The Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) is responsible for the ongoing development and implementation of policies and programmes aimed at achieving the sustainable management of Australia's water resources. Part of this role involves the development of materials that will assist water managers and policy makers to understand and protect the environmental values—aquatic ecosystems, drinking water, recreation and aesthetics, industrial water, primary industries, and cultural and spiritual values—as defined in the National Water Quality Management Strategy.

DSEWPaC engaged Sinclair Knight Merz on 31 January 2012 to develop a report with associated conceptual models to characterise the relationship between water quality and water quantity to help water managers gain a greater insight into some of the key water quality issues that are experienced across Australia. This information will also assist managers in making informed decisions about how water is managed in the landscape to maintain and improve its water quality.

Water quality has a close but complex relationship with water quantity. The nature of the relationship depends strongly on the individual catchment and type of aquatic ecosystem. Changes in the quality or quantity of water may result in immediate changes in the structure and function of ecosystems, including the numbers and types of organisms that can survive in the altered environment. It can equally affect other environmental values such as drinking water quality, primary industries, recreational, aesthetic values and cultural and spiritual values.

The relationships between water quantity and water quality vary for different types of aquatic ecosystems (for example, regulated rivers, unregulated rivers, urban streams, ephemeral streams, estuaries, marine environments, lakes and wetlands) and also vary across Australia due to natural factors such as climate, topography and catchment geology. Some common factors that depict the water quality/quantity relationship are the nature of the water source(s), the watering regime and also the internal processes that can occur. River regulation, catchment land use and water extraction alters the natural flow/watering regimes and associated water quality characteristics.

Depending on circumstances, any combination of these factors can give rise to water quality issues such as eutrophication (and associated algal blooms), contamination with toxins, increasing salinity, cold-water pollution, hypoxic blackwater events and exposure of acid sulfate soils.

Water quality is often managed separately from water quantity. This report has reviewed the water quality/quantity relationships in a range of systems to help draw these interrelated aspects closer together. These generalised relationships and the management implications are summarised in Table 1.

Table 1 Generalised water quality/quantity relationships and management implications

Ecosystem type	Generalised relationship between water quality and water quantity	Management implications
Temperate rivers (wet winter / dry summer)	*Low flows* occur in the summer months. Water temperatures are warmer and there is increased water clarity from the settling of suspended	The management of temperate and tropical rivers could be enhanced by determining how water quality is affected by flow on a site-by-site

Ecosystem type	Generalised relationship between water quality and water quantity	Management implications
	solids onto the stream bed. Increased light penetration and warm temperatures increase rates of biological processes such as primary production and carbon and nutrient cycling. These processes may reduce in-stream nutrient and carbon levels. Dissolved oxygen levels tend to be lower due to warm water temperatures and vary with biological processes. Electrical conductivity (EC) levels can also increase in some systems with saline groundwater interactions. *High flows* occur in the winter months. Rainfall in the catchment washes particulate and dissolved nutrients and carbon into the river, which can be stored in the channel to support food webs. High turbidity / suspended solids result from catchment run-off and stirring up of bed sediments. Lower temperatures and water clarity reduce rates of biological processes.	basis. This could be done by interrogating long-term monitoring data sets and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations and site-specific water quality targets under different flow conditions; and guide catchment investment priorities.
Tropical rivers (monsoonal and wet/dry)	*Low flows / cease-to-flows* occur during the winter dry season. Rivers will often cease flowing in the wet/dry tropics, although some may be sustained perennially by base flows sourced from groundwater. Monsoonal catchments have a more evenly distributed rainfall pattern and therefore have flows in the main river channels for most of the year. As flows steadily decrease in the dry season, water temperatures rise and daily dissolved oxygen concentrations fall. Suspended solids also settle, increasing water clarity. Nitrogen and phosphorus can be low, but clear water and stable hydraulic conditions support rates of gross primary production comparable with rivers with substantially higher nutrient levels. Water loss by evaporation, particularly in the wet/dry tropics, can concentrate salts. *High flows* occur during the summer wet season. 'First-flush' run-off, particularly in the wet/dry tropics, can be acidic with very high concentrations of suspended particulate matter, nutrients, sulfate and some heavy metals (like aluminium). Extreme rainfall events can occur during cyclonic activity, which can liberate and transport large quantities of suspended sediments	

Ecosystem type	Generalised relationship between water quality and water quantity	Management implications
	and nutrients to rivers and marine receiving environments.	
Dryland rivers	*Cease-to-flow* causes water to retract to a series of connected or disconnected waterholes, where water quality is driven by processes such as evaporation, groundwater influence and the concentration or precipitation of compounds. Water quality conditions can be harsh at the local scale from low dissolved oxygen levels, high temperatures, increasing salinities, hardness, alkalinity and cations. Water quality during *flooding flows* is driven by the large volumes of catchment run-off. Flooding entrains organic carbon and nutrients from the productive floodplain areas into the river channels to support food webs. Some systems also have high mineral turbidity, which is characteristic of the local geologies and land use.	Water quality naturally changes temporally and spatially in dryland rivers. This makes developing and applying water quality guidelines and trigger levels very difficult for these rivers. One possible solution is to develop guidelines for both the no-flow and flowing phases. This could be done by collecting and interrogating monitoring data and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in guiding the sustainable use and management of dryland rivers.
Regulated rivers	River regulation can cause lower variability in flow, overall lower flow magnitudes and in some cases seasonal reversal of the flow regime in rivers downstream of storages. Low flows are associated with low oxygen content, temperature extremes, increased concentrations of contaminants, eutrophication and salinisation. Dams also reduce connectivity along the river length, which has implications for nutrient and sediment transport and can affect downstream trophic structure and function. Another water quality issue associated with river regulation is cold-water pollution. This is caused when storage dams thermally stratify during summer and the colder, anoxic bottom waters are released. This cold-water effect can be observed significant distances downstream. Similarly, as large storages have a greater water mass than flowing rivers, they take longer to heat and cool. Therefore, there is a dampening of seasonal temperature trends downstream, where the water is cooler in summer and warmer in winter. Cold water during summer can suppress ecological processes and disturb life cycles of fish.	Determining how water quality is affected downstream of major storages through targeted water quality monitoring programmes can help to set minimum environmental flow recommendations and determine suitable temperatures for release. Cold-water pollution can be managed by having release structures such as multi-level offtakes that allow surface waters to be discharged or have mixing equipment that prevents thermal stratification from developing.
Urban streams	The water quality of urban streams is highly variable and is a significant determinant of overall stream condition. Changes to the hydrologic	Water-sensitive urban design and stormwater management is the key to improving water quality in urban streams. The Council of Australian

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	regimes of urban areas can affect water quality, as the large areas of impervious surfaces lead to increased run-off velocities, erosion and the entrainment and transport of pollutants present on the catchment surface. Generally, surface run-off, referred to as stormwater, transports a variety of materials of chemical and biological origin to the nearest receiving water body. These contaminants can cause toxicity to aquatic organisms and alter ecosystem processes (such as nutrient cycling), resulting in a water body that is fundamentally changed from its natural state.	Governments (COAG) National Urban Water Planning Principles provide tools to plan the development of urban water and wastewater service delivery in a sustainable and economically efficient manner.
Groundwater-fed streams	An important factor determining the water quality in surface systems is the extent of surface water / groundwater interaction. In broad terms, streams can be 'losing' or 'gaining'. A gaining stream is one where for most of the time groundwater flows into the stream, and the quality in the stream is partly or largely a function of the groundwater quality. A losing stream is one where, for most of the time, surface water leaks out of the watercourse and recharges the groundwater system, in many cases creating a fresher groundwater zone beneath and around the watercourse. Many of the watercourses in Australia were historically of this latter type, but, with land use changes such as irrigation or clearing of native vegetation, the watertable has risen and reversed the situation. Where the regional groundwater is saline, this is one of the classic manifestations of the salinity problem in Australia.	Dryland salinity has been an ongoing catchment management issue since the 1970s. Significant progress has been made through salinity action plans, including revegetation efforts, and in changing irrigation practices. Managing saline groundwater intrusion into rivers to prevent adverse salinity impacts to aquatic flora and fauna is complex. It could be enhanced by determining how EC levels are affected by flow on a site-by-site basis. This could be done by interrogating long-term monitoring data and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations and site-specific water quality targets under different flow conditions (for example, base flows v. high flows) and guide catchment investment priorities.
Freshwater wetlands	The hydrology of wetlands depends on their level of connection with water sources. Some wetlands are connected to rivers. Other wetlands may intersect with groundwater. Still others can be isolated and located within low points in the landscape that receive rainfall run-off from the catchment. In urban settings, wetlands can receive water from stormwater drains or industrial discharges. The wetting and drying cycles of wetlands can be important ecologically as well as for water quality purposes. In natural systems, wetlands typically fill during the wet	Water quality monitoring in wetlands and lakes is less common than in river systems. Routine water quality and water level monitoring is recommended in those wetlands with important environmental values (for example, high-value aquatic ecosystems or recreation) or that provide water quality treatment outcomes (for example, stormwater treatment wetlands). This will help to better define the site-specific water quality / water level relationships and inform processes to set environmental watering requirements for these systems.

Ecosystem type	Generalised relationship between water quality and water quantity	Management implications
	season and slowly dry during the dry season. The wet season filling refreshes water quality, dilutes accumulating ions and toxics and entrains organic matter for food webs. It releases nutrients from the soils and organic matter, which encourages the growth of seeds in the refilled wetlands. Nitrification and denitrification processes that remove nitrogen from aquatic systems require aerobic conditions (during the drying of wetland sediment) to convert ammonia to nitrates (nitrification), then anaerobic conditions (during the wetting cycle) suitable for denitrifying bacteria to convert nitrates to nitrogen gas (denitrification), thus removing it from the ecosystem. This is an important feature of wetlands that is utilised for water treatment outcomes in urban and rural environments. Water quality issues arise when the filling of wetlands occurs too infrequently (as is the case in regulated systems or during droughts). This causes the accumulation of large quantities of organic, carbon-rich matter on the margins and floodplain. It can also expose acid sulfate soils. When the next flood occurs, all the material is transported into the wetland (and associated rivers system) and overloads its functioning capacity.	
Lakes	*Inundation—water level rises:* Nutrients and organic matter are imported into lakes via floodwaters and are rapidly released through decomposition of organic material. Sediments on the lake bed can act as a store for these nutrients, which accumulate over time and support complex food webs. This can lead to high productivity, which, when combined with greater habitat availability associated with a rising water level, supports greater biodiversity. *Recession—water level recedes:* Evaporation and reduced inflows may lead to water quality decline. Poor water quality may be attributed to a decrease in the buffering capacity of the system as water levels recede. Observed water quality changes can include increased concentration of nutrients, turbidity conditions, an increase in salinity and potentially thermal stratification depending on	As above.

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	ambient temperatures. In extreme cases, permanent freshwater lakes can recede until they dry out. In instances where a fall in water levels exposes lake sediments, there is potential for acid sulfate soils to be exposed and become oxidised. As the lake is inundated following rainfall, these sediments may lead to acidification of the water body.	
Reservoirs	Water quality in reservoirs is determined by the frequency, magnitude, duration and seasonality and quality of inflows and by in-lake processes. Inflows transport nutrients, sediments and other contaminants, which may then be affected by in-lake processes such as settling of suspended solids and biochemical processes. Bushfire run-off presents the highest risk of contaminant loads in these catchments. Stratification is the separation of the water column into density-based layers caused by differences in temperature or salinity. Thermal stratification of layers affects deep reservoirs and occurs in the warmer, drier months, when reduced inflows result in minimal mixing within the reservoir. Cycles of stratification and mixing of the water column are known to drive algal growth in nutrient-enriched reservoirs. Stratified conditions create calm, still and warm conditions at the surface that are favourable for the growth of algae. The bottom layer becomes depleted of oxygen and under such conditions releases nutrients from the sediment, which further drives algal blooms at the surface. Other water quality issues can occur from stratification in reservoirs. Under stratified conditions, cold-water pollution can occur downstream when the reservoir offtake is below the thermocline. Also, the anoxic conditions in the hypolimnion produce a reducing environment whereby manganese, iron, phosphorus, sulfides and ammonia are released from the sediments. These chemicals can alter the taste, colour and odour of the water, which makes the water displeasing for potable water supply customers.	Algal blooms in reservoirs can be reduced by catchment management works to reduce nutrient loads. Aerators can also be used to keep reservoirs mixed and prevent thermal stratification from developing. Bushfire impacts can be mitigated through creating fire breaks and carrying out fire prevention activities (like controlled burns).

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Salt-wedge estuaries	Under *low-flow conditions*, salt wedges can form and can encroach up the estuary. The lack of mixing between the top (fresh) and bottom (saline) layers creates an anoxic environment that can cause the release of nutrients and toxicants (for example, heavy metals and pesticides) from sediments. It also reduces the habitat available for fish and invertebrates. Under *very low flow conditions*, the flow of the freshwater layer may be slow-moving on top of the salt wedge. This shallow layer creates calm, still and warm conditions which favour the growth of algal blooms. Under *high freshwater inflows*, the force of the water pushes the salt wedge towards the estuary mouth and freshens water quality in the estuary.	Salt-wedge estuaries are managed by catchment freshwater inflows. The management of these estuaries in regulated catchments could be enhanced by determining how water quality in the estuary is affected by flow on a site-by-site basis. This could be done by collecting and interrogating monitoring data (including vertical profiles) and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations.
Heavily modified estuaries	*Low freshwater inflows* cause a loss of flow-induced currents and vertical mixing, which can lead to salt wedges forming and encroaching up the channel, low dissolved oxygen at depth, the release of nutrients from sediment and the formation of toxic algal blooms. *Reduced tidal flushing* causes the partial or full closure of the estuary mouth to occur, which reduces tidal flushing and increases the build-up of sediment and nutrients in the estuary. Water temperatures can also increase, and the still conditions can favour the growth of algal blooms. *High catchment inflows* cause flushing of the estuary under high catchment inflows, which can improve estuarine conditions. However, inflows from urban and agricultural catchments typically have high levels of nutrients, suspended solids, biochemical oxygen demand and pathogens that can degrade water quality in the short term.	The quality and quantity of catchment inflows, coupled with the tidal flushing dynamics, determine estuarine condition. Land use and catchment processes, both current and historical, need to be considered for effective management. The management of these estuaries in regulated catchments could be enhanced by determining how water quality in the estuary is affected by flow on a site-by-site basis. This could be done by collecting and interrogating monitoring data (including vertical profiles) and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations to maintain water quality in the estuary.
Near-shore environments	The effect of freshwater flows on water quality is dependent upon the properties of the inflowing and receiving waters and the magnitude of the flows. Freshwater flows affect a range of water quality properties of the receiving coastal waters, including temperature, salinity, turbidity, total and dissolved nutrients, suspended solids, organic matter content,	Farm management plans and urban stormwater management can help to reduce the sediment and nutrient loads entering near-shore environments during floods. In addition, load assessments are required for any proposed catchment modifications (for example, urbanisation and mining) to ensure that contaminant loads are not

Ecosystem type	Generalised relationship between water quality and water quantity	Management implications
	dissolved oxygen, and presence of chemical pollutants. *Floods* produce plumes of high turbidity in receiving waters. The plumes are particularly distinct in coastal environments that have naturally clear waters. First-flush events have the highest concentrations of sediment and nutrients and are associated with transport of pollutants, including heavy metals, pesticides and herbicides, which can occur at their highest concentrations at the plume front. Deposition of suspended sediment occurs in the near-shore environment of the coast and estuaries, which can function as sediment traps. Dissolved nutrients are transported much further from the coast, and elevated nutrient concentrations can occur over a hundred kilometres from the coast. *Low inflows* from river systems are an important source of carbon for sustaining food webs of near-shore ecosystems. The importance of freshwater flows for near-shore environments is demonstrated by the many examples of positive relationships between commercial fisheries catches and catchment rainfall. The reduction in delivery of fresh water has direct effects on the water quality variability of receiving coastal waters and also the productivity of the coastal environments. Since freshwater flows are important in providing variability to water quality and aquatic habitat to which many coastal species are adapted, reduced flow has a negative effect on recruitment, abundance and diversity.	increasing to these fragile environments from the catchment.

Contents

Tables

Figures

Case studies

1 Introduction

The Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) is responsible for the ongoing development and implementation of policies and programmes to manage Australia's water resources sustainably and efficiently. Part of this role involves the development of materials that will assist water managers and policy makers to understand and protect environmental values as defined in the National Water Quality Management Strategy (NWQMS).

Sinclair Knight Merz was engaged by DSEWPaC to develop a report with associated conceptual models to characterise the relationship between water quality and water quantity to help water managers gain greater insight into some of the key water quality issues that are experienced across Australia. This information will also assist managers to make informed decisions about how water is managed in the landscape to maintain and improve water quality for a range of uses.

1.1 Report structure

This report has been structured into the following sections:

- Section 2—outlines the importance of the water quality and quantity relationship, the historical and current links in national water policy and a review of the role of models in understanding and managing this relationship
- Section 3—describes the key hydrological and ecological relationships that drive water quality, with particular focus on the relationship between water quantity and quality
- Section 4—describes the effects of these relationships on specific systems, including rivers, estuaries, reservoirs, wetlands and near-shore environments. A conceptual model is developed for each of these systems to facilitate management understanding
- Section 5—provides a synthesis of the report findings.

2 The link between water quality and water quantity

This section outlines the importance of the water quality and quantity relationship, the historical and current links in Australian water policy and reviews the role of modelling in management.

2.1 The importance of water quality and quantity

'Water quality' refers to the physical, chemical and biological attributes of water that affect its ability to sustain environmental values (ANZECC & ARMCANZ 1994b, p. 12). 'Water quantity' describes the mass of water and/or discharge and can also include aspects of the flow regime, such as timing, frequency and duration.

Water of adequate quality and quantity is central to the health and integrity of the environment. The presence or absence of water, and its quality, largely determines the species richness and diversity of a particular region. It can also be a trigger to breeding and recruitment behaviours for some species. Changes in the quality or quantity of water may result in immediate change in the structure and function of ecosystems, including the numbers and types of organisms that can survive in the altered environment (ANZECC & ARMCANZ 2000).

Good water quality and quantity are not only important to support healthy ecological communities; they are equally important for human water users. On 30 September 2010, the United Nations Human Rights Council adopted a resolution recognising that the human right to safe drinking water and sanitation is a part of the right to an adequate standard of living (UNHRC 2010). The availability of adequate supplies of clean water is one of the most important building blocks for economic and social structures of society. It determines the viability of a region to support industries such as agriculture, fishing, irrigation, manufacturing and mining. Over history, it has shaped the geographic distribution of human populations and their quality of life and culture.

The NWQMS identifies six environmental values that are conducive to public benefit, safety, health or aesthetic enjoyment and which require protection from the effects of pollution (ANZECC & ARMCANZ 2000) and altered flow regimes. They are:

- aquatic ecosystems
- primary industries (irrigation and general water uses, stock drinking water, aquaculture and human consumption of aquatic foods)
- recreation and aesthetics
- drinking water
- industrial water
- cultural and spiritual values.

2.2 Water quality/quantity link in policy

Water resource management is an integral part of protecting environmental values and balancing competing economic, environmental and social demands (ANZECC & ARMCANZ 2000).

Significant water reforms have taken place over the past two decades to improve the management of water resources in Australia. The Council of Australian Governments (COAG) has been responsible for a number of national reforms in water policy. Major milestones include the COAG Water Reform Framework Agreement of 1994 and the National Water Initiative (NWI) in 2004. The principal COAG mechanism for the management of water quality is the National Water Quality Management Strategy (NWQMS). Another initiative is the National Urban Water Planning Principles, which provide governments and water utilities with the tools to better plan the development of urban water and wastewater service delivery in a sustainable and economically efficient manner.

Implementation of the NWQMS and NWI has led to a number of policy developments and instruments that support the management of water resources, including the quality and quantity of those resources. This section provides an overview of the NWQMS and the NWI. Both take into account the complex link between water quality and quantity, to varying degrees, and aim to assist in resolving some of these complexities for water managers.

2.2.1 National Water Quality Management Strategy

The NWQMS encapsulates the key dimensions of water that are essential for life (quantity and quality) (ANZECC & ARMCANZ 1994a). Although water quantity and quality are naturally variable, they are also affected by human-induced changes associated with water use demands and land use. Water quality in particular can be managed in some contexts using technology to deliver end-use requirements (for example, drinking water).

The NWQMS provides the policies, processes, guidelines, information and tools necessary for government and the broader community to manage water resources sustainably with a primary objective to 'Achieve the sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development' (ANZECC & ARMCANZ 1994a, p. 4).

The NWQMS comprises three core considerations—policies, process and guidelines—and is a key component of the 1994 COAG Water Reform Framework. The NWQMS is primarily the responsibility of the Standing Council on Environment and Water. All states and territories are committed to its implementation and have adopted a number of the policies and guidelines that support the NWQMS, such as the ANZECC & ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

The NWQMS is complemented by a number of natural resource management initiatives, including the Australian Government's Caring for Our Country programme, the former National Action Plan for Salinity and Water Quality and the former Natural Heritage Trust.

In a review of the NWQMS, Bennett (2008) suggested that the NWI be modified to include an obligation to implement and report on the NWQMS. Like the NWC (2011), Bennett (2008) also indicated that there was a need to maintain linkages between management of water quantity and quality. These linkages are best captured at the catchment scale and should reflect the environmental values that guide the activities of water resource managers. These environmental values should be waterway specific, reflect consistent value-setting processes that are transparent to stakeholders and incorporate all the activities water resource managers are responsible for (water quality management, water quantity management and resource management). Bennett (2008) proposed that this common value-setting approach would lead to integrated management of water resources.

The NWQMS was developed jointly by governments, resulting in a nationwide approach to water quality improvement which can be enhanced through incorporation of best available science and alignment with other water reform processes. The NWQMS is currently undergoing a review of its strategic directions to improve its efficiency and effectiveness.

See the Department of the Environment and Energy website for more information on the National Water Quality Management Strategy.

2.2.2 National Water Initiative

The NWI is an intergovernmental agreement signed at the 25 June 2004 COAG meeting. The Tasmanian and Western Australian governments signed in June 2005 and April 2006, respectively. The purpose of the NWI is to optimise social, economic and environmental outcomes through the management of Australia's water resources. The NWI aims to achieve a nationally compatible market and regulatory and planning based systems for managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes.

Elements of water management under the NWI are:

- water access entitlements and planning framework
- water markets and trading
- best-practice water pricing
- integrated management of water for the environment and other public benefit outcomes
- water resource accounting
- urban water reform
- knowledge and capacity building
- community partnerships and adjustment.

The relationship between water quantity and quality is captured under the 'integrated management of water for the environment and other public benefit outcomes' category. The intent of this commitment is to identify environmental outcomes and develop and implement management practices and institutional arrangements that deliver these outcomes.

The NWI is complemented by a number of other natural resource management initiatives such as the Australian Government's Water for the Future initiative and programmes funded through the National Water Commission.

In 2011, the National Water Commission carried out its third biennial assessment of the NWI, which was aimed at reviewing the extent to which the initiative has improved the sustainable management of Australia's water resources and contributed to the national interest. Recommendation 6 of this review emphasises the importance of the relationship between water quality and quantity and the need to further understand and embed this relationship in water management (NWC 2011, p. 13), as follows:

> Recommendation 6: Water quality objectives should be more fully integrated into the reform agenda, with better connections between water quality and quantity in planning, management and regulation to achieve improved environmental outcomes. There is also a need for a more coordinated and structured approach to urban water quality regulation at a national level.

Addressing Recommendation 6 is a critical task for the future of water resource management. The NWI was developed to primarily target water quantity issues in the midst of a drought and includes a limited number of actions that specifically aim to maintain or improve the quality of Australia's water resources (NWC 2011). In general, there is a lack of integrated management of water quality and water quantity issues. In summary the NWC (2011, p. 12) states that:

> Contemporary water management requires a recognition of the interactions between quality and quantity and the potential economic uses of water of differing quality.

Actions to integrate water quality and quantity into water management require consideration of the quantity and quality of inflows, particularly in relation to point and diffuse sources of pollution. If the timing, magnitude, and duration of inflows are managed to optimise environmental outcomes, but the quality of the environmental water is poor, then the intended outcomes may not be realised and other impacts may occur. It is therefore important for water managers to understand the quantity and timing of water needed by environmental assets, the source of environmental water and the quality of that water in conjunction with watering requirements.

Refer to the Department of Agriculture and Water Resources website for more information on the NWI.

2.3 Role of modelling in managing water quality and water quantity

Water quality and quantity is influenced by a complex array of both natural and anthropogenic factors at the catchment scale through to the micro scale. Contemporary thinking is moving to using multiple lines of evidence in order to understand and manage these aspects of aquatic systems. Coupling of routine monitoring data with modelling approaches is emerging as a useful mechanism to understand, simulate and also communicate water quality and water quantity relationships and the factors that influence them.

Flow, water quality and biological and other catchment data and information has been collected for many years in most aquatic systems throughout Australia. These data sets provide valuable information for developing a detailed understanding of how various ecosystems function. Hence, these data sets are increasingly being used to develop and calibrate models that are guiding decision making by water resource managers.

Two general types of models are used:

- A fundamental model is a conceptual model. A conceptual model summarises the current understanding of the key catchment processes, dependencies and impacts on the water resource and is typically presented graphically, in cross-section or block diagram format, with supporting descriptions. Use of a conceptual model guides field data gathering programmes and helps ensure that any subsequent numerical models are 'fit for purpose' in the level of detail it captures.

- A numerical, or mathematical, model solves equations describing physical processes using a stepwise approximation. Solutions are obtained by performing successively improved approximations at each step until the numerical answer satisfies all the equations being used. Such numerical models can be used to understand system processes and assess the likely effects of proposed management actions.

The predictive power of models increases with data availability, ongoing research into understanding catchment and in-stream processes and through incorporating algorithms into models to reflect that increased understanding and additional data (SKM 2011).

For a scientific purpose, models can be useful for:

- improving the understanding of aquatic systems through integrating catchment, hydrological, water quality and ecological factors
- helping predict the impact of various water management options or changes to catchment condition and assisting in the optimisation of management solutions
- helping synthesise data and encapsulate current understanding of aquatic systems. Models are often used to interpolate the available (but limited) data both in space and time as a cheaper and quicker option than intense data collection.

From a management perspective, models offer:

- a means of education and communication. For example, where there are multiple stakeholders in the development of a management plan, a model can be used to illustrate the relative involvement of each of the stakeholders in the issues and the possible solutions. A prerequisite is that the stakeholders must have been involved in the calibration of the model and must have developed trust in its reliability
- a means of setting reference conditions in modified systems
- a means of setting targets and objectives for water quality and targets for on-the-ground actions
- a means of checking compliance with management plans based on water quality variables. Examples are the use of the Murray-Darling Basin Authority (MDBA) model MSM–BigMod in quantifying the Salinity ‘Credits’ and ‘Debits’ arising from the actions of three states and the Commonwealth, and the Pilot (nutrient) Pollution Trading Scheme in the lower Hawkesbury–Nepean in New South Wales
- guidance in the day-to-day management of systems.

Appendix 1 provides an overview of the structure of numerical water quality models, a discussion of the different types of models available and some examples of models applied within Australia.

3 How water quantity affects water quality

Water quantity is a fundamental driver of water quality. The nature of the relationship between water quantity and quality is complex and depends strongly on the characteristics of individual catchments.

Water quality can be directly attributable to the following three characteristics of catchment and local hydrology, which cause daily and seasonal fluctuations in water quality:

- source of water (snow melt, rainfall/surface run-off, groundwater, tidal waters, irrigation transfers, flow releases from dams or point and diffuse sources)
- hydrological variability, referred to as the flow/watering regime (magnitude, timing, frequency and duration of flows)
- in-stream processes (transport/retention, evapo-concentration/dilution, mixing/stratification, reaeration, and nutrient and carbon cycling).

These three characteristics are discussed below.

3.1 Source of water

Water quality varies amongst different catchments and different types of aquatic ecosystems. Much of this variation can be explained by the sources of water. Natural sources of water include snow melt, rainfall/surface run-off, groundwater and tidal waters. Human-derived modifications to catchments have altered the quantity, quality and balance of these natural sources and introduced new water movement pathways—for example, irrigation transfers, flow releases from dams and point and diffuse sources. The quality of source water shapes the evolution and ecology of aquatic ecosystems.

In natural, unmodified catchments, inputs to the water cycle include snow melt and/or rainfall with associated surface run-off to rivers and wetlands and groundwater recharge. Groundwater discharge can support base flows in rivers, lakes and wetlands. The hydrology of lakes and wetlands depends on their level of connection with water sources. Some lakes and wetlands are connected to rivers, while others can be isolated and located within low points in the landscape that receive rainfall run-off from the catchment. Estuarine and near-shore marine environments have a unique blend of fresh catchment inflows and marine tidal waters. Each of these sources is characterised by differences in water quality (for example, temperature, salinity, alkalinity, nutrients and organic carbon and metal concentrations), which can be also be a function of altitude, topography, soil type and vegetation cover.

Human-derived catchment modifications and land use have not only altered the natural water cycle but also changed the water quality of natural sources (Baker 2003, Quinn et al. 1997). For example, water tables in the Murray–Darling Basin have risen as a consequence of extensive irrigation. This has led to increasing salinity in some streams from saline groundwater discharge during low flows. Another example is the construction of large dams on waterways, which has led to changed flow regimes and water quality downstream (for example, cold-water pollution) (Bunn & Arthington

2002a, Poff et al. 1997). It is clear from the literature that water quality is directly attributable to the following characteristics of the catchment:

- percentage of native vegetation and riparian zone cleared and/or replaced with other species (Bunn et al. 1999, Rutherford et al. 2004)
- extent and intensity of agriculture and nature of agricultural practices in a catchment, including animal stocking rates and rates of application of fertilisers and other agricultural chemicals (Byers et al. 2005, Sauer et al. 1999, Young & Huryn 1999)
- density of human population, urbanisation and effluent disposal practices (Brabec et al. 2002, Walsh et al. 2005)
- catchment geology, mining and erosion (Jenkins 1998).

Dissolved and particulate substances, such as eroded soils, nutrients, salts, toxins, pathogens and other contaminants, are transported from the surrounding catchment into aquatic ecosystems after rainfall. They can enter waterways and wetlands by point or non-point (diffuse) pathways. Point sources are typically continuous and from a specific location (usually a pipe or drain). They include stormwater and sewage treatment plant or industrial discharges. Sewage treatment plant wastewater discharges are common sources of nutrients in waterways. The load of point source inputs to waterways is typically proportional to the level of urbanisation in the catchment (Walsh 2000).

Non-point sources are not as easily identifiable. These sources of contaminants include run-off from farms, roads or lawns and erosion within a catchment. Leakage from septic tanks or sewer exfiltration from underground pipe networks can also be classified as diffuse sources. Nutrients and suspended solids are common in non-point source run-off from farms and agricultural land, from use of fertilisers, stock access to waterways and effluent management.

The geology and soils of a catchment can influence water quality—for instance, easily eroded clay soils can lead to increased turbidity (Jenkins 1998). Soil erosion can also be related directly to land use and, in particular, the amount of land-clearing (Prosser et al. 2003, Wallbrink 2004). The major forms of soil erosion are gully, rill and stream bank erosion. All forms are caused by poor ground cover, drought, intense rainfall and/or unstable soils. Erosion is a major source of sediment, nutrients, and pesticides in surface water from catchments dominated by agricultural land (Prosser et al. 2003). Influence from non-point sources increases markedly during periods of heavy rainfall and increased run-off and is sometimes referred to as the 90:10 rule whereby 90 per cent of contaminants are delivered to aquatic systems 10 per cent of the time.

Mining operations (like coal mining or coal-seam gas operations) may also affect water quality through dewatering discharges to waterways/storages, generation of sediment-laden run-off, chemical handling and storage, water and sewage operations, creek redirections and subsidence. Contaminants of concern in mine-affected water include salts, heavy metals, anions, cations, process chemicals, acid mine drainage and suspended solids (Hart 2008). One of the major impacts to water quality can result from the cumulative effects of concurrent waste discharges (including dewatering) from large numbers of mines in the catchment and also from the discharge of floodwater from mines after heavy rainfall (DERM 2009).

3.2 Hydrological variability

Water quality responds rapidly to short-term changes in flow (Poff et al. 1997). Much of this variability in water quality results from changes and relative contributions in the sources of water (storm flows containing catchment run-off versus base flows). Groundwater is an important contributor to flows in many rivers and wetland systems. It is a relatively constant and stable source of water compared with surface flows and can maintain water levels in ecosystems during extended dry periods. Groundwater quality varies and can often contain higher salinity levels, dissolved nutrients and metals than surface water run-off. Therefore, water quality in river systems and wetlands can vary depending on the relative proportion of groundwater contributions to surface inflows.

Wetlands and lakes are inundated with water either permanently or seasonally. Unmodified wetlands and lakes typically fill during the wet season and slowly dry during the dry season. These wetting and drying cycles can be important ecologically as well as for water quality purposes. The wet season filling refreshes water quality, diluting salinity levels and entraining organic matter for food webs. The drying cycles are important for releasing carbon and nutrients that promote subsequent growth by algae, bacteria, plants and animals (Corrick & Norman 1980).

In natural river systems, water quality is supported by a variable flow regime whereby each flow component (high flows, low flows and cease-to-flows) fulfils particular functions to restore or maintain water quality and a range of ecological and geomorphological functions (Bunn & Arthington 2002a, Poff et al. 1997). For instance, low flows provide warm, clear conditions suitable for nutrient cycling and primary production. Higher flows provide dilution of ions and toxins and entrainment of a fresh supply of nutrients and carbon to support ecological services. Cease-to-flow periods in temporary streams can dry out the sediments, releasing carbon and nutrients that enable new life to flourish when flows return.

Extremes in flow variability, which occur during severe droughts and major floods, often cause extremes in water quality. Although such extreme events have a low frequency of occurrence, when they do occur they often have major consequences for water quality in aquatic systems. Water quality impacts from such extreme events can compromise the availability and suitability of water resources for its environmental values and beneficial uses.

Droughts can cause rivers to experience prolonged low flows or cease-to-flow periods. Wetlands, lakes and reservoirs experience very low water levels or dry out completely. Consequently, these water bodies may experience extremes in water temperature, low dissolved oxygen levels, thermal or saline stratification of the water column, evapo-concentration of ions and toxins and algal growth supported by calm, warm water conditions (Bates et al. 2008). Floods can cause widespread catchment erosion resulting in unprecedented nutrient, suspended solids and toxicant loads to fragile near-shore environments (Prosser et al. 2001). They can also cause sewage treatment plants and sewers to overflow, delivering pathogens (including water-borne illnesses), nutrients and toxicants to waterways (Howe et al. 2005).

Flow variability is closely related to the physical, chemical and biological components of water quality. These are discussed in the next section (Section 3.3).

3.3 In-stream processes

Physical, chemical and biological processes that occur within a water body are important drivers of water quality. These processes are described in Table 2. Each of these processes is influenced by flow and can dictate the contaminant loads and in-stream concentrations. They can either improve or degrade water quality. For example, sedimentation is an in-situ process that occurs when the velocity of the flowing water slows to allow suspended particles to settle out. This process increases water clarity, which is important to provide light for photosynthesis by aquatic plants.

Table 2 In-situ physical, chemical and biological processes that affect water quality

Physical processes	**Description**
Reaeration	Reaeration is the transfer of oxygen from the atmosphere to a body of water at the air/water interface. It can be influenced by riffles or wind-induced waves. It affects the dissolved oxygen levels.
Sedimentation	Sedimentation is the settling of suspended particles. Rates of sedimentation are determined by the size of the particles, the velocity of the water and the ionic environment. Sedimentation affects the water clarity.
Adsorption	Adsorption is the reversible binding of molecules to a particle surface. This process can bind dissolved phosphorus and pathogens to particles.
Evapo-concentration	Evapo-concentration is the process by which water is evaporated and the substances present, particularly salts, concentrate.
Dilution	Dilution is the process of making a substance less concentrated by adding water. This can lower the concentrations of ions, toxins and other substances.
Stratification	Stratification is the formation of density layers (either temperature or salinity derived) in a water body through lack of mixing. It can create favourable conditions for algal blooms and can lower dissolved oxygen levels in the bottom layers with the associated release of nutrients, metals and other substances.
Heating/cooling	Water temperature is determined primarily by air temperature and is also impacted by stratification and flow/water level. Temperature affects the rates of chemical and biological reactions. It also affects the solubility of dissolved oxygen.
Chemical processes	
Precipitation of minerals	Precipitation is when a dissolved substance forms a solid that settles out of the water.
Flocculation	Flocculation is the aggregation of colloidal (very fine) particles into larger particles that then settle. This occurs in high-salinity environments (for example, in estuaries).
Chemical transformations	Chemical transformations of substances can occur through acid–base reactions or redox reactions. For example, changes to ammonia and metal toxicity and/or availability occur under varying temperatures, pH and oxygen levels.
Biological processes	
Carbon cycling / decomposition of organic matter	Carbon cycling involves the oxidation of complex organic matter into simpler forms (like CO_2, phosphate or ammonia). It is one of the key steps in the decomposition

Physical processes	Description
	of organic matter. This provides bacteria, protozoa and fungi (at the base of the food web) with the energy for cellular metabolism and growth. This process consumes oxygen.
Primary production	Primary production is creation of new organic matter by photosynthesis. Oxygen is produced during this process. Primary productions occur in aquatic systems and include algae and macrophyte growth.
Nutrient cycling	The nutrient cycle describes how nutrients move from the physical environment into living organisms and then subsequently are recycled back to the physical environment. This movement of nutrients, sometimes referred to as nutrient spiralling, is essential for life and is a vital function of the ecology of aquatic ecosystems. There are four biological processes that participate in the cycling of nitrogen. They are: • nitrogen fixation: N2 → NH4+ • decay: Organic N → NH4+ • nitrification: NH4+ → NO2− → NO3− • denitrification: NO3− → N2+ N2O.
Bioaccumulation	General term describing a process by which chemical substances are accumulated by aquatic organisms from water, either directly or through consumption of food containing the chemicals.

Many of these in-stream processes have been affected by anthropogenic land uses such as agriculture and urbanisation (Baker 2003, Quinn et al. 1997). This has affected the water quality in many systems. Eutrophication is a symptom that an ecosystem has exceeded its assimilative capacity of nutrients from excessive anthropogenic inputs (Heisler et al. 2008). Not all of the available nutrients are able to be processed through nutrient cycling and therefore the water body becomes nutrient enriched. The most acute symptoms of eutrophication are algal blooms. Eutrophication results not only from point sources, such as wastewater discharges with high nutrient loads (principally nitrogen and phosphorus), but also from diffuse sources such as run-off from livestock feedlots or agricultural land fertilised with organic and inorganic fertilisers. While diffuse sources dominate water quality during high flows, point sources generally dominate water quality during periods of low flow due to dry weather contaminant discharges (EPA Victoria 1995).

4 Managing ecosystems for water quality

This section describes water quality issues, provides case studies and presents conceptual models to assist water managers in understanding the general water quality and water quantity relationship in rivers, reservoirs, estuaries, wetlands and near-shore marine environments. The water quality issues for particular ecosystem types were chosen as representative of common challenges facing managers across Australia.

4.1 Understanding for management

The relationships between water quantity and water quality vary for different types of aquatic ecosystems (rivers, estuaries, lakes, groundwater systems, wetlands and near-shore environments) and vary across Australia due to natural factors such as climate, topography and catchment geology. River regulation, catchment land use and water extraction alters the natural flow/watering regimes and associated water quality characteristics. Valuable environmental water allocations are available in some systems—for example, Commonwealth environmental water holdings, where managers have an opportunity, and a significant responsibility, to create environmental benefits by delivering water to these ecosystems at the most appropriate times and in the most appropriate ways.

A good understanding of how water quality interacts with flow/volumes is very useful when making decisions regarding water management. Some water quality indicators respond almost immediately to environmental change, particularly in response to changes in flow or water volume. Also, a decline in water quality is often the first sign that ecosystems are under stress—for example, hypoxic blackwater events in regulated systems, algal blooms in stagnating pools or acid generation when acid sulfate soils are exposed then rewetted. In these situations, understanding the water quantity and quality relationships is essential to guide management responses in a timely manner.

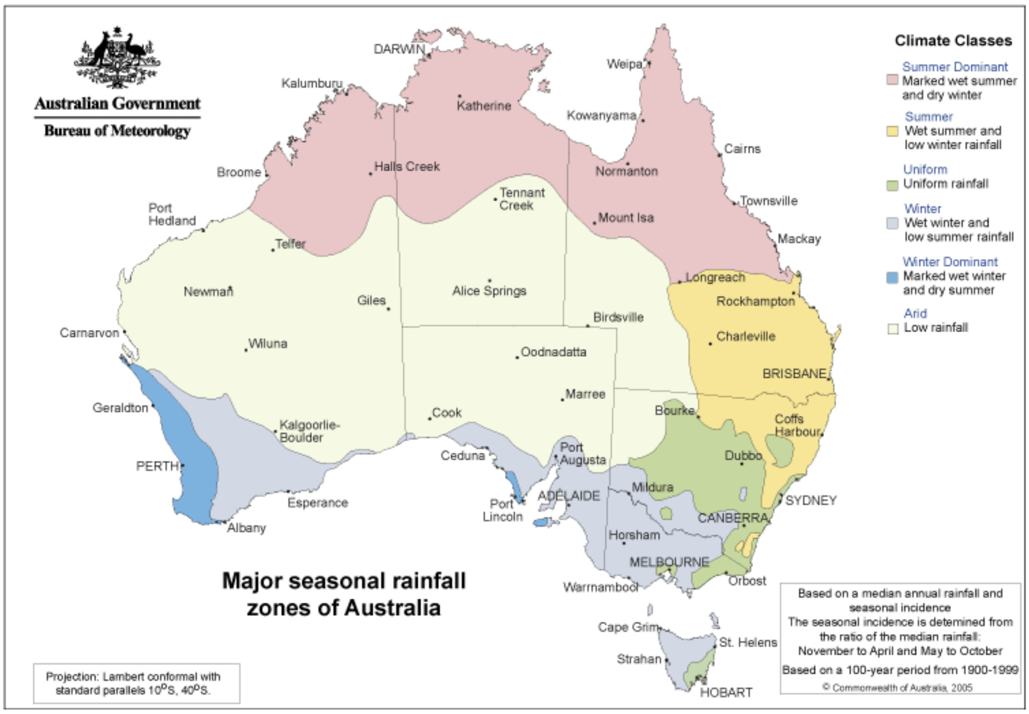
Water management becomes particularly important during extreme weather events such as drought and floods, which can adversely affect water quality. Water quality generally declines during drought conditions, where prolonged low flow levels or cease-to-flow events provide favourable conditions for algal blooms, increased water temperatures, evapo-concentration of toxins and low dissolved oxygen levels. During droughts, contaminants from point sources, such as sewage treatment plants, industrial releases, irrigation returns and dairy effluent, can increase in proportion to the river flow and degrade water quality. In contrast, large floods can initiate erosion and diffuse run-off in the catchment as well as sewage overflows and mobilisation of contaminants from mining sites. This can result in the release of suspended solids, nutrients and other contaminants into waterways, estuaries and near-shore marine environments.

Water management objectives should be established to maintain natural processes through delivering a range of flow/watering components sufficient to preserve water quality. This begins with a thorough understanding of how water quality is influenced by water quantity in a range of systems.

4.2 Natural rivers

This section describes how natural hydrological regimes affect water quality in different river systems across Australia. Australia has six major seasonal rainfall zones (Figure 1) and this variability is reflected in the flow regimes of rivers across Australia. South-eastern and south-western corners of Australia experience wet winters and drier summers, which results in high river flows in winter and low flows in summer. The tropical northern and subtropical eastern areas of Australia experience the opposite, with wet summers and drier winters. Semi-arid or arid landscapes are particularly well represented in Australia, with 75 per cent of the continent’s land area being classified as having low rainfall (Davies et al. 1994). ‘Dryland rivers’ in this area are typically temporary, which means that they do not have surface water flow all year around. In this section, we describe a temperate (wet winter / dry summer) system, a tropical summer-dominated river system and a dryland river system.

Figure 1 Australian climate zones



Source: Bureau of Meteorology

4.2.1 Temperate rivers

Southern Australia (including Tasmania) is classified as having a temperate climate according to the Köppen climate classification. The climate is generally mild, ranging from warm to cool, with four seasons (spring, summer, autumn and winter) evident in the weather patterns in these areas.

In Australia, the temperate region has the most fertile soils and supports high levels of agriculture. It also supports the vast majority of Australia’s population in the major centres, Sydney, Brisbane, Melbourne, Canberra, Adelaide, Hobart and Perth. As a result, temperate rivers have experienced high levels of regulation and urbanisation, which has disturbed the relationships between water quality and flow and led to water quality issues that are discussed in Section 4.3.

This scenario describes the relationship between flow and water quality for unmodified, unregulated temperate rivers to set the baseline for how such rivers would naturally function. Temperate regions can have varying rainfall patterns (for example, they can be winter or summer dominated); however, this scenario focuses on the regions where the majority of rainfall occurs in the cooler winter months, followed by a drier summer (see Figure 1). The flow regime of these rivers follows the seasons, with high flows in winter–spring and low flows during summer–autumn—for example, the Ovens River in Victoria (see Case study 1).

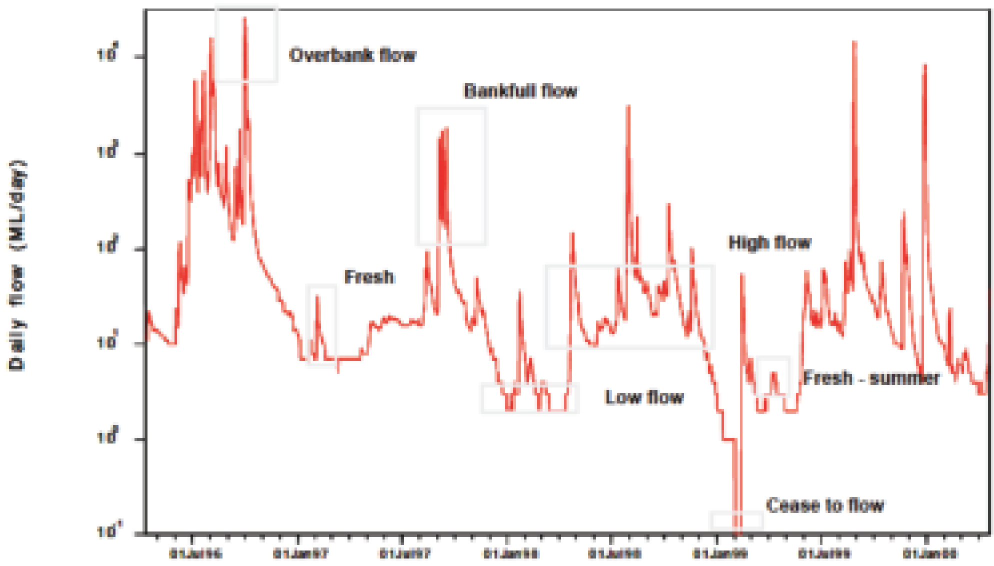
Water quality, as well as important ecological and geomorphological functions of a river, depends on the magnitude, duration, frequency and seasonality of flows. Unmodified, unregulated temperate rivers (with wet winters / dry summers) typically have some or all of the following flow components (Figure 2):

- summer cease-to-flow—no discernible flow in the river or recorded at a gauge. Not all temperate rivers experience cease-to-flow events
- summer low flow / base flow—a small flow that generally provides a continuous flow through the channel, often derived from groundwater
- summer freshes—small and short-duration peak flow events that exceed the base flow (low flow) and last for at least several days, often in response to localised storms
- winter high flow—persistent increases in the seasonal base flow that remain within the channel
- winter bankfull flow—completely fills the channel, with little flow spilling onto the floodplain
- winter overbank flows—these flows are greater than bankfull flow and result in surface flow on the floodplain habitats.

Water quality is intrinsically linked to each of the flow components.

Low flows occur over the warmer summer/autumn months. Groundwater inputs often support these flows but can be saline (see Section 4.3.3). The ecosystem is most productive under these flow conditions, with higher rates of nutrient and carbon cycling. Low turbidity levels and slower flow rates allow photosynthesis by aquatic plants and attached algae within the river channel, which produces bioavailable organic carbon to support food webs. The conceptual model in Figure 3a demonstrates these relationships. Water quality issues such as excessive plant growth are limited by the low nutrient concentrations and shading from an intact riparian zone. This functioning relationship between flow and water quality is described in the Riverine Productivity Model by Thorp & Delong (1994).

Figure 2 A theoretical flow regime showing flow components for a wet winter / dry summer temperate river



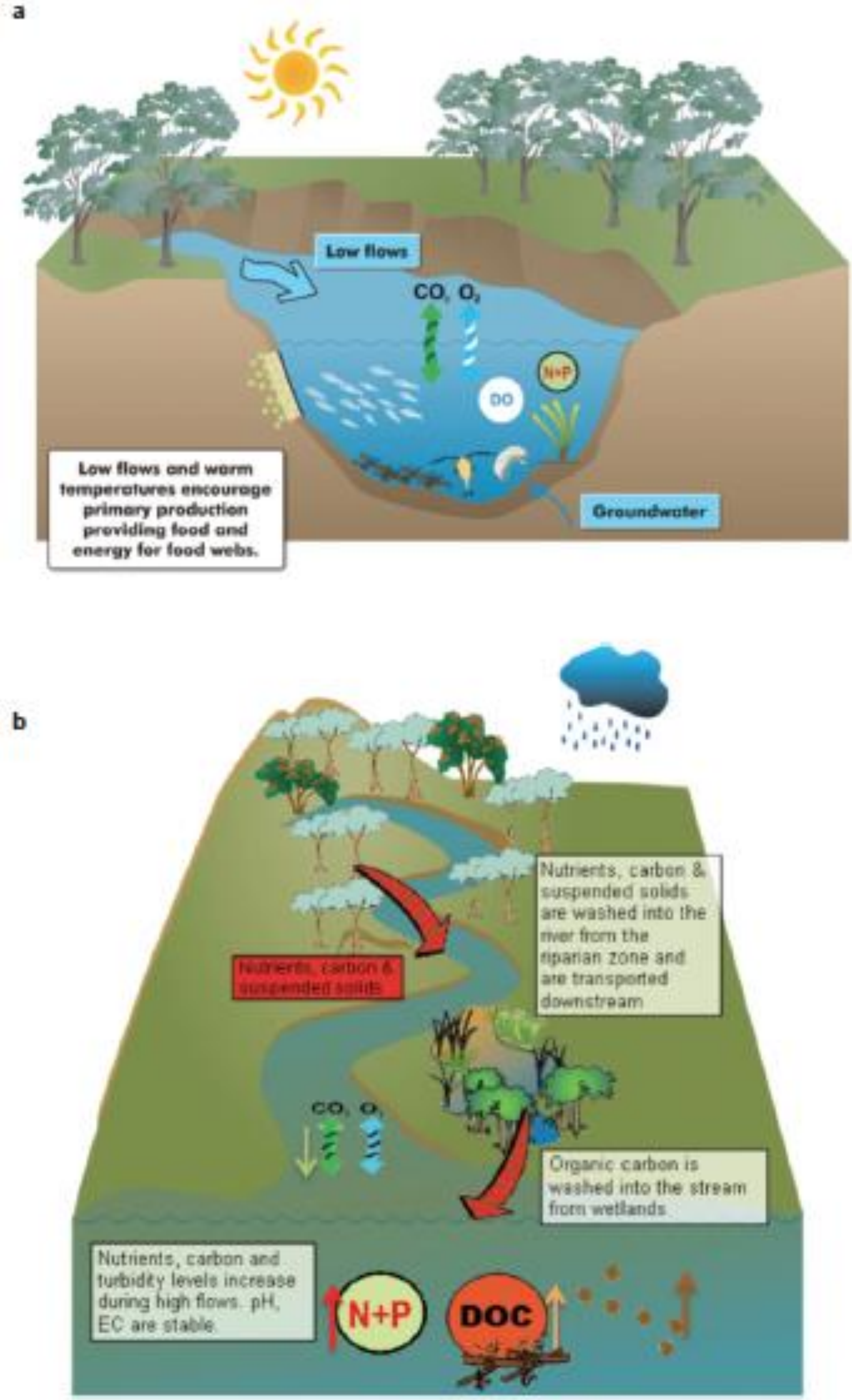
Freshening flows in summer and winter play an important role in maintaining water quality by adding flow variability and disturbance to long periods of stable flow. These flows mix the water column, refresh habitat, control salinity levels, transport nutrients and carbon downstream and reduce the risk of excessive plant growth.

High flows, winter bankfull and overbank flows are important to connect rivers with wetlands and the floodplain (see the conceptual model in Figure 3b). The Flood Pulse Concept, proposed by Junk et al. (1989), recognises that these events entrain organic matter and nutrients from the floodplain into the channel to build and sustain food webs. The organic matter sources are typically plant material from riparian zones that are buried or stored in the channel and slowly break down. These high-flow events occur regularly during winter/spring, when the low water temperatures and sustained high flows manage water quality issues such as hypoxic blackwater events (see Section 4.4.1) and increased plant growth that result from increased organic carbon and nutrients.

Australian temperate rivers have experienced high levels of regulation (for example, the Murray–Darling Basin), which has disturbed natural relationships between water quality and flow and led to water quality decline. Environmental flows studies have been commissioned by river managers on many temperate rivers in Australia to determine the flows required to restore more natural flow patterns. These studies set minimum flow recommendations to improve the ecological health of rivers. They specify the magnitude, timing, duration, frequency and rate of change for various flow components based on the natural flow regime and the ecological (fish, macroinvertebrates, vegetation) and geomorphological requirements (for example, the Victorian FLOWS method (NRE 2002)).

Although water quality is considered in most studies, it is not a major focus when setting specific flow recommendations. The preference has been to recommend complementary works to improve water quality by focusing on reducing catchment contaminant loads at the source through on-ground catchment management actions (like fencing, farm management plans, reducing industrial and sewage treatment plant discharges). Restoring a more natural flow regime is likely to have positive water quality outcomes through improving ecological structure and function. However, through developing a good understanding of the catchment-specific relationships between water quality and flow (for example, through modelling or monitoring), it may be possible to include more water quality focused environmental flow recommendations in future studies. For example, in a recent environmental flows study for the Lang Lang River, Victoria, modelling of the water quality and flow relationships showed there was a high probability of low dissolved oxygen when flows were below 5 megalitres per day. A minimum low flow recommendation of 5 megalitres per day was therefore recommended (SKM 2012).

Figure 3 Conceptual models for a. low flow and b. high flow in temperate rivers (wet winter / dry summer)



Case study 1 The unregulated Ovens River, Victoria

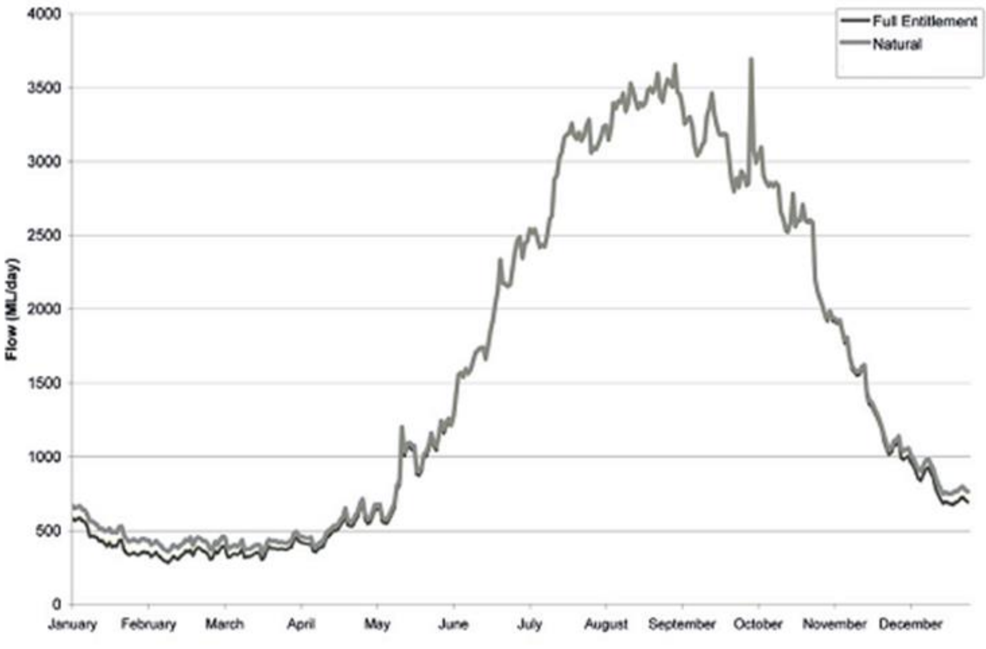
The Ovens River rises in the Great Dividing Range between Mt Feathertop and Mt Speculation. It flows approximately 150 kilometres to join the Murray River in the backwaters of Lake Mulwala. The Ovens River is one of the last largely unregulated rivers in the Murray–Darling Basin and is particularly important as a reference against which to assess the state of other lowland rivers in the region. Two small impoundments have been constructed for water storage: Lake Buffalo on the Buffalo River and Lake William Hovell on the King River. The lower section of the Ovens River, from Wangaratta to the Murray River, has been designated a Heritage River because of the uniqueness of its riverine and floodplain habitat and its importance as a habitat for endangered fish such as the Murray cod (SKM 2006).

The Ovens Basin is dominated by native vegetation on public land (48 per cent) and dryland cropping and grazing pasture (42 per cent). The remaining land is used for a mixture of pine plantations (4 per cent), irrigated horticulture and grazing (1 per cent) and urban development (<1 per cent) (SKM 2006). The following environmental values have been identified: largely unmodified aquatic ecosystems; recreation and aesthetics; drinking water; and cultural and spiritual values (SEPP 2003).

Flow in the Ovens catchment is modified by three processes: the presence and operation of Lake Buffalo (24,000 megalitres) and Lake William Hovell (13,700 megalitres); progressive extraction of water for irrigation and town water supply; and changes to the form of the channel due to channelisation, substrate and snag extraction and flood levees.

However, these changes have not significantly changed the flows in the river from natural conditions (Figure 4).

Figure 4 Average daily natural and current flows (1891–2005) for the Ovens River upstream of the Buckland River



Source: SKM 2006

The natural flow regime (including both high and low flows) maintains chemical, geomorphological, biological and ecological processes. The river maintains a diversity of habitats (abundant large woody debris, cobbles, riffles, pools, bars, anabranches, and floodplain and wetland/billabong features) that support threatened species, including up to 10 native fish species of state and national conservation significance and icon species such as Murray cod. Riparian vegetation is intact for large sections of the river.

Water quality is rated good to excellent, as it complies with the State Environment Protection Policy (Waters of Victoria) objectives, although there is some nutrient enrichment from agricultural and urban areas (SKM 2006). The good water quality supports viable and diverse ecosystems. No water quality impacts were detected due to changes to the flow regime associated with current levels of regulation and diversion of water (SKM 2006). The river maintains good connectivity between the river channel and its floodplain. The Ovens River is valued for its links with the Murray River, being important for water yield, water quality and fish migration.

4.2.2 Tropical rivers

According to the Köppen climate classification, the northern parts of Australia have a tropical climate, consisting of a tropical monsoonal climate in North Queensland and a tropical wet/dry climate in the Northern Territory.

Tropical rivers have a predictable annual hydrological cycle of distinct wet and dry seasons that underpins the seasonal inundation of floodplains during the summer months and the contraction of the rivers to their channel during the winter dry season (Douglas et al. 2005). Flood events occur in most of the rivers in most years and have a higher degree of hydrologic predictability than many other rivers in Australia (Hunt et al. 2012, Kennard et al. 2009). Tropical monsoonal rivers have a more evenly distributed rainfall pattern than tropical wet/dry rivers. During the dry season, stream flow will often cease in the wet/dry tropics although, in some rivers, flows in the main river channels are sustained perennially by base flows sourced from groundwater (for example, the Daly River, Northern Territory; and the Nicholson River, Queensland) and from additional inputs from a more evenly distributed rainfall pattern in the monsoonal climate of headwater catchments (for example, the Mitchell River, Queensland—see Case study 2).

The very distinct variation in discharge and the interaction of flow with the landscape in tropical rivers result in strong seasonal variation in water quality. Physical, chemical and biological changes occur during the different stages of the hydrograph. During the dry season, perennial rivers are characterised by base flows and stable hydraulic habitat with low velocities and low suspended particulate matter. Consequently, water clarity is often high (see the conceptual model in Figure 5a).

Such physical conditions, together with the high light availability in tropical regions, are very favourable for in-stream primary production, particularly attached macro-algae (Hunt et al. 2012, Townsend & Padovan 2005). The generally low nutrient availability in these rivers, which are typically in areas of low development, limits the accumulation of primary producer biomass (Webster et al. 2005). The supply of oxygen by photosynthesis is important in maintaining dissolved oxygen at concentrations to sustain fish and invertebrate communities, particularly when accumulation and decomposition of organic matter during low flows may result in high rates of oxygen consumption by bacterial respiration (Hunt et al. 2012, Pollard & Ducklow 2011).

Evaporation rates in northern Australia are high, and range between 2,000 millimetres in the monsoonal tropics to over 3,600 millimetres in the wet/dry tropics annually (Australian Bureau of Meteorology). Evaporation is greatest at high temperatures and low humidity and increases over the course of the dry season in northern Australia, with monthly evaporation rates increasing from 100 to 250 millimetres in June to 200 to 350 millimetres in November (Butler 2008). In addition, as discharge declines or ceases during the dry season, evaporation rates increase due to the longer water residence times. The effect of water loss by evaporation on water quality during the dry season can result in significant increases of dissolved and suspended fractions, including nutrients, particulate matter and salts. Electrical conductivity (EC) can be an effective indicator of increased water loss by evaporation because the concentrations of major ions are not affected by the biophysical processes that influence nutrients and other dissolved or suspended fractions, and consequently they increase in accordance with predicted evapo-concentration rates (Butler 2008). However, it may not be a good indicator in groundwater-fed systems if the groundwater is saline.

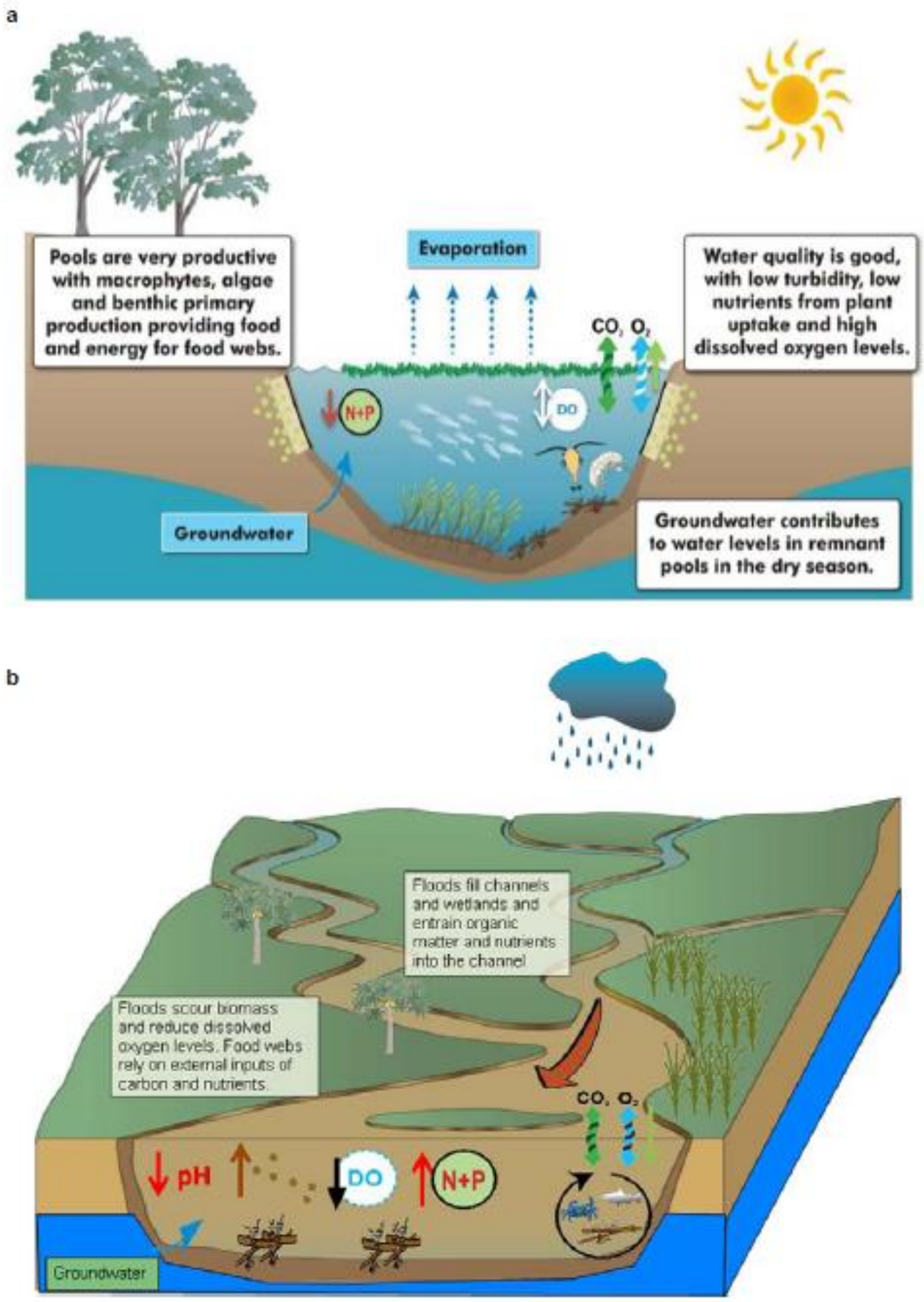
Storm events at the onset of the wet season typically result in low volumes of overland flow, with much of the rainfall soaking into dry catchment soils (Butler 2008). As soils become more saturated and storm activity increases, catchment run-off results in distinct river discharge events. The first-flush events result in very rapid changes in both water quality, due to the interaction of rainfall run-off with the terrestrial environment, and water quantity. Water quality of first-flush run-off is typically acidic (pH 5.8–6.0), dilute (< 50 µS/cm) and turbid, with very high concentrations of suspended particulate matter (organic and inorganic) and dissolved nutrients (Butler 2008, Furnas et al. 1997). Fish kills attributed to high aluminium levels have been observed in northern Australia during the transition from the dry to wet season, when first-flush water enters lagoons and other permanent water bodies (Brown et al. 1983). Hart et al. (1987) found that first-flush flows in the Magela Creek system in the Northern Territory had high EC (750 µS/cm), were acidic (pH 4–5), high sulfate concentrations (about 200 mg/L) and heavy metal concentrations (particularly aluminium) caused by groundwater brought to the surface by rising watertables over acid sulfate affected floodplain.

A substantial proportion of the mobilisation and downstream transportation of the nutrients and suspended sediments during the wet season occurs during the rising limb of the hydrograph of the first high-flow events and may last only short periods (several days), with concentrations fluctuating rapidly (see the conceptual model in Figure 5b) (Butler & Burrows 2006). The amount of particulate matter in suspension during the rising stages of early flow increases with stream order, and concentrations may exceed extremely high levels (10,000 mg L-1) for brief durations in large river catchments with erosion-prone soils (Butler 2008).

The rapid change in water quality and quantity during and after first-flush events has strong effects on biological processes. The increased depth and turbidity together with often overcast conditions reduce light availably in the water column and riverbed. The increase in velocity exerts drag disturbance on attached algae and macrophytes and reduces biomass (Townsend & Padovan 2005). As a consequence, primary production and the supply of oxygen are substantially reduced. Oxygen demand is increased by the import of organic matter into the river, which drives high rates of respiration from microbial decomposition. When the first high-flow events result in very low concentrations of dissolved oxygen, the hypoxic conditions can be hazardous for aquatic fauna and have been identified as causes of fish kills (Butler 2008, Townsend & Edwards 2002).

The longitudinal transport of dissolved and suspended fractions during floods is an important process both in the river itself and in the receiving coastal waters. Due to the magnitude of the wet season flows, the total mass of suspended and dissolved matter is very high and essential for the delivery of sediments, inorganic nutrients and organic matter to downstream environments and in driving estuarine processes (Devlin & Brodie 2005, Gillson 2011, Hamilton & Gehrke 2005).

Figure 5 Conceptual models for tropical a. dry season and b. flood flows



Case study 2 Mitchell River, Queensland

The Mitchell River is a large river in north-eastern Queensland. It flows from east to west into the Gulf of Carpentaria and has a catchment area of approximately 73,230 square kilometres (NRM&E 2004). Flows in the main channel are typically year-round, with only three cease-to-flow events recorded in the lower catchment since 1972 (Smith et al. 2006). The upper catchment includes perennial streams originating in the wet tropics. The major tributaries all flow intermittently. Mean annual discharge is approximately 12,357,000 megalitres and is 14 per cent of Queensland's total annual discharge (NRM&E 2004). Lake Mitchell—a large, private, unmanaged impoundment (129,000 megalitre capacity) located in the upper catchment of the Mitchell River—has substantial impacts on local hydrology, although it is upstream of confluences with perennial streams draining the wet tropics (Smith et al. 2006). Land use is dominated by irrigated agriculture in the upper catchment and grazing in the mid and lower catchment. The Mitchell River environmental values are largely unmodified aquatic ecosystems; primary industries; aquaculture; stock watering; drinking water; recreation and aesthetics; and strong cultural and spiritual values (Queensland Environment Groups 2006).

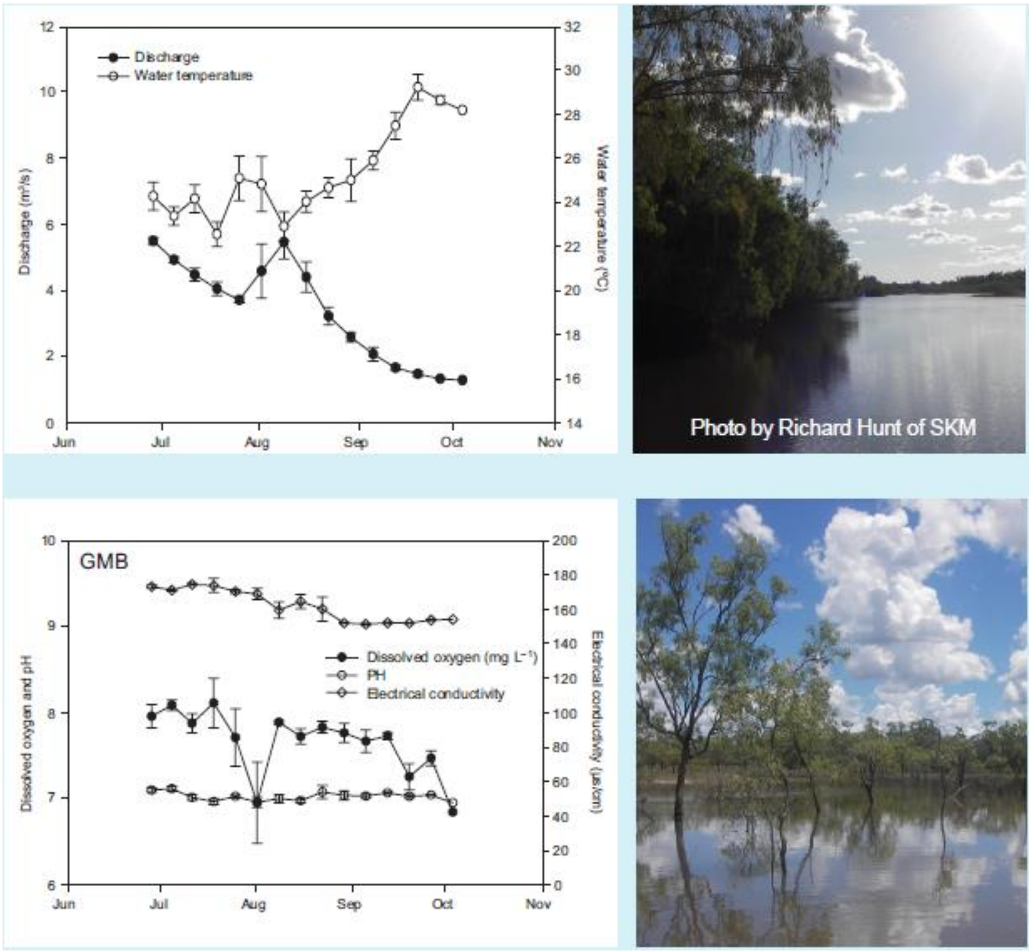
Low flows—during the dry season (May to November 2008) discharge decreased steadily, particularly lower in the catchment; water temperature increased; and daily dissolved oxygen concentrations fell (Figure 6). Turbidity was low, with minima of ~ 2 NTUs, but run-off from isolated dry season showers resulted in spikes of suspended matter with short periods of high turbidity exceeding 100 NTU. Total and dissolved nitrogen and phosphorus were low but high light availability, clear water and stable hydraulic conditions supported rates of gross primary production comparable with rivers with substantially higher nutrient levels. Despite the high water temperature and the high rates of respiration lower in the catchment, daily minima of dissolved oxygen concentrations remained above ~ 5.8 mg L-1 and were likely to be sustained from instream photosynthesis. Decreasing discharge did not correlate with electrical conductivity, suggesting the effect of evapo-concentration interacted with rainfall inputs from the upper catchment and alluvial ground water sources originating lower in catchment (Hunt et al. 2012).

Flood flows—the large catchment area of the Mitchell River results in very high discharges during the wet season. Figure 6 shows that in 2008 discharge peaked at the start of July then decreased throughout July, reached a similar peak in early-mid August and decreased to a low in mid-October at the limit of the data. Water temperature over the same period fluctuated between 22 and 24 degrees until an increase began in mid-August, peaking at 30 degrees in October. Dissolved oxygen over the same period showed a sharp decline in August then recovered to steady levels before another decline in October. The pH was consistent at 7 throughout the period. Electrical conductivity was steady between 160 and 180 microSiemens and was lowest from September to October. The catchment soils are also susceptible to high rates of erosion and can supply large quantities of suspended sediments (Brooks et al. 2008). The annual export of suspended and dissolved matter from the mouth of the Mitchell River is estimated to be 2.9 megatonnes of fine sediment and 6.5 kilotonnes and 1.5 kilotonnes of total nitrogen and total phosphorus respectively.

The flood plain inundation period of the Mitchell (~2 months) is shorter than other rivers such as the Daly River in the Northern Territory (~4 months) or large rivers of South America (~6 months).

Despite the relatively short period of inundation, the deposition of sediments in the floodplain is estimated at 3.4 megatonnes per year and exceeds the quantities exported from the river mouth. The productivity of the floodplain is likely to be high during the floods and the importance of resources derived from the floodplain to sustain higher consumers, including fish communities linked to commercially important fisheries, has been recently demonstrated (Hunt et al. 2012, Jardine et al. 2012a, Jardine et al. 2012b).

Figure 6 Water quality and discharge at Gamboola gauging station (GMB), mid catchment of the Mitchell River during the dry season 2008



Source: Hunt et al. 2012. Photos from R Hunt.

4.2.3 Dryland rivers

Dryland rivers flow through semi-arid or arid landscapes and are the most common type of river, in terms of river length, in Australia. Australian dryland rivers have flow regimes that are among the most variable and unpredictable in the world (Bunn et al. 2006). Most are temporary (unless their headwaters are in tropical regions or are supported by groundwater), which means they do not have constant surface water flow for the entire year. Rather, they experience large floods followed by extended cease-to-flow periods where water retracts to a series of isolated waterholes (Bunn et al. 2006, Puckridge et al. 2000). Much of the research on dryland rivers in Australia has been conducted on Cooper Creek and Diamantina River (Bunn et al. 2003, Bunn et al. 2006, Davies et al. 1994, Fellows et al. 2009, Sheldon & Fellows 2010).

Despite their variable flow regimes, dryland rivers provide a crucial source of water for dry landscapes. They support significant aquatic and terrestrial biodiversity, including many unique species. Large intermittent dryland rivers in the arid zone, such as Cooper Creek (see Case study 3) and Diamantina River, also fill permanent wetlands and waterholes that provide internationally significant habitats for waterbirds and aquatic flora and fauna (Robson 2008). Dryland rivers also support consumptive and recreational water users and are widely used for agricultural and town supplies in inland Australia (for example, within the Murray–Darling Basin) (Robson 2008). These rivers are often also important to Indigenous peoples, with sacred sites and other culturally important requirements (Robson 2008).

Dryland floodplain rivers in Australia are described as having a ‘boom and bust’ ecology, which is driven by flow. The boom phase occurs during large floods and floodplain inundations that encourage high levels of primary and secondary production. This is followed by the retraction of water to refuge pools, known as the bust phase (Bunn et al. 2006). The permanence of waterholes is determined by waterhole morphology and evaporative loss. Some waterholes can persist for two years or more without surface flow connection, while others dry out quickly (Bunn et al. 2006). Waterholes can be sustained by surface flows and potentially groundwater contributions.

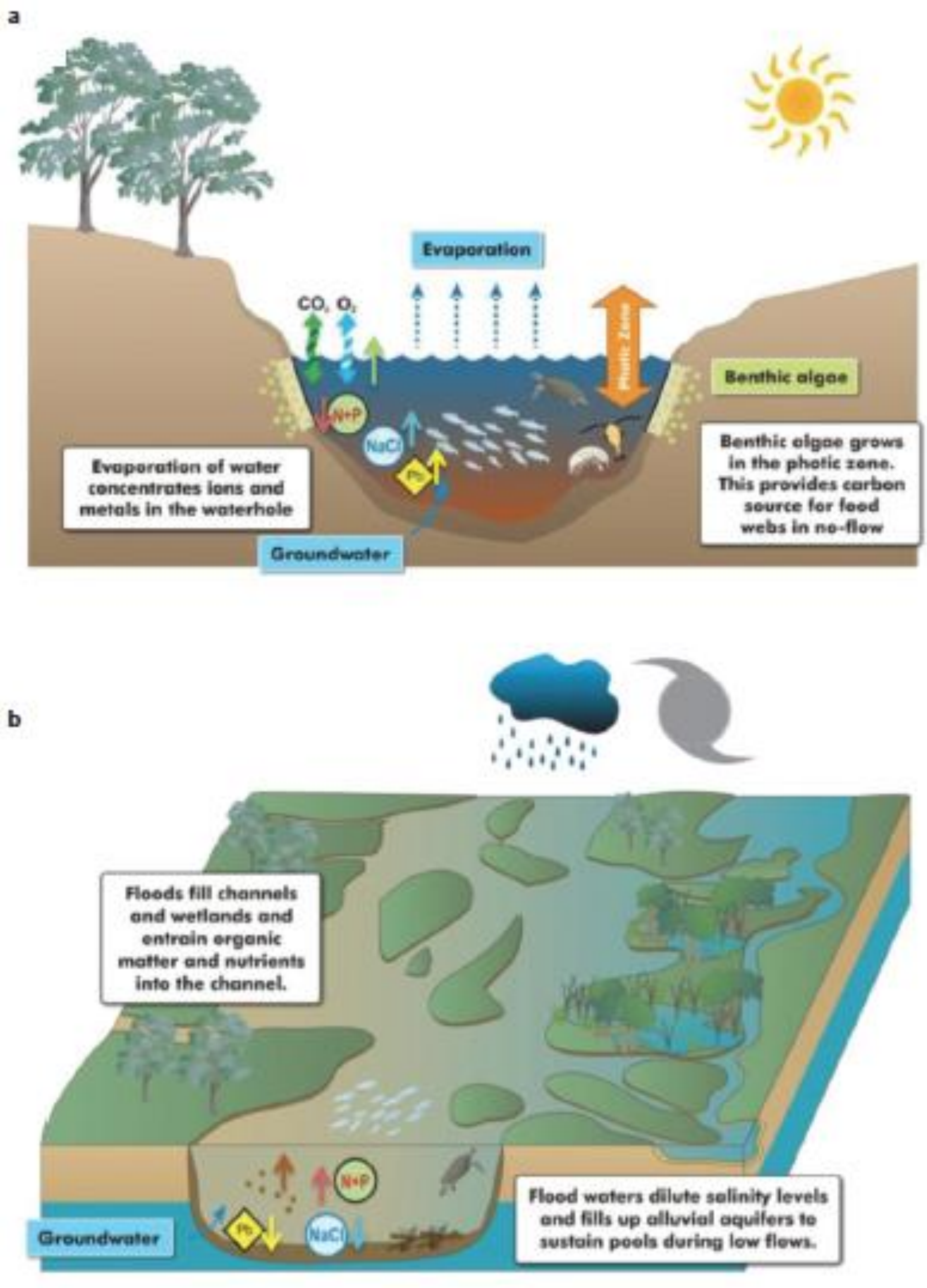
Along with hydrology, water quality is a major driver in the compositional changes of many faunal groups and functional processes (Sheldon & Fellows 2010). Water quality during the boom phase is driven by the large volumes of catchment run-off. A unique feature of some Australian dryland rivers is their permanent high mineral turbidity, which is characteristic of the local geologies and land use (Sheldon & Fellows 2010). This leads to fine clays in suspension even under no-flow conditions (Bunn et al. 2003). Flooding also entrains organic carbon and nutrients from the productive floodplain areas into the river channels to support food webs. Flood waters dilute salinity levels and fill up alluvial aquifers to sustain pools during low flows. There is an increase in nitrogen and phosphorus (see the conceptual model in Figure 7b).

Under the bust phase, when waters retract to waterholes, water quality is driven by processes such as evaporation, groundwater influence and the concentration or precipitation of compounds (see the conceptual model in Figure 7a) (Sheldon & Fellows 2010). Water quality conditions can be harsh at the local scale from low dissolved oxygen levels, high temperatures, increasing salinities, hardness, alkalinity and cations (Sheldon & Fellows 2010).

In-situ primary production by benthic algae was found to be the major source of energy-supporting waterhole food webs in Cooper Creek during no-flow conditions (Bunn et al. 2003). It provides significant food sources for invertebrates, fish and turtles in these waterholes (Fellows et al. 2009). Sustained high turbidity levels limit light availability in many of the dryland river systems. Benthic algae can only grow where the waterhole bottom is shallow enough to receive at least 1 per cent of the incoming light. Consequently, production is influenced by changes in water turbidity and interactions between water level changes and waterhole morphology. This has led to the ‘bath-tub hypothesis’, whereby evaporation of water concentrates ions and metals in the waterhole allowing highly productive bands of benthic filamentous algae to grow around the perimeter of the waterhole in the photic zone (Bunn et al. 2003). This provides a carbon source for food webs when flows cease (see the conceptual model in Figure 7a).

Water quality naturally changes temporally and spatially in dryland rivers. This makes developing and applying water quality guidelines and trigger levels very difficult for these rivers. One possible solution is to develop guidelines for both the no-flow and flowing phases (Sheldon & Fellows 2010).

Figure 7 Conceptual model of a. dryland isolated pool and b. flooding flow

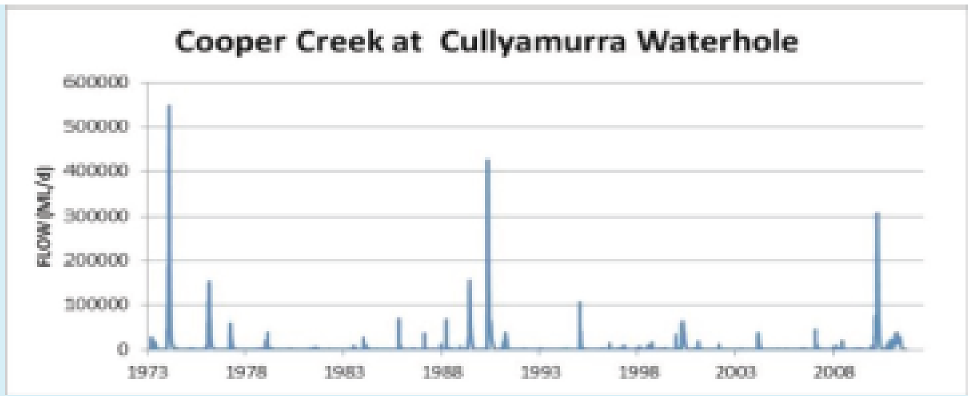


Case study 3 Cooper Creek, Queensland and South Australia

Cooper Creek is one of three major river systems that flow into the Lake Eyre Basin. At 1,300 kilometres in length, it is the second-longest inland river system in Australia after the Murray–Darling system. The headwaters of Cooper Creek are in the monsoonal region of eastern Queensland, where the majority of the flow originates. It then flows inland and south-west through semi-arid and arid landscapes into South Australia towards Lake Eyre. The environmental values include aquatic ecosystems; primary industries; recreation and aesthetics; industrial water; drinking water and cultural and spiritual values (NWC 2000). Inter-annual rainfall variability is very high, with the catchment on average receiving less than 400 millimetres of annual rainfall compared with an annual evaporation of approximately 3 metres (Bunn et al. 2006).

Cooper Creek has one of the most unpredictable flow regimes of any river in the world (Puckridge et al. 2000). There are long periods of no flow (Figure 8) and, during these periods, channel waterholes become important refugia for aquatic organisms and other wildlife dependent on permanent water (Davies et al. 1994).

Figure 8 Daily flows for Cooper Creek at Cullyamurra Waterhole, South Australia



Flows in Cooper Creek are sourced from flooding summer monsoonal rainfalls in the headwaters of the catchment. These episodic flooding flows can take many weeks to travel down the complex floodplain system of anastomosing channels and wetlands (Puckridge et al. 2000). Floods can cover tens of thousands of square kilometres. In most years, the intermittent flows fill channels and the many permanent waterholes and lakes and evaporate without reaching Lake Eyre. In very wet years, however, it manages to flood the entire Channel Country and reaches Lake Eyre after flowing through the dry areas of Strzelecki Desert, Sturt Stony Desert and the Tirari Desert. There has been very little development of water resources of the Lake Eyre Basin, including Cooper Creek, and flow regimes are largely unmodified. Most of the basin is used for sheep and cattle grazing on natural grasslands.

Water quality in Cooper Creek is spatially and temporally variable. A study of the water quality in Cooper Creek by Sheldon & Fellows (2010) showed that the greatest temporal variation is attributed to flow, whereas the greatest spatial variation occurs when water retracted to waterholes (Sheldon & Fellows 2010). Water quality generally declined when waters retracted to waterholes from processes such as evaporation, saline groundwater intrusion and the concentration or precipitation of compounds (Sheldon & Fellows 2010). This caused concentration of major anions (bicarbonate) and cations (calcium and magnesium), which led to raised hardness and alkalinity of the water (Sheldon & Fellows 2010).

Cooper Creek has naturally high turbidity levels, even under low-flow conditions. Therefore, light does not penetrate very far into the water. Under these conditions, it might be expected that rates of photosynthesis of phytoplankton and benthic algae would be very low. However, many waterholes have a highly productive band of algae restricted to the shallow water at the edge of the waterhole. A study of ecosystem processes in the permanent pools of Cooper Creek, near Windorah in Queensland, has revealed a highly productive littoral band of benthic filamentous cyanobacteria as a 'bath-tub ring' (Bunn et al. 2003). The vertical distribution of this productive band is clearly light-limited in these highly turbid systems. Despite the high turbidity, benthic gross primary production in this narrow zone was very high (1.7—3.6 g C m-2 day-1), about two orders of magnitude greater than that measured in the main channel (Fellows et al. 2009). Nutrient concentrations were high on all sampling occasions. Stable carbon isotope analysis confirmed that this 'bath-tub ring' of algae was the major source of energy for aquatic consumers, ultimately supporting large populations of crustaceans and fish.

Figure 9 A photo showing benthic algae growing in the photic zone of a pool

Source: DSEWPaC 2003

4.3 Modified rivers

Since European settlement, there have been extensive human-induced modifications of flow regimes of rivers in Australia. River regulation was introduced to efficiently control water movement in catchments to support agriculture and potable drinking water supplies. The creation of urban centres and increasing urban sprawl has caused ecological degradation of streams in a manner described as 'urban stream syndrome' (Walsh et al. 2005). Saline groundwater intrusion into streams in agricultural landscapes has also become a major water quality issue, particularly in the Murray–Darling Basin. These modified rivers and some of their key water quality issues (cold-water pollution, urban pollution and salinisation) are discussed in this section.

4.3.1 Regulated rivers

River regulation relates to measures taken to efficiently control water movement in a river system for economic gain. It supports beneficial uses such as potable water supply, irrigation and hydro power generation. It can also support social values such as navigation, recreation and flood mitigation. Dams and/or weirs and the associated headworks and channels are built to harvest and control the flow of water. River regulation then determines the manner, magnitude and frequency of flow releases downstream.

In addition to the impacts of construction and inundation of habitat through the building of dams, weirs and infrastructure, the operation of dams through river regulation also affect aquatic ecosystem values in the river catchment. This can occur through seasonal reversal in the flow regime (particularly in irrigation supply systems) and thermal pollution from cold-water releases. Downstream of dams, the effects of river regulation on the flow regime may be more variable or more constant flows and/or increased or reduced flow volumes (Bunn & Arthington 2002b). For example, dams used for irrigation may generate short-term variable flows during peak demand and constant flows otherwise. It may also cause a long-term reduction in flows through diversions and evaporation (Walker 1985). Also, changes in flow below a hydro-electric power dam may be transient and rapid in the short term and show less seasonal amplitude (Walker 1985).

Environmental flow studies have been conducted for river reaches downstream of major dams to determine the minimum flows required to restore a more natural flow regime to maintain and/or improve the conditions of ecological values. However, aquatic organisms have water quality requirements as well as flow-habitat requirements (Scherman et al. 2003). Thermal pollution is a common water quality issue associated with water released from storages.

Thermal pollution refers to a significant increase or decrease in river water temperatures compared to natural conditions, caused by anthropogenic influences (like dam releases, cooling water discharges from power stations). Discharges from large dams are typically colder than natural during the warmer months of the year and warmer than natural for cooler months of the year (NOW 2011a). This is because large masses of water in dams heat and cool at slower rates to shallow, flowing rivers. Cold-water pollution from dam releases is a significant problem in Australia because of the warm climate (Nilsson & Renofait 2008). It is caused by unseasonably cold releases from the deeper layers of thermally stratified dams during summer (see the conceptual model in Figure 10 and Case study 4).

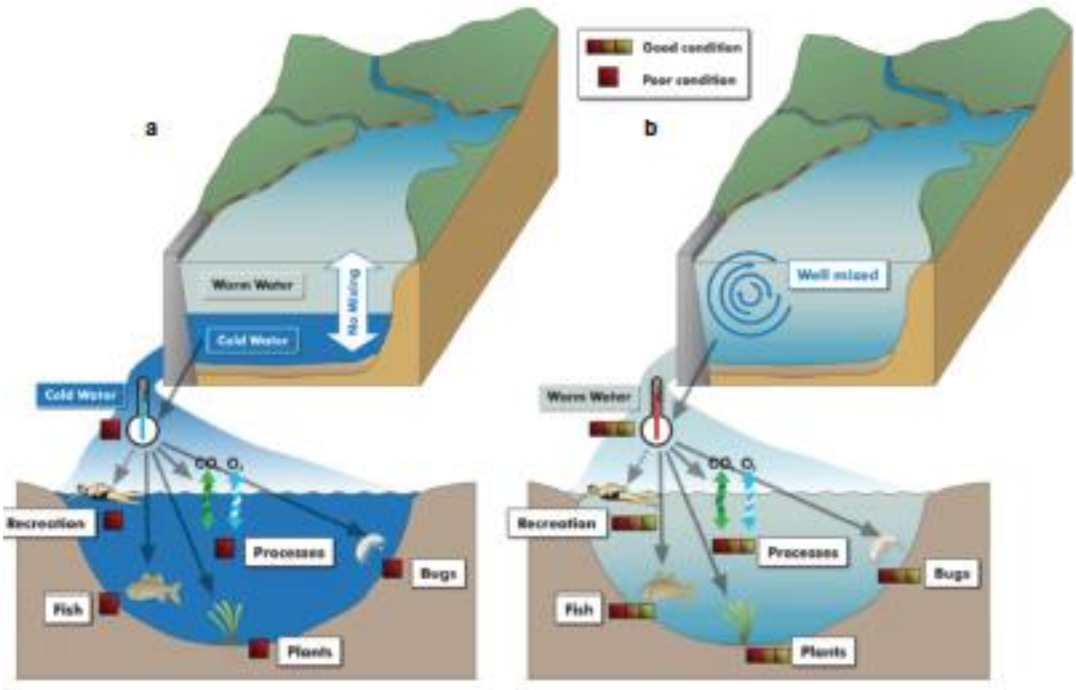
A study scoping the cold-water pollution situation across the Murray–Darling Basin had the following findings (Lugg 2002):

- Dams are typically most strongly stratified in summer and mixed in winter.
- Summer depressions in temperature are typically around 8 to 12° Celsius downstream of major storages that release from below the thermocline although may be up to 16° Celsius compared to natural conditions.
- Winter elevations in temperature downstream of reservoirs are typically 2 to 4° Celsius although can be up to 9° Celsius.
- Seasonal variations in water temperature can be reduced by between 4° Celsius and 10° Celsius. Seasonal variations can also be delayed by up to 13 weeks.
- The length of river affected downstream of a dam depends on discharge rate, river flowing depth and local climate, but effects have been observed hundreds of kilometres downstream on dams of major rivers (Preece 2004).

Thermal pollution poses a threat to the survival of many native fish species and other aquatic organisms (Sherman et al. 2007). Water temperature can affect primary productivity (including algal growth) and organic matter decomposition rates, affect dissolved oxygen saturation, change the toxicity of many contaminants, affect the spread of disease and interfere with breeding cycles of aquatic organisms (see the conceptual model in Figure 10). It can also affect other beneficial uses of waterways, including recreation. However, thermal pollution can be managed by having release structures such as multi-level offtakes that allow surface waters to be discharged or have mixing equipment that prevents thermal stratification from developing.

Other water quality issues associated with river regulation are caused by low variability in flow and overall lower flow magnitudes in some reaches downstream. Low flows are associated with low oxygen content, temperature extremes, increased concentrations of contaminants, eutrophication and salinisation. Dams also reduce connectivity along the river length, which has implications for nutrient and sediment transport which can affect downstream trophic structure and function (Bunn & Arthington 2002a, Poff et al. 1997). Clear-water erosion can also occur downstream of reservoirs (Graf 2006). The location of a dam within a river system, its age, depth and surface area, the hydraulic residence time, the regional climate, operation of the dam and chemistry of the inflowing waters all influence how impoundment affects downstream water quality (Ahearn et al. 2005).

Figure 10 Conceptual models for cold-water pollution showing a. stratified system and b. well-mixed system and the impacts to water quality and environmental values downstream



Case study 4 Murrumbidgee River, New South Wales

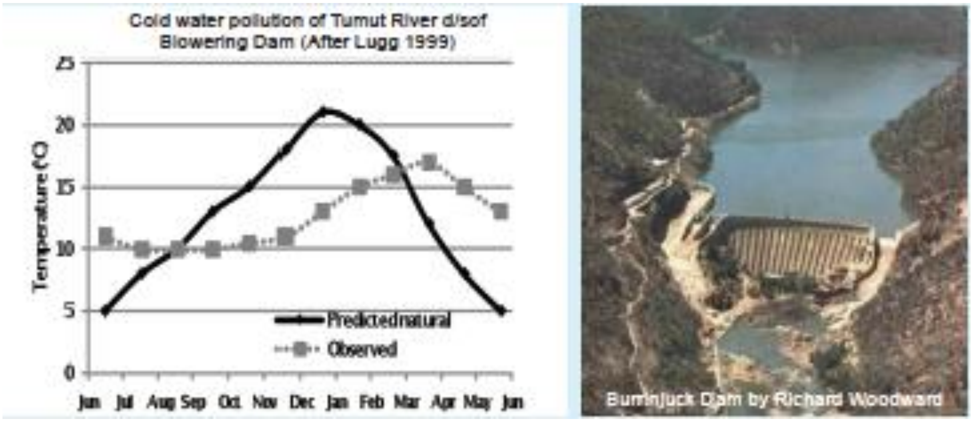
The Murrumbidgee River is one of the largest and most heavily regulated rivers in Australia.

It has 14 dams and eight large weirs, including Burrinjuck Dam near Yass (1.026 million megalitre capacity) and Blowering Dam near Tumut (1.628 million megalitre capacity) (NSW SOC 2010). These dams harvest water for the Murrumbidgee and Coleambally Irrigation Areas. More than 10,000 kilometres of irrigation channels transport water from the dams for irrigation of pastures, rice, grains, vegetables, citrus and grape crops in the catchment (NSW SOC 2010). Water from the Murrumbidgee River catchment supplies Australia's capital, Canberra, and the other major towns of Wagga Wagga, Griffith and Tumut. It also supports the Lower Murrumbidgee Floodplain, one of the largest wetland systems in the Murray–Darling Basin and of national importance (Kingsford 2003). The environmental values are aquatic ecosystems; primary industries; recreation and aesthetics; drinking water; industrial water; and cultural and spiritual values (Davies et al. 2008).

The process of river regulation has led to a major alteration of the natural flow regime of the Murrumbidgee River. Much of the flow in the river under natural conditions (pre-dams) would have occurred as spring floods when winter snow melted in the Snowy Mountains. Under current conditions, the spring floods encounter a number of dams and weirs in the headwaters of the Murrumbidgee and on the lowland floodplain that harvest water and create lower than natural flows during winter/spring. Irrigation releases during summer/autumn artificially increase flows downstream of the major dams. These changes to the flow regime due to river regulation have resulted in cold-water pollution, degraded in-stream habitat and stream bank instability during summer (NSW SOC 2010). They have also reduced connectivity between the river and high-value floodplain wetlands (Kingsford 2003).

The headwaters of the Murrumbidgee River have two dams that present a high risk for cold-water pollution downstream (Preece 2004). They are the Blowering Dam on the Tumut River (a tributary) and the Burrinjuck Dam on the upper Murrumbidgee River. Blowering Dam was the highest-ranked structure in New South Wales for severe cold-water pollution (Preece 2004). It is located on the Tumut River and provides regulated flows of up to 8,200 megalitres per day for summer irrigation. Water stored in the dam thermally stratifies from November to May and has large temperature differences between the surface and bottom waters (for example, 28° Celsius and 11° Celsius respectively). The intake draws water from below the thermocline, resulting in summer temperature differences between natural and current of 13 to 16° Celsius (Preece 2004) (Figure 11a). Temperature differences persist, but slowly mitigate, up to 200 to 300 kilometres downstream (Preece 2004). This includes the remaining length of the Tumut River to the confluence with the Murrumbidgee River (approximately 80 kilometres downstream), and then downstream including combined impacts of cold-water releases from the Burrinjuck Dam (Preece 2004). Burrinjuck Dam, on the upper Murrumbidgee River, also provides regulated flows for irrigation in the Murrumbidgee Valley from September to March each year (Figure 11b). The peak January flow is 5,200 megalitres day, compared to flows of only 615 megalitres per day outside the irrigation season. A 10° Celsius difference is common between surface and bottom waters. Release from fixed-level intakes below the thermocline results in a downstream temperature depression of 7 to 8° Celsius compared to natural conditions. The cold-water pollution largely dissipates before the Tumut River confluence, but the effect is still present hundreds of kilometres downstream (Preece 2004).

Figure 11 Cold-water pollution in Tumut River downstream of Blowering Dam and a photo of Burrinjuck Dam



Source: After Lugg 1999. Photo from R Woodward.

Cold-water pollution has contributed to the degradation of macroinvertebrate and native fish communities, including the elimination of trout cod, Macquarie perch and freshwater blackfish, from large sections of the Murrumbidgee River downstream of these dams (Gilligan 2005, MDBC n.d, NOW 2011b). It is a high priority for reservoir management in New South Wales, as outlined by the New South Wales guidelines for managing cold-water releases (NOW 2011a).

4.3.2 Urban streams

An urban stream can be defined as 'a stream where a significant part of the contributing catchment consists of development where the combined area of roofs, roads and paved surfaces results in an impervious surface area characterising greater than 10% of the catchment' (Findlay & Taylor 2006). Urbanisation is rapidly occurring in most parts of the world from population growth and the mass movement of populations from rural to urban centres (Goonetilleke et al. 2005). It is important that this continual urban growth is astutely managed and innovative strategies are adopted to ensure the protection of key environmental values in a region.

Urban streams are valued greatly as environmental, aesthetic and recreational assets. They may support floodplains and riparian zones that become local biodiversity hotspots or refuges, providing corridors for otherwise isolated flora and fauna populations and their habitat. They may also provide benefits such as water supply, flood mitigation and disposal of wastewater (Findlay & Taylor 2006).

Urban streams are often heavily degraded due to the increased rate, volume and movement of pollutants into waterways from run-off from impervious surfaces (Goonetilleke et al. 2005). This causes deterioration in water quality, degradation of stream habitats and flash flooding. The consistently observed ecological degradation of streams draining urban land is described as 'urban stream syndrome' (Walsh et al. 2005). The symptoms of the urban stream syndrome fall under four broad categories: stream hydrology, stream geomorphology, water quality and ecology and biodiversity. The hydrological and water quality impacts are described below.

Stream hydrology
Urbanisation alters stream hydrology. This results in runoff occurring more readily and quickly during rainfall events. There are three main pathways for the hydrological impacts. They are removal of vegetation resulting in reduced evapotranspiration, surface roughness and catchment storage; increased impervious surfaces resulting in reduced infiltration losses; and direct stormwater and drainage connections resulting in increased hydraulic conveyance efficiency (Goonetilleke et al. 2005).

Hydrological changes that urban catchments commonly exhibit are:

- decreased base flow. The increased impervious areas mean that there is less opportunity for water to infiltrate. Therefore, groundwater storage and discharge are reduced (Ladson 2004).
- small to moderate increases in flow during small rain events. These flows are frequent in urban areas resulting from direct surface run-off in small rain events.
- large increases in peak flows from larger rain events but of shorter duration than natural. That is, stream flow rises more rapidly during storms and recedes more rapidly after storms, which is described as a 'flashy' stream flow.
- first flush is an important and distinctive phenomenon that produces higher pollutant concentrations early in the run-off and a concentration peak preceding the peak flow.

Water quality
The water quality of urban streams is highly variable and is a significant determinant of overall stream condition (Findlay & Taylor 2006). Changes to the hydrologic regimes of urban areas can affect water quality, as the increased run-off velocities lead to erosion and the entrainment and transport of pollutants present on the catchment surface (Walsh et al. 2005). Generally, surface run-off, referred to as stormwater, transports a variety of materials of chemical and biological origin to the nearest receiving water body. These contaminants can cause toxicity to aquatic organisms and alter ecosystem processes (such as nutrient cycling), resulting in a water body that is fundamentally changed from its natural state (Goonetilleke et al. 2005).

The main pollutants in urban run-off and their impacts are described below:

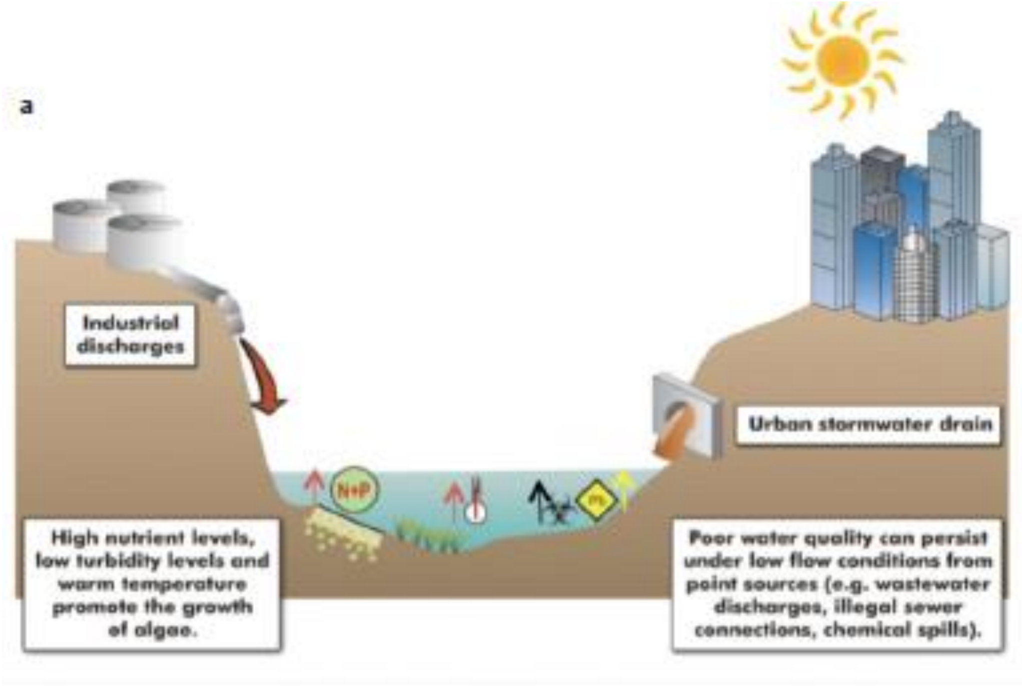
- *Litter (paper, plastics, glass, cigarette butts)*—litter impacts on the visual amenity of the waterways, as it tends to float on the surface. It can also degrade habitat for aquatic biota and clog the drainage system, impeding the flow of stormwater. Some litter contains volatile solids that may be toxic to some organisms.
- *Sediments and suspended solids*—suspended solids are transported from streets and paved areas, rooftops, construction sites and other areas. Loads are generally 10 to 100 times greater in urban run-off than from undisturbed land and can be transported and deposited at any time as flow velocities decrease. There are both physical and chemical impacts associated with sediment transport. The physical impacts include siltation and smothering of ecosystems, blocking of sunlight and reduction in water clarity. Chemical impacts relate to the transport of pollutants, such as nutrients and pathogens, which attach to the sediments.
- *Nutrients*—urban streams often show higher nutrient concentrations and less efficient nutrient uptake rates (Walsh et al. 2005). This causes eutrophication and aquatic growth stimulated by nutrients entering the water, which can alter the visual appearance of the water, lowering its beneficial value. Visual impacts may include floating matter (algal blooms) and slimes. Other

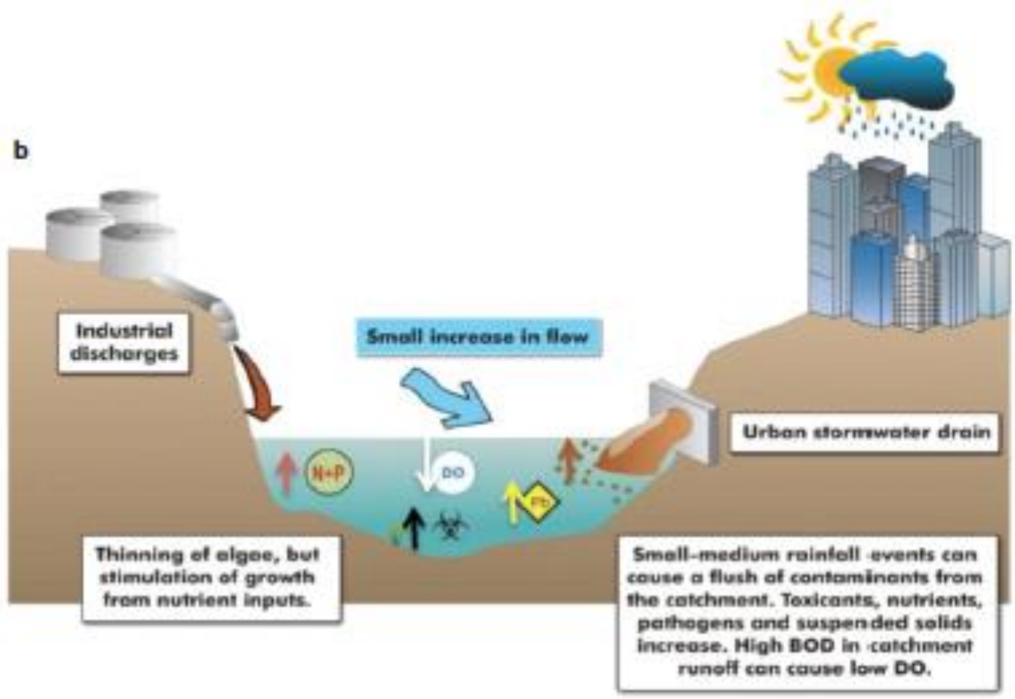
impacts can include dissolved oxygen depletion and objectionable taste and odour from algal blooms.

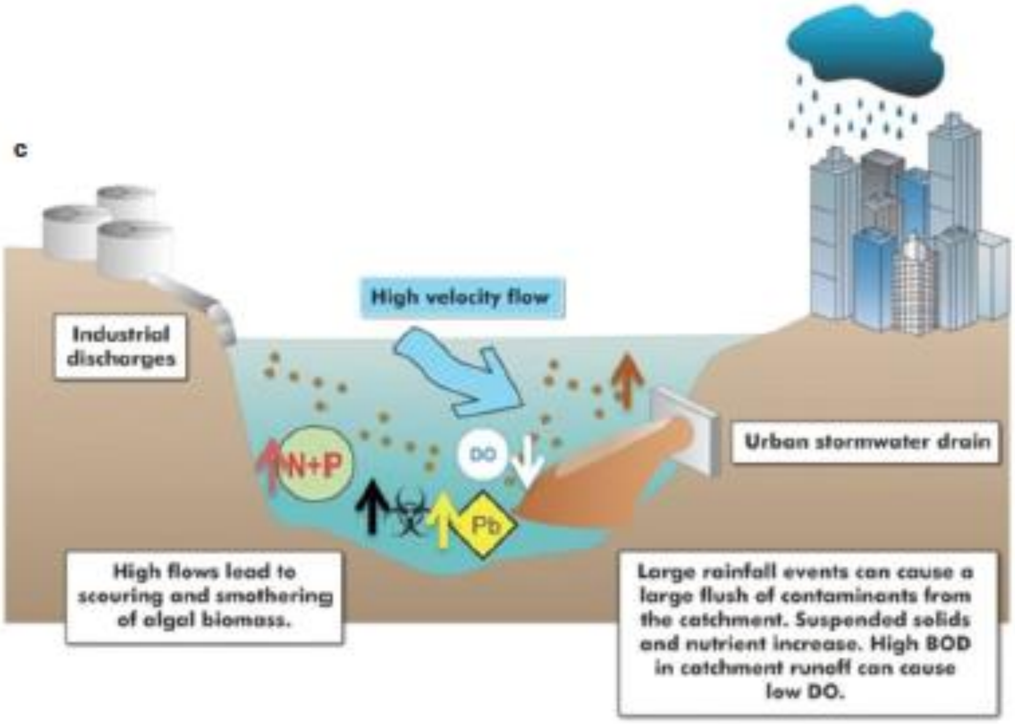
- *Heavy metals*—stormwater run-off from urban areas (including roads, roofs and industrial sites) contains significant loads of heavy metals, which are of concern because of their potential toxicity to aquatic organisms.
- *Hydrocarbons*—hydrocarbons can enter stormwater from vehicle wear and emissions and chemical spills. They can be directly toxic to aquatic organisms and bioaccumulate through the food chain. Hydrocarbons can also cause oil slicks on the surface of the water, degrading the visual amenity of the waterway.
- *Organic carbon*—organic carbon is a major pollutant in urban stormwater run-off. The most common impact is the reduction in dissolved oxygen in water through its microbial consumption. This can lead to anaerobic conditions, resulting in fish kills, foul odours, discolouration and slime growth.
- *Pathogens*—pathogens are sourced from animal faeces and sewage overflows. They are vectors of disease that can reduce the recreational and aesthetic amenity of the receiving water body.
- *Temperature*—streams that receive water from conventionally drained urban areas usually have elevated water temperatures, most likely due to heating by impervious surfaces and dominant piped pathways for water to the streams. Warmer water can stimulate physiological processes in streams and worsen the problems of nuisance algal growth. Other streams adapted to cooler temperatures may suffer thermal stress (Walsh et al. 2005).

The following conceptual models show the water quality changes anticipated in an urban catchment under low flows, first flush and high flows (Figure 12). High nutrient levels, low turbidity levels and warm temperatures promote the growth of algae. Poor water quality can persist under low flow conditions from point sources (e.g. wastewater discharges, illegal sewer connections, chemical spills). Some increase in flow and thinning of algae can result in stimulation of growth from nutrient inputs. Small to medium rainfall events can cause a flush of contaminants from the catchment. Toxicants, nutrients, pathogens and suspended solids increase and there is an increase in nitrogen and phosphorus. High flows lead to scouring and smoothing of algal biomass. Large rainfall events can cause a large flush of contaminants from the urban catchment. A case study for an urban stream, Lane Cove River, is provided in Case study 5.

Figure 12 Conceptual model of urban stream during a. low flows, b. first flush and c. high flows




b
Industrial discharges
Small increase in flow
Urban stormwater drain
N+P
DO
Pb
Thinning of algae, but stimulation of growth from nutrient inputs.
Small-medium rainfall events can cause a flush of contaminants from the catchment. Toxicants, nutrients, pathogens and suspended solids increase. High BOD in catchment runoff can cause low DO.


c
Industrial discharges
High velocity flow
Urban stormwater drain
N+P
DO
Pb
High flows lead to scouring and smothering of algal biomass.
Large rainfall events can cause a large flush of contaminants from the catchment. Suspended solids and nutrient increase. High BOD in catchment runoff can cause low DO.

Case study 5 Lane Cove River, New South Wales

The Lane Cove River is a tributary of the Parramatta River, rising in the Pennant Hills area and flowing into Sydney Harbour. A weir located just upstream of Fuller Bridge marks the tidal limit. The Lane Cove River catchment covers approximately 80 square kilometres and comprises both urban and industrial land uses and bushland (Preston 1995). Within the catchment there are 17 creeks which directly feed into the river. Current uses and environmental values for the Lane Cove river system include maintaining healthy aquatic ecosystems, primary and secondary recreation and aesthetics.

The river and its tributaries have undergone substantial degradation from their natural state as a result of the high levels of urban and industrial development, which have resulted in poor water quality and changed flow regimes. The natural channels have been concrete lined and channelised. Wetlands have been destroyed or degraded and, where natural remnant vegetation exists, it is often affected by weeds and rubbish. The hydrology of the Lane Cove River catchment is one of rapid peaks and falls (Preston 1995). At certain times of the year the weir can be overtopped as a result of large river flows but also as a result of extremely high tides.

The quality of the river has been degraded by two principle sources. The first is non-point source pollution from high levels of diffuse run-off from suburban properties, gardens and roads. The second is point source pollution from stormwater and inadequate sewage systems along many of the creeks and drainages (Preston 1995). Typical water quality issues include elevated faecal coliforms, algal growth, reduced oxygen levels, high nutrient loads and high levels of gross pollutants. The impervious surfaces (like roads, roofs and concrete) are also releasing elevated and unnatural levels of minerals that are slowly dissolving and changing the quality of stormwater (Wright et al. 2011). Whilst these problems are at their worst during heavy rain, moderate rainfall events contribute large volumes of stormwater that carry high pollutant loads into the river.

The effects of pollution in the Lane Cove River are compounded by the many introduced water plants and fish species, which can exacerbate the issue, particularly during different flow conditions. During low flows, introduced plants contribute to a reduction in the circulation of water and may increase the growth of algae. Introduced fish species, as opposed to native species, prefer the slower-flowing water.

Sampling in the Lane Cove River system identified the urban waterway as having poor ecosystem health as reflected by a low number of sensitive macroinvertebrate taxonomic groups. This loss of ecosystem health is caused by complex changes known as the ‘urban stream syndrome’ (Walsh et al. 2005). The syndrome in the Lane Cove River catchment is a result of the changes to hydrology, hydraulics, water quality, habitat, pest species, geomorphology, erosion and sedimentation (Wright et al. 2011). Generally, the Lane Cove River (compared to non-urban reference streams) had more variable water quality with much higher pH, electrical conductivity and alkalinity. It also suffers from elevated levels of excessive nutrients and contaminants, along with depleted dissolved oxygen (Wright et al. 2011).

Figure 13 Urban waterway fully lined with concrete and a chemical factory on Lane Cove River

Source: Ian Wright

4.3.3 Groundwater-fed streams

An important factor determining the water quality in surface systems is the extent of surface water / groundwater interaction. In broad terms, streams can be 'losing' or 'gaining'. A gaining stream is one where for most of the time groundwater flows into the stream, and the quality in the stream is partly or largely a function of the groundwater quality. Key examples of gaining streams are the Daly River in the Northern Territory and the Gellibrand River in Victoria. Groundwater is important for sustaining flows and/or refuge pools in these rivers, particularly during dry periods.

A losing stream is one where for most of the time surface water leaks out of the watercourse and recharges the groundwater system, in many cases creating a fresher groundwater zone beneath and around the watercourse. Many of the watercourses in Australia were historically of this type, but, with land use changes such as irrigation or clearing of native vegetation, the watertable has risen and reversed the situation. Where the regional groundwater is saline, this is one of the classic manifestations of the salinity problem in Australia.

Saline groundwater results from the long-term action of rainfall bringing ocean salt inland (UNSW 2011). Water quality affected by this mechanism is known as 'primary salinity'. Saline water bodies from groundwater interactions were already present in Australian water bodies pre-settlement, of which Lake Eyre is an example. Human-induced salinity is known as 'secondary salinity'. Large-scale irrigation developments are a major cause. The addition of irrigation water as an input to the hydrologic cycle causes increased run-off and increased recharge to the groundwater system, bringing the watertable towards the surface. The added irrigation water can often amount to some 400 to 800 millimetres per year in areas typically having 250 to 450 millimetres of rainfall. Consequently, the emergence of salinity within a decade or two of irrigation commencing is not uncommon (GHD 1970).

Dryland salinity can also occur where clearing of deep-rooted native vegetation decreases evapo-transpiration on the output side of the hydrologic cycle. This too causes increased run-off and increased recharge to groundwater. However, Rancic & Acworth (2008) point out that climate also plays a role in dryland salinity. Inter-decadal climate variation, specifically the wetter phase in New South Wales between 1947 and 2000, correlates well with an increasing incidence of dryland salinity.

In Australia, the areas most at risk of dryland salinity are the western slopes of the Great Dividing Range and south-west Western Australia (NHT 2001). Salinity can occur in ephemeral streams in catchments as small as a few square kilometres through to major regulated rivers with catchments of around one million square kilometres.

The effects of salinity on stream ecology can be severe. Saline groundwater intrusion into streams causes salinity levels to rise. Increasing salinities can exceed the salt tolerances of many fish and invertebrate species. Some freshwater algae and aquatic plants also have a low tolerance of salt. Therefore, increasing salinities may cause a shift in aquatic fauna and plant communities towards one that is more salt tolerant. Hence, some sensitive native species are lost from the system.

When the groundwater base flow salinity is relatively high and the stream flow salinity is low, saline stratification can occur. In such cases, a fresh surface layer floats upon a saline bottom layer. There is limited mixing between the two layers, which results in high salinity and low dissolved oxygen levels in the bottom layer (Western et al. 1996). This reduces habitat for fish and other aquatic organisms. The surface layer can experience extremes in water temperature and can create still, calm conditions suitable for the growth of algae in slow or non-flowing pools.

Groundwater intrusion into riverbeds is considered a very likely dominating process in the potential formation of acid sulfate soils (ASS) in inland river and wetland systems (Baldwin & Fraser 2009). In affected areas, the groundwater creates a saturated environment within the base of the river during extreme low-flow periods (prolonged anaerobic conditions) providing a source of dissolved sulfate ($SO4^{2-}$) and iron minerals that create an environment very conducive to ASS formation. Dissolved sulfate, organic matter and dissolved iron minerals must be present within an anaerobic environment long enough to cause reducing conditions and allow sulfate-reducing bacteria to convert sulfate to sulfide (Fitzpatrick & Shand 2008). Any free sulfide that is produced can bind to free iron and accumulate in the sediments. In 23 out of a total of 24 case studies of observed inland ASS in Australia, Fitzpatrick & Shand (2008) concluded that the dominant formation processes was sulfate-rich groundwater discharge into anoxic surface water environments (like wetlands) and/or shallow watertables.

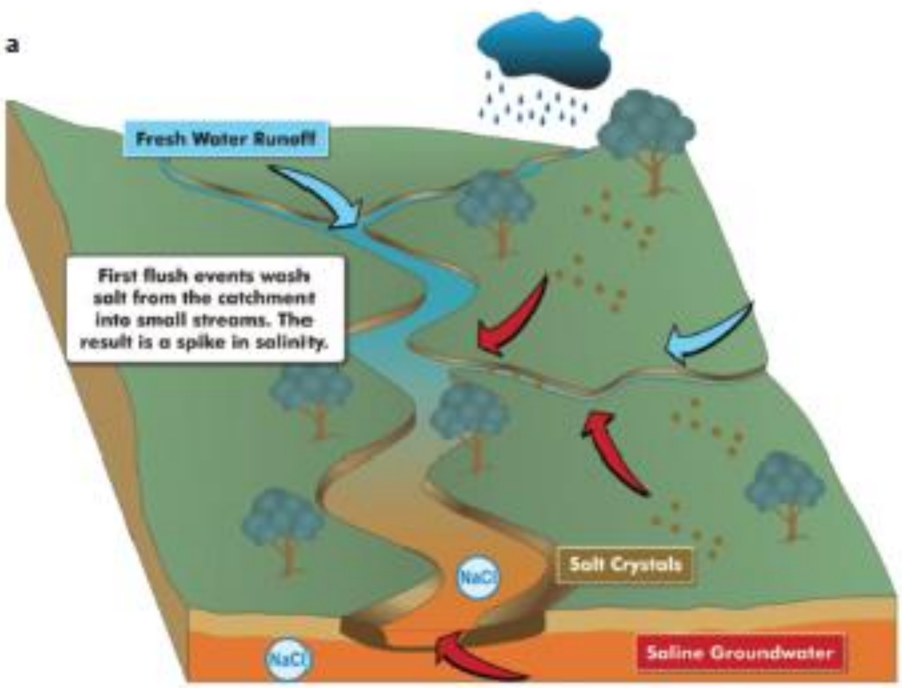
Freshwater inflows are important to control the salinity levels in saline-affected streams. In the first flush after a rainfall event (see the conceptual model in Figure 14a), the initial front of surface run-off displaces the saline dregs in the stream, and smaller sub-streams wash salt accumulated on the surface into the main stem. The result is a spike of salinity on the leading edge of the run-off event.

Typically, salinity concentrations are lowest during flooding flows because the flow is high enough to dilute the salt load (see the conceptual model in Figure 14b). The pressure of the surface flows can reduce groundwater intrusion into the waterway. When high flows recede, the water that has infiltrated the banks of the river/creek (bank storage) returns to the creeks and groundwater base flow continues (Figure 14c). The groundwater base flow tends to dominate, so this phase is characterised by increasing salinities as the salt load and flow dwindle away.

Low-flow/cease-to-flow conditions (see the conceptual model in Figure 14d) have higher salinity from a high proportion of intruding groundwater compared to fresh surface flows. Evaporation from the water surface in the rivers/creeks can also concentrate salinity levels. A case study of a saline stream, Axe Creek, is provided in Case study 6.

Figure 14 Conceptual models showing a. first flush, b. flood, c. recessional flow and d. dry phase

a



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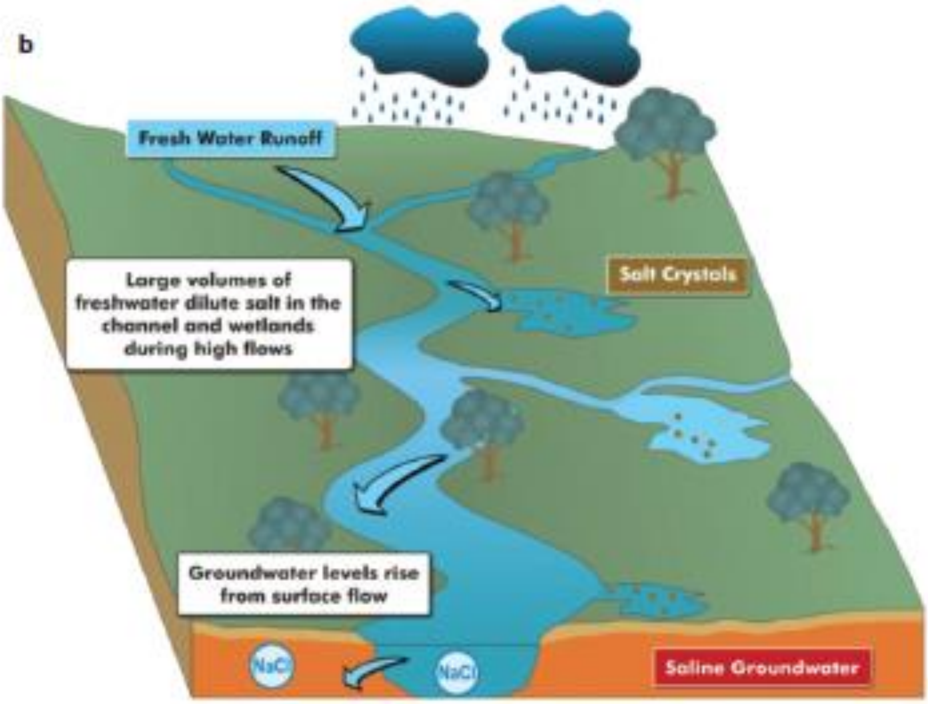

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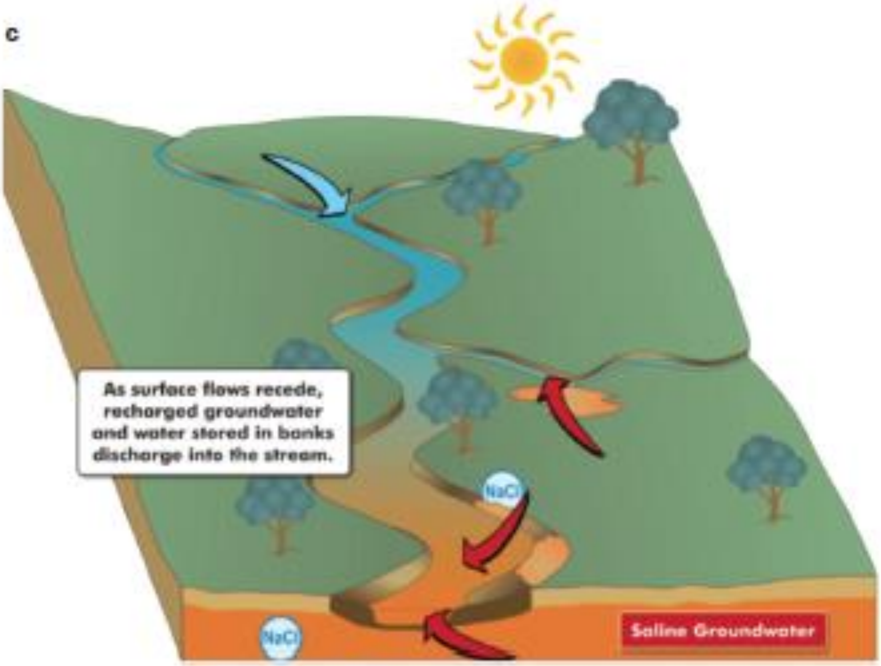

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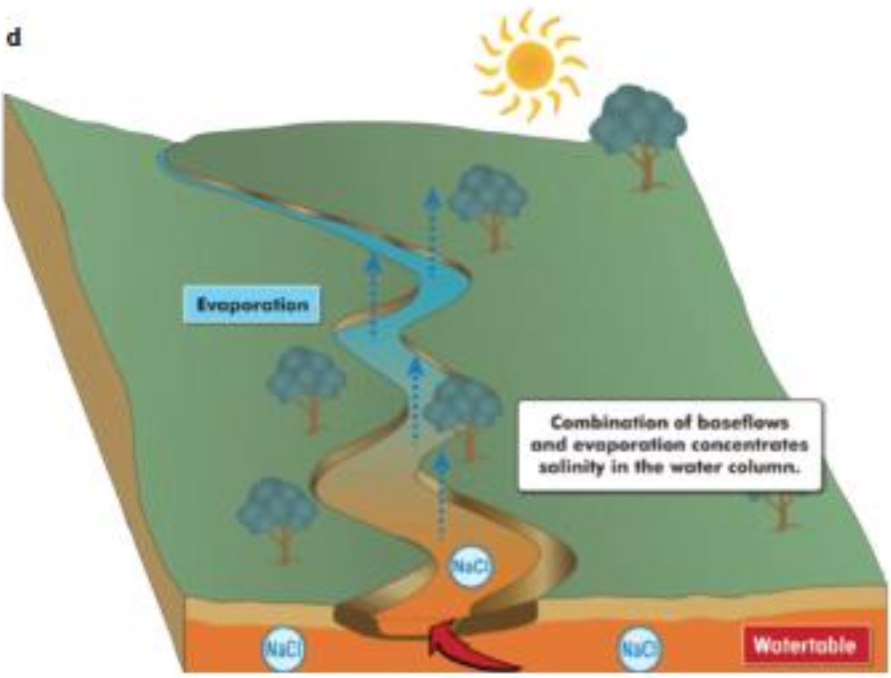


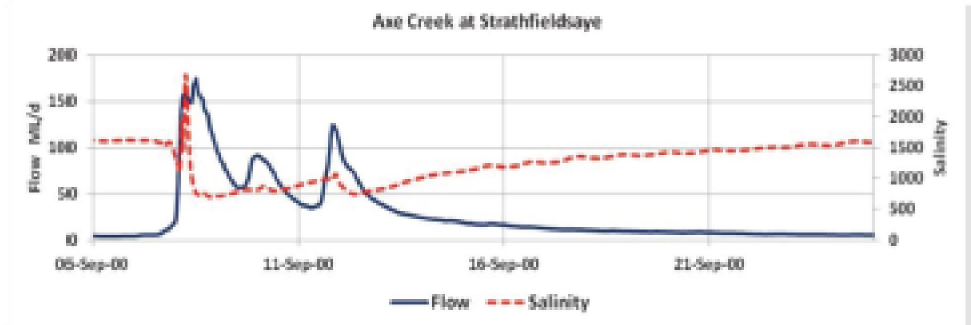
Note: The orange colouring and red arrows indicate salt movement.

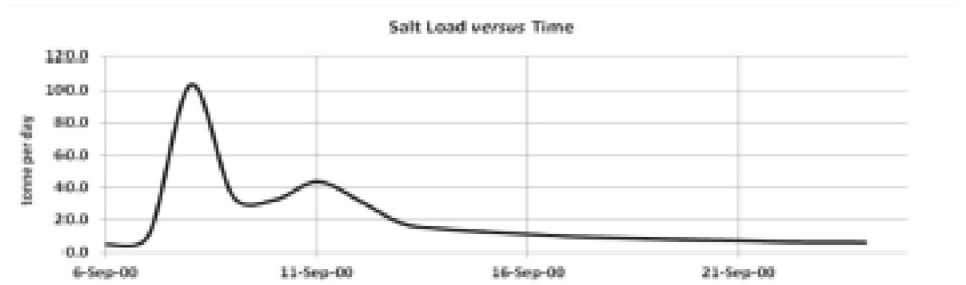
Case study 6 Axe Creek at Strathfieldsaye, Victoria

Axe Creek is an intermittent stream on the inland slopes of the Great Dividing Range in an area with an average annual rainfall of 550 millimetres. As such, it is typical of streams likely to be affected by dryland salinity. Its catchment of 83 square kilometres has a mix of forested and cleared land. The highest point in the catchment is 350 metres AHD and at the exit point at Strathfieldsaye the land is about 200 metres AHD. The environmental values are aquatic ecosystems; primary industries; recreation and aesthetics; drinking water; industrial water; and cultural and spiritual values (SEPP 2003).

The geology is characterised by weathered granite and weathered sedimentary rock with overlays of sand and clays in some places. Depth to watertable can be anywhere between 1 and 10 metres, depending on location in the catchment. Groundwater salinity is typically 7,000 to 9,000 µS/cm, but some observations have been at less than 1,000 µS/cm. A run-off event in September 2000 was initiated by widespread rainfall of 24 to 29 millimetres up to 9 am on 8 September. This was followed by a fortnight of only light rainfall, allowing examination of a complete run-off event 'cycle'. The two charts below show, firstly, flow and salinity (electrical conductivity) versus time; and, secondly, salt load versus time (Figure 15).

Figure 15 Changes in salinity concentrations and loads in response to a run-off event in September 2000 in Axe Creek





All of the 'features' of a saline ephemeral stream are illustrated, including the salinity spike associated with the first flush, the lowest salinity during the peak flow and the long decay period with rising salinity. The salt load chart shows the highest salt load occurring during the peak of the flow. Salt loads also decline in the aftermath of the flood.

4.4 Reservoirs and wetlands

This section describes the relationship between water quality and quantity in three types of non-flowing (lentic) waterbodies: wetlands, lakes and reservoirs.

4.4.1 Freshwater wetlands

Freshwater wetlands are saturated areas that are inundated with water either permanently or seasonally. There are many different types of wetlands in the landscape. They are frequently classified based on water depth, frequency of inundation, salinity and dominant vegetation (for example, the Corrick & Norman (1980) wetland classification system used in Victoria). The main classifications of freshwater wetland groups are lacustrine wetlands (for example, deep, permanent freshwater lakes), palustrine wetlands (for example, shallow floodwater in swamps) and riverine wetlands (for example, those associated with river channels and floodplains). Wetlands support aquatic plant communities, waterbird populations and macroinvertebrate communities. Fish populations can also reside in permanently inundated wetlands or use them intermittently for breeding. Wetlands are also valued for water treatment and purification, flood mitigation, recreation, aesthetics and cultural purposes (Mitsch & Gosselink 2000).

The hydrology of wetlands depends on their level of connection with water sources. Some wetlands are connected to rivers. Other wetlands may intersect with groundwater. Still others can be isolated and located within low points in the landscape that receive rainfall run-off from the catchment. In urban settings, wetlands can receive water from stormwater drains or industrial discharges.

The wetting and drying cycles of wetlands can be important ecologically as well as for water quality purposes (see the conceptual model in Figure 16). In natural systems, wetlands typically fill during the wet season and slowly dry during the dry season. During the drying phase, nutrients and carbon are released from sediment and dissolved organic carbon, nitrogen and phosphorus levels increase. The wet season filling refreshes water quality, dilutes accumulating ions and toxins, entrains organic matter for food webs, waters fringing vegetation communities and draws colonially nesting waterbirds to the site (Young 2001). It releases nutrients from the soils and organic matter, which encourages the growth of seeds in the refilled wetlands. The released nutrients and carbon are available for use by plants and animals. The wetting cycle also causes many invading terrestrial plants to die, giving habitat for valuable aquatic or semi-aquatic plants. High-flow/flood events in nearby rivers may fill river connected wetlands through flood runners or distributary channels during the wet season. This provides movement opportunities for fish into these wetlands, which provides a variety of food sources, breeding habitat and nursery conditions for some native fish species as the wetlands dry.

The slow drawdown of water during the dry season exposes mudflats that provide food for waterbirds and habitat for aquatic plants (Young 2001). Some aquatic plants that cannot grow in dry conditions remain dormant until the next flood. Other semi-aquatic plants, such as river red gums, rely on the dry season for their seeds to germinate and allow their seedlings to take hold. The wetting and drying cycle is therefore very important for maintaining a diversity of plant species.

The wetting and drying cycle is a driver of ecosystem functions in wetlands that influence water quality outcomes. Wetting and drying cycles are important for releasing carbon and nutrients that promote subsequent growth by algae, bacteria, plants and animals (Corrick & Norman 1980).

Nutrient and carbon cycling rely on the wetting and drying cycle of wetlands. This is an important feature of wetlands that is utilised for water treatment outcomes in urban and rural environments. Wetlands are often used as pollution mitigation for sensitive rivers or coastal environments (Verhoeven et al. 2006). Nitrification and denitrification processes that remove nitrogen from aquatic systems require aerobic conditions (during the drying of wetland sediment) to convert ammonia to nitrates (nitrification), then anaerobic conditions (during the wetting cycle) suitable for denitrifying bacteria to convert nitrates to nitrogen gas (denitrification), thus removing it from the ecosystem. Nutrient uptake by plants during their growing phase also removes nitrogen and phosphorus from the water.

Carbon is entrained into wetlands from the floodplain or surrounding environment during the wetting cycle. It can accumulate in the form of leaf litter on the margins of the wetland during the dry season. Particulate and dissolved organic carbon sources are important energy inputs to stream food webs through organic matter breakdown (respiration) and primary production (photosynthesis). These functions are also important drivers of dissolved oxygen dynamics in wetlands and rivers. Primary production in river channels is based on carbon that has come from the river’s floodplain (Junk et al. 1989). Therefore, it is important that there is the opportunity for flooding to occur to allow the movement of carbon from the floodplain wetlands to the river channel (Howitt et al. 2007).

Water quality issues arise when the filling of wetlands occurs too infrequently (as is the case in regulated systems or during droughts). This causes the accumulation of large quantities of organic, carbon-rich matter on the margins and floodplain. When the next flood occurs, all the material is transported into the wetland (and associated rivers system) and overloads its functioning capacity. The organic matter rapidly decomposes, releasing tannins, reducing dissolved oxygen levels and causing fish kills. It can also drain back into the river, causing water quality problems downstream. The result is a blackwater event (see the conceptual model in Figure 17).

A blackwater event is a flood event with elevated levels of dissolved organic carbon sufficient to give the water column a dark ‘tea’ colour (Howitt et al. 2007). It is typically associated with acidic, low dissolved oxygen conditions with high tannin concentrations (Baldwin et al. 2001). Tannins are naturally occurring plant polyphenols that act as a defence mechanism in plants against pathogens, herbivores and hostile environmental conditions. Tannins will persist in the water until flushed; however, if enough sunlight (UV) enters the water, the tannins are broken down into carbon dioxide (Baldwin et al. 2001). Blackwater also adsorbs more sunlight and heats up more than clear water, which can lead to heat shock of susceptible aquatic species. Fish kills (Baldwin et al. 2001, Gehrke et al. 1993, Lugg 2000, McGraw 2006) and mass organism movement out of the blackwater (McGuckin 2001) are common occurrences during blackwater events. The specific drivers for the fish kills are likely to be a combination of the typical conditions (low dissolved oxygen, low pH, tannin concentrations and heat stress). A case study for Barmah–Millewa Forest is provided in Case study 7.

ASS can also be an issue in wetlands that have disrupted wetting and drying cycles (Baldwin et al. 2007, Glover et al. 2011). In the Murray–Darling Basin, 21 per cent of wetlands surveyed by Hall et al. (2006) had sulfidic sediments. Wetlands provide ideal conditions for the formation of sulfidic sediments due to their high organic carbon loading, anoxic conditions and prolonged inundation (Hall et al. 2006). Acid-forming conditions tend not to build up to harmful levels in wetlands that have frequent (annual) wetting and drying cycles (Baldwin et al. 2007). This is because the drying phase oxidises the sulfur and prevents the build-up of sulfides in the sediment (see Section 4.3.3).

Figure 16 Conceptual models showing a. a drying phase and b. a wetting phase and the associated water quality and biological responses

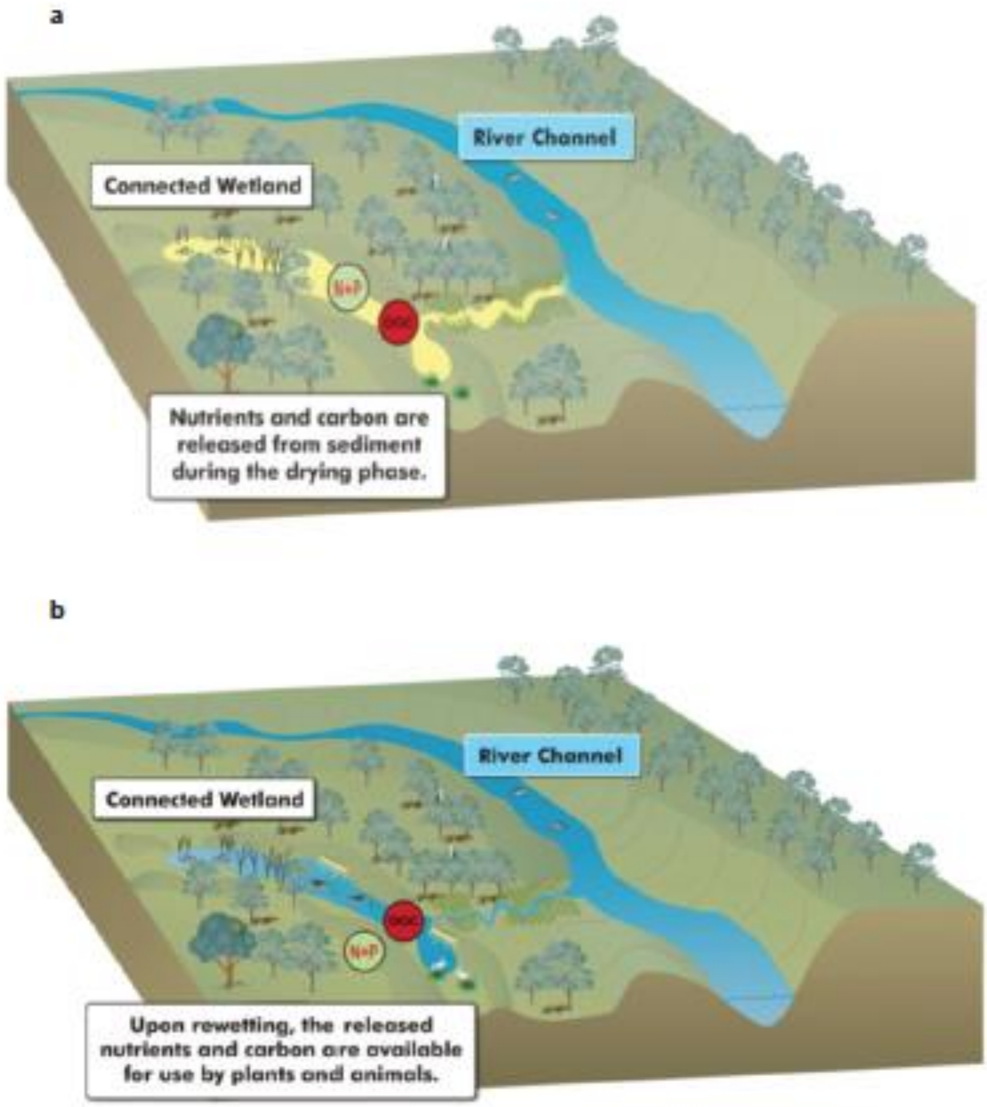
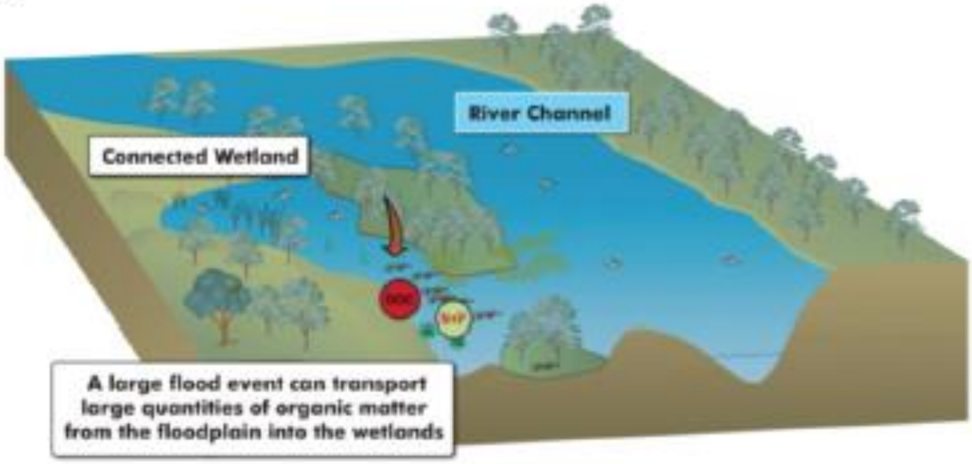


Figure 17 Conceptual models showing a. a flooding event and b. the flood recession with associated blackwater event

c



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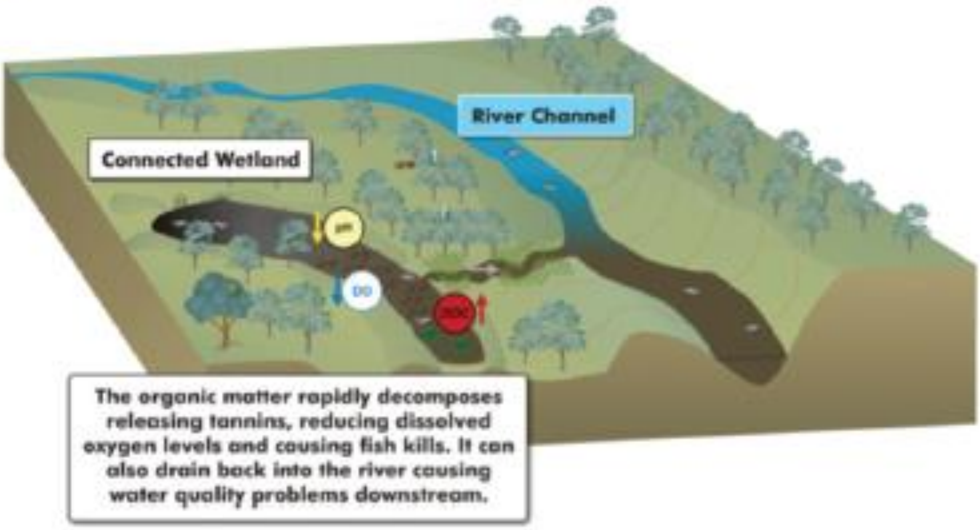


Case study 7 Barmah–Millewa Forest, New South Wales and Victoria

Barmah–Millewa Forest covers an area of 66,000 hectares across the floodplain of the Murray River between Echuca, Deniliquin and Tocumwal. It straddles the New South Wales and Victorian border, with the Barmah Forest located in Victoria and the Millewa group of forests located in New South Wales. The Barmah Forest is a Wetland of International Importance listed under the Ramsar Convention on Wetlands (DSE 2003). It is also one of six Living Murray Icon sites. The forest is the largest river redgum forest in the world (DSE 2003). The environmental values are aquatic ecosystems; recreation and aesthetics; and cultural and spiritual values.

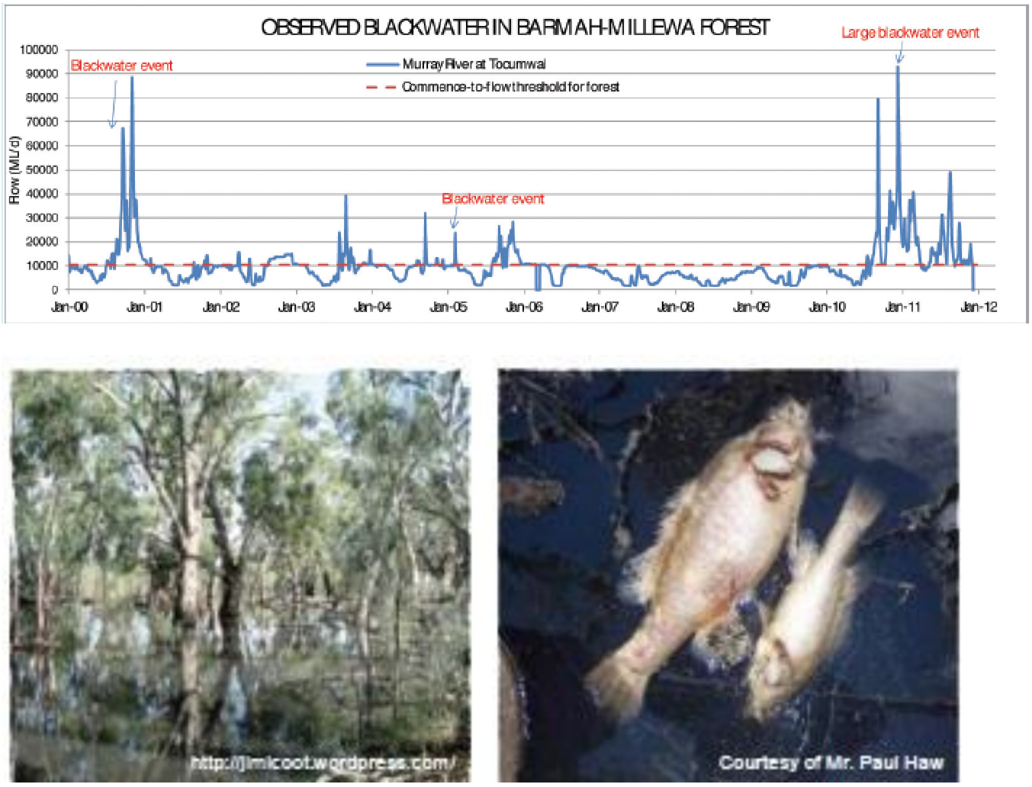
The Barmah–Millewa Forest supports a range of permanent and temporary wetlands, including lakes, swamps, billabongs, grassland plains and flooded forest (DSE 2003). The forest is significant for its ecological, recreational, tourist, scientific, educational, cultural, scenic and aesthetic values (Stewart & Harper 2002). It has especially high ecological diversity because of its size, variety of communities and high productivity. The forest provides habitat for significant numbers of waterbirds, including breeding colonially nesting waterbirds, for which it is protected under migratory bird agreements between Australia, China and Japan. The forest also provides significant breeding habitat for fish and amphibians (Stewart & Harper 2002).

The Barmah–Millewa Forest naturally has a watering regime characterised by flooding in the winter and spring months of most years alternated with dry conditions during the summer and autumn. This natural cycle of wetting and drying is required to sustain the ecosystem and its values (Chong & Ladson 2003). However, the natural flooding cycle associated with the forest has been significantly altered by regulation of the Murray River since the Hume Dam began operating in 1936 (Stewart & Harper 2002). The watering regime has been changed in two ways: there are fewer large winter/spring events that inundate extensive areas because floods are mitigated by irrigation storages; and there are more small summer/autumn events that flood low-lying areas from the way the river is operated to supply irrigation demand (Chong & Ladson 2003).

This has had a negative effect on the overall health of the forest ecosystem (Stewart & Harper 2002).

The decrease in winter and spring flooding, and more late spring / summer flooding, has contributed to the occurrence of blackwater events in the forest (Howitt et al. 2007, MDBA 2011) (Figure 18). The spatial extent of the blackwater (including the forest and downstream along the Murray River) has varied from major events to localised areas of blackwater, with varying ecological effects (Howitt et al. 2007). Ecological impacts in the river can be minimised by managing river flows to dilute the blackwater draining from the forest.

Figure 18 Observed blackwater events in the Barmah–Millewa Forest overlaid on the hydrograph for the Murray River at Tocumwal (site 409202) and illustrative photos of the Barmah Forest in flood and a fish kill



4.4.2 Lakes

Lake systems of Australia are highly complex drainage structures that occur on the coast and inland regions of the continent. A number of different lake types are classified in *A directory of important wetlands in Australia* (Environment Australia 2001). They are:

- permanent freshwater lakes (>8 hectares), includes large oxbow lakes
- seasonal/intermittent freshwater lakes (>8 hectares), floodplain lakes
- permanent saline/brackish lakes
- seasonal intermittent saline lakes.

Permanent freshwater lakes, also termed lacustrine wetlands, are typically deep and fed by a reliable water source, except during times of drought. The morphology of these different lake types is primarily determined by the origin of the lake and underlying geology (Lewis 2010). However, it is climatic conditions and the nature of inflows that determine the water levels of these lakes (Price & Gawne 2009). Seasonal/intermittent lakes may fill during certain climatic conditions such as La Niña years, whilst permanent lakes may dry out during El Niño years.

Lakes can be closed or open systems, with water quality of open systems largely dependent on the quality of inflows, residence times and flushing rate. The diversity of biota is also greatly influenced by inflows and residence times. According to Timms (2001), the abundance of invertebrates and fish in lake environments fluctuates greatly relative to inflows. Birdlife tends to respond later in the flood cycle and where there are more persistent waters. Where waters are more permanent, there is a mosaic of environments that can support a variety of invertebrates and biota that feed on these invertebrates, such as birds and fish (Timms 2001).

Freshwater lakes in the arid zone of Australia are typically episodic due to the high variability of flows and the elevated evaporation rates experienced in these regions (Timms 2001). They are generally terminal lakes that have relatively high evaporative losses, such as Lake Eyre in Central Australia and Coongie Lakes in South Australia.

A number of lake systems in Australia are threatened by water abstraction and river regulation. Coongie Lakes on Cooper Creek and the Paroo Lakes in the Northern Murray–Darling Basin are primary examples of systems that could be influenced by irrigation practices upstream (Timms 2001). At the end of the Murray–Darling system, the Lower Lakes are affected by a combination of river regulation and abstraction (see Case study 8). Abstraction and regulation of flow can reduce lake water level variability—that is, the natural flooding and associated fluctuations in water level that trigger a number of ecological responses. Without this variability, some habitats may be lost or impaired (Timms 2001). For these reasons, variability of inflows should be a key focus for water managers responsible for the health of lake systems.

There are two key physical factors that influence the water quality of Australian freshwater lakes: wind stress and water level fluctuations.

Wind stress
Surface mixing that arises from wind stress can be observed as waves on the lake surface. However, depending on the energy and dynamics of the wind, there may also be vertical mixing attributed to turbulence (Monismith 1985). As lakes generally have lower velocities relative to their tributaries, wind stress can often be the driving factor of water quality, particularly where a lake is shallow and the turbulence leads to resuspension of materials on the lake bed.
Wind-driven circulation is common in shallow lake systems and can promote complete mixing.

Wind stress can have a significant effect on thermal stratification where it influences the middle layer of the water column (metalimnion). Monismith (1985) stated that, where the top layer (epilimnion) is shallow relative to the middle layer and bottom layer of a lake, the surface layer may be very active and well mixed relative to the layers below. However, wind action is something relatively beyond the control of water managers and other devices are used to promote lake mixing such as aerators.

Water level fluctuations
Water quality of freshwater lakes is largely dependent on the wetting and/or drying phase. The cycle of wetting and drying of lake systems was examined by Price & Gawne (2009), who developed conceptual models for inundation of a number of different lake types such as commonly wet freshwater lakes, periodically inundated freshwater floodplain lakes and non-floodplain (depression) lakes, and saline lakes. The inundation phase was directly linked to water chemistry and character. Discussed below are the key changes in water quality associated with inundation and recession of water level in a freshwater lake.

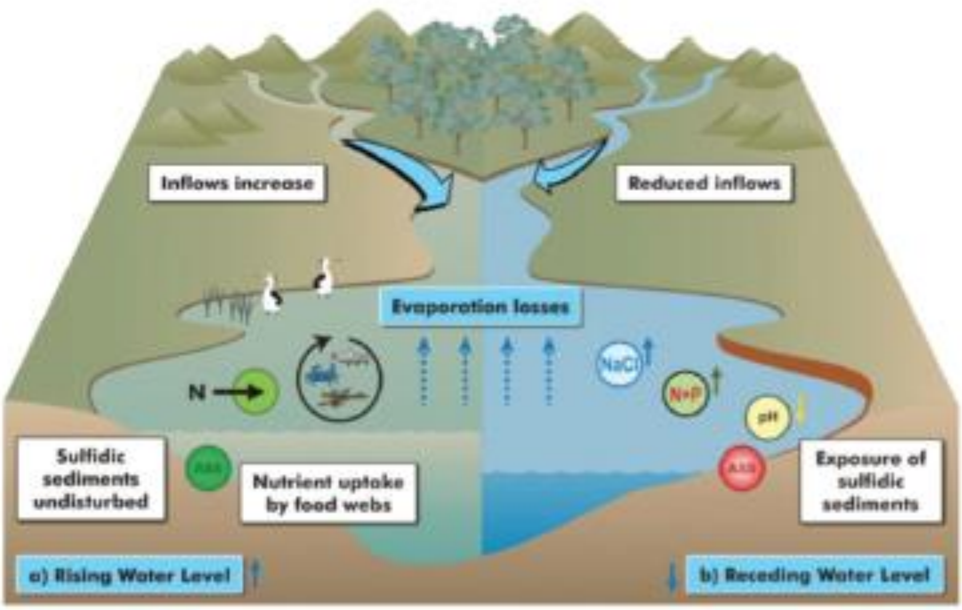
Inundation: water level rises—nutrients can enter lake systems attached to particles or in dissolved form when a flood occurs. Sediments on the lake bed can act as a store for these nutrients, which accumulate over time and support complex food webs. Nutrients and organic matter are imported into lakes via floodwaters, and nutrients are rapidly released through decomposition of organic material (Price & Gawne 2009). This can lead to high productivity, which, when combined with greater habitat availability associated with a rising water level, supports greater biodiversity. The uptake and transformation of nutrients and carbon, when lake water levels rise, is the role of primary and secondary producers.

Recession: water level recedes—evaporation and reduced inflows may lead to water quality decline. Poor water quality may be attributed to a decrease in the buffering capacity of the system as water levels recede (Price & Gawne 2009). Observed water quality changes can include increased concentration of nutrients, turbidity conditions, an increase in salinity and potentially thermal stratification depending on ambient temperatures (Price & Gawne 2009). For example, a decrease in inflows to Lake Bolac, Victoria, corresponded with a dramatic increase in the salinity levels of the lake, as large flow events that would otherwise flush the system via an effluent stream (Salt Creek) had not occurred for several years (Gervasi 2006).

In extreme cases, permanent freshwater lakes can recede until they dry out. In instances where a fall in water levels exposes lake sediments, there is potential for ASS to be exposed and become oxidised. Case study 8 provides an outline of how this issue can be managed in lake systems with ASS.

The conceptual model in Figure 19 illustrates the key water quality management issues associated with rising and receding lake levels and demonstrates the importance of managing lake levels. Exposure of ASS and the potential release of heavy metals arising from a lower pH are discussed in Case study 10.

Figure 19 Conceptual models of water level fluctuations in a freshwater lake



Case study 8 Lower Lakes, South Australia

The Lower Lakes, which form the terminus of the Murray River system in South Australia, comprise two large freshwater lakes that support a diversity of flora and fauna. Lakes Alexandrina and Albert, in conjunction with the Coorong, have been recognised for their international importance and listed under the Ramsar Convention on Wetlands (SEWPaC 2010). The overall environmental values for the Ramsar site include aquatic ecosystems; primary industries; recreation and aesthetics; and cultural and spiritual values. In order to maintain its ecological character, inflow and outflow regimes have been studied to determine the optimal flow regimes to support these environmental values (Heneker 2010, Lester et al. 2011).

Determining optimal inflow and outflow regimes for the lakes requires consideration of key water quality issues, particularly salinity and potential for acidification when water levels fall and expose acid sulfate soils (ASS). Due to the susceptibility to increases in salinity, lake outflows are controlled through barrages situated at five different localities separating the lakes and the Coorong to manage this issue (Heneker 2010).

Over the past decade, lakes Alexandrina and Albert have been under significant stress due reduced inflows of water. The low inflow conditions between 2006 and 2009 led to the lakes receding to unprecedented low water levels, resulting in exposure of up to 20,000 hectares of sediments (ASS) around the lake margins (Fitzpatrick et al. 2008, SEWPaC 2010). These sediments pose minimal threat of acidifying if they remain submerged and undisturbed. However, their exposure results in the formation of sulfuric acid (pH<4) that can be transported to the water body following rewetting, lowering lake pH when alkalinity is consumed (Fitzpatrick et al. 2010). A lowering of pH in sulfidic/sulfuric soil materials also led to the release of metals into the water (Simpson et al. 2008).

Figure 20 Mouth of the Murray River

Source: Theresa Myburgh (DWLBC)

The Murray-Darling Basin Ministerial Council recognised the seriousness of this environmental issue and approved a strategy to mitigate acidification in the Lower Lakes. Approved on 14 November 2008, the strategy aimed at managing water levels and monitoring alkalinity to determine the effectiveness of mitigation measures for neutralising acidity. Management of ASS risks in the Lower Lakes was subsequently identified within a State Priority Project under the

Intergovernmental Agreement on the Murray–Darling Basin, and funding was allocated to address the issue and retain the environmental values of the Lower Lakes.

The former Environment Protection and Heritage Council and former Natural Resource Management Ministerial Council developed National Guidance for the Management of Acid Sulfate Soils in Inland Aquatic Ecosystems (EPHC/NRMMC 2011). This document provides an overview of ASS across Australia, including the Lower Lakes, and measures for their management to mitigate impacts on aquatic ecosystems.

As part of Murray–Darling Basin reforms, the Murray-Darling Basin Authority has completed a Basin Plan, while the Australian Government is acquiring water entitlements with the objective of returning more water to the environment. These water entitlements become part of the Commonwealth environmental water holdings and are managed via an Environmental Watering Plan that will increase flows to rivers and wetlands. Environmental watering and revised river operations aim to achieve more 'natural' wetting and drying cycles and improving productivity while also flushing salinity and other toxicants from the system. In combination, this should improve water quality and reduce risks such as those posed by the exposure of ASS, algal blooms or salinity.

4.4.3 Reservoirs

Reservoirs are large natural or artificial lakes that are used for water supply purposes such as potable drinking water supplies and irrigation. They can be on-stream, which is a reservoir created in a river valley by the construction of a dam wall; or off-stream, which is built by excavation in the ground or by conventional construction techniques. Reservoirs are typically located in the high-rainfall headwaters of catchments. They harvest and store water, particularly during the wet periods, to meet catchment demands all year round.

Water quality in reservoirs is determined by the frequency, magnitude, duration and seasonality and quality of inflows and by in-lake processes. River water that flows or is pumped into reservoirs transport nutrients, sediments and other contaminants, which may then by affected by in-lake processes such as settling of suspended solids and biochemical processes (SCA 2009). Reservoirs that harvest water for potable drinking water supplies are best placed in protected forested catchments where rural and urban activities are restricted. This maximises the water quality of inflows by reducing the risk of contaminants. Bushfire run-off presents the highest risk of contaminant loads in these catchments. Other reservoirs require a lesser quality of water (for irrigation) and may have increased levels of development in the catchment.

One of the major water quality issues within reservoirs is algal blooms. There are many types of algal blooms, including toxic blue-green algal species (or cyanobacteria). They affect the amenity of the water, making it unsuitable for potable supply, stock watering and recreation. They can also foul water treatment processes. There are many factors that contribute to the types and abundance of algal growth (Table 3). Increased light, temperature and nutrient concentrations are the primary factors, the former explaining why algal blooms are most often observed in summer and autumn. Other factors contributing to the development of algal blooms include still, calm waters with decreased mixing (stratification), water depth and residence time of water in the reservoir (Ryding & Rast 1989).

Stratification is the separation of water column into density-based layers caused by differences in temperature or salinity (Perks 2007). Thermal stratification of layers affects deep reservoirs and hence is a more common phenomenon in temperate reservoirs than tropical reservoirs because of the pronounced seasonal variations in temperature (Meybeck et al. 1996). Stratification occurs in the warmer, drier months, when reduced inflows result in minimal mixing within the reservoir. The surface layer of the water column heats up, resulting in decreasing density. It then floats upon a colder, denser layer and there is a resistance to vertical mixing (Meybeck et al. 1996). The warm surface layer is known as the epilimnion and the colder water trapped beneath is the hypolimnion. Between the layers is a shallow zone called the metalimnion or thermocline, in which temperature changes more rapidly with depth than in other layers. Once the reservoir has stratified, a large amount of energy is required to break down the layers during summer. The breakdown of stratification, commonly referred to as 'turnover', occurs naturally by a decrease in surface temperatures and wind-induced mixing. This often occurs in autumn and remains throughout winter and some of spring until a rise in ambient temperatures may initiate next season's stratification (Perks 2007).

Table 3 Risk factors that can contribute to the risk of poor water quality and algal blooms

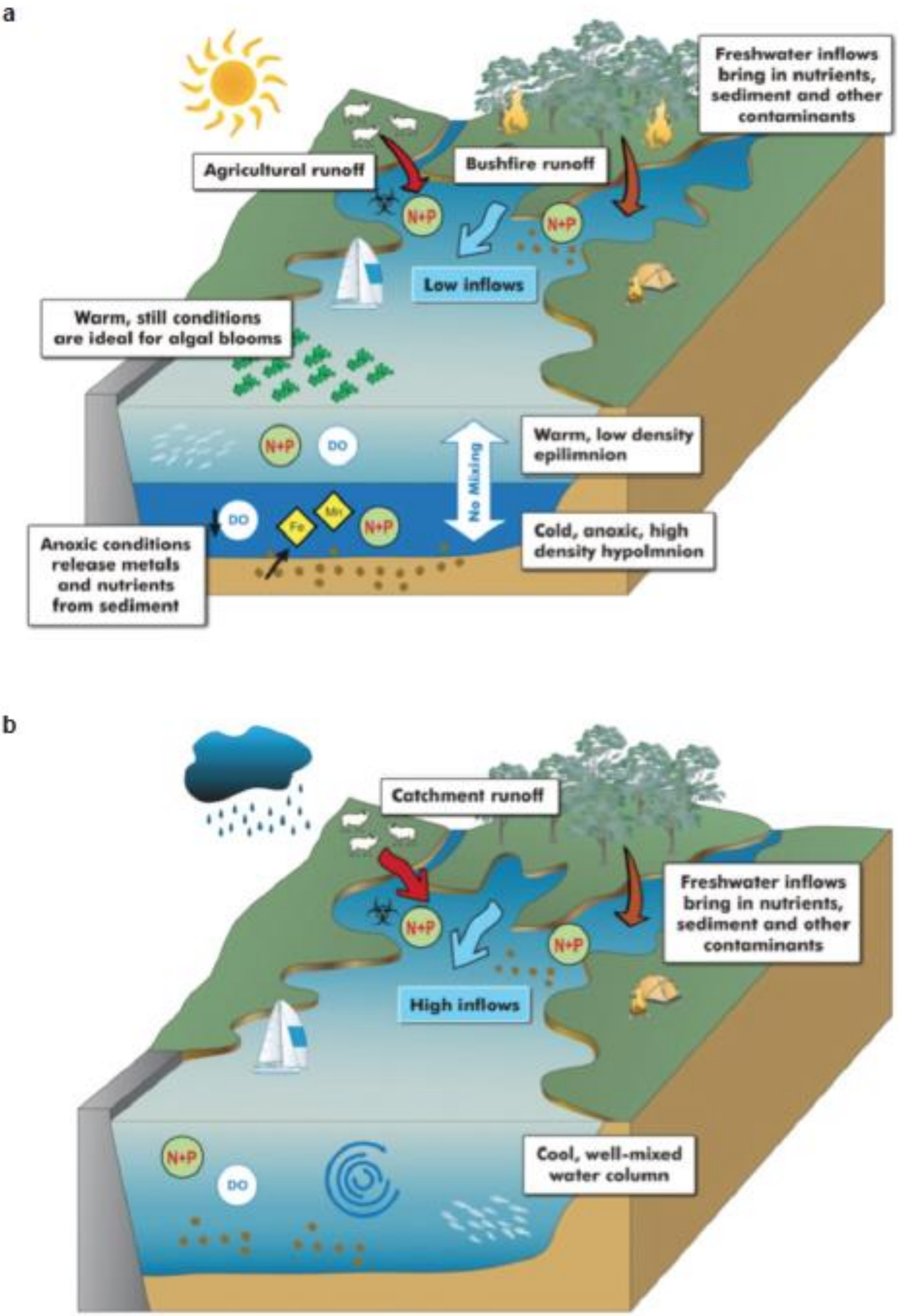
Risk factor	Description
Average and maximum depth (m)	Shallow water bodies are at greater risk of algal blooms because light is able to penetrate the full depth of the water column and heat to a greater degree than in a deeper reservoir.
Retention time (mean annual lake volume / mean annual outflow)	Short retention times do not allow for nutrients to be recycled and bound to sediments; thus, they are available for algal growth. Long retention times enable removal of nutrients from the water column through sedimentation and adsorption.
Volume and area quotients (catchment area / lake volume)	The larger the volume or area quotient, the greater the influence of the catchment with respect to nutrient loadings and the less reservoir dilution that can occur.
Strength of stratification	Under stratified conditions, nutrients can be released from sediment and later become available for algal growth. The stronger the stratification, the greater the potential for nutrient release from sediments and the greater the risk of algal blooms.
Frequency of algal blooms	Past history of algal blooms provides some indication of the likelihood of future algal blooms. A reservoir with a history of frequent blooms is more likely to bloom in the future compared to one with a low frequency.
Maximum algal abundance	The maximum abundance of past blooms provides an indication of the potential size of future blooms and reflects the available nutrient status.
Reservoir nutrient concentration	The water column nutrient concentration or annual load provides an indication of the potential nutrient pool available for algal growth. The greater this pool, the higher the risk of algal blooms.
Nutrient concentration in inflows	Nutrient concentrations in inflows provide an indication of the potential nutrient loads to the reservoir and hence the risk that this poses to blooms.

Source: Ryding & Rast 1989

Cycles of stratification and mixing of the water column are known to drive algal growth in nutrient-enriched reservoirs (see the conceptual model in Figure 21). Stratified conditions create calm, still and warm conditions at the surface that is favourable for the growth of algae. The bottom layer becomes depleted of oxygen and under such conditions releases nutrients from the sediment, which further drives algal blooms at the surface (see Case study 9). Other water quality issues can occur from stratification in reservoirs. This occurs when the reservoir offtake is below the thermocline. Under such conditions, cold-water pollution can occur downstream (see Section 4.3). Also, the anoxic conditions in the hypolimnion produce a reducing environment whereby manganese, iron, phosphorus, sulfides and ammonia are released from the sediments. These chemicals can alter the taste and odour of the water and can stain, which makes the water displeasing for potable water supply customers.

Stratification of reservoirs can be managed by artificially mixing the water. This mixing replenishes oxygen lost from the bottom layer, creates a more uniform temperature profile in the water column and prevents the chemical reduction of metals entering the water from the sediments (SCA 2009).

Figure 21 Conceptual model of a. stratified and b. mixed reservoir



Case study 9 Lake Argyle, Western Australia

Lake Argyle is an irrigation reservoir located within the Ord River catchment in the Kimberley Region of Western Australia. It was formed following the construction of the Ord River Dam in 1963–1972. The lake is the second-largest freshwater lake in Australia, with extensive shallow areas but also deep water in the drowned river canyons (Felsing & Glencross 2004). The lake has an average depth of approximately 10 metres and a maximum depth of 51 metres, and water levels within the lake fluctuate annually by between 2 and 10 metres as a result of variable flow, water use and evaporation (Felsing & Glencross 2004).

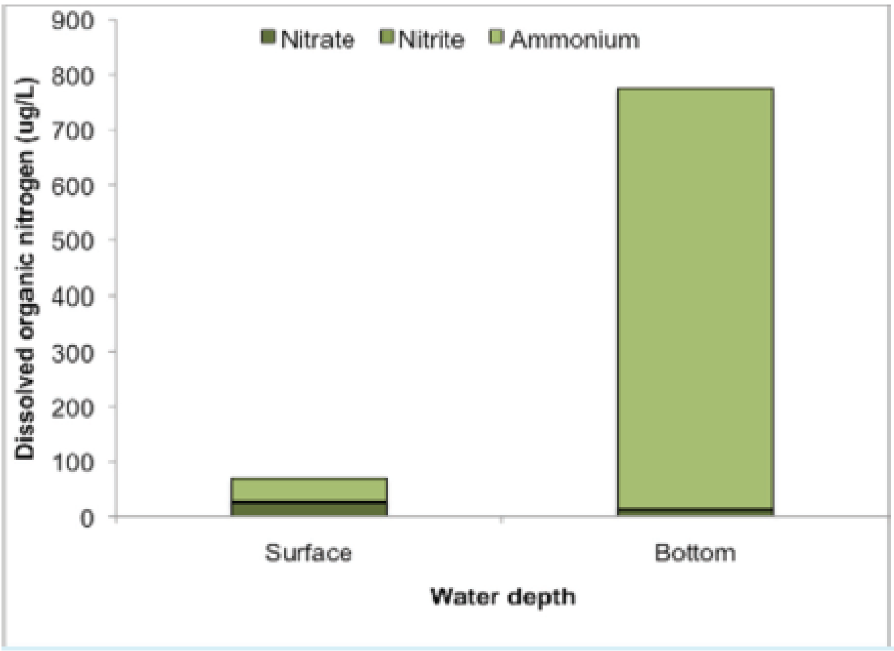
Lake Argyle supports a number of values and uses. The environmental values are aquatic ecosystems; primary industries; recreation and aesthetics; drinking water; industrial water; and cultural and spiritual values. The water within the reservoir supports a large-scale irrigation industry, domestic use and the production of hydroelectricity (Hale & Morgan 2011). The lake and downstream environments support tourism (lake cruises and fishing trips), aquaculture and visual amenity (Felsing & Glencross 2004).

Lake Argyle has a full supply level capacity of over 10,000 gigalitres and additional temporary flood storage. Storage fluctuates seasonally, peaking in March/April at the end of the wet season, and is lowest in October/November at the end of the dry season (Hale & Morgan 2010). Storage volume is influenced by rainfall and catchment inflows (as a result of rainfall), evaporation and release for irrigation and power generation. Average annual inflows are approximately 4,250 gigalitres per year but can range from less than 200 to as much as 15,000 gigalitres per year (Hale & Morgan 2011).

Lake Argyle seasonally stratifies as surface waters heat up with increasing air temperatures and solar irradiation during the build-up to the wet season. Algal blooms occur frequently during this time. As the weather cools in the dry season (April to October), the temperature of the epilimnion drops to a temperature approaching that of the hypolimnion (Felsing & Glencross 2004).

Lake turnover occurs between March and July, when surface waters have cooled to the extent that only the slightest wind movement is sufficient to cause mixing. As the poor-quality water (for example, water with low dissolved oxygen, high ammonia and high metal content) from the bottom rises to the surface, surface water quality is reduced (Figure 22). In the past this has caused problems for the barramundi stocked in the lake/reservoir with increased fish stress and in some cases mortality. However, because the turnover occurs with little warning, it is difficult for the industry to prepare. The impact of lake turnover on aquaculture (namely Barramundi) depends on the volume and water quality characteristics of the epilimnion and hypolimnion before mixing.

Figure 22 Average dissolved organic nitrogen in Lake Argyle, May 2003



Source: Hale & Morgan 2011

4.5 Estuaries and marine environments

Estuaries and near-shore marine environments are highly productive ecosystems due to the combination of freshwater inflows and marine tidal influence. Changes to freshwater inflows and tidal flushing from catchment modifications will affect physical, chemical and biological processes within these ecosystems. This section addresses how these processes affect water quality in salt-wedge and heavily modified estuaries and near-shore marine environments.

4.5.1 Salt-wedge estuaries

Estuaries have a changing mixture of fresh and saline water and experience tidal flows. The ecology of estuaries is complex and has strong linkages to other ecosystems (Pierson et al. 2002). For example, the brackish estuarine water protects the receiving bays from high sediment loads by causing suspended particles from turbid freshwater inputs to flocculate and settle out. As a result, there is a plentiful supply of benthic organic matter, which, combined with the nutrient-rich freshwater inputs and the highly oxygenated tidal water, means that estuaries are highly biologically productive ecosystems (Pierson et al. 2002). The dynamic physical and chemical nature of estuarine environments also makes them tolerable to a large diversity of freshwater and marine species.

Compared with rivers, measuring and maintaining water quality in estuaries is more complex due to the gradient of the fresh and saline waters and the resultant dispersal processes of nutrients and contaminants. The health of estuaries depends on the intricate interactions between the physical, chemical, biological, water quality, sediment movement and salt wedge characteristics. The freshwater inputs influence all these characteristics and contribute to the vitality of the environmental values/assets of these estuaries.

Significant threats to estuaries result from reduced freshwater inputs. Some of the potential effects include increased salinity and vertical stratification of the water column and the penetration of salt wedges upstream (potentially contaminating groundwater and surface water resources). This increases the frequency of benthic anaerobic conditions (it can cause the release of pollutants from sediment) and the loss of biodiversity. Reduced freshwater inputs can also cause increases in erosion due to the decreased sediment flux (Pierson et al. 2002). Environmental cues (that is, saline gradients) for species to spawn can also be disrupted. In extreme cases, reduced freshwater flows can cause the mouth of the estuary to completely or partially close up, which affects the saline gradient and water quality and obstructs migratory patterns of biota (Pierson et al. 2002).

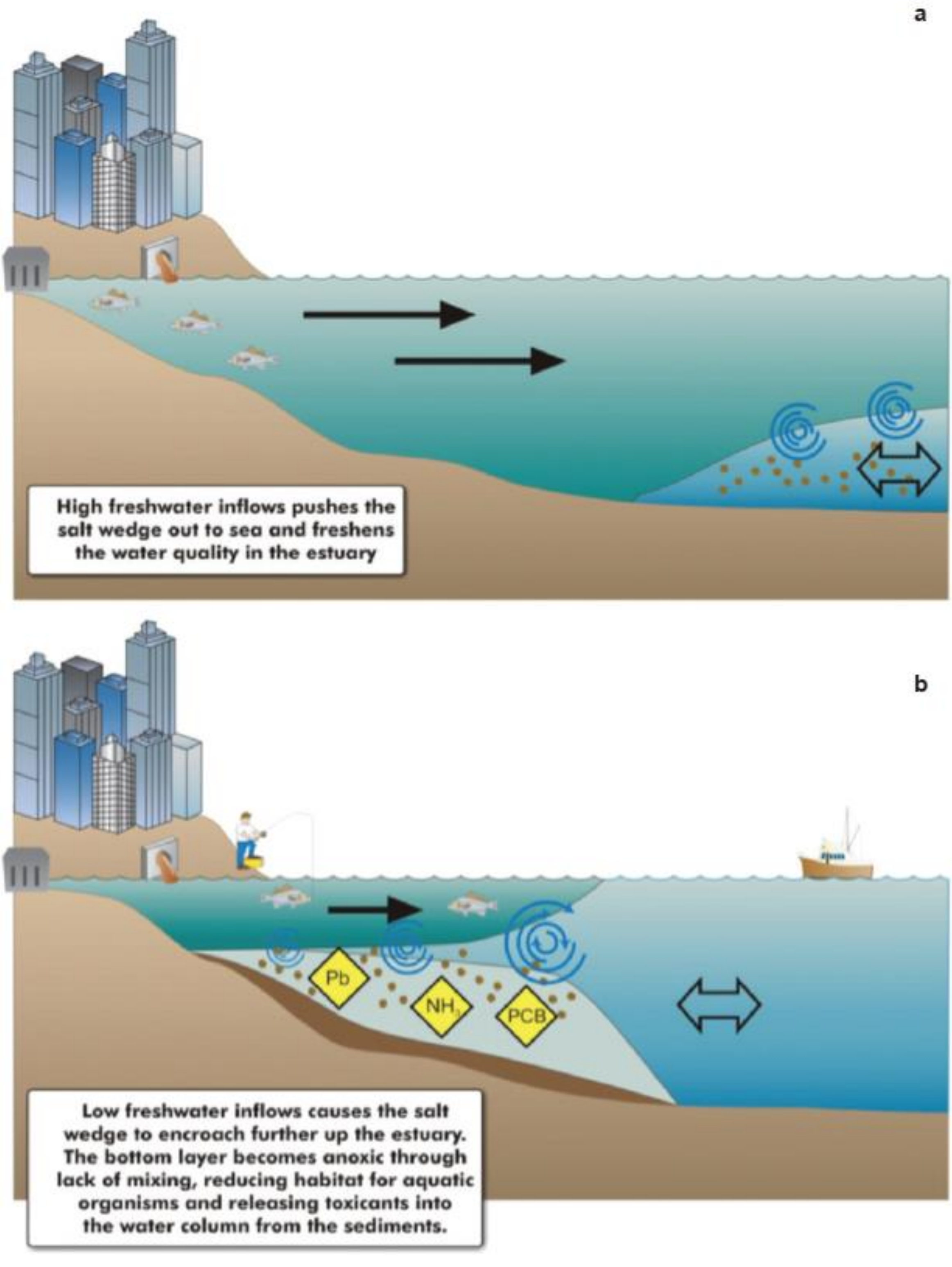
Salt wedges form in estuaries with enough freshwater inflows that it pushes back the sea water. This creates a sharp boundary that separates an upper, less salty, layer from an intruding wedge-shaped salty bottom layer (for example, the Yarra River in Victoria—see Case study 10). The lack of mixing between the two layers is due to the density differences between fresh and salt water. Salt water is denser than fresh water because of the high concentrations of dissolved salts. Fresh water floats on top of the sea water in a layer that gradually thins as it moves seaward. The denser sea water moves landward along the bottom of the estuary, forming a wedge-shaped layer that is thinner as it approaches land.

The bottom seawater layer moves up and down the estuary with the tides. The top freshwater layer is unidirectional and flows out to sea. A velocity difference develops at the upstream interface between the two layers, creating shear forces, which gradually mixes the sea water upward with the fresh water.

Under high freshwater inflow conditions, the force of the water pushes the salt wedge towards the estuary mouth and freshens water quality in the estuary (see the conceptual model in Figure 23a). However, under low-flow conditions, the salt wedge can encroach further up the estuary. The lack of mixing between the top (fresh) and bottom (saline) layers creates an anoxic environment that can cause the release of nutrients and toxicants (like heavy metals and pesticides) from sediments. It also reduces the habitat available for fish and invertebrates (see the conceptual model in Figure 23b). Under very low flow conditions, the flow of the freshwater layer may be slow-moving on top of the salt wedge. This shallow layer creates calm, still and warm conditions which favour the growth of algal blooms.

Salt wedges can be managed by delivering the freshwater inflows required to prevent the encroachment up the estuary. This inflow volume can be determined by hydrodynamic modelling.

Figure 23 Conceptual model of salt-wedge estuaries under a. high and b. low freshwater inflows



Case study 10 Yarra River Estuary, Victoria

The Yarra River Estuary is located in the Melbourne Central Business District and brings aesthetic, recreational, cultural and aquatic ecosystem environmental values to the city.

The Yarra River Estuary has been classified as a 'salt-wedge' estuary (Beckett et al. 1982). The hydrodynamics of the Yarra estuary are influenced by the freshwater inflows over Dights Falls and the interaction of this flow with the salt water that extends upstream from Hobsons Bay under tidal influence. The surface layer flows continually downstream to Hobsons Bay, while the lower layer moves up and down the estuary with inflowing and outflowing tides. The lower Yarra Estuary has been modified over time to form a series of docks and wharves and is dredged to maintain access (Beckett et al. 1982).

Toxicant contamination (particularly heavy metals and polychlorinated biphenyls) in the sediments of the Yarra Estuary is an ongoing concern for the community (Ellaway et al. 1982, GHD 2006). In 2005 the Victorian Government issues health warnings about consumption of fish and eels from the estuaries due to levels of polychlorinated biphenyls above Maximum Residue Limits in food (EPA Victoria 2007). The estuarine dynamics influence the sources and remobilisation processes that allow the accumulation and release of such toxicants in the estuary.

Sources

The Yarra Estuary has a long history of urban and industrial activities and it has only been in the last 30 years that industrial discharges have ceased (EPA Victoria 2007). Although there has been considerable progress made to clean up the water of these river systems, the legacy of past activities is evident in the accumulation of toxicants in the sediments of the estuaries (GHD 2006). Current levels of urbanisation and other catchment influences are also continually adding to these toxicants' concentrations. Sediment sampling conducted by the EPA in 2005 showed heavy metal contamination consistent with an urban catchment in the lower reaches of both rivers. There were also some high heavy metal levels, particularly for mercury and lead recorded around the industrial Yarraville Precinct (GHD 2006).

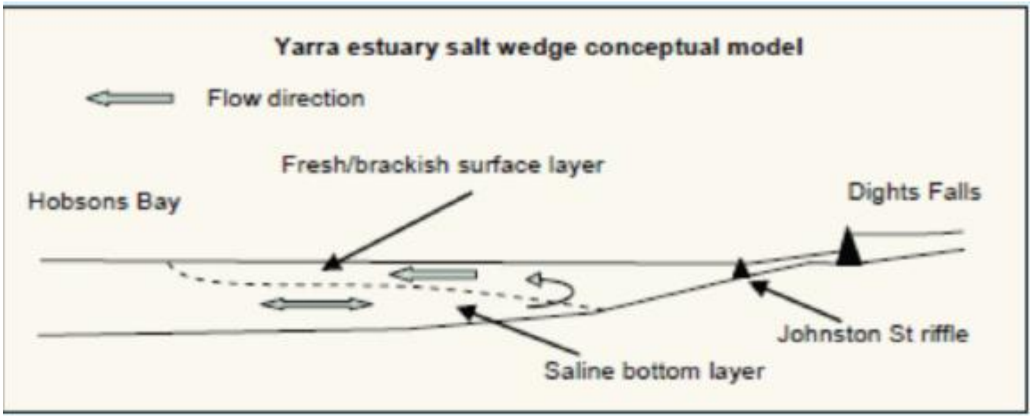
Estuaries are a depositional area for suspended particulate matter (Ellaway et al. 1982). When the sediment and toxicant-laden freshwater and stormwater inflows meet the higher salinity estuarine environment, the sediment particles flocculate together, settle out of the water column and accumulate on the stream bed. Many toxicants, including heavy metals, nutrients and pesticides, are known to bind to these sediment particles and therefore accumulate along with the sediment on the bottom of the estuary. These toxicants can accumulate to toxic levels and can bioaccumulate in bottom-dwelling organisms and enter the food chain (EPA Victoria 2007). The estuarine sediments contain higher concentrations of cadmium, copper, lead, mercury, tin and zinc than the corresponding sediment fraction in the freshwater section and Hobsons Bay region (Ellaway et al. 1982).

Remobilisation

The hydrodynamics of the estuary can adversely affect its water quality. Prolonged low freshwater inflows that result in a long residence time and the encroachment of the salt wedge can lead to anoxic conditions. This anoxic bottom layer reduces dissolved oxygen levels at the sediment/water interface, which controls the fluxes of nutrients, heavy metals and other toxicants (ammonia, hydrogen sulfide, pesticides and organics) from the sediments (Pierson et al. 2002). Contaminants are released from the sediments to the water column when the sediment/water interface is anoxic and vice versa when it is oxygenated.

Turbulent high flows of fresh water entering the estuary can also disturb the bed sediments and release toxicants and nutrients. Dredging of the sea bed has the same effect but on a greater scale, with much larger amounts of sediment becoming exposed.

Figure 24 Salt wedge dynamics in the Yarra Estuary



4.5.2 Heavily modified estuaries

Estuaries are the confluent point of sediments, nutrients, run-off and groundwater flows yielded by a catchment (Pierson et al. 2002). The quality and quantity of fresh water inflows into estuaries are sensitive to catchment landscape processes. With a large proportion of Australia's population living in coastal regions, catchment areas have been subject to landscape modification, be it for urban development, industry or agriculture. Landscape modification has involved land clearing, river channel modification (diversions, irrigation drains and dams) and changes to surface properties (pasture and urban land use). These land use changes affect sediment and nutrient transport, rainfall–runoff balance, river flow regimes and water quality.

In a modified catchment, water is subject to competing demands for use in industrial processes, as irrigation supply for agriculture and for potable residential supply. It is also important to consider environmental flows needed to maintain ecological function in a system. Water supply is also temporally variable with climatic fluctuations in rainfall. The amount of rainfall received, how it is received (short duration / high intensity or long duration / low intensity) and the spatial distribution all affect catchment run-off infiltration balance. This balance determines whether water flows as surface run-off or groundwater flow into rivers and hence the volume and timing of fresh water flows entering an estuary. This natural variability coupled with anthropogenic influences results in variable flow regimes entering an estuarine system.

The tidal flushing that occurs in an estuarine environment depends on the freshwater inflows and the morphology of the estuary mouth. The volume and velocity of freshwater inflow affects the tidal reach, salinity levels and extent of saltwater and freshwater mixing. The morphology of the estuary mouth at the ocean is also particularly important, as this influences the amount of sea water coming into the estuary and also the amount of fresh water flowing out. Estuarine mouths can close under very low freshwater inflow conditions. This can significantly affect the flushing of sediments and nutrients and the resultant environmental state of the estuary.

Estuarine water quality is sensitive to catchment processes. Drainage networks flowing into an estuary transport nutrients and sediments, with volumes of each dependent on flow regimes. This transport and type of nutrients and sediments will specifically relate to flow pathways, flow duration and magnitude and the occurrence of peak flow (channel-forming) events. Estuaries have very low relief, which means that small changes—for example, roads and levees—can have significant impacts on hydrological flows and downstream environments reliant on those flows. Land clearing and increased surface run-off regimes can also increase the amount of water, sediment and nutrients transported into rivers. Resulting in-stream flows in rivers will influence surface water residence time and flow velocities, both of which will affect processes of nutrient attenuation within the system. These factors all influence sediment transport, stream morphology and connectivity and nutrient flushing downstream, ultimately influencing water quality in the receiving estuary. Catchment modifications and changed flow regimes can also disturb or aggravate ASS. Understanding this connection between upstream and downstream processes is important to effectively manage an estuarine environment.

Nutrient enrichment is a widespread water quality issue in rivers as well as estuaries. This is caused by application of fertilisers, intensive stocking of animals and wastewater discharges from sewage treatment works. The impact of this is a function of the total nutrient load, the chemical form of the nutrients and water residence times (Harris 2001). With reduced freshwater flow volumes and decreased outflow to the ocean from an estuary, nutrients can accumulate and build up in the estuaries. Increased nutrient loads stimulate the growth of plants, particularly macro-algae. The species of algae will be dependent on other environmental conditions but often tend to be fast-growing species able to cope with changing salinities, such as red and green algae (rhodophytes and chlorophytes).

Estuarine dynamics depend on a range of variables unique to each system. These variables include catchment land use, existing environmental state, current climate and anthropogenic modifications to the estuarine environment. Examples of the potential physical, biological and ecological effects of low freshwater inflows and reduced tidal flushing are summarised in
Table 4.

Table 4 Reduced freshwater flows and tidal flushing in estuaries and resultant ecological effects

Water flow regime	Physical and chemical processes	Potential ecological effects
Low freshwater inflows	• higher reach of saline marine water up the estuary (salt wedge) and associated higher salinity levels at depth • loss of flow-induced currents and vertical mixing • stratification induced deoxygenation, causing the releases of toxicants from estuary-bed sediments (Pierson et al. 2002)	• salinity levels determine extent and type of biota • physiological stress to flora and fauna dependant on tolerance levels • species competition • shift in biotic community structure • reduced suspension of eggs and larvae

Water flow regime	Physical and chemical processes	Potential ecological effects
	• loss of connectivity between estuary and river systems and adjacent water bodies and wetlands, with decreased water depth • decreased flushing of sediments and organic material from estuary bed • low dissolved oxygen at depth from resident organic load • reduced inputs of nutrients and organic material from catchment • reduced dilution of pollutants.	• potential for algal blooms in upper to middle estuary • impacted upstream–downstream species migration • loss of suitable breeding and nursery habitat—that is, loss of hard substrates with sediment accumulation.
Reduced tidal flushing	• with low freshwater flows—sediment infill from marine environment (potential for mouth closure and reduced tidal flushing) • build-up of sediments and nutrients in the system • increased plant growth—formation of organic ooze on estuary bottom • reduced oxygen content in sediment—release of nutrients if built up in sediment • increased salinity through surface evaporation in warmer temperatures.	• impacted marine–estuary species migration • algal blooms • increased plant growth leads to further decreased oxygen content in water at night (Brearley 2005) • loss of system diversity, including invasion by weeds.

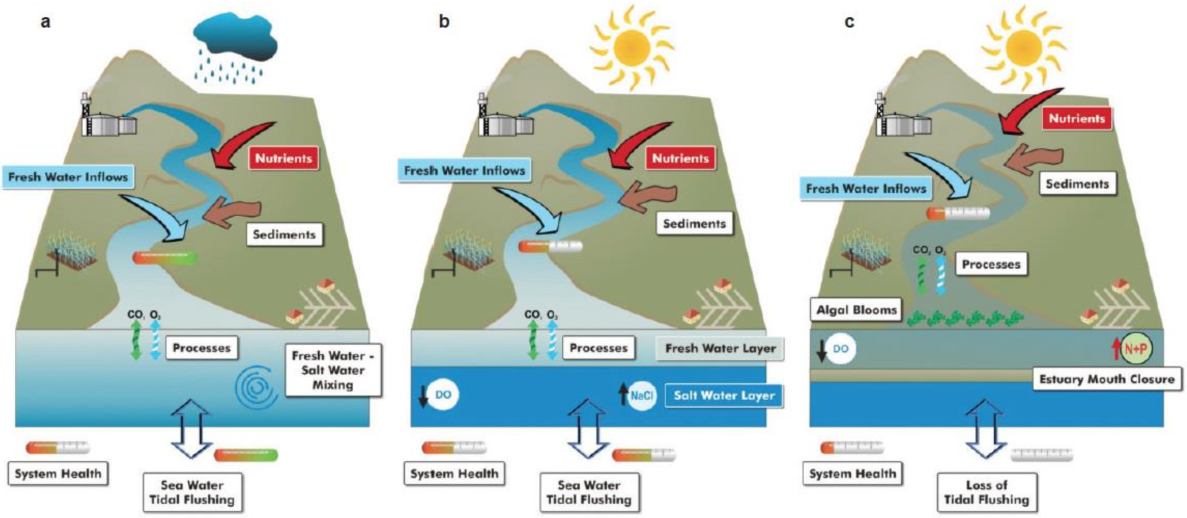
A large proportion of estuary systems around Australia are situated within a catchment that has been subject to land use modification, presenting competing demands for water and affecting natural flow regimes. The Murray–Darling Basin is a classic example of how land use and water allocations affect water quantity and quality within a system and the connection between upstream and downstream processes. The Swan–Canning Estuary in Western Australia is at the centre of the state’s major city, Perth, and has experienced a range of issues, such as surrounding urban development and also low rainfall. The Peel–Harvey Estuary, also in Western Australia, is a good example of an estuary in a modified landscape and provides for interesting discussion of management options implemented to manage water quality. This is explored in Case study 11.

The conceptual models in Figure 25 illustrate a modified estuarine system showing the impacts to water quality and ecosystem condition under:

a) good fresh water inflows with seawater tidal flushing and mixing, resulting in average to good system health
b) a reduction in fresh water inflows with seawater tidal flushing and stratification of fresh and salt water layers, resulting in average system health

c) ongoing reduced fresh water inflows resulting in closure of the estuary mouth and loss of tidal flushing, increased instances of algal blooms, and poor system health.

Figure 25 Conceptual models for a modified estuarine system showing a. good fresh water inflows; b. a reduction in fresh water inflows and c. ongoing reduced fresh water inflows and estuary mouth closure and the impacts to water quality and system processes



Case study 11 The Peel–Harvey Estuary, Western Australia

The Peel–Harvey Estuary in south Western Australia forms part of the Peel–Yalgorup system, a designated Ramsar site. The system comprises the interconnected Peel Inlet (75 square kilometres) and Harvey Estuary (61 square kilometres). The environmental values are aquatic ecosystems (Peel–Yalgorup System Ramsar site), commercial and recreational waterway, fish and shellfish harvesting, aesthetics and cultural and spiritual values. Flowing into the estuary are numerous rivers and agricultural drains, the main rivers being the Serpentine, Murray and Harvey rivers. The majority of flows entering the estuary are from the Murray River, which contributes approximately 50 per cent of flows annually; and the Harvey River, contributing approximately 30 per cent. Rainfall in the catchment area is winter dominant, with about 90 per cent of the water reaching the estuary between May and October. The volume of water flowing into the estuary varies from year to year depending on rainfall amount and distribution. In winter, surrounding areas of wetland habitat are also inundated if water flow is sufficient.

The estuary is connected to the ocean by two channels. One is the natural Mandurah Channel—a narrow stretch of water about five kilometres long which has been partially walled. The second channel is a man-made, two and a half kilometre cut, being the Dawesville Channel made to promote tidal flushing within the system.

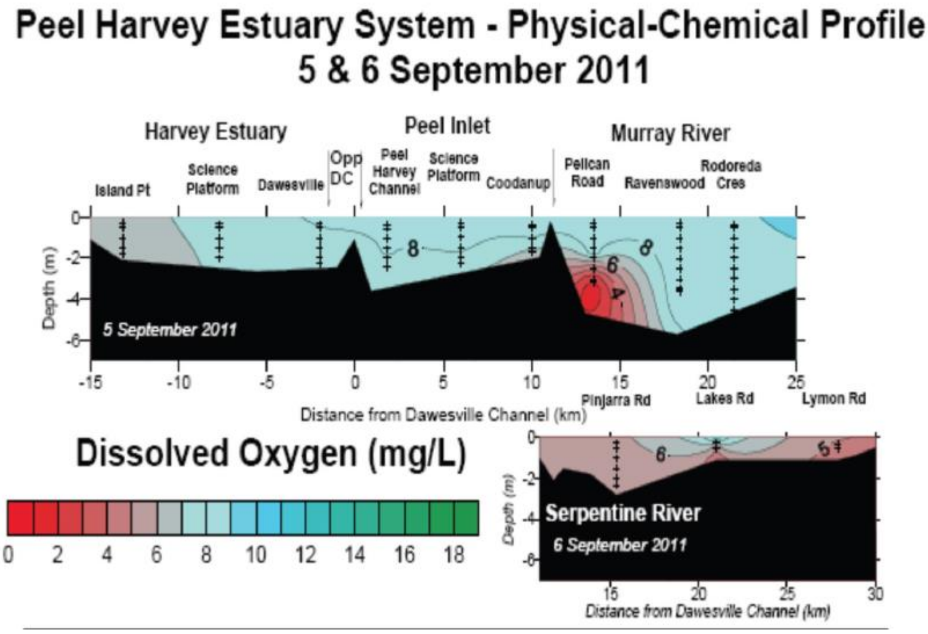
The surrounding catchment area has been modified for a variety of land uses, including residential developments, industry and agriculture. This has involved significant land clearing (around 85 per cent) and modification of drainage patterns. Land clearing has led to an increase in surface run-off, whilst dams constructed on-stream in the upper catchment have reduced stream flows. A large number of drainage channels have also been constructed, predominantly for agricultural purposes to provide irrigation supply, and also provide a conduit for water transport from agricultural land to the lower estuary; hence this has affected the pre-existing flow regimes by reducing surface water retention in the catchment, increasing peak flow rates and decreasing the duration of flow events (PHCC 2010). Given the agricultural land use and associated application of fertilisers, a large amount of nutrients has been transported into the estuary. The straight-form channels of the constructed drains provide a pathway for rapid transportation of sediments and nutrients to the estuary. These anthropogenic modifications, coupled with natural rainfall variability, determine the overall condition of the Peel–Harvey system at any given time.

Prior to construction of the Dawesville Channel, the large amounts of fertilisers from agriculture increased nitrogen and phosphorus levels in the estuary. This was exacerbated by the fact that the system had poor tidal flushing, which allowed nutrients to build up in the system. This lead to blooms of cyanobacteria, *Nodularia spumigena* in the Harvey Estuary and extensive macroalgae growth in the Peel Inlet (PHCC 2010). Over time, nutrients have built up in sediments and algal growth has led to the formation of organic ooze on the estuary bottom (Brearley 2005). This forms a feedback cycle whereby the organic ooze decreases oxygen content in bottom sediment, which in turn leads to release of further phosphorus into the water column, promoting more plant growth. The problem of eutrophication in the estuary then has impacts on fish populations, recreational fishing practice and use of the estuary for other forms of recreation.

The Dawesville Channel was constructed in 1994 to promote tidal flushing in the estuary. This has improved water quality in the lower estuary in the main bodies of the Peel Inlet and Harvey Estuary. The increased flushing has led to increased salinity in the lower estuary to levels which are too high for *Nodularia spumigena* to germinate (Brearley 2005). Better mixing of salt and fresh water has also allowed dissolved oxygen concentrations in the main estuary to become more stable. Conditions in the Harvey Estuary and Peel Inlet range from hypersaline in the summer months to saline and well mixed in the winter months.

However, not all problems in the system have been solved. Rather, the dynamics and areas of impact have shifted. Greater tidal flushing has allowed movement of a salt wedge further upstream into the lower reaches of the Murray and Serpentine rivers. This has led to stratification of the water column during lower freshwater flows. Low dissolved oxygen can be observed lower in the water column for both the Murray River and Serpentine River and in parts of the Harvey Estuary. These low dissolved oxygen conditions develop near the estuary bed, which can lead to release of nutrients from bed sediments (Figure 26). This is an issue for the Peel–Harvey system given the excess nutrient loads which have accumulated in the sediments. This has led to an increase in toxic cyanobacteria and dinoflagellate blooms in the lower Murray and Serpentine rivers (PHCC 2010).

Figure 26 Dissolved oxygen profile of the Peel–Harvey Estuary, September 2011



Source: DOW 2011

The Peel–Harvey estuary shows the complex nature of estuarine systems and how land use and catchment processes, both current and historical, need to be considered for effective management. Further management plans in the Peel–Harvey catchment include reforms to the management of drainage channels, increasing surface water resident time in the upper and middle catchment, restoration of river reaches, revegetation and assessment of ecological water requirements.

4.5.3 Near-shore environments

The export of sediments and nutrients from rivers drives processes that affect near-shore ecosystems. Changes in water quality properties from freshwater flow relate to key ecological aspects of freshwater, estuarine and marine species, including distribution and community composition, food web structure and productivity (Gillson 2011).

The effect of freshwater flows on water quality is dependent upon the properties of the inflowing and receiving waters and the magnitude of the flows. Freshwater flows affect a range of water quality properties of the receiving coastal waters, including temperature, salinity, turbidity, total and dissolved nutrients, suspended solids, organic matter content, dissolved oxygen, and presence of chemical pollutants (Gillanders et al. 2011, Lewis et al. 2009).

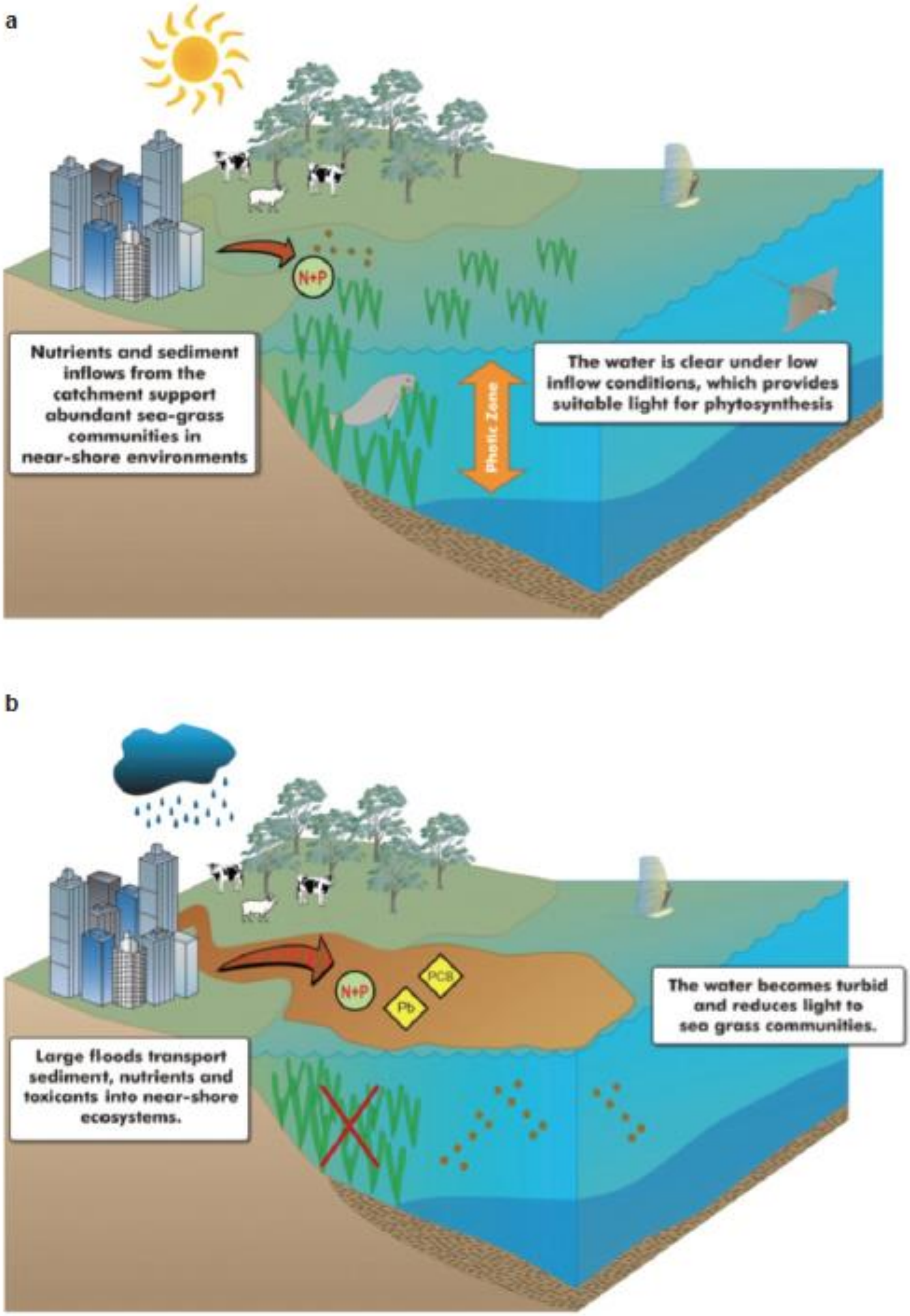
Discharge from flooded rivers produces plumes of high turbidity in receiving waters (see conceptual model in Figure 27). The plumes are particularly distinct in coastal environments that have naturally clear waters. First-flush events have the highest concentrations of sediment and nutrients (Butler & Burrows 2006, Furnas et al. 1997) and are associated with transport of pollutants including heavy metals, pesticides and herbicides, which can occur at their highest concentrations at the plume front (Lewis et al. 2009). Deposition of suspended sediment occurs in the near-shore environment of the coast and estuaries, which can function as sediment traps (Packet 2007). Dissolved nutrients are transported much further from the coast and elevated nutrient concentrations can occur over a hundred kilometres from the coast (Devlin & Brodie 2005).

Discharges from river systems are an important source of carbon for sustaining food webs of these ecosystems. The importance of freshwater flows for near-shore environments is demonstrated by the many examples of positive relationships between commercial fisheries catches and catchment rainfall (Gillson 2011).

The alteration of flows from impoundments and water abstraction in regulated river systems affects sediment delivery, erosion processes, river plume fronts, nutrient inputs, salinity regimes and dissolved oxygen concentrations (Gillson 2011). The reduction in delivery of fresh water has direct effects on the water quality variability of receiving coastal waters and also the productivity of the coastal environments (Gillanders et al. 2011). Since freshwater flows are important in providing variability to water quality and aquatic habitat to which many coastal species are adapted, reduced flow has a negative effect on recruitment abundance and diversity (Gillson 2011).

Whilst the supply of nutrients and sediments to near-shore environments is integral to their functioning, delivery of excessive loads have negative impacts upon the health of the ecosystem (see the conceptual model in Figure 27). Nutrients and sediment inflows from a catchment support abundant seagrass communities in near-shore environments. The water is clear under low inflow conditions, which provides suitable light for photosynthesis. Large floods transport sediment, nutrients and toxicants like lead and PCBs into near-shore ecosystems. The water becomes turbid and reduces light to seagrass communities. Land use practices, in particular agriculture, has resulted in increased soil erosion and nutrient loss from catchments (Brodie 2002). They also contribute harmful chemical such as herbicides (see Case study 12).

Figure 27 Near-shore environments under a. low and b. high flow conditions



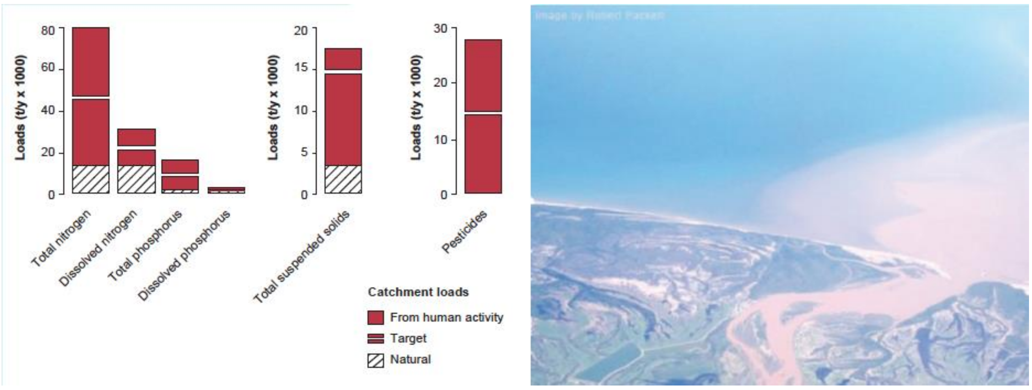
Case study 12 Great Barrier Reef catchments

The Great Barrier Reef (GBR) is the largest and best-known coral reef ecosystem in the world, spanning 2,300 kilometres (Reef Plan 2011). The environmental values are aquatic ecosystems; aquaculture; recreation and aesthetics; and cultural and spiritual values. River catchments on the north-east coast of Australia which drain into the GBR include those of the wet tropics rivers in the north, totalling an area of (22,000 square kilometres), and the large wet–dry tropical southerly catchments of the Fitzroy River and Burdekin River, with an area approximately 15 times larger (297,000 square kilometres).

Differences of nutrient and sediment quantities exported from rivers to coastal waters are strongly influenced by catchment area and the associated land uses (like grazing in the Fitzroy and Burdekin catchments or coastal cropping in the wet tropics) (Australian Government and Queensland Government 2011). The largest contribution of total suspended sediment load is from the Burdekin and the Fitzroy regions (4.7 and 4.1 million tonnes respectively) (Reef Plan 2011). Annual loads of dissolved nitrogen are 31,000 tonnes from agricultural fertiliser use. The total annual pesticide loads are approximately 28,000 kilograms and the highest loads are from the Mackay–Whitsunday and wet tropics regions (approximately 10,000 kilograms each per year) (Australian Government and Queensland Government 2011) (Figure 28a).

Most nutrient and sediment load is exported during floods and produces discharge plumes that are very distinctive in the clear coastal waters of the GBR (Figure 28b). High-rainfall events can rapidly mobilise very large quantities of suspended sediment and nutrients. In the wet tropics, of suspended sediment, 858 tonnes of nitrogen, 314 tonnes of phosphorus and 2,214 tonnes of organic carbon were exported from the Johnstone River over four days following rains from Cyclone Sadie (Hunter 1997).

Figure 28 Nutrient, sediment and pesticide loads and a flooded river plume



Source: after Reef Plan 2011. Photo from R Packet.

When flood waters reach the coast, water quality in the plume changes rapidly with the falling flow velocity and mixing with saline marine waters. For a typical flood event in the Fitzroy River, about 90 per cent of the suspended sediment is deposited close to the river mouth, extending only five kilometres into the coastal waters. Although sediment transport distances and rate of deposition are dependent upon the sediment-trapping efficiency of the estuary and the magnitude of the flood discharge, the impacts are generally within 10 kilometres of the river mouth and the effect on coral reef communities is limited (Devlin & Brodie 2005, Packet 2007) (see Figure 28b).

In contrast, dissolved nutrients can be transported great distances within flood plumes into the generally nutrient-limited waters of the GBR. Dissolved inorganic nutrients can disperse within the plume due to the high turbidity which limits light availability, phytoplankton growth and nutrient uptake and thus have the ability to influence biological activity on much of the inner shelf of the GBR (Devlin & Brodie 2005).

Development has occurred throughout the catchment of the GBR, and natural vegetation has been replaced with agricultural land use practices, including grazing and irrigated cropping—particularly sugar cane, which is supported by the higher rainfall of the wet tropics (Kelley et al. 2006). The extensive clearing of vegetation and agricultural development has resulted in a sharp increase of sediment, nutrients and pesticide concentrations in rainfall run-off since European settlement. Very high rates of soil loss are associated with a threefold increase of phosphorus and fivefold increase of nitrogen entering the coastal waters from GBR catchments as a result of agricultural development (Kelley et al. 2006). Pollutants associated with agricultural development also have an impact on the receiving coastal waters and ecosystems. Elevated herbicide concentrations, associated with sugar cane cultivation in catchments of the wet/dry tropics and the wet tropics, can be transported to, and disturb, sensitive marine ecosystems already affected by other pressures (Lewis et al. 2009).

Whilst the pollution of coastal regions of the Great Barrier Reef World Heritage Area (GBRWHA) is dominated by river discharge associated with agricultural development of the adjacent catchments (Devlin & Brodie 2005), the flood flows are important for affecting water quality and habitat and sustaining productivity, food webs and commercial fisheries. Coastal environments that are naturally low in nutrients, including the GBR, are particularly dependent upon nutrients derived from terrestrial sources (Gillson 2011). The influence of freshwater flows from GBR catchments on salinity gradients, suspended sediment, dissolved oxygen and nutrient concentrations are integral to near-shore fishery production (Gillanders et al. 2011). In the near-shore receiving environments of the Fitzroy River, wet season freshwater flows are important drivers of finfish growth and the blooms of prey species upon which they feed; the reduction of wet season flows from water resource development could impact upon fisheries production and the ecosystems which sustain them (Halliday et al. 2008).

5 Synthesis

Water quality has a close but complex relationship with water quantity. The nature of the relationship depends strongly on the individual catchment and type of aquatic ecosystem. Changes in the quality or quantity of water may result in immediate changes in the structure and function of ecosystems, including the numbers and types of organisms that can survive in the altered environment. It can equally affect other environmental values such as drinking water quality, primary industries, industrial water, recreational values, aesthetic values, and cultural and spiritual values.

The relationships between water quantity and water quality vary for different types of aquatic ecosystems (regulated rivers, unregulated rivers, urban streams, ephemeral streams, estuaries, marine environments, lakes and wetlands) and also vary across Australia due to natural factors such as climate, topography and catchment geology. Some common factors that depict the water quality/quantity relationship are the nature of the water source(s), the watering regime and also the in-stream processes that can occur. River regulation, catchment modifications and water extraction alters the natural flow/watering regimes and associated water quality characteristics. This can result in water quality issues in many ecosystems such as eutrophication (and associated algal blooms), contamination with toxins, increasing salinity, cold-water pollution, hypoxic blackwater events and exposure of acid sulfate soils.

Water quality is often managed separately from water quantity. This report has reviewed the water quality/quantity relationships in a range of systems that will help to draw these interrelated aspects closer together. Tables 5 to 16 provide a summary of the generalised relationships between water quality and flow for a range of different ecosystems, including management implications.

5.1 Knowledge gaps

Generalised relationships between water quality and water quality are well described in the literature for a range of aquatic ecosystems. However, generalised relationships can only go so far towards providing useful information to guide management decisions. The water quality/quantity relationship is better defined and is more informative at a catchment, reach or individual site scale. One of the main knowledge gaps is the ability to translate these generalised relationships to individual catchments or sites to support decision making and real-time management of flow-related water quality issues.

Part of the issue is the frequency of water quality monitoring. Most water quality monitoring programmes are designed for long-term trend analysis, consisting of monthly monitoring of surface water quality at a large number of sites. However, these programmes are not necessarily suitable to characterise the water quality/quantity relationships at critical times or at particularly sensitive locations that are important for ecosystem values (for example, fish, macroinvertebrates, aquatic plants or aesthetics) and processes (primary production, organic matter decomposition, nutrient cycling, salt-wedge dynamics or stratified pools). Considerable progress could be made by implementing continuous or event-based water quality monitoring programmes at representative sites (nearby to gauged flow / water level loggers) to fill such knowledge gaps.

These knowledge gaps can also be addressed by identifying trends and patterns through interrogating routine monitoring data sets using emerging modelling tools. As the relationship between water quality and water quantity is complex, regressions of water quality concentrations versus flow / water level do not provide good fits for most water quality indicators. This is because using flow magnitude or water level as predictors does not take into account other important factors, such as the proportion of flow from different sources (like first flush, groundwater, stormwater, catchment run-off or point sources), in-stream processes (carbon and nutrient cycling, sedimentation or stratification) and antecedent conditions (for example, the amount of time since the last flood). Modelling is a useful way to try to capture some of these factors in order to understand and then predict water quality outcomes. Such methods can be used to explain variability in water quality data and set flow-related water quality load and concentration targets. Through developing a good understanding of the catchment-specific relationships between water quality and flow, it may be possible for authorities to better integrate water quality considerations in determining environmental flow requirements for rivers and environmental watering requirements for wetlands.

Table 5 Summary of temperate rivers (wet winter / dry summer)

Definition	Rivers located in areas where the majority of rainfall occurs in the cooler winter months. The flow regime follows the seasons with high flows in winter/spring and low flows during summer/autumn.
Examples	Ovens River, Victoria (case study); Tasmanian rivers; Victorian rivers; and southern Western Australian and South Australian rivers.
Nature of quality/quantity relationship	*Low flows* occur in the summer months. Water temperatures are warmer and there is increased water clarity from the settling of suspended solids onto the stream bed. Increased light penetration and warm temperatures increase rates of biological processes such as primary production, carbon and nutrient cycling. These processes may reduce in-stream nutrient and carbon levels. Dissolved oxygen levels tend to be lower due to warm water temperatures and vary with biological processes. Electrical conductivity levels can also increase in some systems with saline groundwater interactions. *High flows* occur in the winter months. Rainfall in the catchment washes particulate and dissolved nutrients and carbon into the river, which can be stored in the channel to support food webs. Higher turbidity / suspended solids result from catchment run-off and stirring up of bed sediments. Lower temperatures and water clarity reduce rates of biological processes.
Water quality issues	Some possible flow-related water quality issues are: • low dissolved oxygen under low flow / drought conditions • post-bushfire run-off high in nutrients, ash and suspended solids • blackwater from excessive carbon entrainment from floodplain rivers (particularly during summer months) • saline groundwater intrusion under low flows (see 'Groundwater-fed rivers') • high suspended solids and nutrients from erosion and agricultural run-off • seasonal reversal of flow regime from river regulation (see 'Regulated rivers')

	• stormwater run-off from urban areas (see 'Urban rivers').
Management implications	The management of temperate rivers could be enhanced by determining how water quality is affected by flow on a site-by-site basis. This could be done by interrogating long-term monitoring data sets and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations, site-specific water quality targets under different flow conditions (for example, base flows versus high flows) and guide catchment investment priorities.

Table 6 Summary of tropical rivers (monsoonal and wet/dry)

Definition	Tropical rivers are located in either the tropical monsoonal climate in North Queensland or the tropical wet and dry climate in the Northern Territory. The tropical rivers have high rainfall during the summer compared with winter. Flows can spill out onto the floodplains during the summer months and then contract to the river channels during the dry season.
Examples	Mitchell River, Queensland (case study); monsoonal rivers, northern Queensland; wet/dry rivers, Northern Territory.
Nature of quality/quantity relationship	*Low flow/cease to flow*—during the winter dry season, rivers will often cease in the wet/dry tropics, although some may be sustained perennially by base flows sourced from groundwater. Monsoonal catchments have a more evenly distributed rainfall pattern and therefore have flows in the main river channels for most of the year. As flows steadily decrease in the dry season, water temperature rise and daily dissolved oxygen concentrations fall. Turbidity levels also decline, increasing water clarity. Nitrogen and phosphorus can be low, but clear water and stable hydraulic conditions support rates of gross primary production comparable with rivers with substantially higher nutrient levels. Water loss by evaporation, particularly in the wet/dry tropics, can concentrate salts. *High flows* occur during the summer wet season. 'First-flush' run-off, particularly in the wet/dry tropics, can be acidic, with very high concentrations of suspended particulate matter, nutrients, sulfate and some heavy metals (like aluminium). Extreme rainfall events can occur during cyclonic activity that can liberate and transport large quantities of suspended sediments and nutrients to rivers and marine receiving environments.
Water quality issues	Some possible flow-related water quality issues are: • high catchment suspended solids and nutrients loads during extreme rainfall events, impacting on rivers and receiving near-shore marine environments • first flush of acidic, heavy metal laden water into rivers • low dissolved oxygen under low-flow/cease-to-flow periods

	• regulation of headwater catchments impacting on flow and water quality downstream.
Management implications	The very distinct variation in flow and the interaction of flow with the landscape in tropical rivers result in strong seasonal variation in water quality. The management of tropical rivers could be enhanced by determining how water quality is affected by flow on a site-by-site basis. This could be done by collecting and interrogating monitoring data sets and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in guiding the sustainable use and management of tropical rivers, including setting site-specific water quality targets under different flow conditions (for example, wet season or dry season) and incorporating water quality specific recommendations into environmental flows studies.

Table 7 Summary of dryland rivers

Definition	Dryland rivers flow through semi-arid or arid landscapes and are the most common type of river, in terms of river length, in Australia. They have highly variable and unpredictable flow regimes. Most are temporary, which means they do not have constant surface water flow for the entire year. Rather, they experience large floods, followed by extended cease-to-flow periods where water retracts to a series of isolated waterholes.
Examples	Cooper Creek, Queensland (case study); rivers in the semi-arid and arid zones of western Queensland and New South Wales, the southern part of Northern Territory and northern part of South Australia, and central and northern Western Australia.
Nature of quality/quantity relationship	*Cease to flow*—flow retracts to a series of connected or disconnected waterholes, where water quality is driven by processes such as evaporation, groundwater influence and the concentration or precipitation of compounds. Water quality conditions can be harsh at the local scale from low dissolved oxygen levels, high temperatures, increasing salinities, hardness, alkalinity and cations. *Flooding flows*—water quality during the flooding phase is driven by the large volumes of catchment run-off. Flooding entrains organic carbon and nutrients from the productive floodplain areas into the river channels to support food webs. Some systems also have high mineral turbidity, which is characteristic of the local geologies and land use.
Water quality issues	Some possible flow-related water quality issues are: • very high turbidity levels that affect the beneficial end uses of the water • low dissolved oxygen and increasing salinities under low-flow/cease-to-flow periods.
Management implications	Water quality naturally changes temporally and spatially in dryland rivers. This makes developing and applying water quality guidelines and trigger levels very difficult for these rivers. One possible solution is to develop guidelines for both the no-flow and flowing phases. This could be done by collecting and interrogating monitoring data and developing conceptual, probabilistic and/or numerical

	models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in guiding the sustainable use and management of dryland rivers.

Table 8 Summary of regulated rivers

Definition	Regulated rivers have been modified to efficiently control water movement for potable water supply, irrigation or hydro power generation. Dams and/or weirs and the associated headworks and channels are built to harvest and control the flow of water. River regulation determines the manner, magnitude and frequency of flow releases downstream.
Examples	Murrumbidgee River, New South Wales (case study); most rivers in the Murray–Darling Basin and others scattered through agricultural and urban areas.
Nature of quality/quantity relationship	River regulation can cause lower variability in flow, overall lower flow magnitudes and in some cases seasonal reversal of the flow regime in rivers downstream of storages. Low flows are associated with low oxygen content, temperature extremes, increased concentrations of contaminants, eutrophication and salinisation. Dams also reduce connectivity along the river length, which has implications for nutrient and sediment transport and can affect downstream trophic structure and function. Another water quality issue associated with river regulation is cold-water pollution. This is caused when storage dams thermally stratify during summer and the colder, anoxic bottom waters are released. This cold-water effect can be observed significant distances downstream. Similarly, as large storages have a greater water mass than flowing rivers, they take longer to heat and cool. Therefore, there is a dampening of seasonal temperature trends downstream, where the water is cooler in summer and warmer in winter. Cold water during summer can suppress ecological processes and disturb life cycles of fish.
Water quality issues	Some possible flow-related water quality issues are: • cold-water pollution • heavy metals, sulfides and ammonia released from bottom waters of reservoirs into rivers • dampening of seasonal temperature trends • nutrient and carbon transport disrupted from weirs • eutrophication and salinisation downstream.
Management implications	Cold-water pollution can be managed by having release structures such as multi-level offtakes that allow surface waters to be discharged or have mixing equipment that prevents thermal stratification from developing. Determining how water quality is affected by flow downstream of major storages through targeted water quality monitoring programmes can help to set minimum environmental flow recommendations and determine suitable temperatures for release.

Table 9 Summary of urban streams

Definition	An urban stream can be defined as 'a stream where a significant part of the contributing catchment consists of development where the combined area of roofs, roads and paved surfaces results in an impervious surface area characterising greater than 10 per cent of the catchment'.
Examples	Lane Cove River, New South Wales (case study); rivers and streams in major cities and towns.
Nature of quality/quantity relationship	The water quality of urban streams is highly variable and is a significant determinant of overall stream condition. Changes to the hydrologic regimes of urban areas can affect water quality as the increased run-off velocities lead to erosion and the entrainment and transport of pollutants present on the catchment surface. Generally, surface run-off, referred to as stormwater, transports a variety of materials of chemical and biological origin to the nearest receiving water body. These contaminants can cause toxicity to aquatic organisms and alter ecosystem processes (such as nutrient cycling), resulting in a water body that is fundamentally changed from its natural state.
Water quality issues	Some possible flow-related water quality issues are: • point sources of pollution can dominate water quality (for example, water treatment plant discharges and storm water) • flashy storm water flows bring litter and high biochemical oxygen demand, heavy metals and nutrients from run-off from impervious surfaces • low dissolved oxygen levels occur after stormwater • high nutrients, combined with shallow open channels (sometimes concrete lined), cause nuisance plant and algal growth.
Management implications	Water-sensitive urban design and stormwater management is the key to improving water quality in urban streams. The COAG National Urban Water Planning Principles provide tools to plan the development of urban water and wastewater service delivery in a sustainable and economically efficient manner.

Table 10 Summary of groundwater-fed streams

Definition	A groundwater-influenced stream has strong surface water–groundwater interaction.
Examples	Axe Creek, Victoria (case study); dryland salinity regions on the western slopes of the Great Dividing Range and south-west Western Australia.
Nature of quality/quantity relationship	An important factor determining the water quality in surface systems is the extent of surface water / groundwater interaction. In broad terms, streams can be 'losing' or 'gaining'. A gaining stream is one where, for most of the time, groundwater flows into the stream, and the quality in the stream is partly or largely a function of the groundwater quality. A losing stream is one where, for most of the time, surface water leaks out of the watercourse and recharges the groundwater system, in many cases creating a fresher groundwater zone beneath

	and around the watercourse. Many of the watercourses in Australia were historically of this latter type, but, with land use changes such as irrigation or clearing of native vegetation, the watertable has risen and reversed the situation. Where the regional groundwater is saline, this is one of the classic manifestations of the salinity problem in Australia.
Water quality issues	Some possible flow-related water quality issues are: • groundwater levels rise and can intrude into streams increasing salinity levels • saline stratification of pools and wetlands may cause high salinity and low dissolved oxygen in bottoms of pools and release of nutrients/toxins from sediment.
Management implications	Dryland salinity has been an ongoing catchment management issue since the 1970s. Significant progress has been made through salinity action plans, including revegetation efforts, and in changing irrigation practices. Managing saline groundwater intrusion into rivers to prevent adverse salinity impacts to aquatic flora and fauna is complex. It could be enhanced by determining how electrical conductivity levels are affected by flow on a site-by-site basis. This could be done by interrogating long-term monitoring data and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations, site-specific water quality targets under different flow conditions (for example, base flows or high flows) and guide catchment investment priorities.

Table 11 Summary of freshwater wetlands

Definition	Wetlands are saturated areas that are inundated with water either permanently or seasonally. There are many different types of wetlands in the landscape. The main classifications of freshwater wetland groups are lacustrine wetlands (such as deep, permanent freshwater lakes), palustrine wetlands (such as shallow floodwater in swamps) and riverine wetlands (for example, those associated with river channels and floodplains).
Examples	Barmah–Millewa Forest, Victoria and New South Wales (case study); large and small wetlands connected to rivers, in low lying areas or in urban environments.
Nature of quality/quantity relationship	The hydrology of wetlands depends on their level of connection with water sources. Some wetlands are connected to rivers. Other wetlands may intersect with groundwater. Still others can be isolated and located within low points in the landscape that receive rainfall run-off from the catchment. In urban settings, wetlands can receive water from stormwater drains or industrial discharges. The wetting and drying cycles of wetlands can be important ecologically as well as for water quality purposes. In natural systems, wetlands typically fill during the wet season and slowly dry during the dry season. The wet season filling refreshes water quality, dilutes accumulating ions and toxics and entrains organic matter for food webs. It releases nutrients from the soils and

	organic matter, which encourages the growth of seeds in the refilled wetlands. Nitrification and denitrification processes that remove nitrogen from aquatic systems require aerobic conditions (during the drying of wetland sediment) to convert ammonia to nitrates (nitrification), then anaerobic conditions (during the wetting cycle) suitable for denitrifying bacteria to convert nitrates to nitrogen gas (denitrification), thus removing it from the ecosystem. This is an important feature of wetlands that is utilised for water treatment outcomes in urban and rural environments. Water quality issues arise when the filling of wetlands occurs too infrequently (as is the case in regulated systems or during droughts). This causes the accumulation of large quantities of organic, carbon-rich matter on the margins and floodplain. When the next flood occurs, all the material is transported into the wetland (and associated rivers system) and overloads its functioning capacity.
Water quality issues	Some possible flow-related water quality issues are: • hypoxic blackwater events • algal blooms • acidity from acid sulfate soil exposure • increasing salinity.
Management implications	Water quality monitoring in wetlands is less common than in river systems. Routine water quality and water level monitoring is recommended in those wetlands with important environmental values (for example, high-value aquatic ecosystems or recreation) or that provide water quality treatment outcomes (for example, stormwater treatment wetlands). This will help to better define the site-specific water quality / water level relationships and inform processes to set environmental watering requirements for these systems.

Table 12 Summary of lakes

Definition	Lake systems of Australia are highly complex drainage structures that occur on the coast and inland regions of the continent. A number of different lake types are classified in the *Directory of Important Wetlands in Australia*. They are: • permanent freshwater lakes (>8 ha), includes large oxbow lakes • seasonal/intermittent freshwater lakes (>8 ha), floodplain lakes • permanent saline/brackish lakes • seasonal intermittent saline lakes.
Examples	Lower Lakes, South Australia (case study); Lake Eyre; Paroo Lakes; Coongie Lakes; Kerang Lakes; Hattah Lakes.
Nature of quality/quantity relationship	*Inundation: water level rises*—nutrients and organic matter are imported into lakes via floodwaters and are rapidly released through decomposition of organic material. Sediments on the lake bed can act as a store for these nutrients which accumulate over time and support

	complex food webs. This can lead to high productivity, which, when combined with greater habitat availability associated with a rising water level, supports greater biodiversity. *Recession: water level recedes*—evaporation and reduced inflows may lead to water quality decline. Poor water quality may be attributed to a decrease in the buffering capacity of the system as water levels recede. Observed water quality changes can include increased concentration of nutrients, turbidity conditions, an increase in salinity and potentially thermal stratification depending on ambient temperatures. In extreme cases, permanent freshwater lakes can recede until they dry out. In instances where a fall in water levels exposes lake sediments, there is potential for acid sulfate soils to be exposed and become oxidised. As the lake is inundated following rainfall, these sediments may lead to acidification of the water body.
Water quality issues	Some possible flow-related water quality issues are: • algal blooms • thermal or saline stratification • acidity from acid sulfate soil exposure • increasing salinity.
Management implications	Water quality monitoring in lakes is less common than in river systems. Routine water quality and water level monitoring is recommended in lakes with important environmental values (for example, high-value aquatic ecosystems or recreation). This will help to better define the site-specific water quality / water level relationships and inform processes to set environmental watering requirements for these lake systems.

Table 13 Summary of reservoirs

Definition	Reservoirs are large natural or artificial lakes that are used for water supply purposes (like potable drinking water supplies and irrigation). They can be on-stream, which is a reservoir created in a river valley by the construction of a dam wall; or off-stream, which is built by excavation in the ground or by conventional construction techniques.
Examples	Lower Lakes, South Australia (case study); typically located in the high-rainfall headwaters of catchments.
Nature of quality/quantity relationship	Water quality in reservoirs is determined by the frequency, magnitude, duration, seasonality and quality of inflows and by in-lake processes. Inflows transport nutrients, sediments and other contaminants, which may then by affected by in-lake processes such as settling of suspended solids and biochemical processes. Bushfire run-off presents the highest risk of contaminant loads in these catchments. Stratification is the separation of water column into density-based layers caused by differences in temperature or salinity. Thermal stratification of layers affects deep reservoirs and occurs in the warmer, drier months, when reduced inflows result in minimal mixing within the reservoir. Cycles of stratification and mixing of the water

	column are known to drive algal growth in nutrient-enriched reservoirs. Stratified conditions create calm, still and warm conditions at the surface that is favourable for the growth of algae. The bottom layer becomes depleted of oxygen and under such conditions releases nutrients from the sediment, which further drives algal blooms at the surface. Other water quality issues can occur from stratification in reservoirs. Under stratified conditions, cold-water pollution can occur downstream when the reservoir offtake is below the thermocline. Also, the anoxic conditions in the hypolimnion produce a reducing environment whereby manganese, iron, phosphorus, sulfides and ammonia are released from the sediments. These chemicals can alter the taste and odour of the water and can stain, which makes the water displeasing for potable water supply customers.
Water quality issues	Some possible flow-related water quality issues are: • thermal stratification • algal blooms • declining water quality in bottom waters from low dissolved oxygen, heavy metals (for example, iron and magnesium) • cold-water pollution downstream • contaminant-laden bushfire run-off.
Management implications	Algal blooms in reservoirs can be reduced by catchment management works to reduce nutrient loads. Aerators can also be used to keep reservoirs mixed and prevent thermal stratification from developing.

Table 14 Summary of salt-wedge estuaries

Definition	Salt wedges form in estuaries with enough freshwater inflows that it pushes back the sea water. This creates a sharp boundary that separates an upper, less salty layer from an intruding wedge-shaped salty bottom layer.
Examples	Yarra River, Victoria (case study); Swan–Canning Estuary, Western Australia; Coral Creek, Queensland.
Nature of quality/quantity relationship	*High freshwater inflows*—the force of the water pushes the salt wedge towards the estuary mouth and freshens water quality in the estuary. *Low flow conditions*—the salt wedge can encroach further up the estuary. The lack of mixing between the top (fresh) and bottom (saline) layers creates an anoxic environment that can cause the release of nutrients and toxicants (like heavy metals and pesticides) from sediments. It also reduces the habitat available for fish and invertebrates. Under very low flow conditions, the flow of the freshwater layer may be slow-moving on top of the salt wedge. This shallow layer creates calm, still and warm conditions which favour the growth of algal blooms.
Water quality issues	Some possible flow-related water quality issues are: • salt wedge encroachment up catchment • declining water quality in bottom waters from low dissolved oxygen, heavy metals and toxicants

	• algal blooms.
Management implications	Salt-wedge estuaries are managed by catchment freshwater inflows. The management of these estuaries in regulated catchments could be enhanced by determining how water quality in the estuary is affected by flow on a site-by-site basis. This could be done by collecting and interrogating monitoring data (including vertical profiles) and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations.

Table 15 Summary of heavily modified estuaries

Definition	An estuary that has a catchment and hydrology that has been highly modified for agriculture and/or urbanisation.
Examples	Peel–Harvey Estuary, Western Australia (case study); Patterson Lakes, Victoria; Brisbane River, Queensland; Coomera River, Queensland; River Torrens, South Australia.
Nature of quality/quantity relationship	*Low freshwater inflows*—a loss of flow-induced currents and vertical mixing can lead to salt wedges forming and encroaching up the channel, low dissolved oxygen at depth, the release of nutrients from sediment and the formation of toxic algal blooms. *Reduced tidal flushing*—the partial or full closure of the estuary mouth can occur, which reduces tidal flushing and increases the build-up of sediment and nutrients in the estuary. Water temperatures can also increase and the still conditions can favour the growth of algal blooms. *High catchment inflows*—flushing of the estuary occurs under high catchment inflows, which can improve estuarine conditions. However, inflows from urban and agricultural catchments typically have high levels of nutrients, suspended solids, biochemical oxygen demand and pathogens that can degrade water quality in the short term.
Water quality issues	Some possible flow-related water quality issues are: • salt wedge encroachment up catchment • declining water quality in bottom waters from low dissolved oxygen, heavy metals and toxicants • algal blooms.
Management implications	The quality and quantity of catchment inflows, coupled with the tidal flushing dynamics, determine estuarine condition. Land use and catchment processes, both current and historical, need to be considered for effective management. The management of these estuaries in regulated catchments could be enhanced by determining how water quality in the estuary is affected by flow on a site-by-site basis. This could be done by collecting and interrogating monitoring data (including vertical profiles) and developing conceptual, probabilistic and/or numerical models that incorporate flow, catchment and in-stream influences. Such an understanding would assist in setting environmental flow recommendations to maintain water quality in the estuary.

Table 16 Summary of near-shore environments

Definition	An estuary that has a catchment and hydrology that has been highly modified for agriculture and/or urbanisation.
Examples	Great Barrier Reef, Queensland (case study); Port Phillip Bay, Victoria.
Nature of quality/quantity relationship	The effect of freshwater flows on water quality is dependent upon the properties of the inflowing and receiving waters and the magnitude of the flows. Freshwater flows affect a range of water quality properties of the receiving coastal waters, including temperature, salinity, turbidity, total and dissolved nutrients, suspended solids, organic matter content, dissolved oxygen and presence of chemical pollutants. *Floods*—discharge from flooded rivers produce plumes of high turbidity in receiving waters. The plumes are particularly distinct in coastal environments that have naturally clear waters. First-flush events have the highest concentrations of sediment and nutrients and are associated with transport of pollutants, including heavy metals, pesticides and herbicides, which can occur at their highest concentrations at the plume front. Deposition of suspended sediment occurs in the near-shore environment of the coast and estuaries, which can function as sediment traps. Dissolved nutrients are transported much further from the coast, and elevated nutrient concentrations can occur over a hundred kilometres from the coast. *Reduced inflows*—discharges from river systems are an important source of carbon for sustaining food webs of near-shore ecosystems. The importance of freshwater flows for near-shore environments is demonstrated by the many examples of positive relationships between commercial fisheries catches and catchment rainfall. The reduction in delivery of fresh water has direct effects on the water quality variability of receiving coastal waters and also the productivity of the coastal environments. Since freshwater flows are important in providing variability to water quality and aquatic habitat to which many coastal species are adapted, reduced flow has a negative effect on recruitment abundance and diversity.
Water quality issues	Some possible flow-related water quality issues are: • high suspended solids and nutrients loads from the catchment • reduced freshwater inflows from extractions and regulation • restriction of light degrading seagrass communities • nutrient enrichment can reduce species diversity and cause invasion by weeds.
Management implications	Farm management plans and urban stormwater management can help to reduce the sediment and nutrient loads entering near-shore environments during floods. In addition, load assessments are required for any proposed catchment modifications (for example, urbanisation or mining) to ensure that contaminant loads are not increasing to these fragile environments from the catchment.

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Glossary

Acidic	Having a high hydrogen ion concentration (low pH).
Adsorption	The reversible binding of molecules to a particle surface. This process can bind dissolved phosphorus and pathogens to particles.
Algae	Comparatively simple chlorophyll-bearing plants, most of which are aquatic and microscopic in size.
Alkalinity	The quantitative capacity of aqueous media to react with hydroxyl ions. The equivalent sum of the bases that are titratable with strong acid. Alkalinity is a capacity factor that represents the acid-neutralising capacity of an aqueous system.
Anastomosing channels	Rivers that have multiple channels that intertwine across a floodplain.
Anoxia	No or very low dissolved oxygen. Levels are typically less than 2 mg/L.
Aquatic ecosystem	Any watery environment from small to large, from pond to ocean, in which plants and animals interact with the chemical and physical features of the environment.
ASS/Acid sulfate soils	The common name given to soils and sediments containing iron sulfides, the most common being pyrite. When exposed to air due to drainage or disturbance, these soils produce sulfuric acid, often releasing toxic quantities of iron, aluminium and heavy metals.
Benthic	Referring to organisms living in or on the sediments of aquatic habitats (lakes, rivers or ponds).
Bioaccumulation	General term describing a process by which chemical substances are accumulated by aquatic organisms from water, either directly or

	through consumption of food containing the chemicals.
Bioavailable	The fraction of the total of a chemical in the surrounding environment that can be taken up by organisms. The environment may include water, sediment, soil, suspended particles and food items.
Chemical transformations	Transformations of substances that can occur through acid–base reactions or redox reactions. For example, ammonia and metal toxicity and/or availability changes under varying temperatures, pH and oxygen levels.
Carbon cycling / decomposition of organic matter	Carbon cycling involves the oxidation of complex organic matter into simpler forms (for example, carbon dioxide, phosphate or ammonia). It is one of the key steps in the decomposition of organic matter. This provides bacteria, protozoa and fungi (at the base of the food web) with the energy for cellular metabolism and growth. This process consumes oxygen.
Contaminant	Biological (for example, bacterial and viral pathogens) and chemical (see Toxicants) introductions capable of producing an adverse response (effect) in a biological system, seriously injuring structure or function or producing death.
Dilution	The process of making a substance less concentrated by adding water. This can lower the concentrations of ions, toxins and other substances.
Ecological services	Ecological services include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth.

Environmental values	Environmental values, as defined in the NWQMS (Doc 4, Chapter 2.1.3, pp. 2–6), include aquatic ecosystems; primary industries; recreation and aesthetics; drinking water; industrial water; and cultural and spiritual values.
Ephemeral streams	Streams that receive water only for a short period very occasionally and highly unpredictably.
Episodic streams	Streams that fill occasionally and may last months or years during unpredictable rainfall.
Evapo-concentration	The process by which water is evaporated and the substances present, particularly salts, concentrate.
Flocculation	The aggregation of colloidal (very fine) particles into larger particles that then settle. This occurs in high-salinity environments (e.g. estuaries).
Heating/cooling	Water temperature is determined primarily by air temperature and is also impacted by stratification. Temperature affects the rates of chemical and biological reactions. It also affects the solubility of dissolved oxygen.
Hypoxia	Deficiency of oxygen (typically less than 5 mg/L).
Intermittent streams	Streams that receive water quite frequently, either predictably or unpredictably.
Nutrient cycling	The nutrient cycle describes how nutrients move from the physical environment into living organisms and then subsequently are recycled back to the physical environment. This movement of nutrients, sometimes referred to as nutrient spiralling, is essential for life and is a vital function of the ecology of aquatic ecosystems. There are four biological processes that participate in the cycling of nitrogen. They are Nitrogen fixation: $N_2 \rightarrow NH_4^+$; Decay: Organic N $\rightarrow NH_4^+$; Nitrification: $NH_4^+ \rightarrow NO_2^-$

	→ NO_3^-; and Denitrification: NO_3^- → N_2+ N_2O.
Oxidation	The combination of oxygen with a substance or the removal of hydrogen from it or, more generally, any reaction in which an atom loses electrons.
Photosynthesis	The conversion of carbon dioxide to carbohydrates in the presence of chlorophyll using light energy.
Precipitation of minerals	When a dissolved substance forms a solid that settles out of the water.
Primary production	Refers to the creation of new organic matter by photosynthesis. Oxygen is produced during this process. Primary production occurs in aquatic systems and includes algae and macrophyte growth.
Reaeration	The transfer of oxygen from the atmosphere to a body of water at the air–water interface. It affects the dissolved oxygen levels.
Sedimentation	The settling of suspended particles. Rates of sedimentation are determined by the size of the particles, the velocity of the water and the ionic environment. Sedimentation affects the water clarity.
Stratification	The formation of density layers (either temperature or salinity derived) in a water body through lack of mixing. It can create favourable conditions for algal blooms and can lower dissolved oxygen levels in the bottom layers with the associated release of nutrients, metals and other substances.
Temporary stream	A general term for non-permanent systems, alternating between wet and dry phases.
Thermocline	A steep temperature gradient in a body of water such as a lake, marked by a layer above and below in which the water is at different temperatures.

Toxicant	A chemical capable of producing an adverse response (effect) in a biological system at concentrations that might be encountered in the environment, seriously injuring structure or function or producing death. Examples include pesticides and heavy metals.
Water quality	Refers to the physical, chemical and biological attributes of water that affect its ability to sustain environmental values.
Water quantity	Describes the mass of water and/or discharge and can also include aspects of the flow regime, such as timing, frequency and duration.

6 Appendix 1

This section gives a technical overview of numerical water quality models, including presenting classifications based on their primary function, describing the basic components of a water quality model, and giving a brief overview of various modelling platforms, or software packages, in current use.

6.1 Classification of water quality models

There are various types of water quality models (SKM 2011):

- catchment models, which simulate run-off and water quality from land types and land use in the upland catchment
- in-stream models, which simulate the transport of water quality constituents in surface waters. This may include water bodies such as rivers, lakes, dams, estuaries and wetlands. Such a model may or may not be a hydrodynamic model, which simulates detailed water movement, including depth and velocity of flows
- ecological response models, which simulate the response of the ecosystem to flow and water quality
- groundwater models, which simulate flow and transport of water quality constituents through aquifers and may link to a catchment or an in-stream model.

A numerical model, as used in this report, refers to a software package that can perform the mathematical computations. It can be a simple spreadsheet-based model or a complex, user-interface software program. A single modelling platform can generally only simulate one of the water quality modelling aspects described above, and usually multiple models are linked together in order to simulate a natural system (e.g. a catchment and in-stream model are linked to model water quantity and water quality in a river).

6.2 Modelling components

Water quality models require estimates of flows which may be estimated within the model itself (e.g. rainfall–run-off modelling) or provided as an input data set derived from historical records or from an independent hydrologic model. Hydrologic models can be classified in various ways, including empirical versus physically-based, deterministic versus stochastic (randomness), lumped versus distributed (spatial variation) and steady state versus dynamic (temporal variation) (Kalin & Hantush 2003). This report focuses on dynamic models for Australian rivers, as the flows in Australian waterways are highly variable.

There are three basic components to water quality modelling: generation, delivery and transport of the water quality constituents. Generation and delivery components relate to catchment models, and the transport component relates to both catchment and in-stream models. Various models handle each component to varying degrees of complexity (CRCCH 2005):

- generation—estimates the amount of constituent produced in the catchment. Typical approaches employed by models are described below. The first three are used by 'empirical' models and the later is used by process-based models:
  - average annual area export rates for a given land use (mass/area/yr)

  - Event Mean Concentration (EMC, mass/volume)—loads are estimated based on average export concentrations and the input series of flow
  - EMC and Dry Weather Concentration (DWC, mass/volume)—takes into account that high-flow ‘events’ generally provide different average concentrations than low flows. This approach is preferred over EMC if data is available and the timestep of the model captures events (for example, a monthly model will not capture such events)
  - process-based approaches—detailed processes in soil and water are represented mathematically. The mathematical relationships can become very complex and require considerable data to calibrate parameter values
- delivery—estimates how the constituent moves through the catchment to the stream:
  - net generation—no explicit process of delivery is represented, but the generation rates are decreased to incorporate the effects of delivery. Interpreting the effects of management interventions can be complex and uncertain
  - delivery ratio—a proportion of the amount generated is estimated to enter the stream. This may be constant (similar to the ‘net’ approach above) or a function of attributes (like vegetation type or terrain)
  - explicit pathways/process-based—pathways of movement and transformations from the source to the stream are explicitly modelled by algorithms. This is a comprehensive approach but requires considerable data to calibrate parameters as well as appropriate expertise
- transport—estimates how a constituent is transported downstream. The first two approaches assume the water quality constituent is conservative, while the third assumes the load changes through various processes:
  - no explicit transport—assumes that the constituent is conservative and all inputs are simply lagged (to account for travel times) and summed
  - routing—represent the movement of water through the system through some form of hydrologic or hydraulic routing
  - routing allowing for transformations—constituents are routed and in-stream water quality processes are simulated (for example, deposition and resuspension of sediment or nutrients altering form). Approaches include assuming a simple decay function or algorithms that represent complex interactions between other constituents or the environment. Complex models require a large amount of data for calibration and a high level of expertise to implement.

Salinity can adequately be modelled as a conservative constituent. However, nutrient modelling is much more complex than conservative element modelling because:

- the nutrients can be in soluble form or part of living organisms
- the nutrients can also be fixed to suspended solids
- the nutrients can change from one form to another as they progress downstream.

Other water quality environmental variables such as temperature and dissolved oxygen are also altered along the waterway or water body and can be simulated based on various algorithms that consider interactions between other constituents or the environment.

6.3 Examples of water quality models in Australia

In Australia, water quality modelling has been applied on various scales and to various levels of complexity. A number of examples of such water quality models are described below.

The eWater Source Integrated Modelling System (IMS) is a spatially lumped whole-of-catchment scale modelling platform that generates run-off and water quality constituents from sub-catchments, which are then routed, filtered and lost through in-stream processes through a node-link network that represents river reaches. The models operate at a daily time step.

Source offers a choice of constituent generation and transport models that operate at a catchment, river network or in-stream scale. These models are only suitable for conservative constituents and do not simulate transformation processes, such as denitrification.

Constituent generation models can be parameterised for a type of functional unit (or hydrological response unit, such as land use) within a sub-catchment and include:

- EMCDWC (event and dry weather concentration) models, where a value for constituent concentration is defined for event and dry weather conditions to calculate loads
- export rate, which applies a fixed constituent rate to a functional unit to calculate total annual constituent load
- power function, which fits a rating curve describing the relationship between constituent concentration or load and discharge in linear space
- for some node models (e.g. storages, extractions), constituent concentrations can be specified using the expression editor to build custom relationships from observed data.

A number of filtering models are available to remove constituents from within sub-catchments, such a percentage removal, sediment and nutrient delivery ratios to simulate riparian buffer strips and first-order kinetic decay losses. In-stream loss models include a half-life decay model, and sediment or nutrient deposition based on a delivery or enrichment ratio based on loads.

Source has been used for assessing end-of-catchment constituent load estimates, with the capacity to assess areas of high constituent load generation, the effects of changing land use and management, and variable hydrological and climate conditions. Analysis tools are available to assess the relative contributions of land use activities to constituent loads from sub-catchments.

A notable case study of water quality modelling with Source is the combined monitoring and modelling project that is part of the Queensland Government Reef Plan 2009. The Reef Plan 2009 is a commitment between the Queensland and federal governments to minimise the risk to the Great Barrier Reef ecosystem of declining water quality from adjacent catchments. The modelling involves scenario analysis of water quality improvements towards achieving Reef Plan 2009 load reduction targets by 2013, spanning 35 priority Great Barrier Reef catchments. Custom water quality models were built by Queensland Department of Environment and Resource Management (DERM) Catchment Modellers in order to better model the variability of sediment and nutrient loads with land use change.

An example of a simple model is Melbourne Water's water quality metric, which allows the downstream nutrient benefits of on-farm nutrient reduction measures to be estimated. MUSIC, e-water's urban catchment model, is a relatively simple model that is often used to model the impacts of various management options (for example, constructed wetlands or swales) on water quality in urban developments.

Sydney Catchment Management Authority (SMCMA) uses a 3D ELCOM—CAEDYM to model Lake Burragorang (Warragamba Dam) (Kristiana et al. 2011). Management authorities responsible for managing estuaries have also developed water quality models, such as the Hydromodel in South

Australia, which uses a 3D ELCOM–CADYM model as well as Source Catchments to model the lower Murray River (Frizenschaf 2009). A Botany Bay ecological response and water quality model was built using 3D ELCOM–CADYM for the SMCMA. It was built to identify hotspots of poor water quality (algal blooms) and to identify areas in the catchment that should be targeted for management actions in order to improve water quality in the estuary (SMCMA 2009).

RMA has been used in Moreton Bay in Queensland and Darwin Harbour in the Northern Territory to model sediment transport and water quality. RMA has additionally been used in Wallis Lake in New South Wales to study coliform and virus transport, and it has been used in Lake Macquarie in New South Wales to study sediment transport and power station hot water plumes (SKM 2011).

TUFLOW has been used to estimate water quality impacts of dredging and reclamation works in both Port Curtis and Port of Townsville in Queensland and to model salinity intrusion in both Hunter River and the Murray Mouth and Lower Lakes (SKM 2011). It is currently being developed to integrate with FABM, a water quality module, and will be used in the Hawkesbury–Nepean water quality model that is under development for Sydney Water. The TUFLOW–FABM linked model will simulate flow and water quality in the river and estuary.

The Monash University–eWater MUSIC Model is used for urban stormwater improvement conceptualisation and is designed to help urban stormwater professionals visualise and scenario test strategies to tackle urban stormwater hydrology and pollution loads. It is often used in EPBC referrals dealing with residential development proposals.

6.4 Some issues with water quality modelling

Monitoring data is usually required to calibrate a model. During the calibration process, the model parameter values are adjusted within reasonable bounds to obtain a better agreement between the simulated and observed data. The availability of monitoring data for such calibration is always an issue when developing a computer model and is often a factor limiting the accuracy of the model. Complex models generally have more model parameters than simple models and hence require more monitoring data to describe the added complexity. Depending on the type and complexity of the model, its intended use and the availability of monitoring data, default parameter values are often adopted when limited or no data is available for calibration. Such default parameter values may come from literature values or be transposed from nearby catchments. However, sufficient data is required to properly calibrate a model (CRC Catchment Hydrology 2005b).

Because flow records can extend back to the 19th century, models that deal exclusively with flow can cover 100 years or more. However, in Australia it is rare for there to be water quality records of sufficient intensity to provide the basis for a model any further back than about 1975.

Water quality data falls into two broad categories:

- routine monitoring data which is usually a single sample collected at regular intervals. This data typically represents water quality between flow events (low or average flow).
- event-based data (high flow event, including sampling during the rise and fall in flow), which is used for estimating soil and nutrient erosion rates and constituent load exports.

Both types of data are important for calibrating and evaluating catchment water quality models. Until more recently, event monitoring has rarely been obtained, as it is generally more difficult and costly to collect. Even when data exists, it is often not available at required spatial and temporal scales (e.g. appropriate location, frequency, duration and quality for modelling) (SKM 2011). The data requirements needed to calibrate and run water quality models, especially more complex models, may require the initiation of data acquisition and monitoring programmes. In complex surface systems, understanding how the system works and its operational rules is arguably more important than the modelling platform. Examples of the intricacies of the management of a system include:

- irrigation and urban demand patterns
- restriction policy in droughts
- minimum or environmental flow rules
- allocation policies when there is more than one user on the system.

A model and its modellers can therefore become the repository of much 'corporate knowledge'.

When selecting a preferred model for water quality modelling, it is a key consideration to identify the simplest model that meets the required objectives. Simpler models require less effort to build and run and may require less data. The trade-off is that a simpler model may not include complex processes that may be important in certain situations (SKM 2011). For example, it may be appropriate to invest in developing and maintaining a complex process-based model if complex hydrodynamic simulation is required.

The scale of a particular issue will determine if a simpler model may be appropriate or if a more complex, process-driven, detailed model is required. Logistical constraints often include the lack of suitable water quality data, as discussed above. Computational constraints often include the long processing times required by detailed, process-driven models, which may take days or even weeks to run (SKM 2011).