CHAPTER 1

Australian waters: diverse, variable and valuable

1.1 THE CHALLENGE FOR AQUATIC ECOLOGISTS

Aquatic ecologists study how organisms in inland waters interact with their environment and each other. Such studies often explore how human activities modify aquatic ecological processes and the quality and quantity of fresh water. Not only do the findings of these studies help water managers, they also add to our basic knowledge of ecology and environmental science. This book is about that basic knowledge and how we can use it to better manage and protect our fresh waters.

Fresh water is essential for all life. Therefore, we must protect and manage aquatic ecosystems that supply fresh water. Aquatic ecosystems provide essential **ecosystem services** (Daily 1997) for humans, ranging from flood control and water purification through to cultural values and recreational benefits (Millennium Ecosystem Assessment 2005). These services are often overlooked because many of them are subtle (e.g. the role of groundwater in supporting many terrestrial plant communities, Section 8.7) but, without them, humans and other dependent organisms could not survive. Most ecosystem services are mediated by ecological processes. Aquatic ecologists investigate how these processes work and how we can sustain them in inland surface waters and groundwaters.

Every day, the media report concerns about the quantity and quality of the country's water resources. Growing anxiety about the effects of climate change and increasing human population densities on finite water resources is not restricted to Australia; worldwide, scientists and managers grapple with unprecedented environmental pressures, burgeoning urbanization, agricultural problems and intensifying threats to biodiversity. Technological advances have helped resolve some of these issues but, ironically, have also exacerbated many of the multiple stressors on aquatic ecosystems such as salinization, eutrophication, sedimentation, acidification and other forms of pollution.

To address these problems, aquatic ecologists need an integrated knowledge of a wide variety of different disciplines such as physics, chemistry, microbiology, hydrology and geomorphology as well as ecology, biology and genetics, along with hybrid fields such as ecohydrology and ecohydraulics (Rice *et al.* 2010). This broader discipline, encompassing the physical, chemical and biological sciences of aquatic ecosystems, is called **limnology**. Our book synthesizes threads of these diverse sciences, focusing on interactions among physical, chemical and biological processes in surface and groundwater ecology. We then outline ways in which this scientific information can be used to tackle problems such as erosion, salinization, eutrophication and urbanization in Australian inland waters. These problems challenge aquatic ecologists worldwide, but across most of Australia their solutions are complicated by the continent's great natural variability in water regimes and the shortage of long-term empirical data for nearly all our aquatic ecosystems.

This is an exciting time to be an aquatic ecologist. Much fundamental science remains to be done, important and complex management issues abound and Australian inland waters are, for the most part, beautiful places to work. We have plenty to learn and do.

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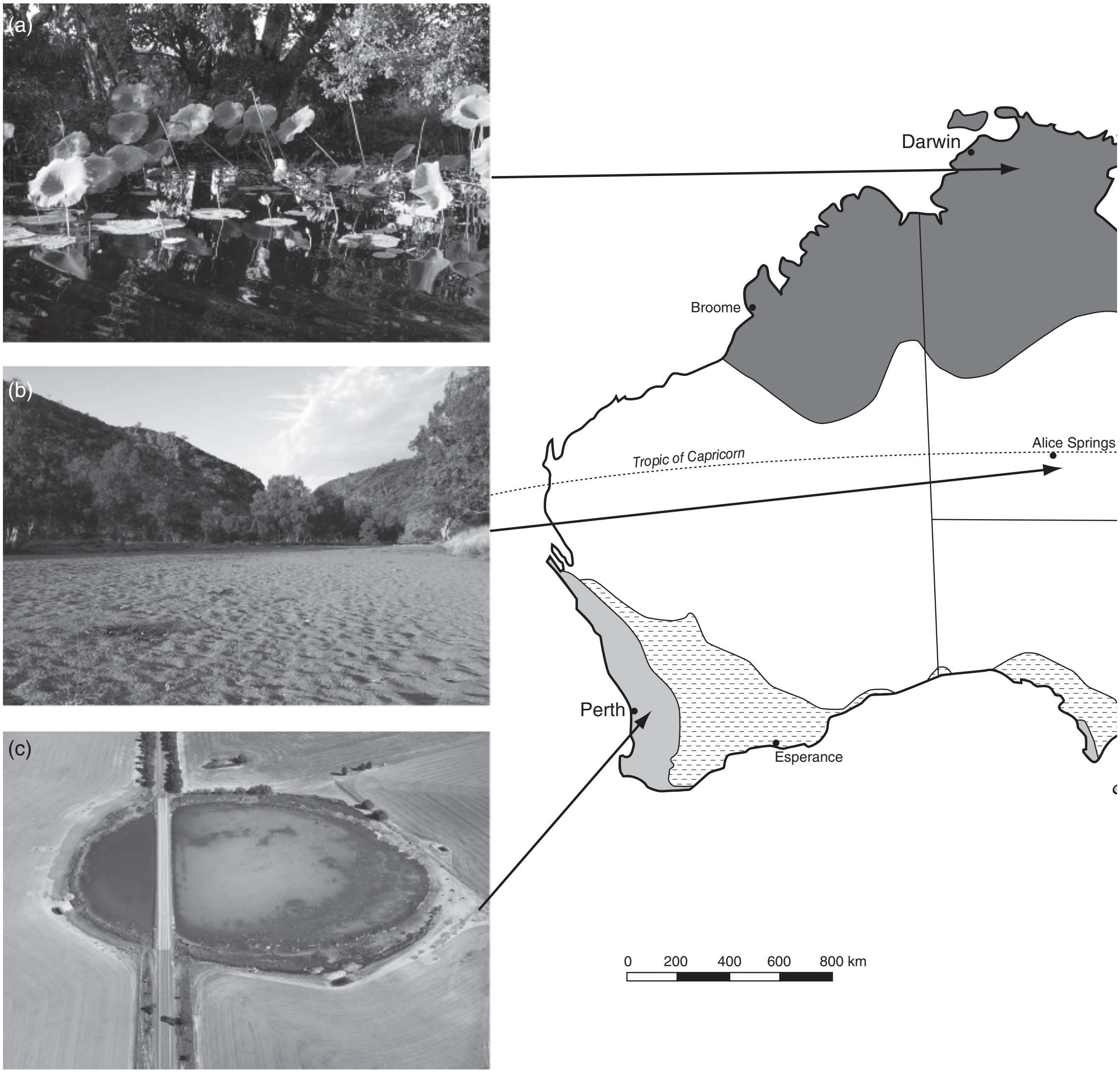

Figure 1.1 Major seasonal rainfall zones of Australia and six examples of inland waters: (a) tropical billabong in Kakadu National Park, NT, (b) temporary river near Alice Springs, NT, (c) salt lake in the WA Wheatbelt.

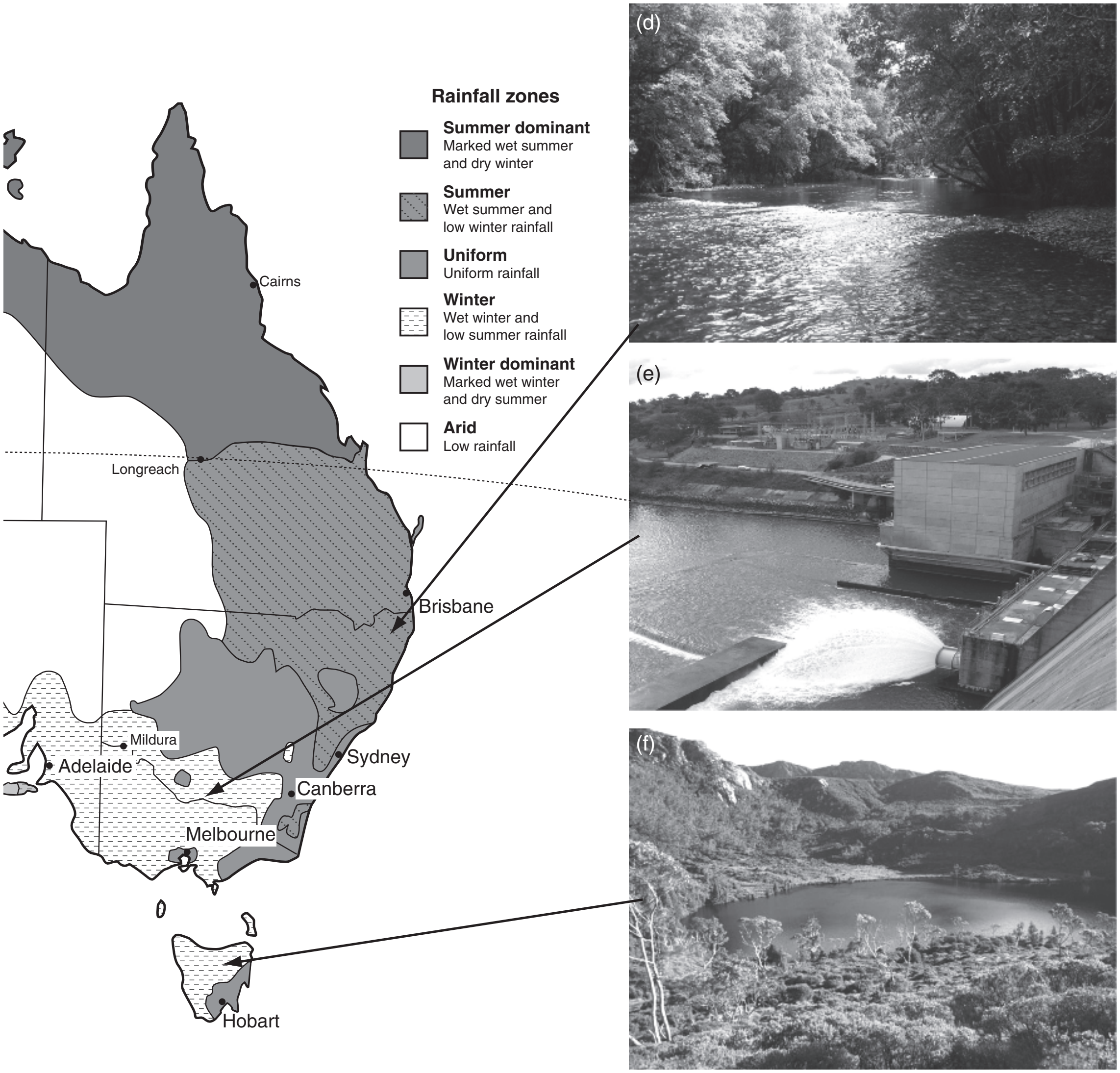

Figure 1.1 (continued) (d) coastal gravel-bed river in northern NSW, (e) Hume Dam near Albury, NSW, (f) Tasmanian mountain tarn). (Source: (a) Jane Chambers; (b), (d) and (e) Darren Ryder; (c) Jenny Davis; (f) Belinda Robson. Map reproduced with permission of the Bureau of Meteorology, Australian Government.)

1.2 DEFINING SOME COMMON TERMS

Before going further, let's define a few terms used repeatedly in this book. In the previous section, we referred to **aquatic** ecologists. Although 'aquatic' means 'associated with water', this book excludes estuarine and marine ecosystems and focuses on the ecology of fresh and saline inland waters, both temporary and permanent as well as groundwaters. Throughout the text, we use 'fresh' to specifically mean non-saline water, and 'aquatic' as a general adjective for all inland waters. All inland waters (encompassing everything from the deepest permanent fresh lake to the most fleeting saline pool) are collectively referred to as 'inland waters', 'waterbodies', 'waters' or 'aquatic ecosystems', and we use the terms interchangeably.

Although there are numerous definitions that seek to capture the diversity of inland waterbody types, we prefer this one that also explicitly recognizes the implications of water regime (Section 1.4) for the biota and ecological processes:

> *Any area of temporarily or permanently waterlogged or inundated land, natural or artificial, with water that is standing or running, ranging from fresh to saline, and where inundation by water influences the biota and ecological processes occurring at any time.*

This functional definition, modified from the widely used one in the Ramsar Convention on Wetlands (Section 12.3), encompasses *physical* features of the water regime, *chemical* features (e.g. salinity, nutrient concentrations) of the aquatic environment and *biological* features (i.e. biota and ecological processes) as well as specifying their interactions and influences.

In the first section of this book, we focus on the linkages and interaction among these three types of features and their ecological implications. In the second section, we show how understanding these linkages and interactions is essential to managing aquatic ecosystems successfully. Throughout the book, we refer to a number of 'themes'. These are intended to help you draw links between the chapters, see how ideas relate to each other, and reiterate important concepts such as the ecological significance of water regime, variability and connectivity. You may want to make a list of them as you read the book and add a few of your own.

1.3 AUSTRALIAN INLAND WATERS: THEIR DIVERSITY AND DISTRIBUTION

Australia boasts a diverse array of types of inland waters, reflecting the size of the continent, its topography, and the fact that it spans multiple climatic zones from northern wet-dry tropics to cool southern temperate areas. In southern temperate areas, winter-dominant rainfall (Figure 1.1) supplies numerous permanent swamps, wetlands and lakes as well as short coastal rivers and streams that drain to the sea. As most Australians live around the south-eastern coastline, many of these running waters have been impounded to provide water for cities and coastal towns. This, of course, creates further types of inland waters in the form of reservoirs, weir-pools and storage tanks.

Inland and further north, much of the continent is arid (Figure 1.1) and usually receives less than 500 mm of rain annually. Across this vast area are numerous shallow lakes that are mostly temporary, saline or both. Most stream and river beds carry water only after unpredictable rain, and may lie dry for years or even decades. A few inland, semi-permanent rivers drain either to Lake Eyre or into the Murray-Darling system, but most of their water evaporates, seeps into the ground or is diverted for irrigation. Occasionally, heavy rains in parts of the catchment result in vast expanses of water across the floodplain that fuel incredible 'booms' in plant and animal life until the inevitable 'bust' when the systems dry out once more.

North of 23°S (Tropic of Capricorn, Figure 1.1), much of the continent has distinct 'wet' and 'dry' seasons, resulting in a predominance of seasonally filled wetlands, lakes and rivers (Box 1.1, Pusey 2011). The key difference between these and the non-permanent surface waters of the rest of the mainland is that the filling and drying of the tropical waters is much more predictable. The fundamental importance of **water regime** – the permanence, predictability and variability of the presence and timing of water – to aquatic ecology is a central theme in this book. In Australia, the wide diversity of inland waters (Figure 1.1) has an equally wide diversity of water regimes. Are there common ecological features among these waters? What are the main differences? What physical, chemical and biological processes operate and when? How do human activities and climate change influence these in the short and long terms? What are the main management issues for these different waters and should we manage them differently?

Box 1.1 Seasonal predictability in Australia's tropical waterbodies

Nowhere is the influence of a highly seasonal water regime more apparent than in Australia's wet-dry tropics (Warfe *et al.* 2011). Each year, the wet season's monsoonal rains dump over a metre of water in just a few months, breaking half a year of baking drought. Groundwater aquifers recharge, dry creeks flood and isolated waterholes swell and connect along the large rivers, which eventually fill before overtopping their banks and spilling out across thousands of square kilometres of coastal floodplains. Within hours of the first waters arriving, creek beds teem with life. Frogs emerge from the earth and their tadpoles soon join the mix while insects arrive from refugial water holes to recolonize the abundant aquatic habitats. Fishes move onto the floodplains where a frenzy of feeding and breeding occurs before they retreat to the main channel as the dry season begins. Energy accrued on the floodplain is either transported downstream to the estuary or upstream to perennial springs or persists in refugial waterholes until the monsoons roll in and this dramatic but predictable seasonal cycle starts all over again.

Michael Douglas, Charles Darwin University

1.4 THE WATER REGIME: 'WHERE, WHEN AND TO WHAT EXTENT WATER IS PRESENT'

The diverse types of inland waters around us are a consequence of hydrology (the sources, distribution and movement of water), geomorphology (shape and changes of landforms), climate and scale. These factors determine the water regime or, in other words, 'where, when and to what extent water is present' (Bunn *et al.* 1997). In standing or lentic waters (Chapters 2–4), water regime varies with depth, which usually influences patterns of circulation within the waterbody. In running or lotic waters (Chapters 5–7), water regime is associated with flow and can be expressed as changes in discharge or water level over time. In temporary waters, surface water is absent for a period of time, and frequency and duration of filling are important. Finally, the water regime of groundwaters (Chapter 8) includes fluctuations in the water table as well as groundwater flux and pressure.

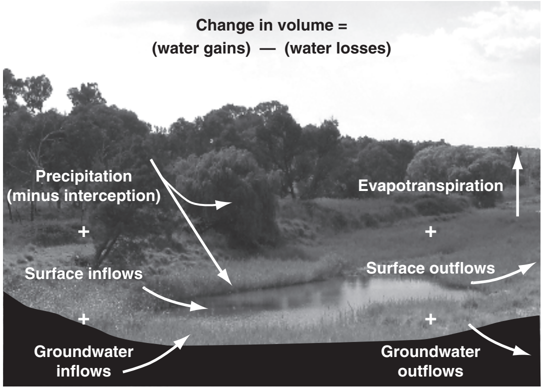

Figure 1.2 In a water budget, the change in volume equals water gains (left-hand side) minus water losses (right-hand side) for a given waterbody over a given time. Some precipitation is intercepted by plants and does not enter the waterbody. Evapotranspiration is the combined loss of water via evaporation and transpiration. (Source: Andrew Boulton.)

1.4.1 Water budgets, scale issues and human influences on water regimes

Changes in the volume of water within a waterbody are usually expressed as a **water budget**, calculated by subtracting gains from losses (Figure 1.2) over a given time. Gains are net precipitation (precipitation less water intercepted by plants), surface inflows and groundwater inflows. Losses are by evaporation, transpiration, and surface and groundwater outflows. Evaporation and transpiration are usually considered together as evapotranspiration because their rates are affected by the same factors of air temperature, humidity and wind speed.

Water budgets are often used to predict the effects of human activities on water regimes (Chapter 9). For example, Krasnostein and Oldham (2004) measured the water budget of Loch McNess, a wetland near Perth, and developed a conceptual model that showed how declines in groundwater would lower the wetland's depth. The predicted fall in its water level is now occurring as a consequence of declining groundwater levels owing to climate change and extraction. Using empirical data on water gains and losses, water managers can apply this model to guide strategies to slow the rate of drying in this groundwater-dependent ecosystem.

Gathering data on water gains and losses is challenging. This is especially true for large waterbodies with diffuse sources of surface inflows or those lying in heterogeneous sediments that have complex groundwater flow paths. Where it is impractical to measure all inputs and outputs, appropriate hydrological models and software are used. However, it is essential to recognize the limitations and uncertainty associated with most modelling approaches, and to temper predictions about changes in water budgets and water regimes accordingly.

Scale, in time and space, influences our perceptions of water regime and must be considered whenever we explore physical, chemical and biological processes (Biggs *et al.* 2005). Most ecological studies tend to be done in only one or a few waterbodies and over a relatively short time frame (say, less than five years). Such studies might only consider the water regime within that time period and only for those waters. However, the water regimes of nearby surface and groundwaters may also be ecologically relevant to the studied waterbodies, as may be their history of water regime prior to the study. Even microtopography can be important; an aquatic plant just a few centimetres higher up the bank than another may experience a very different water regime. Although the term 'water regime' is typically applied at the scale of the waterbody, it can also refer to the water requirements of an organism or its habitat (Roberts and Marston 2011).

Human alterations of water regime (Chapter 9) interact with other major threats to the ecological integrity and biodiversity of inland waters (Chapters 10–12). Successful management of our inland waters entails understanding how our activities affect water regimes and seeking ways to use our water resources without irreparably damaging them (Chapter 13). Throughout this book, we revisit the theme that most physical, chemical and biological processes in surface waters and groundwaters are controlled and constrained by the water regime and its components.

1.4.2 Components of the water regime

The primary components of the water regime in surface waters are **spatial** (related to extent and depth, volume, variability and, in running waters, discharge) and **temporal** (related to timing, frequency, duration and variability of the presence of water) (Bunn *et al.* 1997, Table 1.1). Volume, extent, depth and discharge are inter-related spatial features (Table 1.1) that co-vary in time and space (Figure 1.3) to produce a wide spectrum of hydrological conditions within and among waterbodies. Similarly, the temporal aspects of timing, frequency, duration and variability all interact, governing the life histories of most aquatic plants and animals (Chapters 4 and 7).

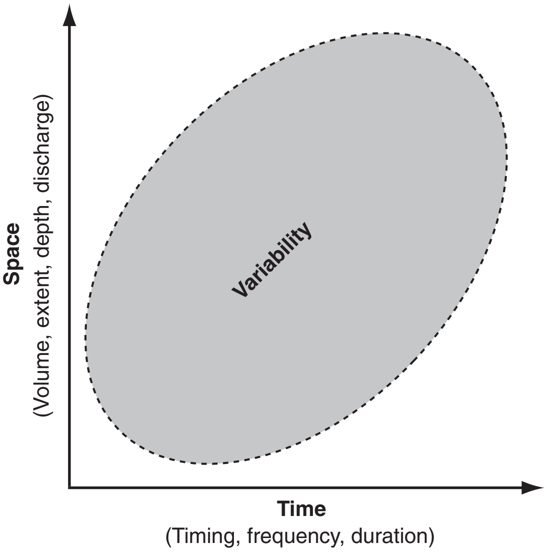

Figure 1.3 The relationship between the spatial and temporal components of water regime. Water regimes of many Australian waterbodies vary widely (grey area) in these components along both axes.

Table 1.1 Components of the water regime of inland surface waters.

Component	Definition
Spatial	
Extent and depth	The area of inundation and the depth of the water.
Volume	Depending on the shape of the waterbody, extent and depth influence the amount of water at any given time.
Discharge	The volume of water flowing through a given cross-sectional area in a specified time period.
Variability	The degree to which the above features change at a range of spatial scales.
Temporal	
Timing	When water is present. Within-year patterns are most important in seasonal waterbodies whereas among-year patterns and variability in timing are relevant to many other temporary waters (Table 1.2).
Frequency	How often filling and drying occur. Ranges from zero (permanent waters) to frequent in very shallow waterbodies that fill and dry many times a year.
Duration	Period of inundation. Days to years, varying within and among waterbodies. Rates of rise and fall may be important (e.g. flood pulses, Walker *et al*. 1995).
Variability	The degree to which the above features change at a range of timescales.

Australia abounds in temporary waters. In this book, we use the term 'temporary' to refer collectively to any waterbody that dries out. Many classifications of temporary waters use the criteria of **permanence** (duration of time that free water exists in the basin or channel) and **predictability** (reliability of filling). On this basis, temporary waters can be arranged from the least predictable and least permanent ephemeral waterbodies to the most predictably permanent ones (Table 1.2, Paijmans *et al.* 1985). Such a classification imposes boundaries upon a continuum of wetting and drying, creating problems in definitions (Williams 2006). Given this, as well as the many different classifications of 'degrees of intermittency' and the tendency for most temporary waters to vary in water regime from year to year, it is best to explicitly show the water regime at a given spatial and temporal scale (e.g. using a hydrograph, see Figure 1.4) to avoid confusion when a precise description is needed.

1.4.3 Water regime variability

Arguably, the **variability** of the water regime of all temporary waters is the major driving factor influencing their physical, chemical and biological features (Larned *et al.* 2010). This variability arises from variation in the components of the water budget (Figure 1.2), especially those associated with water loss through seepage and evapotranspiration. Such variability is crucial when classifying temporary waters. It relates to predictability in that the water regime may be predictably variable (e.g. ephemeral waterbodies), predictably regular (e.g. seasonal waterbodies such as in the wet-dry tropics, Box 1.1) or unpredictably variable. However, the spatial and temporal scales of the variation must also be considered in the context of the target organism or process. For example, an organism with a brief aquatic stage that coincides with the period of filling in a temporary waterbody is less likely to be as affected by the water regime as another whose aquatic

Table 1.2 A classification of inland waters based on predictability and duration of filling.

Waterbody	Predictability and duration of filling
Temporary	
Ephemeral	Only filled after unpredictable rainfall and runoff. Surface water dries within days to weeks of filling and can support only short-lived aquatic life.
Episodic	Annual inflow is less than the minimum annual loss in 90% of years. Usually dry but filled after rare and large, unpredictable rainfall events. Surface water persists for months to years, and often supports longer-lived aquatic life.
Intermittent	Alternately wet and dry but less frequently or regularly than seasonal waters. Surface water persists for months to years, and often supports longer-lived aquatic life.
Seasonal	Alternately wet and dry every year, according to season. Usually fills and dries predictably and annually. Surface water persists for months, long enough for some plants and animals to complete the aquatic stages of their life-cycles.
Permanent or near-permanent (perennial)	Predictably filled, although water levels may vary. Annual inflow exceeds minimum annual loss in 90% of years. During extreme droughts, these waters may dry. Usually supports diverse aquatic life, much of which cannot tolerate desiccation.

life-cycle extends beyond the duration of filling. In this sense, sweeping judgements of the environmental 'harshness' of temporary waters are meaningless; indeed, some species rely on wetting and drying for their persistence (Chapters 4 and 7).

Our perception of variability depends on scale. Therefore, it is crucial to define spatial and temporal scale explicitly. For example, Puckridge *et al.* (1998) assessed the hydrological variability of 52 large rivers worldwide. As their study was a broad-scale one in space, they selected rivers for which they could find at least 15 years of continuous hydrological data. At this inter-annual scale, flow patterns clearly differed between the tropical and dryland rivers. For example, in the tropical Mekong River receiving regular monsoonal rain, the hydrograph (the pattern of discharge over time) appears rather predictable compared to records from a dryland river such as Cooper Creek (Figure 1.4). However, on a finer scale, even the least variable of hydrographs differs from year to year in magnitude, duration and other features. If we compared hydrographs within a year, we would find further variation at monthly and daily scales. At all scales, variations in flow govern ecological processes in every

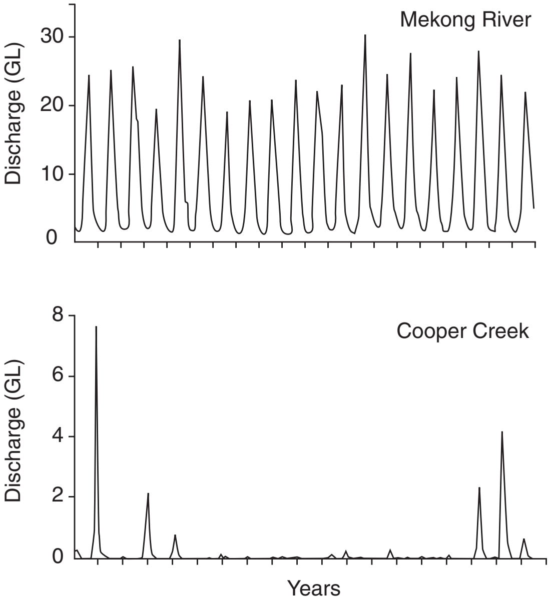

Figure 1.4 Twenty-year hydrographs of a tropical river (Mekong River) and a dryland river (Cooper Creek). GL are gigalitres (10^9 L). Note the different scales on the vertical axes.

river (Biggs *et al.* 2005), and this is why we must explicitly state the scales of our study.

1.5 LINKAGES IN AQUATIC ECOSYSTEMS: FROM MOLECULAR BONDS TO GLOBAL EXCHANGES

Linkages occur across multiple spatial scales, from the finest scale of the chemical linkages in the molecular structure of water that confer many of its unique properties through to the largest scale of the global connections among different components of the hydrological cycle. In between lie the intermediate spatial scales most familiar to ecologists: linkages across habitats, individual waterbodies, catchments and landscapes. Let's look at the finest scale first.

1.5.1 Wonderful water and its molecular linkages

Water is an extraordinary substance with many ecologically significant chemical properties. It owes these special properties to its two types of linkages at the molecular scale: **covalent bonds** and **hydrogen bonds**. Strong covalent bonds link the two hydrogen atoms to the oxygen atom (Figure 1.5), and take a lot of energy to break. These bonds hold the atoms at an angle of 104°27', which causes the water molecule to have a dominance of negative charge at the oxygen atom and a dominance of positive charge at the two hydrogen atoms (Figure 1.5). This 'charged' molecule can now form weak hydrogen bonds with nearby water molecules because the positively charged H atoms of one molecule are attracted to the negatively charged O atoms of another.

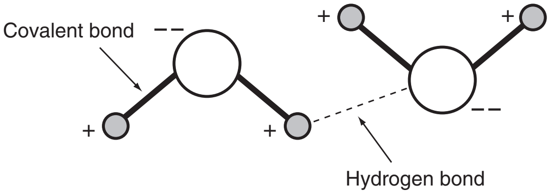

Figure 1.5 The bonds within (covalent) and between (hydrogen bonds) water molecules confer many of water's special chemical and physical properties. The negatively charged O atom is shown by the larger open circle.

The charged (or polar) nature of water molecules means they can 'attack' ionic crystals such as salts and bring them into solution, rendering water a **powerful solvent** of these chemicals. This has major implications for water chemistry such as salinity and dissolved nutrient concentrations in all aquatic ecosystems (Chapters 3, 6 and 8) as well as the management of issues associated with water quality (e.g. salinization and eutrophication, Chapter 11). On the other hand, most atmospheric gases are non-polar compounds and relatively insoluble in water. Their solubility depends on temperature, pressure and their atmospheric concentrations (Section 3.2). One exception is carbon dioxide, a polar molecule that is highly soluble, existing in equilibrium with ions of carbon (i.e. carbonate and bicarbonate) that affect water chemistry, biota and ecological processes in many surface and subsurface waters (Chapters 3–8).

There are other significant physical, chemical and biological implications of these molecular linkages. One is that water can exist in **three phases** at the Earth's surface: a vapour, a liquid and, with the hydrogen bonds forming a block-like lattice, solid ice. This lattice enables ice to float, and means that when deep waterbodies freeze over, aquatic organisms such as fishes can persist in the water below the floating ice. When we heat ice, the molecules are agitated and the hydrogen bonds break or distort, causing the open lattice to fill in. This increases the density of fresh water to a peak at about 4°C. Further heating then reduces the density until, at 100°C, pure fresh water at sea level (a pressure of one 'atmosphere': 1 atm) boils and becomes a vapour. Differences in water density caused by changes in temperature influence physical processes in standing waters (Chapter 2), with major implications for their chemistry (Chapter 3) and biota (Chapter 4).

Heat taken up or given out during changes in phase is termed **latent heat**. For water, the latent heat of fusion (i.e. the energy needed to convert ice to water once melting starts) is quite low. However, the latent heat of evaporation (when liquid water vapourizes) is high because the lattice structure of water must be completely broken down. Water evaporates at temperatures below 100°C as long as the water content of the air in contact with the water surface is below saturation. The latent heat of evaporation cools the remaining water, and can influence fundamental physical

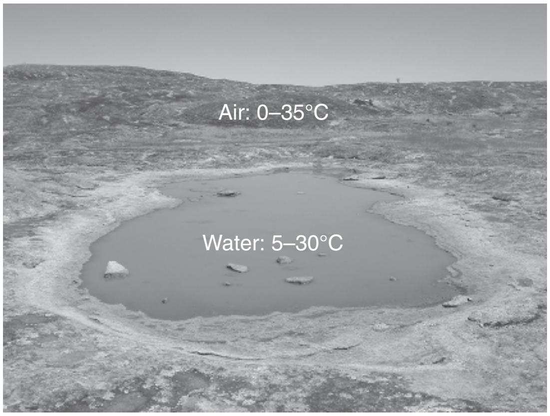

Figure 1.6 The high specific heat capacity of water, as a result of its molecular linkages, means that daily ranges in air temperature typically exceed those of waterbodies in the same area. (Source: Andrew Boulton.)

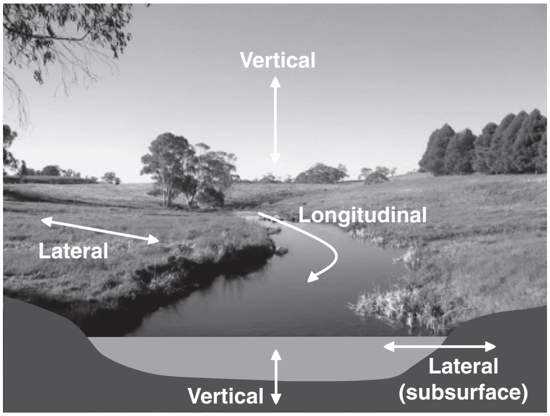

Figure 1.7 Linkages at the catchment scale include lateral linkages between the catchment and the waterbody, longitudinal linkages of upland streams to lowland rivers, and vertical linkages with the air above and groundwater below. (Source: Andrew Boulton.)

processes such as thermal stratification (Section 2.5). The molecular linkages also give water its high **specific heat** capacity. It takes about five times as much heat to raise a given mass of water by 1°C as it does to raise the same mass of dry soil through the same temperature range. One biological consequence of this is to buffer the temperature within a waterbody compared to that of the overlying air (Figure 1.6), shielding aquatic inhabitants from the greater range of temperatures experienced in the surrounding terrestrial area.

Hydrogen bonds among the molecules also mean that water has the second highest **surface tension** (after mercury) of any liquid on the Earth's surface. Surface tension allows capillary forces to wet soil above the water table without filling all the interstitial cracks (Section 8.2). This is essential for plant roots that require not only water but also gases. The high surface tension of water also enables the leaves of certain aquatic plants to float and an assemblage of organisms to hang down from the air-water interface (e.g. mosquito larvae) or to walk on water (e.g. water striders, Section 4.2). Finally, the hydrogen bonds holding the water molecules together contribute to its moderate **viscosity**. It takes a pressure difference (usually a gradient down a slope) to start water moving and to keep it flowing, overcoming friction (Gordon *et al.* 2004). Viscosity affects how animals, especially small ones, move through water or filter-feed using beating limbs and fine combs of bristles or hairs (Chapters 4 and 7).

1.5.2 Linkages at the catchment scale

Between the scales of molecular linkages and the global hydrological cycle (Section 1.5.3) lie the spatial scales of aquatic linkages within and among catchments. One of these linkages is the familiar longitudinal one (Figure 1.7) that extends down streams and rivers. A second is the lateral one between a waterbody and its catchment, often evident during flooding (Figure 1.7). Early recognition of these two linkages spawned the generalization that inland waters act to 'integrate' catchment processes because, ultimately, changes in land cover and land use in the catchment of a waterbody affect its water chemistry, sediment load and biota via these linkages (Chapters 2–7, 9–12).

Vertical linkages are less obvious (Figure 1.7) but still very important. The vertical linkage with the air above controls gaseous exchanges across the air-water interface and therefore water chemistry (Chapters 3 and 6). This linkage also has management

Table 1.3 Estimates of the major compartments, volumes and mean residence times of global water. The mean residence times of temporary lakes and rivers would be even shorter. These estimates vary; we have drawn ours from Brown (1983) and Shiklomanov (1993).

Compartment	Volume ($\times$1000 km^3)	Percentage	Mean residence time
Oceans	1 370 000	94.202	3000–3200 years
Groundwater	60 000	4.126	5000–10 000 years
(Actively exchanging groundwater)	(4 000)	(0.275)	(100–300 years)
Glaciers and ice caps	24 000	1.650	100–8600 years
Lakes and inland seas	230	0.0158	<1–100 years
Soil water	82	0.0056	1–12 months
Atmospheric vapour	14	0.00096	8–15 days
Rivers	1.2	0.00008	2–6 months

implications. For example, atmospheric pollution can increase the acidity of rain with devastating ecological consequences (Section 11.5). A second vertical (and lateral) linkage occurs between surface waters and the groundwater below (Figure 1.7). Many rivers in temperate regions flow because of water gained from the groundwater whereas much water in arid-zone rivers seeps down into the ground or is lost by evaporation. These vertical linkages influence the water regime of many inland waters as well as that of associated shallow groundwaters (Chapter 8).

The three spatial dimensions (i.e. longitudinal, lateral and vertical) of aquatic linkages are the context for most processes occurring in inland waters, and directly or indirectly influence water chemistry and the life in and around them. The linkages may run in both directions, depending on local climatic conditions and the water regime. For example, a flooding river may supply material to the catchment at some times, whereas at other times surface runoff carries material into the river. Evaporation and precipitation and the below-ground hydrological exchange between surface waters and shallow groundwaters operate in both directions (hence the double-headed arrows in Figure 1.7).

1.5.3 Linkages at the global scale: the hydrological cycle

At the global scale of the hydrological cycle, linkages are represented by the pathways potentially travelled by a water molecule among the major compartments of water on and above the planet (Figure 1.8). Water travels vertically and horizontally, and exists in three different phases (gaseous, liquid and solid; Section 1.5.1). A key point here is that the volume and residence time of water within the compartments are as important as the linkages among them. Although estimates vary among authorities and across climatic zones (the ranges in Table 1.3), volumes and residence times of the various compartments of water differ by more than seven orders of magnitude. This causes substantial lag times in some of the aquatic linkages at the global scale, and largely explains the delays common in detecting groundwater pollution (Chapter 8).

The hydrological cycle is the continuous circulation of water between the Earth and its atmosphere, and is powered by gravity and solar energy. Direct solar effects are readily evident. For example, the sun provides the energy for the linkage of evaporation to atmospheric reserves of water. Solar energy also influences the circulation of weather cells, generates wind, and induces the variability in climate. Thus, the relative contributions of the linkages in the hydrological cycle change over time and among regions. Together with human influences, these variations in the hydrological cycle dictate the distribution and water regimes of inland waters across the world (Bengtsson 2010). Predicted climate scenarios imply dramatic changes to local and global volumes of the water circulating through the hydrological cycle, with parts of the world expected to receive greater and more

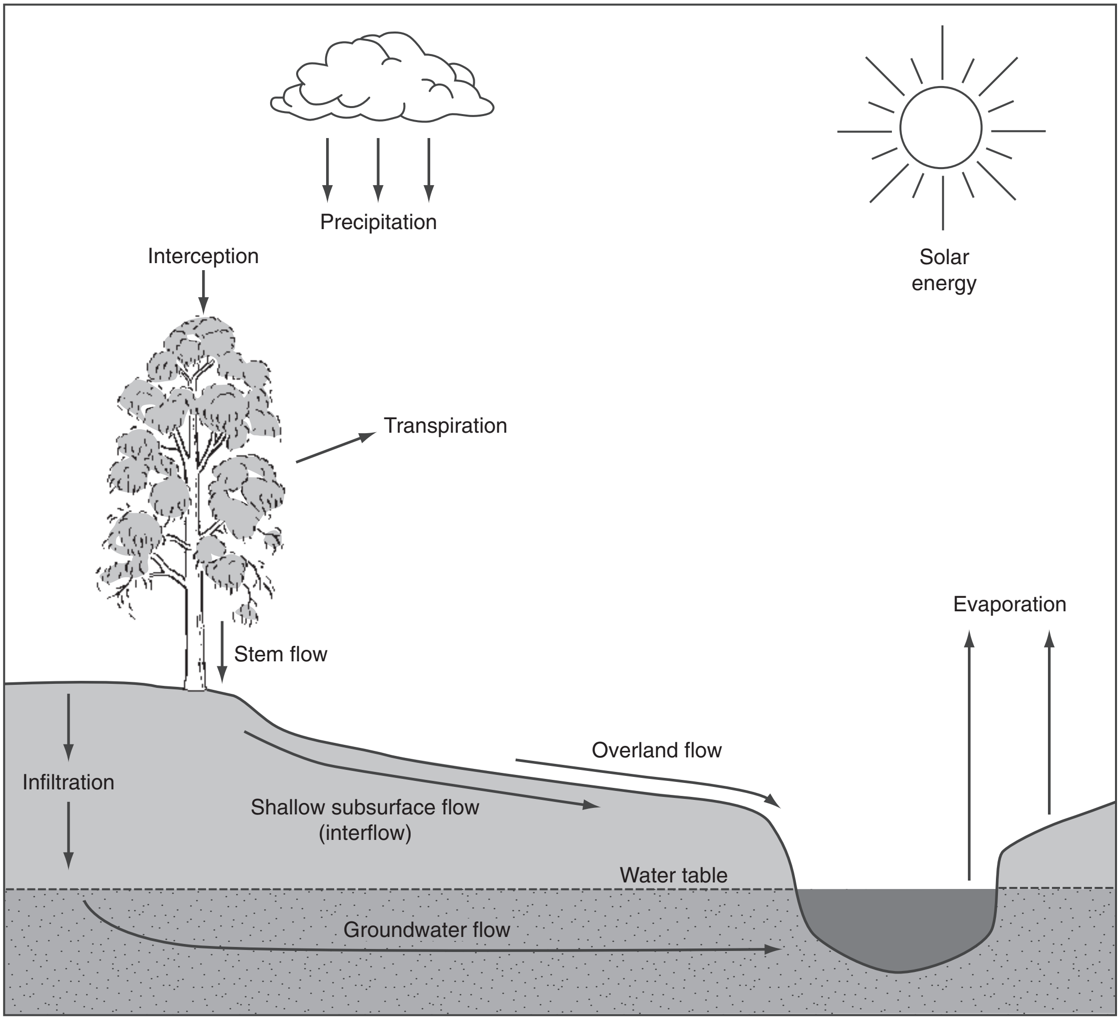

Figure 1.8 Simplified diagram of the hydrological cycle. Some water movements (e.g. capillary movement in soils) have not been included.

variable precipitation while other regions become drier and warmer (Section 12.9). For example, the increase in water vapour in a warmer climate is predicted to lead to more intense precipitation and cyclone activity (Bengtsson *et al.* 2009).

When we consider water gains and losses across the compartments of the hydrological cycle, we are looking at another water budget (Section 1.4.1) but this time at a much grander scale. Globally, some 119 000 km^3 of precipitation annually falls on land (less than one-third of the global surface) and 72 000 km^3 returns by evapotranspiration from land to the atmosphere (Figure 1.9). The difference (47 000 km^3) eventually runs off as surface or groundwater. Evaporation from the oceans exceeds the precipitation that falls on them (Figure 1.9). This spatial ‘imbalance’ in the water

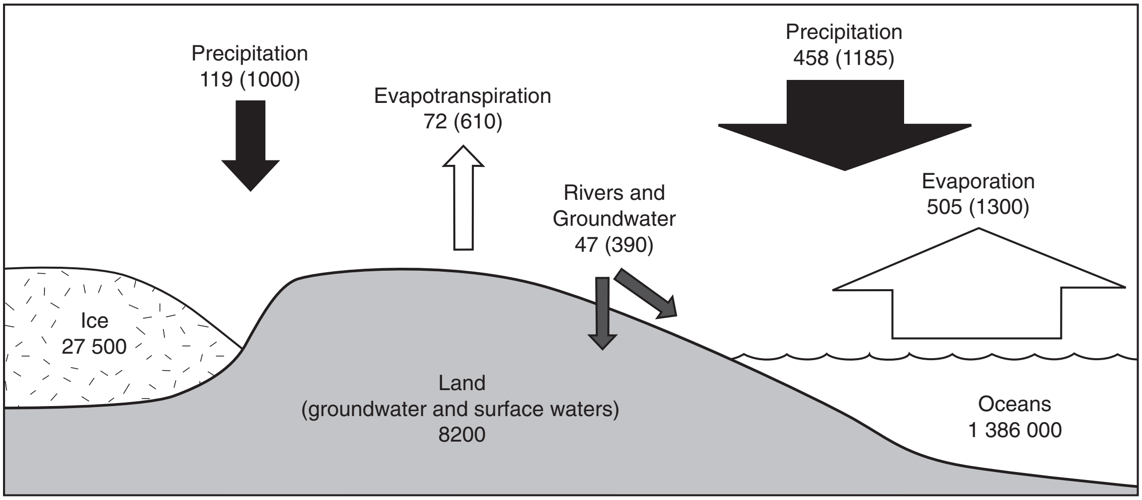

Figure 1.9 Average annual global hydrological cycle and stores of water by volume in thousands of km^3 and, in brackets, as millimetres. A similar but revised estimate based on more recent models is presented in Trenberth *et al.* (2007). (Source: Smith 1998. Reproduced with permission of Oxford University Press Australia and New Zealand.)

budget ensures the existence of lakes and rivers on the land. Patterns of water exchange between land and sea also vary regionally. For example, two-thirds of the net transport of water to the continents comes from the Atlantic, with the rest mainly from the Indian Ocean. Conversely, most of the water in the Pacific Ocean recirculates internally and there is little net transport towards land (Bengtsson 2010).

At the continental scale, the average annual Australian hydrological cycle comprises precipitation of 455 mm, evapotranspiration of 399 mm (88%), river runoff of 52 mm (11%) and groundwater recharge of 4 mm (1%) (Smith 1998). Of course, these values have little practical significance because of the massive annual and spatial variability in rainfall and climate across the continent. Much of this book deals with inland waters on a finer scale, and we shall see that the hydrological linkages at the landscape or catchment scales are usually more relevant. Nonetheless, the continental water budget of precipitation, runoff, storage, evapotranspiration and groundwater exchange dictates the water regime and regional distribution of surface waters in Australia, interacting with topography, catchment characteristics and land use. Therefore, human alterations of this budget, especially through river regulation, water extraction and anthropogenic climate change, have major implications for aquatic ecosystems and pose substantial challenges for management.

1.5.4 Continental linkages and surface waters in Australia

Australia is often described as the 'driest inhabited continent' (Antarctica is drier but not considered inhabited). Low average annual rainfall (Figure 1.10a) and its high proportional loss through evaporation (Figure 1.10b) and transpiration result in a mean annual runoff of only 1% of the world's total (Lake *et al.* 1986). Furthermore, average annual river flows are nearly three times more variable than the world average, and those in Australian arid-zone streams are especially variable (McMahon *et al.* 1992). Two-thirds of the continent receives less than 500 mm of rain annually, and across three-quarters of the land area, evapotranspiration limits runoff to less than 5% of the rainfall.

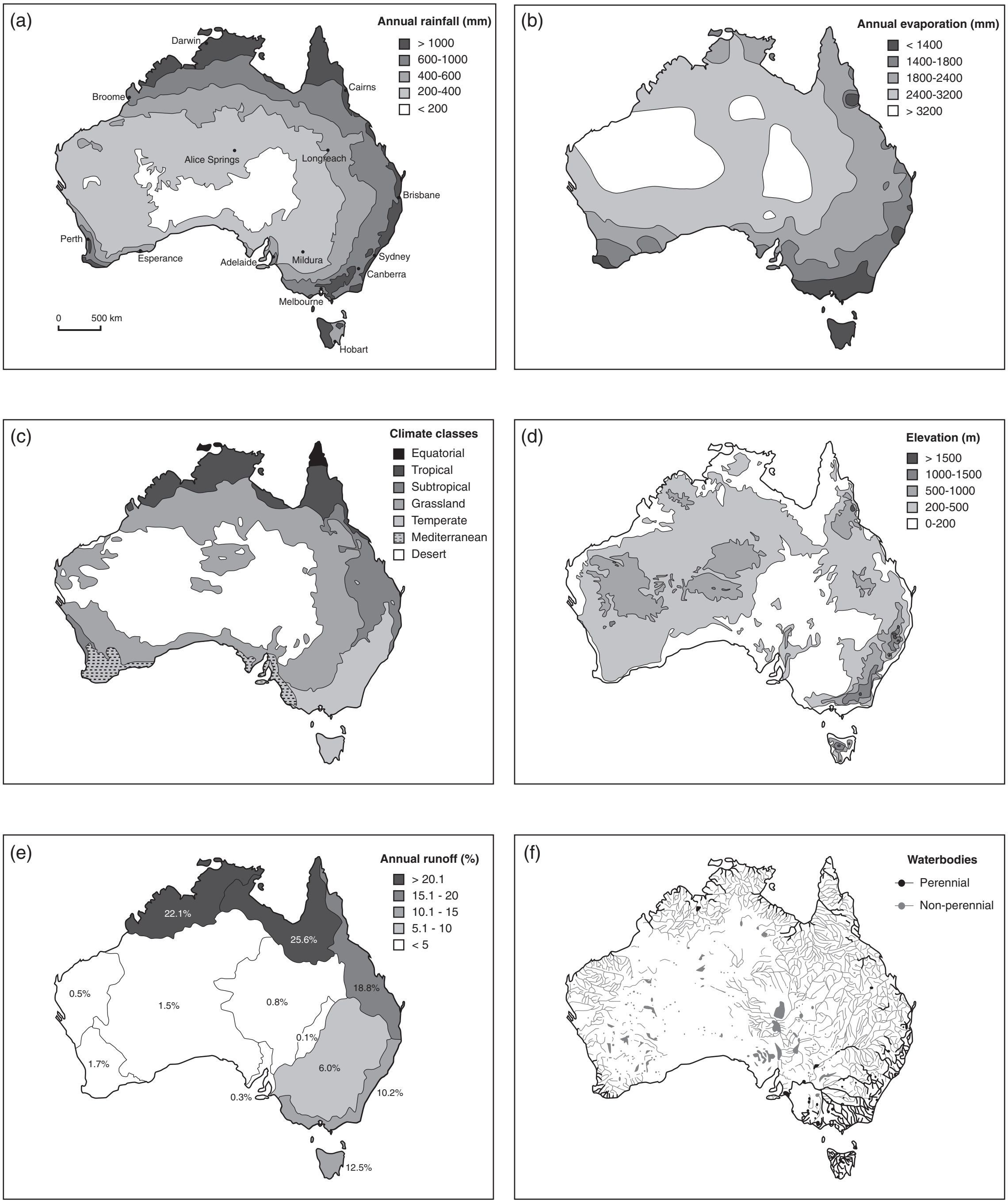

Figure 1.10 Average annual rainfall (a) and evaporation (b), broad climate (c), topography (d), runoff as percent of annual total (e) and surface water permanence (f). (Source: (a), (b) and (c) reproduced with permission from the Bureau of Meteorology, Australian Government, (d) redrawn with permission from GeoScience Australia © Commonwealth of Australia (Geoscience Australia) 2013. This product is released under the Creative Commons Attribution 3.0 Australia Licence, (e) redrawn with permission from the National Water Commission, © Commonwealth of Australia 2006, and (f) reproduced with permission from Australian Government Department of Sustainability, Environment, Water, Population and Community using data from the Australian Hydrological Geospatial Fabric (Geofabric) v1.0; Bureau of Meteorology from the State of the Environment Committee 2011.)

Part of this aridity reflects the continent's geographic location in the mid-latitude, high-pressure belt of the Southern Hemisphere. This means that its climate is controlled mainly by anticyclones moving eastwards. The borders of these pressure cells yield regular monsoonal rains to the north during the wet season (December–February). Occasionally, cyclones sweep further south-east, dumping heavy rain in the arid interior and causing spectacular flooding. In southern Australia, rainfall is usually highest during winter and spring, and the climate is more temperate (Figure 1.10c) but still seasonal.

Another cause of the continent's aridity is its low topographical relief (Figure 1.10d) and lack of large permanent snowfields. Only 2% of the land lies above 1000 m. The Great Dividing Range and its narrow coastal strip receive the majority of rain carried from the east. Thus, most runoff occurs to the north of the continent (tropical climate) and the eastern coast (tropical and warm temperate), with smaller contributions from the south-western and south-eastern corners of the mainland (Figure 1.10e). As you might expect, this is reflected in the distribution of permanent surface waters (Figure 1.10f).

Australia's surface drainages, comprising 245 river basins (listed in www.bom.gov.au/hydro/wr/basins/index.shtml), have been grouped into 13 drainage divisions (Figure 1.11), although older classifications recognized only twelve divisions. The landscape water yields (i.e. surface runoff plus groundwater discharge) from these divisions have been modelled as a function of rainfall and evapotranspiration (Commonwealth of Australia 2011), and vary widely (Table 1.4). Tasmania contributes almost half of Australia's total landscape water yield whereas the seven large drainage regions that comprise the south-western two-thirds of the continent (Figure 1.11) contribute only 13.3%. Conversely, Tasmania's mean annual percentage runoff is less than that from the tropical drainage divisions to the north of the continent (Figure 1.10e).

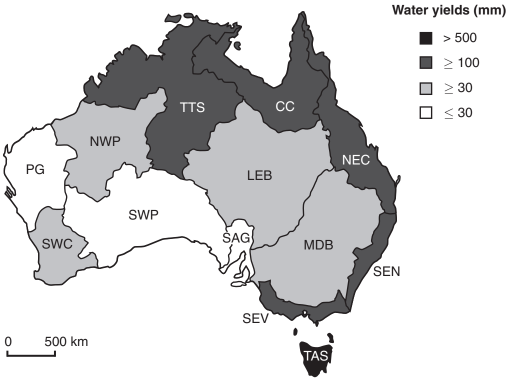

Figure 1.11 The 13 drainage divisions of Australia (acronyms in Table 1.4), shaded by water yield (mm of surface runoff plus groundwater discharge). (Source: Reproduced with permission from the Bureau of Meteorology, Australian Government.)

River systems draining to the sea are described as **exorheic** (literally, 'outer + flowing'). Nearly half of mainland Australia (49%) either has no coordinated drainage (**arheic**) or the rivers drain to inland lakes (**endorheic**, 'inner + flowing'). This contrasts with the pattern of river drainage prevalent in other continents and used as examples in Northern Hemisphere textbooks, and poses its own unique set of ecological and management issues (Chapters 9–13).

One common misconception is that fresh water flowing to the sea is 'wasted', and often there are calls in the media to divert or dam this water for human uses. However, the water that runs to the sea in these exorheic rivers supplies estuarine and near-shore coastal ecosystems with crucial water, nutrients and energy while the waterways themselves act as migration routes for many species of fishes and other aquatic life. When the volume of river runoff to the sea is reduced, the productivity of local estuarine and coastal fisheries often declines sharply (e.g. Logan River, south-east Queensland, Loneragan and Bunn 1999). Preserving the seasonal pattern of river runoff may be just as important (review in Gillson 2011). The water is certainly not 'wasted', and these river-sea linkages provide ecosystem goods and services for coastal communities and most of Australia's capital cities.

One striking example of the ecological impacts of reduced river flows on near-shore coastal waters is the Coorong and Lower Lakes at the mouth of the Murray-Darling system, listed under the Ramsar Convention as a Wetland of International Importance. Hydrological modelling of flows into this estuary-lagoon complex has been used to develop rules for determining the volume and delivery regime of river water to maintain salinities, water levels and freshwater volumes at or below specified thresholds (Box 1.2).

Table 1.4 Areas and average (1911–2010) rainfall, evapotranspiration and landscape water yields of the 13 drainage divisions illustrated in Figure 1.11. (Source: Data collated from the regional reports of the Australian Water Resources Assessment 2010.)

Topographic drainage divisions	Acronym	Area (x 1000 km^2)	Area (%)	Rainfall (mm)	Evapo-transpiration (mm)	Landscape water yield (mm)	Landscape water yield (%)
Pilbara-Gascoyne	PG	478	6.3	259	226	26	1.7
North-Western Plateau	NWP	716	9.4	316	276	36	2.4
Tanami-Timor Sea Coast	TTS	1162	15.3	656	551	108	7.1
Carpentaria Coast	CC	647	8.5	744	622	135	8.8
North-East Coast	NEC	451	5.9	827	698	138	9.0
Lake Eyre Basin	LEB	1200	15.8	242	190	35	2.3
Murray-Darling Basin	MDB	1061	14.0	458	422	35	2.3
South-East Coast (NSW)	SEN	129	1.7	995	829	152	10.0
South-East Coast (Victoria)	SEV	135	1.8	734	608	100	6.5
Tasmania	TAS	68	0.9	1398	629	691	45.3
South Australian Gulf	SAG	118	1.6	306	272	23	1.5
South-Western Plateau	SWP	1093	14.4	232	218	11	0.7
South-West Coast	SWC	326	4.3	439	399	37	2.4

Box 1.2 Requirements of estuaries and coastal lagoons (The Coorong) for fresh water

Exorheic river flows are important to many coastal and marine ecosystems. For example, estuaries such as the Coorong, at the bottom of the Murray-Darling Basin, rely upon freshwater inflows to create a zone of mixing between fresh and marine waters. The diverse habitats from estuarine to hypersaline (salinity $>$ seawater) support a multitude of birds, fish and other aquatic life, making it a wetland of international significance. Using linked hydrological, hydrodynamic and ecological models (Lester *et al.* 2011), we identified freshwater flows and associated characteristics (e.g. water level, salinity) as the primary drivers of biotic assemblages in the Coorong. These models enable us to predict physicochemical and biotic characteristics under climate change, sea level rise and environmental flows. We predict climate change will reduce freshwater inflows to the Coorong, resulting in lower water levels, higher salinities and lower diversity of birds, fishes, benthic invertebrates and aquatic vegetation. Environmental water allocations, such as those legislated under the Murray-Darling Basin Plan, may ameliorate the worst of these impacts, assuming appropriate timing and volumes of water delivery (Lester *et al.* 2013).

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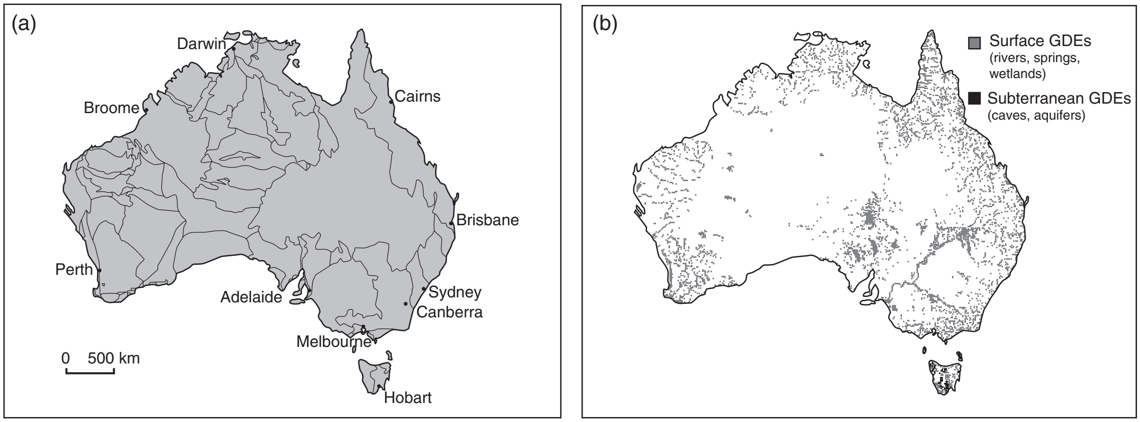

Figure 1.12 Groundwater provinces (a) and some of the main groundwater-dependent ecosystems (GDEs) (b) in Australia. The largest basin is the Great Artesian Basin. (Source: (a) reproduced with permission from the Australian Government Department of Sustainability, Environment, Water, Population and Communities - National Land and Water Resources Audit 2001, Australian Water Resources Assessment 2000, National Land and Water Resources Audit, Canberra, ACT, (b) reproduced with permission of the Bureau of Meteorology, Australian Government.)

1.5.5 Continental linkages and groundwaters in Australia

Groundwaters are hidden from view of the casual observer and are often challenging to access and sample. Therefore, the study of their ecology has lagged far behind that of surface waters, and aquatic ecology textbooks devote little attention to them. However, there have been recent advances in our knowledge about the ecology of Australia's groundwaters as well as greater recognition of the dependence of many of our surface ecosystems upon groundwater (Section 8.5.5). Groundwater can be defined as 'water that is present in soils and geologic formations for sufficient time to undergo physical or chemical changes resulting from interactions with the aquifer environment' (Tomlinson and Boulton 2008). This water occupies the saturated interstitial spaces below the Earth's surface – spaces that can range from minute voids less than a tenth of a millimetre through to vast caves hundreds of metres wide that contain underground lakes and streams.

Australia is well endowed with groundwater, and major sedimentary aquifers of variable water quality lie under some 60% of the continent. Surface drainage divisions are of limited use for describing the distribution of groundwater reserves because surface and groundwater catchments may not coincide. Thus, groundwater resources are separately assessed in 61 'groundwater provinces' (Figure 1.12a). Nonetheless, many surface waters feed or are fed by groundwaters at some time (Chapter 8). One theme of this book is the need to recognize that surface waters and groundwaters should be studied and managed as a single resource (Winter *et al.* 1998). This is all the more important when we realize that many terrestrial, aquatic and even coastal marine ecosystems rely on groundwater. These **groundwater-dependent ecosystems** (GDEs) are widespread (Figure 1.12b), and frequently diverse and beautiful, such as the ones on North Stradbroke Island, Queensland (Box 1.3).

Historically, the availability of groundwater facilitated the inland spread of European settlement (and the construction of all those iconic windmills). Even today, groundwater is the most important water resource in much of inland Australia because it is more reliable and less prone to evaporation than the sparse surface waters. Perhaps the best known example is the Great Artesian Basin (Figure 1.12a), which is among the world's largest aquifers at 1.7 million km^2 and up to 3000 m thick. It has been heavily exploited and, in some places, natural springs that used to be

Box 1.3 Groundwater-dependent ecosystems of North Stradbroke Island

Queensland's North Stradbroke Island is one of the world's largest sand islands. It comprises wind-blown sand in Pleistocene- and Holocene-aged dunes up to 219 m high, overlying bedrock well below sea level. Rainfall readily permeates the dunes to recharge a 930-GL regional aquifer forming a mound up to 40 m above sea level within the sand, plus numerous local perched aquifers formed by layers of low permeability within the sand mass. Surface expressions of groundwater support many freshwater wetlands. These occur as mosaics of permanent and ephemeral streams, perched and window lagoons and lakes, and fringing wet heath communities. Most are oligotrophic, with acidic and very fresh water, sometimes stained brown with humic substances. They support a depauperate, but specialized biota with several endemic species (Marshall *et al.* 2011). Intimate association with groundwater insulates these wetlands from short-term rainfall variability, making them relatively stable aquatic environments and likely climate refuges. Blue Lake is a fine example; recent evidence suggests hydrological stability over thousands of years (Barr *et al.* 2013). However, this dependency means that regional groundwater use must consider potential impacts on the surface wetlands and streams.

Jonathan Marshall, Queensland Government

permanent have now dried up. Effective management and conservation of groundwaters, such as those of the Great Artesian Basin, must include the complex hydrological linkages among aquifers and with surface waters.

1.6 THE STRUCTURE OF THIS BOOK

In this book, we have divided our treatment of surface waters into standing and running because flow modifies so many physical, chemical and biological processes. We emphasize a **process-oriented approach** because this best illustrates the mechanisms by which physical, chemical and biological attributes govern the ecology of aquatic ecosystems. Although the processes discussed in Chapters 2–7 are common to all surface waters, they may produce different outcomes. For example, a given volume of rainfall may fill a dry inland lake whereas the same amount could cause flooding in a permanent river. The physical, chemical and biological consequences of this event will differ among lentic and lotic permanent and temporary waters at a range of scales. Furthermore, each process may yield different results depending on the type and shape of the waterbody, its water regime, the history of the process at a range of scales, and human activities in the waterbody and its catchment. The chapter on processes and management in groundwaters (Chapter 8) also addresses the groundwater-dependence of many surface ecosystems, emphasizing the vertical linkages and connectivity.

We then turn our attention to management issues, with the underlying theme that understanding physical, chemical and biological processes is essential to effective management of surface and groundwaters so that we can manage ecological causes of the problems instead of simply treating the symptoms. Alterations of water regime (Chapter 9), physical features of the waterbody and its catchment (Chapter 10) and water quality (Chapter 11) are the three fundamental modifications wrought by human activities. Superimposed on these 'big three' are allied issues that affect biodiversity, including the effects of invasive species and climate change (Chapter 12). Attempts to restore aquatic ecosystems and protect their biodiversity rely on a sound understanding of ecological processes and how these are likely to be affected by factors such as climate change and invasive species. Aquatic ecologists contribute to wise water resource management through their basic research, field monitoring and collaboration with policy makers, social scientists, economists, consultants, managers and the public. However, this collaboration comes with its own challenges and opportunities, and discussion of these provides a fitting conclusion (Chapter 13) for a book on freshwater ecology and management.