Section 1

Natural history and ecology of the Lake Eyre Basin

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The Lake Eyre Basin – one of the world's great desert river systems

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Introduction

The Lake Eyre Basin dominates central Australia, covering about a seventh of the continent – the heart of our land mass (Kingsford *et al.* 2014; Fig. 1.1). Only ~60 000 people live in this vast area (Measham and Brake 2009), with the majority concentrated in its major towns such as Alice Springs (~25 000), Longreach (~3400) and Winton (1600; Fig. 1.1). The rivers of the Lake Eyre Basin connect the top to the bottom and the east to west of the basin, mostly flowing north to south to reach the amazing Kati Thanda-Lake Eyre in South Australia (Fig. 1.2). Small rivers and creeks, high in the catchment, run into the large rivers which join with other rivers and creeks as they flow south to Kati Thanda-Lake Eyre. River water stays within the Lake Eyre Basin, either flowing onto its floodplains, into waterholes and lakes, seeping into the ground, transpiring from the vegetation or evaporating. It is a system formed over millennia, from a once mighty river where megafauna roamed its banks, including 3 m long diprotodonts, giant kangaroos (2 m high), the large flightless bird *Genyornis newtoni* (2 m high), the giant goanna *Megalania prisca* (5.5 m long) and the marsupial lion *Thylacoleo carnifex* (2 m long) (Habeck-Fardy and Nanson 2014). About 100 000 years ago, this basin had much more water than today, supporting a contrasting environment, when the lake was 25 m deep at today's lowest point (Habeck-Fardy and Nanson 2014). By ~35 000 years ago, where Kati Thanda-Lake Eyre currently lies, Lake Dieri, a massive freshwater lake three times the size of today's predominantly salty lake, dominated the landscape. Long-gone aquatic animals lived here, including platypus, dolphins and even four flamingo-like species.

At 40 000–50 000 years ago, Aboriginal people established themselves in central Australia, living off the land and its rivers (Smith 2013; Tobler *et al.* 2017), which formed major trade routes to other river basins. They survived major changes in the climate as the continent became considerably drier and deserts formed. Extinction struck the megafauna and most of the large freshwater animals (Cohen *et al.* 2015). Aboriginal peoples knew their country, moving along the rivers with their permanent waterholes, and supplementing their water supplies from natural groundwater wells (Hercus and Clarke 1986) and plants. They lived on edible plants such as nardoo *Marsilea drummondi*, and harvested fish and waterbirds from the rivers. Ducks were caught with nets across the rivers. On the Coongie Lakes (Fig. 1.1), Yandruwandha people corralled colonies of pelican chicks (Fig. 1.3) until they were large enough to be harvested (Reid 2009). This strong connection to country continues today for many Aboriginal people who live within the Lake Eyre Basin.

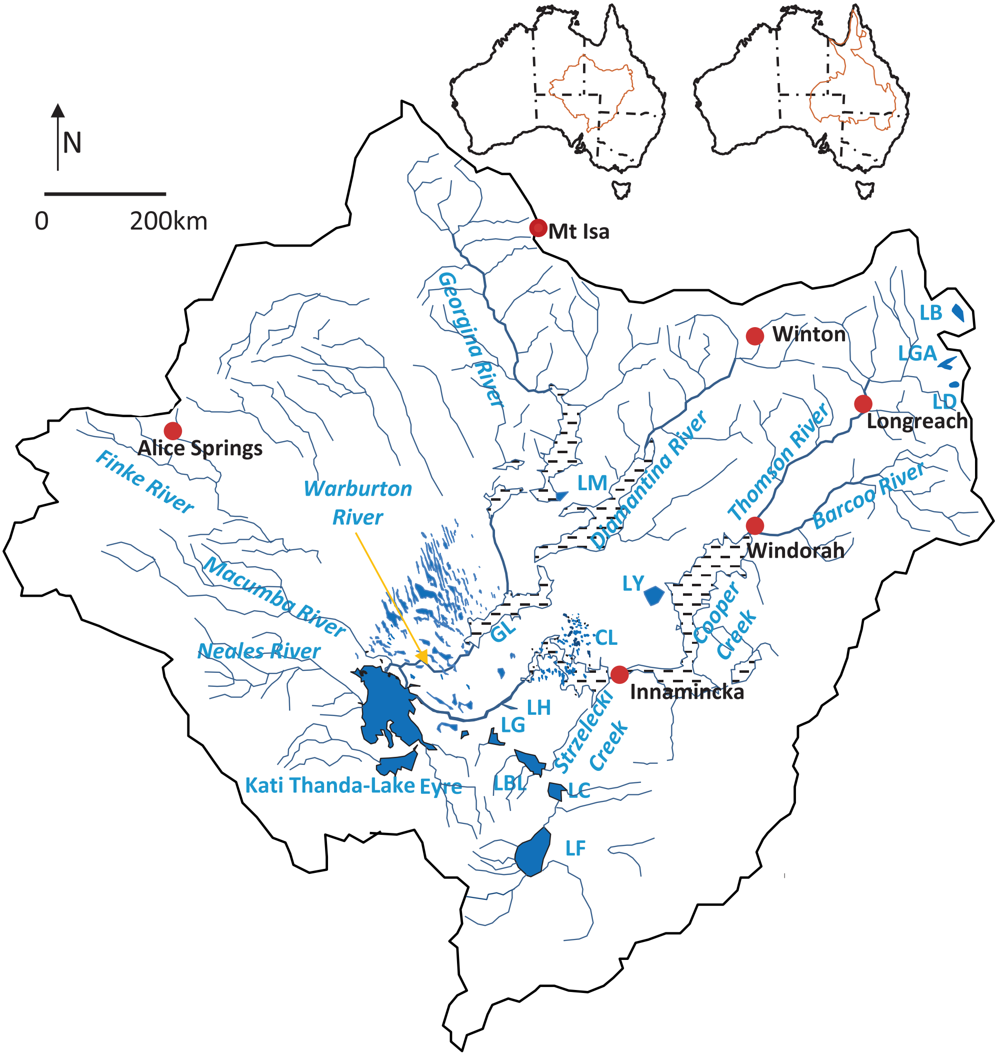

Fig. 1.1. The Lake Eyre Basin, its major rivers and wetlands and key towns in central Australia. Left inset shows the Lake Eyre Basin while the right inset shows the Great Artesian Basin. Major floodplains (hatched), include Goyders Lagoon (GL), while major lakes (filled) include Coongie Lakes (CL), Lake Blanche (LBL), Lake Buchanan (LB), Lake Callabonna (LC), Lake Dunn (LD), Lake Frome (LF), Lake Galilee (LGA), Lake Hope (LH), Lake Gregory (LG), Lake Machattie (LM) and Lake Yamma Yamma (LY).

In the 1800s, European explorers including Edward John Eyre, John McDouall Stuart and Major Warburton struck out across this landscape, searching for productive lands and water. The 1860 expedition of Robert O'Hara Burke and William John Wills from Melbourne to northern Australia remains the most notorious. Their deaths, on Cooper Creek (Fig. 1.4), were a lesson in both the harshness of these deserts and also European arrogance in the dismissal of life-saving Indigenous knowledge. Burke and Wills's party survived by eating spore cases of the ubiquitous floodplain fern, nardoo, but neglected to

Fig. 1.2. Kati Thanda-Lake Eyre receives water regularly but very seldom fills enough to provide large productive areas for fish and waterbirds (photo, R.T. Kingsford).

Fig. 1.3. Australian pelicans form large breeding colonies on some of the large lakes of the Lake Eyre Basin where there are islands, such as Lake Machattie (photo, R. T. Kingsford).

Fig. 1.4. Memorial to Robert O'Hara Burke, who died on Cooper Creek on 28 June 1861. He was the leader of the ill-fated Burke and Wills expedition to northern Australia (photo, R. T. Kingsford).

roast it to remove the damaging enzyme 'thiaminase', which contributed to their demise. Misreading these landscapes, Charles Sturt, a successful explorer of the continent's Murray–Darling Basin rivers, underestimated the size and importance of Cooper Creek, naming it a creek in 1845, presumably unconvinced that it was sufficiently large to be called a river. Two rivers (the Barcoo and the Thomson) flow into the Cooper, which can flood across up to 80 km of floodplain – clearly a substantial river.

Colonisation was sometimes brutal to Aboriginal people in many parts of Australia, including the Lake Eyre Basin (see Chapter 9). Large grazing properties were established as the settlers and cameleers moved in (Lockyer 2012). This included the legendary Sidney Kidman who built an empire of large pastoral properties across inland Australia. To this day, pastoral land management for cattle and sheep remains the most widespread commercial activity across the Lake Eyre Basin. In contrast, there are a few – and relatively small – areas established for irrigated agriculture (see Chapter 20). The other major economic activity is the mining of minerals, oil and gas (see Chapter 19. Tourism is also rapidly increasing in importance, particularly because of its contribution to economic viability in the more remote parts of the Basin (see Chapter 13). All people and their industries are supported by large regional centres, such as Longreach and Alice Springs, as well as some iconic smaller towns such as Birdsville, Innamincka and Windorah (Fig. 1.1). The sustainability of many of these industries and people is inextricably intertwined with the ecology of the rivers of the Lake Eyre Basin.

For its size, cultural and environmental values, the Lake Eyre Basin is truly one of the world's great desert rivers. It is also unique because its rivers remain largely unregulated, without major dams, flow diversions or floodplain developments. In 2014, the Lake Basin Partnership won the Australian Riverprize, followed by the International Riverprize in 2015. This was particularly significant as it was the first time in 17 years that the judging panel had awarded the prize to a free-flowing river for protection (see Chapter 7). Many of the world's rivers are highly developed, with large dams and weirs fundamentally altering flows (Nilsson *et al.* 2005) and affecting livelihoods and dependent biodiversity (Vörösmarty *et al.* 2010).

In this chapter, I briefly describe the Lake Eyre Basin rivers and dependent wetlands, their boom and bust cycles, dealt with in more detail later (see Chapter 2), followed by their ecological values, supplementing the chapters on fish (Arthington and Balcombe 2017; Chapter 3), turtles (see Chapter 5) and small mammals (see Chapter 6). Finally, I focus on the direct and indirect human impacts on the Basin's rivers and wetlands, given the long history of water resource development in Australia, and I canvas the impact of feral animals and plants, grazing and climate change on the region's globally important environmental and cultural values.

The rivers and wetlands of the Lake Eyre Basin

The Lake Eyre Basin in the centre of Australia (1.14 million km^2) includes large parts of Queensland, the Northern Territory and South Australia, and a small slice of New South Wales (Habeck-Fardy and Nanson 2014; Fig. 1.1). Another great basin, the Great Artesian Basin (1.7 million km^2), lies underneath the Lake Eyre Basin, as well as stretching further to the north (Fig. 1.1). Most of the focus of this book is on the surface waters of the Lake Eyre Basin, although reliable groundwater from the Great Artesian Basin has been critical to pastoral properties and towns. For example, bores along the famous Birdsville Track allowed stock to be walked to the railhead in Maree (Gibbs 2006). Also, the Great Artesian Basin naturally erupts to the surface, creating artesian springs with their own unique ecosystems, including endemic fish species (see Chapters 3 and 4). Access to groundwater also represents an important part of a broad search for sustainability, particularly in relation to its use by mining (see Chapters 19 and 20) and outback communities.

The vast Lake Eyre Basin has large areas of wetlands (~8.5 million ha; Bino *et al.* 2016), including artesian springs, waterholes, river channels, swamps, floodplains, and freshwater and saline lakes, predominantly supplied by its network of rivers and creeks (Fig. 1.1). The Great Artesian Basin supplies the springs, but most other wetlands are dependent on flows in the rivers. There are two major north–south catchments where most of the water flows (Cooper Creek and the Georgina–Diamantina catchment), and there are four smaller and more temporary rivers flowing east into Kati Thanda-Lake Eyre (Fig. 1.2), including the Neales and Macumba Rivers (Fig. 1.1). The Cooper Creek catchment is the most easterly of the large catchments, flowing south-west from Great Dividing Range. Its two main rivers, the Thomson and Barcoo Rivers (Fig. 1.1), are supplied by various creeks (e.g. Aramac Creek) and rivers (e.g. Alice River) before joining to form Cooper Creek, just upstream of the town of Windorah. The famous Channel Country is downstream of this confluence, where the Cooper can have a flood front which extends up to 80 km across, before it channelises and flows south-west into South Australia. This vast floodplain is like a sponge, soaking up water from the river and reducing the amount of water flowing downstream (Knighton and Nanson 1994). The river then flows past the small town of Innamincka, where it divides in large floods. Strzelecki Creek flows south to eventually reach the lakes north of the Flinders Ranges (Lake Blanche, Lake Gregory and Lake Callabonna, Fig. 1.1). However, most of the flow goes west where Cooper Creek bifurcates to supply the network of Coongie Lakes and a south arm, detailed in Chapter 2. The massive complex of lakes is within the Innamincka Regional Reserve (1.3 million ha), and includes the internationally recognised wetland of Coongie Lakes National Park, listed for its high environmental values (Puckridge *et al.* 2010). Once many of the lakes in this complex have filled, the northern branch flows south to join the southern branch of the Cooper (see Chapter 2), before flowing south-west again, where it floods a series of freshwater lakes and swamps (Kingsford *et al.* 1999). It then becomes confined to a channel before eventually reaching the eastern part of Kati Thanda-Lake Eyre. Flow patterns are highly variable (Kingsford *et al.* 2014): the Lower Cooper can flow every four years, and the Cooper reaches Kati Thanda-Lake Eyre about every 13 years (Kingsford *et al.* 1999).

To the west of this large catchment, water flows down the Georgina and Diamantina Rivers (Fig. 1.1). Water flows south-west along the Diamantina River, past the town of Winton and then past Birdsville, before forming the massive floodplain of Goyders Lagoon. To the west, the Georgina River and its tributaries flow south to meet Eyre Creek and its vast floodplain (Fig. 1.5), which includes large freshwater lakes (e.g. Lake Machattie). It also receives water from the Mulligan River, on the eastern edge of the Simpson Desert, before flowing south to join the Diamantina River's water in Goyders Lagoon. Once this floodplain is inundated, the river channel reforms as the Warburton River before flowing on to reach Kati Thanda-Lake Eyre. Four separate smaller rivers (e.g. Neales River) flow into the lake from the west (Fig. 1.1); their flows are more temporary than the rivers to the east, given their catchments lie in the most arid part of the continent (Kingsford *et al.* 2014).

Booms and busts and 'in between' flows drive this 'water environment'

Rivers of the Lake Eyre Basin are among the most variable in the world (Puckridge *et al.* 1998; McMahon *et al.* 2008). They oscillate between periods of extensive floods, driven primarily by summer seasonal rains of the Northern Australian Monsoon (Allan 1985), and extreme dry periods when there is little water in the landscape. Large tropical weather systems, particularly in La Niña years, can drive sequences of floods which may take many months to flow through the remarkably flat landscape all the way to Kati Thanda-Lake Eyre in South Australia (Kotwicki and Allan 1998; Puckridge *et al.* 2000; Costelloe *et al.* 2006). Kati Thanda-Lake Eyre receives water reasonably frequently, but rarely fills unless these

Fig. 1.5. The Georgina River catchment, including Eyre Creek, creates vast areas of Channel Country where water spreads out across the floodplain through a network of small channels (photo, R. T. Kingsford).

sequential floods occur (Kingsford *et al.* 2014). Floods which cover most of the lake return about every eight years (Kotwicki and Isdale 1991). Small floods or 'in between' flows are also critical to ensuring that waterholes are replenished and retain water through long dry periods (Bunn *et al.* 2006a). Variation in flows and flooding occurs up and down the rivers, varying in time and area. No two floods are the same. Minor changes in the rivers can alter where the water goes. Boom and bust cycles drive much of the ecology of the rivers and wetlands, producing tremendous responses in biological productivity during floods, which then 'shut down' during the bust periods.

This complex variability in timing and extent of river flows imposes its signature on the network of rivers and wetlands. These can be broadly grouped into five different habitat types: waterholes, the main and ephemeral channels, floodplains, freshwater lakes and salt lakes. There are also many small claypans, swamps and interdunal areas that are not necessarily connected to the rivers and fill from local rainfall. They are an important part of the ecology, often with high concentrations of frogs (Main and Bentley 1964; Kingsford *et al.* 2006a) and invertebrates, such as freshwater crabs (*Austrothelphusa transversa*) and tadpole shrimps (*Triops australiensis*). Artesian springs supplied by the Great Artesian Basin (Fig. 1.1), also independent of the main rivers, are extremely important wetlands, supporting communities of plants, invertebrates and fish often found nowhere in the world except in these isolated inland pools, described in Chapter 3.

Ubiquitous waterholes along the main rivers (Fig. 1.6), some permanent, are the most reliable (and iconic) natural aquatic habitats in this system, despite varying considerably in their ephemerality (Silcock 2010). They are usually 4–6 m deep, although some can be up to 25 m deep (McMahon *et al.* 2008; Kingsford *et al.* 2014). These waterholes are critically important during dry periods, providing survival refuges for aquatic animals such as fish (see Chapters 3 and 4) and turtles (see Chapter 5). Algae around their edges drives their ecology during these dry periods, providing food for the animals (Bunn *et al.* 2003; Fellows *et al.* 2007). Even in dry times, fish may breed in these waterholes (Kerezsy *et al.* 2011). As dry periods continue, evaporation lowers water levels and water quality declines considerably, with drying of some waterholes causing widespread death of fish and turtles (see Chapter 4). Many of the plants stop growing or die, leaving seeds behind to germinate in a subsequent flood (Brock *et al.* 2006). During dry periods, concentrations of fish and shrimps inevitably mean that Australian pelicans (*Pelecanus conspicillatus*), cormorant species (*Phalacrocorax* sp.), darters (*Anhinga novaehollandiae*) and yellow-billed spoonbills (*Platalea flavipes*) often concentrate on these waterholes (Fig. 1.6). Subsequent boom periods come when the tributaries run and fill the main channels and waterholes of the major rivers.

Once the waterholes are full, water spreads across the adjacent floodplain through a network of ephemeral channels. The floodplains are extensive in some places (40–80 km wide; Kingsford *et al.* 2014). This is the Channel Country, where myriads of channels intertwine to take water out over the vast floodplains. The larger floodplains of Lake Eyre

Fig. 1.6. Dry periods leave only the waterholes with water where fish, turtles and some waterbirds congregate, waiting for the next flood (photo, A. Emmott).

Basin rivers are downstream of Windorah on Cooper Creek, and upstream of Birdsville, Goyders Lagoon and Eyre Creek in the Diamantina–Georgina system (Fig. 1.1). When the water reaches the floodplains, there is tremendous increase in algal (Costelloe *et al.* 2005; Bunn *et al.* 2006b) and plant productivity, with the germination and rapid growth of plants (Brock *et al.* 2006; Capon and Brock 2006). Invertebrates hatch from dormant eggs and proliferate (Boulton *et al.* 2006). These floodplains form vast areas for foraging fish, turtles, waterbirds (Kingsford *et al.* 1999), as well as many small terrestrial mammals and other animals (see Chapter 6). Native fish species respond much better to these floods than alien species do, capitalising on the widespread availability of invertebrate and plant food (Costelloe *et al.* 2010). Waterbirds arrive on the floodplain from nearby lakes or other river basins, sometimes from thousands of kilometres away (Roshier *et al.* 2002; Roshier *et al.* 2006; Kingsford *et al.* 2010). They breed in their thousands in these areas, utilising nesting areas provided by flooded vegetation. Colonies of ibis (*Threskiornis* sp.), egrets and herons (*Ardea* sp.) and rufous night herons (*Nycticorax caledonicus*) can return to traditional nesting areas on the floodplains of Eyre Creek and Goyders Lagoon. These floodplains dry within months (Kingsford *et al.* 2010), with many plants and animals completing their life cycles in this short time, and those more dependent on water moving back into waterholes or the lakes.

The salt and freshwater lakes are widespread and particularly important for the ecology of the Lake Eyre Basin rivers. They include Lake Galilee in the north-east, Lake Machattie in the west and Kati Thanda-Lake Eyre in the south. They fill when the rivers or creeks run. For example, Lake Machattie fills from Eyre Creek while Lake Yamma Yamma fills from Cooper Creek. Kati Thanda-Lake Eyre fills from both the major river catchments, Cooper Creek and Georgina–Diamantina, as well as from the eastern flowing rivers and even creeks from the south. Some, like Lake Galilee, have their own internal catchment, which doesn't connect with the major river systems. The lakes of the Lake Eyre Basin vary in salinity from freshwater lakes (e.g. Coongie Lakes and lower Cooper lakes) to highly saline lakes such as Kati Thanda-Lake Eyre (Fig. 1.2). Freshwater lakes are important areas for biodiversity, supporting large populations of waterbirds, fish, invertebrates and other organisms (Kingsford *et al.* 1999; Kingsford *et al.* 2010; Puckridge *et al.* 2010). Many of these lakes, even if within the major river system, can also fill from local rainfall and also become saline in the final stages of their drying (e.g. Lake Hope, Fig. 1.1; Kingsford *et al.* 1999). Once flooded, salt plays a particularly critical part in the ecology of the salt lakes; it forces the clay particles to come together so they drop out of the water column by force of gravity, clearing the water. This allows sunlight to penetrate to the lake bed where aquatic plants (e.g. sea grasses) can grow in dense concentrations (Porter *et al.* 2006), contributing to incredible productivity for invertebrates and waterbirds (Kingsford and Porter 1994). These lakes, particularly where there are islands, provide habitat for colonies of Australian pelicans (e.g. Lake Eyre: Waterman and Read 1992; Coongie Lakes: Reid 2009). Importantly, salt and freshwater lakes often retain water for much longer than the floodplains – sometimes up to three or four years – providing a critical refuge for fish, turtles and waterbirds (Kingsford *et al.* 1999; Kingsford *et al.* 2010).

Development and other threats to the rivers

There are considerable pressures on the world's biodiversity and natural resources, primarily from direct and indirect effects of human development, including habitat loss and degradation, invasive species, overharvesting, pollution and climate change (Kingsford *et al.* 2009). The rivers of the Lake Eyre Basin and their dependent organisms, people and cycles are similarly affected by human pressures, although the degree of this impact varies considerably. The most serious threat is habitat loss and degradation through the potential large-scale diversion of water from the rivers and their wetlands (Kingsford *et al.* 2014).

There is a long history of changing the flows of rivers in the Lake Eyre Basin. Aboriginal people formed small dams across claypans (Gibbs 2009). Chinese 'gardeners' in the 19th century first diverted water from the rivers' waterholes to irrigate paw-paw, bananas and oranges (Silcock 2009). There was even a waterwheel built at Cullyamurra Waterhole, near Innamincka (Fig. 1.1) while sophisticated weirs were built on the Diamantina River near Winton in the 1880s to control water for local gardens (Silcock 2009; Fig. 1.7). After colonisation by Anglo-Europeans, most governments and communities in Australia began developing water resources on our rivers by building dams and diverting water, predominantly for irrigation. The aim was to improve the regularity and predictability of water (Gibbs 2009), which is – somewhat ironically – the antithesis of the behaviour of the rivers of the Lake Eyre Basin (Walker *et al.* 1997). In the 1930s, the Bradfield Scheme was the 'grand plan' for the Lake Eyre Basin, with the Thomson River to receive water diverted from coastal rivers such as the Tully River, engineered to 'flow' over the Great Dividing Range through tunnels, similar to the Snowy Mountains Hydroelectric Scheme (Gibbs 2009). In ensuing decades, sporadic small irrigation developments have occurred along the rivers of the Lake Eyre Basin, and continue to this day (see Chapter 20), but there has been no large-scale irrigation development (i.e. equivalent to that along the rivers of the Murray–Darling Basin (Kingsford 2000a)). Water is also diverted to supply the towns in the Lake Eyre Basin, sometimes using weirs to hold water back (e.g. the weir at Longreach on the Thomson River).

Large-scale developments of rivers come at considerable environmental, cultural and economic cost. Around the world, the impacts of water resource developments, the building of dams, diversion of water and development on floodplains have caused widespread degradation of rivers (Lemly *et al.* 2000; Kingsford *et al.* 2006b; Kingsford 2015; Kingsford *et al.* 2016). The impacts include loss of biodiversity, pressure on ecosystem services, damage to Aboriginal cultural sites and declining socio-economic viability. There is also increasing recognition that the environmental and cultural values of river basins also have real economic value (see Chapter 18). In Australia, there is no worse example of the size and scale of severe ecological degradation than the rivers and wetlands of the Murray–Darling Basin, where there is widespread death of floodplain eucalypts, including river red gums, other plants, declining invertebrates, waterbirds, frogs, native fish and even woodland birds and small mammals (Kingsford *et al.* 2015). Development of water resources has come at considerable economic cost, severely affecting the livelihoods of pastoralists (see Chapter 14). Some rectification of this problem, by returning some water to the environment, has cost the Australian taxpayer more than 12 billion dollars and considerable public angst.

Fig. 1.7. Chinese 'gardeners' were among the first developers of the rivers of the Lake Eyre Basin, creating weirs, such as this one on the Diamantina waterholes, which controlled water that could then be diverted to irrigate vegetables (photo, R. T. Kingsford).

Development of the rivers of the Lake Eyre Basin could easily have followed a similar path, when the Currareva development proposal on Cooper Creek was put forward in 1995 (see Chapter 17). This was essentially an irrigation development similar in size and volume to those already established in the more easterly Murray–Darling Basin rivers, with the potential to harvest and store water from small, medium and large floods in off-river storages. There is no more notorious example of the ecological and social impacts of such development than that on the Condamine–Balonne River system, the last major river to be developed in the Murray–Darling Basin (Kingsford 2000b), where small-scale irrigation developments were ratcheted up under increasing pressure from the irrigation industry, often abetted by different Queensland Government agencies (see Chapter 21). This has had considerable impacts on socio-economic values downstream (see Chapter 15).

Increasingly, there is concern that exploration and development of mining projects, particularly their use of significant volumes of water and their exploration and development footprint on floodplains, may affect the sustainability of the Lake Eyre Basin rivers. Depending on the size of such developments, flow patterns of the rivers may be severely altered, affecting both environmental values and human communities downstream. Pollution of waterways is a serious threat, evidenced by the disastrous spillage of pollutants from the Lady Annie mine into the Georgina River catchment in 2009 (see Chapter 19).

Climate change has the potential to exacerbate the problem of water resource development, although there is considerable uncertainty in climate predictions for the inland desert regions.

Rainfall and evaporation, the two most important drivers of the ecology of the rivers, are the variables most likely to be affected by climate change. Predictions for rainfall remain considerably uncertain, with potentially more intense rainfall, but there is high confidence for increasing temperatures (Reisinger *et al.* 2014), which means increasing evaporation. Inevitably, this will restrict the amount of time that different plants and animals have to complete their life cycles during boom periods, when most reproduction and recruitment occur.

The most widespread threat to the rivers, their dependent biodiversity and human livelihoods comes from the large range – and number – of invasive species. Control of these species can take considerable resources (Firn *et al.* 2015a; Firn *et al.* 2015b), even though some species have been deliberately introduced by government agencies. Feral animals within the Lake Eyre Basin include species from tropical Australia, such as sleepy cod (*Oxyeleotris lineolata*) and redclaw crayfish (*Cherax quadricarinatus*), as well as alien species from other parts of the world, such as the goldfish (*Carassius auratus*) and mosquito fish (*Gambusia affinis*) (see Chapter 3). These adaptable and widespread animals have the potential to out-compete native species and disrupt ecosystems. Within the last 10 years, introduced cane toads (*Rhinella marina*) have become common along Cooper Creek and may be driving a decline in goanna populations, as elsewhere. Introduced mammals are also widespread, including camels (*Camelus dromedarius*), pigs (*Sus scrofa*), foxes (*Vulpes vulpes*) and cats (*Felis catus*). Camels and pigs can damage watering areas while foxes and cats prey on small mammals, birds, reptiles and invertebrates. Similarly, invasive plant species are widespread across the catchment, forcing a strong focus on control given their impacts on biodiversity and grassland productivity for livestock (Firn *et al.* 2015b). These species include various cactus species, prickly acacia (*Vachellia nilotica*), rubber vine (*Cryptostegia grandiflora*), parkinsonia (*Parkinsonia aculeate*) and buffel grass (*Cenchrus ciliaris*).

People have a strong connection to waterholes (Silcock 2010), which is manifested in increasing tourist visitation leading to pollution around waterholes and damage to vegetation through the felling of logs for camp fires and trampling of sensitive riparian groundcover plants. Livestock grazing may also contribute to some loss of plant cover, as well as increased sedimentation of waterholes, although there remains relatively little evidence of widespread change in over more than a century (Silcock *et al.* 2013). The practice of stocking and destocking in unison with natural boom and bust cycles may create some resilience to livestock grazing impacts in the landscape.

Conclusion

Knowledge of the environmental values and threats to the sustainability of the rivers of the Lake Eyre Basin has rapidly increased in the last decade. This knowledge continues to reinforce the iconic status of this magnificent river basin which covers such a large part of the continent (Pisanu *et al.* 2015). Indeed, it was the combination of significant cultural and environmental values and free-flowing status that resulted in the Lake Eyre Basin Partnership receiving the prestigious Australian and International Riverprizes in 2014 and 2015 respectively. The Basin is clearly one of the great desert river systems of the world, and one of few unaffected by dams, major diversions of water or developments on its productive floodplains. Development of the rivers for irrigation will inevitably continue to be a major threat, as long as there is potential for governments and their communities to believe that a 'traditional' development path is the way forward. Adequate assessment of the impact of water resource development on cultural and environmental values remains critical (see Chapter 18), as does recognition of the global importance of the free-flowing status of the rivers. Clearly the prudent, sensible and responsible approach for the future is to maintain this globally unique river system in good health – anything less will represent a failure of our nation to learn from past mistakes.

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2

Water – where, when, how much? Challenges in understanding and managing flow in rivers of the Lake Eyre Basin

Justin Costelloe

Introduction

The floods and zero flow periods of the unregulated rivers of the Lake Eyre Basin drive spectacular booms and busts in ecosystem responses (Kingsford *et al.* 1999; Puckridge *et al.* 2000). In addition to their renowned environmental value, the rivers are central to the economy of the arid zone, sustaining pastoralism (see Chapters 10 and 11) and tourism (see Chapter 13), and their flow patterns affect the infrastructure of important energy industries (oil, gas and geothermal). While the rivers are unregulated and currently experience only minor water resource use (see Chapter 20), they are experiencing constantly changing pressures on land use and increasing demands on water resources, particularly from expanding energy industries (Kingsford *et al.* 2014; see Chapter 19).

Arid zone river systems are significantly challenging for describing the basics of flow – where, when and how much? Traditionally, hydrological analysis occurs when there is either a potential for substantially changing the river for human use, such as building a dam, or for managing a river where there are already significant diversions for human use. It could be argued that detailed observations of flows and construction of complex hydrological models are not warranted for Lake Eyre Basin rivers, but this ignores the ever-present management challenges. Natural resource managers need to be able to identify changes in the flow regime of these rivers from stressors, including water extraction, floodplain modifications and climate change. Hydrological models are essential for estimating how proposed changes may affect the rivers and their biota. Therefore, monitoring of flows and flooding patterns in these rivers is not an academic exercise – both are central to the sustainable management of Lake Eyre Basin rivers.

Current state of monitoring

One of the major challenges for the management of the water resources of the Lake Eyre Basin is the paucity of conventional hydrological data. The Lake Eyre Basin is a similar size to the Murray–Darling Basin, both just over 1 million km^2, but there are only 13 gauging stations (Fig. 2.1) in the Lake Eyre Basin, with records of more than 15 years of data compared to more than 160 gauges in the Murray–Darling Basin (Kennard *et al.* 2010). The number of gauging stations shrank in the 1990s in the Lake Eyre Basin (see Table 2.1), but there has been a recent resurgence due to increased investment by the Bureau of Meteorology and the Queensland and South Australian governments, and some industry monitoring (e.g. Santos

Fig. 2.1. Cullymurra waterhole in South Australia, near Innamincka, is the site of one of only 13 river gauges in a river of ~1300 km (photo, R.T. Kingsford).

Limited). This scarcity of monitoring data makes understanding the hydrology of these complex rivers extremely difficult. And yet major decisions that depend on this understanding and being able to determine the impacts of flow regime changes on downstream landholders and the environment need to be made about the future of these rivers.

Where – spatial variability

Spatial variability is a major feature of Lake Eyre Basin river flows. Rainfall, run-off and river flow vary considerably across the Lake Eyre Basin (McMahon *et al.* 2008a; McMahon *et al.* 2008b). Measurement of the most important input into any hydrological model, rainfall, is also particularly difficult, given the relatively few rain gauges in the Lake Eyre Basin (McMahon *et al.* 2008a). This contributes to the uncertainties of measuring the flow in Lake Eyre Basin rivers, an important area for research. Added to this, the complex flow paths and channel networks on the large, spectacular floodplains of the major Lake Eyre Basin rivers are confronting to monitor and model. The few gauging stations (Table 2.1) are naturally where flow convergence most efficiently measures flow volumes. But we have little information about what is happening to flow between these monitoring points, often hundreds of kilometres apart.

In the magnificent Channel Country of Cooper Creek, between the junction of the Thomson and Barcoo Rivers and South Australia, flow can follow incredibly complex, anastomosing channels and floodplain paths, as it slowly moves downstream (Fig. 2.2). The

Table 2.1. Changes in the number of stations in state government gauging station networks in major catchments of the Lake Eyre Basin during different periods.

Unrated and non-telemetered water level logger sites installed since 2000 as part of research projects or the Lake Eyre Basin Rivers Assessment (LEBRA) monitoring project were not included.

Catchment	Pre-1966	1966–1990	1990–2010	Post 2010
Cooper	5 (3[a])	11	9	13 (4[a])
Diamantina	1	2	1	4 (1[a])
Georgina	0	4	0	2
Finke	0	8 (5[a])	8 (5[a])	3
Macumba	0	0	0	1[a]
Neales	0	0	0	2[a]

[a] gauging stations with no rating curve (only flow levels monitored and not discharge).

hydrology and geomorphology of this reach are reasonably well known after 20 years of research, which shows that small flows follow channelised pathways and experience low 'transmission losses', compared to the medium to large floods, which cover more of the floodplain and hence experience higher proportional losses (Knighton and Nanson 1994; Knighton and Nanson 2001; McMahon *et al.* 2008a). A 'transmission loss' means the water doesn't progress further downstream, but in fact it is not a loss at all because the water is critically important to the spectacular ecology of the floodplain and landholders who graze

Fig. 2.2. During floods Cooper Creek breaks out of its major channels and spreads out along complex flow paths across the floodplain (photo, R. T. Kingsford).

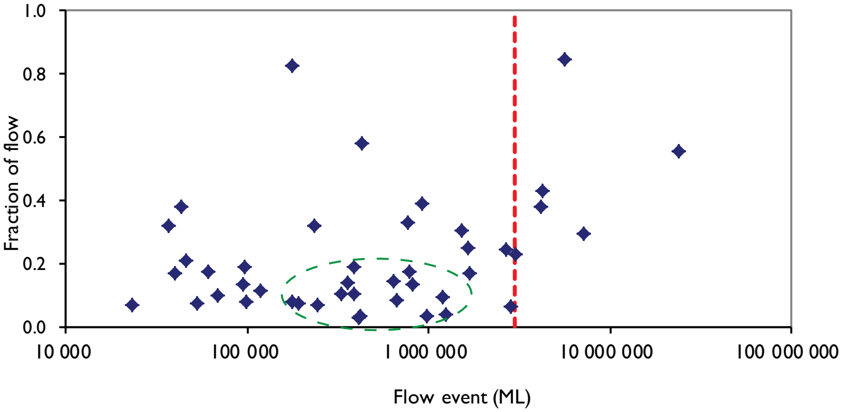

Fig. 2.3. Fraction of flow in the Channel Country of Cooper Creek reaching the border of South Australia (measured at the Nappa Merrie gauge), relative to total flood event volume (log scale) measured at the Currareva gauge (near Windorah). Daily flow data supplied by the Queensland Department of Natural Resources and Mines (1950–88). The dashed oval shows the medium volume floods that experience some of the highest relative volume reductions in this reach.

their livestock on these highly productive floodplains (see Chapters 10 and 11). These ‘transmission losses’ can be huge. For instance, for some medium-volume floods which return every one to three years, 90–95% of the volume that passes the town of Windorah does not flow into South Australia (see the circled flood data in Fig. 2.3). This water evaporates, infiltrates the channel (where it can recharge groundwater; Cendón *et al.* 2010) and the floodplain, or lies on the floodplains (Knighton and Nanson 1994), where it fuels an ecological boom cycle (see Chapter 1). Understanding the fate of this floodwater is challenging. Adding to the complexity of estimating transmission losses is accounting for inflows to the reach from rainfall and tributary flow. Some flood events may be entirely composed of run-off generated in the Thomson and Barcoo catchments while others (e.g. those with flow fractions greater than 0.3 in Fig. 2.3) can receive substantial contributions from local rainfall and run-off in the Channel Country (Fig. 2.4).

The composition of floodwaters flowing into South Australia shows relatively little change to that measured at Windorah (Larsen 2012), indicating that some flow channels are very efficient in transporting water downstream (i.e. without much evaporative loss and concentration of the ionic composition) while others move water onto the floodplain. This suggests that most of the water loss measured at the downstream gauging station is due to pooling of water on the floodplain or wetlands (i.e. no longer connecting with downstream flow). This water then evaporates, infiltrates the sediment of the floodplain where it supplies plant transpiration, or recharges groundwater (Cendón *et al.* 2010). Surprisingly, the actual channels that convey flow during flood events of different magnitudes have never been accurately mapped nor their different functions identified. This is an important knowledge gap and a focus for our research (e.g. Mohammadi *et al.* 2017) because, for instance, if there was irrigation extraction from an efficient pathway, there would be a much greater downstream effect (in terms of flow reaching South

Fig. 2.4. Local storms in the Lake Eyre Basin make a contribution to the flow of the rivers in the Lake Eyre Basin into waterholes, floodplains and lakes (photo, A. Emmott).

Australia) than the same volume and rate of extraction from a pathway which predominantly supplied the floodplain, where the impact would be predominantly on the ecosystem and landholders, depending on the floodplain.

A second example of spatial variability is in South Australia, where the Cooper changes from an anastomosing channel system to a distributary channel system. Here, the Cooper splits into three distinct flow paths: Strzelecki Creek (only receiving flow from Cooper Creek during very large floods), the Main Branch (with two subsequent branches) and the North-west Branch (Fig. 2.5). The latter flow path supplies the iconic, Ramsar-listed Coongie Lakes (Fig. 2.6). To estimate how changes in the flow regime would affect inflows to Coongie Lakes, we need to know the thresholds and how much water flows down each of the flow paths for the range of different events. During April 2012, the flood pulse from Queensland (see Fig. 2.7) had approximately an annual recurrence interval and the North-west Branch received 53% of the channel flow while the rest (47%) went down the two channels that form the Main Branch. However, a flow double this volume in 2011 pushed a higher percentage of flow down one of the Main Branch channels (see Fig. 2.5): 34% compared to 20% of the flow in 2012. Flood conditions prevented the other Main Branch channel and the North-west Branch channel from being measured in 2011. Clearly, the percentage of flows down the different channels varies with the volume of the flow, but this is difficult to determine even in a medium volume flood, requiring substantial effort to collect such critical data in this remote and challenging environment. Unless these changes in the percentages in

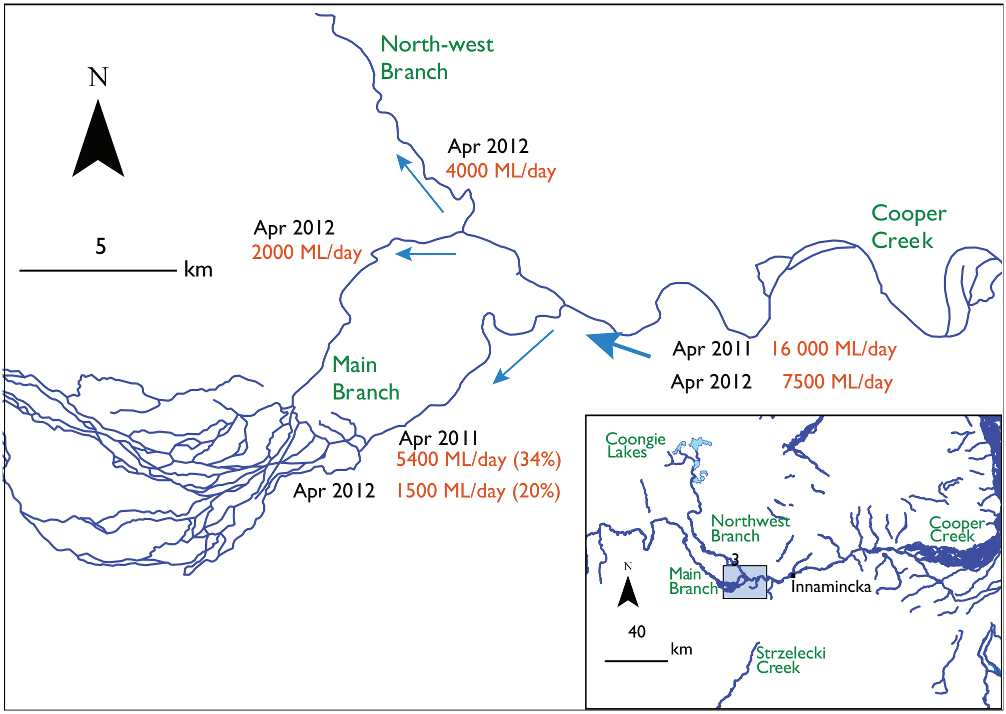

Fig. 2.5. Changes in flow volume in 2011 and 2012 at the split in Cooper Creek between the North-west Branch (flowing towards Coongie Lakes) and the two channels of the Main Branch (flowing towards Lake Eyre). The inset figure shows the lower Cooper where it changes from an anastomosing channel system to a distributary system downstream of Innamincka. The shaded rectangle in the inset figure shows the location of the North-west Branch and Main Branch split.

flow between the major flow paths of the lower Cooper are known, we will be unable to represent this behaviour in a hydrological model.

When – temporal variability

In addition to the spectacular spatial variability of the Lake Eyre Basin rivers, their flows rank highest among the most temporally variable large rivers of the world (Puckridge *et al.* 1998; McMahon *et al.* 2008b). In particular, this high variability in flows between years (interannual variability) drives the boom–bust ecological response to flow events. Very large floods (e.g. those in 2010) inundated greater than 10 000 km^2, but this shrinks in relatively dry years (e.g. 2013), with more than an order of magnitude lesser flow volume (Fig. 2.7).

For many parts of Lake Eyre Basin, we have no records of when rivers flowed. There is improvement with expansion of the monitoring network (Table 2.1), but the available records are short, relative to the high interannual variability of these rivers. For instance, monitoring of flows in the 34 000 km^2 catchment of the Neales River (western Lake Eyre Basin) from March 2000 to November 2009 identified an average of 2.5 flows per year, with one or two flows in any one reach of the river. However, there were another 22 flows between November 2009 and April 2011, coinciding with a La Niña episode (Fig. 2.8a). This increased the average

Fig. 2.6. The spectacular Coongie Lakes, an internationally important wetland, are supplied by the North-west Branch of Cooper Creek and support high biodiversity, particularly during dry periods when fish and waterbirds congregate (photo, R. T. Kingsford).

number of flow events to 4.2 events for the period 2000–2011. Observed flow events in the Neales River, for 2000–09, were significantly higher than for modelled flows during the pre-2000 period (Fig. 2.8b; see also Costelloe *et al.* 2005), emphasising the necessity for multi-

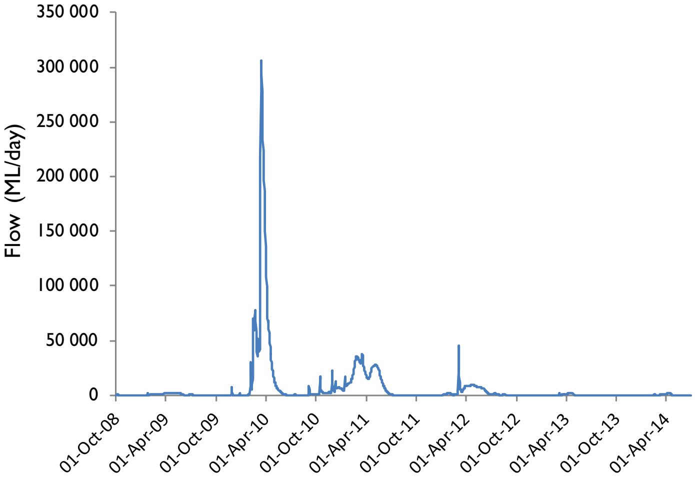

Fig. 2.7. The interannual variability of Cooper Creek is illustrated using daily flow data from Cullyamurra gauging station, near Innamincka (South Australian Department for Environment, Water and Natural Resources, Fig. 2.1), 2009–13. Note the small volume of the 2009, 2013 and 2014 floods compared to the period 2010 to 2012.

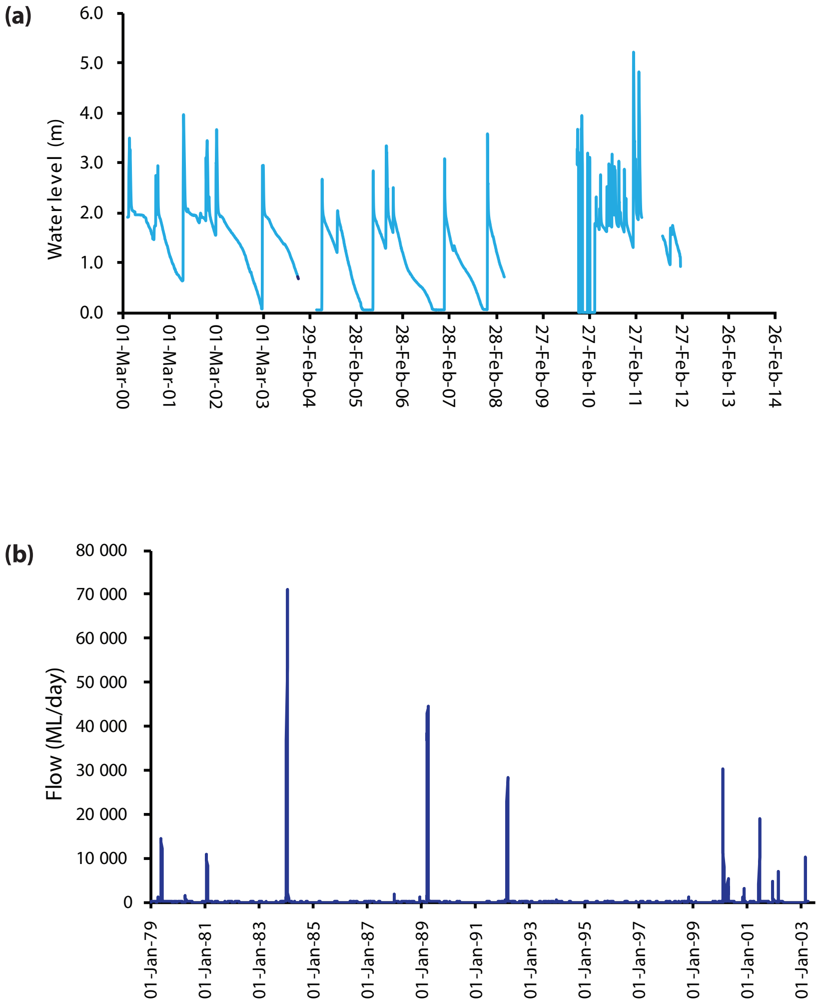

Fig. 2.8. Algebuckina Waterhole on the Neales River showing (a) observed water level with increased frequency of flows, 2009–2011 and (b) modelled daily flow (Costelloe *et al.* 2005), illustrating that the period of observed data (post-1999) had more frequent flow events than the preceding 20 year period.

decadal records before temporal variability can be quantified. We need to have knowledge of flow variability for infrastructure development adjacent to the river or its tributaries. This information can be generated by developing rainfall run-off models, but without observed flow data to calibrate or evaluate the model, there will be a large degree of uncertainty in the results. The consequences of inaccurate estimation of flood frequencies can affect estimates of impacts on ecosystems, ecosystem services and infrastructure (e.g. roads).

The high interannual flow variability of Lake Eyre Basin rivers has implications for extraction of water from the rivers. Variability in magnitude and timing means that water extraction would be relatively unreliable for agricultural or mining requirements using flow-based thresholds. For example, current extraction rules for inactive irrigation licences in the

Windorah–Nappa Merrie reach of Cooper Creek require that the river has a minimum flow of 3220 ML per day before extraction can occur, with a maximum extraction allowed of 120 ML per day without a storage. This means that no water could be extracted in the driest 10–20% of years of the flow record at the Currareva gauge. These extraction rules minimise the effects of potential water extraction. However, once established an operation could lobby for increased access to reliable, rather than opportunistic, water extraction.

How much – future requirements of monitoring and modelling for the Lake Eyre Basin

The rivers of the Lake Eyre Basin experience water extraction volumes that are very low (see Chapter 20), compared to the far more heavily regulated rivers of the neighbouring Murray–Darling Basin (Kingsford 2000). In the Murray–Darling Basin, Commonwealth and state governments are spending more than $13 billion on water management and environmental flows to redress historical over-allocation of water resources (Murray–Darling Basin Authority 2012). The overriding management paradigm in the Murray–Darling Basin is to identify and provide the minimum amount of environmental water, and appropriate temporal patterns of flow, that will maintain acceptable levels of ecological health for the rivers. In contrast, essentially all of the river flow in the Lake Eyre Basin rivers is needed to support its natural patterns of boom and bust and the current good state of ecological health (Leigh *et al.* 2010). Therefore, the management paradigm in the Lake Eyre Basin should determine how any development (and associated change in flow regime) will affect the present ecological health of the rivers (see Chapter 22), and use this understanding to guide acceptable levels of extraction or changes to flow patterns, rather than aiming to define minimum environmental flow requirements.

Conclusion

The 'where' and the 'when' issues for rainfall and flow illustrate the complexities and challenges in determining a sound response to the 'how much water?' question for the rivers of the Lake Eyre Basin. The most difficult aspect of 'how much?' lies in answering the question of 'how much effect would water extraction, or infrastructure development that changes flow patterns, have on the flow regime and ecology of downstream ecosystems?' This is particularly hard to answer because of the difficulty in identifying hydrological and ecological change in this highly variable system with short and incomplete flow records. Changes are likely to have the most effect on the smaller flow events, depending on extraction rules or placement of pumps, weirs and dams. For this reason, modelling of the large Lake Eyre Basin rivers must include the capacity to accurately simulate small flow events, rather than concentrating on simulating mean or large flow events. It is not acceptable to make broad policy and management decisions based on insufficient modelling, given the potential long-term consequences. Modelling of small flow events requires more emphasis on which flow paths are activated, and the relationship between flow volume and how much water is required by floodplains. Modelling flows in the small rivers of the Lake Eyre Basin must also address acceptable accuracy when simulating smaller flows. Here, the challenge is not so much the spatial variability of flow paths, as typically these smaller rivers have simple channel systems, but whether the rainfall data can capture the spatial variability of rainfall patterns. For instance, is the rainfall station network capable of accurately measuring rainfall from isolated thunderstorms (Fig. 2.4) in comparison to widespread rainfall from fronts or larger tropical weather systems?

The Lake Eyre Basin presents considerable, but not insurmountable, challenges to hydrological modelling. Despite the lack of extensive monitoring infrastructure, we can make targeted use of satellite data to improve our capacity to model the flow regimes of these rivers with improved accuracy and predictive power. For instance, rigorous mapping of flood patterns across a range of flood volumes, using existing satellite systems, can be combined with the new generation of digital elevation data (e.g. Karim *et al.* 2012; Mohammadi *et al.* 2017). This approach would allow the gathering of important information on flow paths that occur between the gauging stations. We can also add value to the increased government and private industry investment in flow-monitoring stations of the past few years. A commitment to gathering discharge (i.e. river flow) data at these newly monitored locations would greatly contribute to the capacity of hydrological models to manage these rivers by allowing the quantitative estimation of flow into different parts of the river systems.

A combination of a long-term commitment to data gathering and targeted research will greatly increase our capacity to confidently analyse or model the effects of changing flow regimes on the magnificent arid-zone rivers of the Lake Eyre Basin and their dependent ecosystems and ecosystem services. While we move towards steadily improving our hydrological understanding of the system, we need to be mindful of current limitations when assessing the effects of water resource use and floodplain infrastructure developments. Our capacity to monitor or model changes to the smaller volume flow events is prone to considerable uncertainty and hence our confidence in analysing the effect of flow regime changes on particular assets is presently poor.

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3

Fish distribution, status and threats in the rivers and springs of the Queensland Lake Eyre Basin

Adam Kerezsy

Introduction

Even a cursory glance at a map of central Australian waterways tells the story: there aren't many, and there are really only three big rivers (Fig. 3.1). The Cooper, the Diamantina and the Georgina Rivers are the collective engine-room of Australian arid-zone aquatic ecosystems, and run-off from unpredictable monsoon rains is their fuel. The study of fish ecology in the Lake Eyre Basin is patchy. Despite the fact that most permanent waters are within Queensland (Silcock 2009), both the earliest fish surveys (Glover and Sim 1978; Glover 1979) and ecological studies (Puckridge 1999) were in South Australia. Sites from the upper and mid-reaches of the three big rivers in Queensland have only been sampled since 2000 (Bailey and Long 2001; Costelloe *et al.* 2004), with the Cooper consistently receiving most attention (Arthington *et al.* 2005; Balcombe *et al.* 2007; Balcombe and Arthington 2009). Long-term repeated sampling of multiple riverine sites throughout all three major rivers of the Queensland Lake Eyre Basin occurred between 2006 and 2010 (Fig. 3.1; Kerezsy 2010; Kerezsy 2011) and then from 2010 onwards through the implementation of the Lake Eyre Basin Rivers Assessment, administered by a combination of natural resource agencies based in Queensland, South Australia and the Northern Territory. No fish species present in the rivers of the Queensland Lake Eyre Basin is currently listed under either state or federal endangered species legislation, and none is a species on the international Red List of Threatened Species (International Union for the Conservation of Nature 2016).

Though far smaller in area, the Great Artesian Basin spring complexes in Queensland – the Barcaldine group in the north-east, the centrally located Springvale group and the Mulligan group on the eastern edge of the Simpson Desert – have received comparatively more attention over a longer time than the riverine environments (Fig. 3.1). This disparity has been due largely to the notable numbers of endemic plants, invertebrates and fish within these springs (Ponder and Clark 1990; Fairfax *et al.* 2007; Fensham *et al.* 2011; Kerezsy and Fensham 2013). Spring complexes – or groups – are characterised by multiple shallow, groundwater-fed ponded and/or damp areas. All are associated with faulting, and it is the presence of faults that has enabled water from the Great Artesian Basin to reach the surface over a prolonged period. Most native fish species present in Great Artesian Basin spring complexes in Queensland are listed as vulnerable, endangered or critically endangered under relevant Australian legislation (*Nature Conservation Act 1992*; *Environment Protection and*

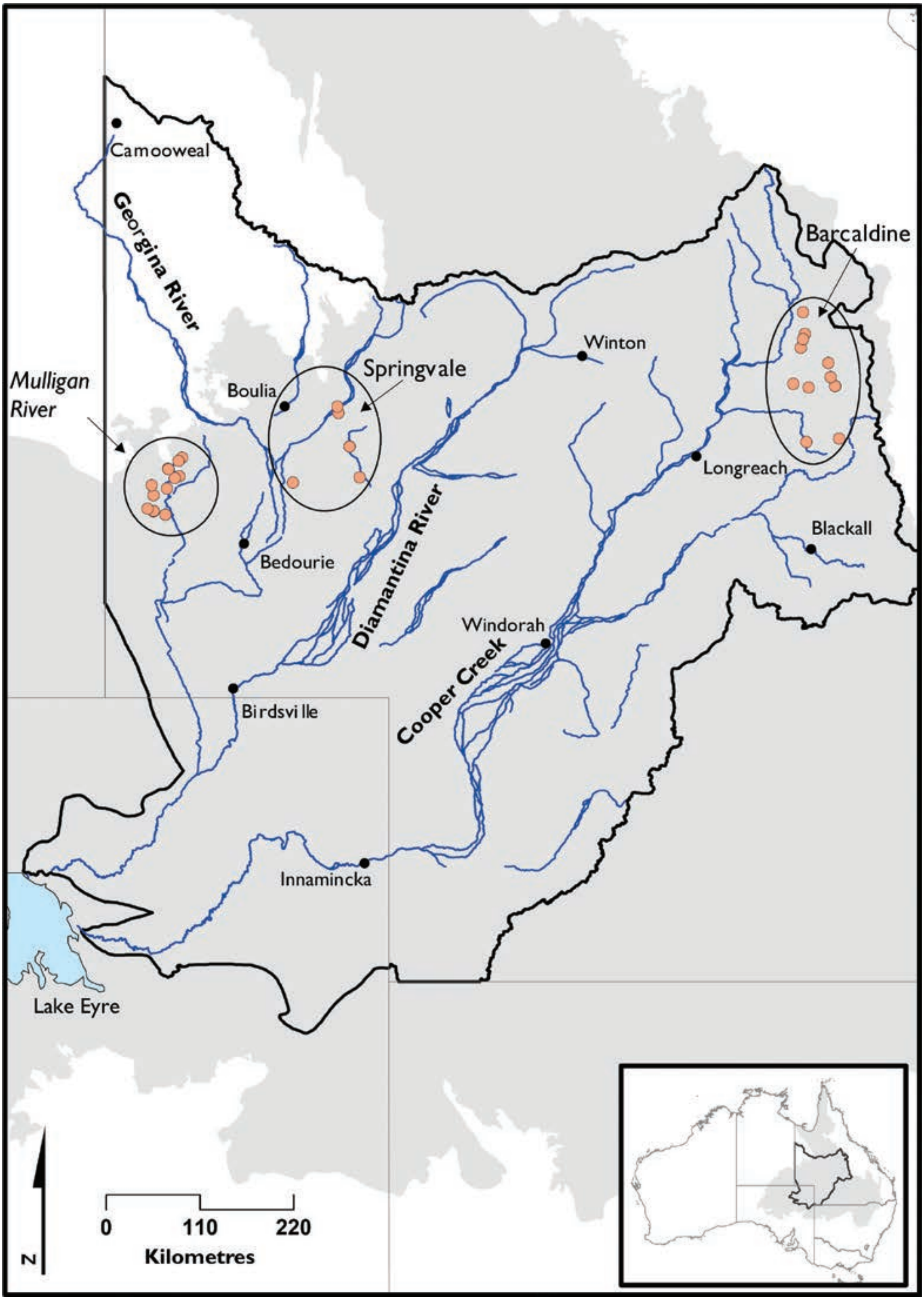

Fig. 3.1. Location of Great Artesian Basin springs (orange circles) in groups (circled as Mulligan River, Springvale and Barcaldine) in the Queensland Lake Eyre Basin (black outline) and within the Great Artesian Basin (grey shading). Mapping courtesy Jen Silcock.

Biodiversity Conservation Act 1999) and also on the Red List of Threatened Species (International Union for the Conservation of Nature 2016).

Widespread fish species

Despite the comparative paucity of studies of fish within Queensland's western rivers, some general patterns have been observed. Some species occur across all catchments, from the Bulloo River in the east to the highly temporary Mulligan River on the edge of the Simpson Desert, in permanent and ephemeral waterholes and across a wide range of habitats (Table 3.1). This group includes the algivore/detritivore bony bream, the carnivore spangled perch, two species of catfish, the silver tandan and the larger Hyrtl's tandan, and two small-bodied species, the desert rainbowfish and glassfish (Table 3.1). Most can move at least 300 km into ephemeral habitats following flooding. Many also continuously recruit, maintaining populations in both dry and wet periods. Large-bodied species such as Barcoo grunter, Welch's grunter and yellowbelly possess similar adaptations to living in the Australian arid zone, but tend not to move as far into temporary desert habitats, probably due to their longevity (around 10 years) and adult size (at least 300 mm).

Fish species confined to particular rivers

The waterholes and reaches of the Cooper catchment (the Barcoo, Thomson and Wilson Rivers, Kyabra Creek and many more headwater subcatchments; Fig. 3.1) provide habitat for three species that do not live in the western rivers of the Lake Eyre Basin: carp gudgeon, Australian smelt and the endemic Cooper Creek catfish (Table 3.1).

Carp gudgeon are widespread in all catchments east of and including the Cooper, although their origin remains unclear (P. Unmack, pers. comm.). The similarly located Australian smelt reflects a more traceable story. It is more closely related to southern cousins in the South Australian Murray–Darling Basin than to eastern populations in Queensland and New South Wales (Hammer *et al.* 2007), suggesting it may have colonised the Lake Eyre Basin from the south, when the continent was wetter.

The Lake Eyre Basin's most curious aquatic inhabitant is arguably the Cooper Creek catfish (Fig. 3.2). This large bottom-dwelling species is probably older or more ancestral than the other widespread catfish species (P. Unmack, pers. comm.). It is the only endemic riverine fish species from the Cooper, found in the Thomson and Barcoo Rivers and downstream in Cooper Creek, but nowhere else. Cooper Creek catfish produce relatively few large eggs (~1000, 3–4 mm diameter; Unmack 1996). It is possible that they may guard their eggs, or make shallow nests in the substrate in a similar fashion to freshwater catfish from southern Australia (e.g. *Tandanus tandanus* from the Murray–Darling Basin). However, the life history of Cooper Creek catfish is yet to be studied in detail.

The Diamantina and Georgina River catchments also provide habitat for species that have not been able to cross the catchment divide into the Cooper Creek catchment, or successfully colonise via Kati Thanda-Lake Eyre during wet periods. For example, the banded or barred grunter is widespread across northern Australia (Allen *et al.* 2002), with either an advance or ancient population living only in the Diamantina and Georgina River

Table 3.1. Names and some life history characteristics of fish species in the rivers and springs of the Queensland Lake Eyre Basin.

See Fig. 3.1 for the locations of springs and rivers.

Species	Common name	Distribution	Life history	References
Riverine native species				
Nematolosa erebi	Bony herring	All catchments	Extreme dispersal ability, continuous recruitment	Bailey and Long 2001; Arthington *et al.* 2005; Balcombe *et al.* 2007; Balcombe and Arthington 2009; see Chapter 4; Puckridge 1999; Wager and Unmack 2000; Kerezsy *et al.* 2011; Kerezsy and Fensham 2013; Kerezsy *et al.* 2014; Cockayne *et al.* 2015
Neosiluroides cooperensis	Cooper Creek catfish	Cooper Creek catchment	Poorly known benthic species, spring/summer spawning	
Neosiluris hyrtlii	Hyrtl's tandan	All catchments	Conservative dispersal to deep areas, flow-dependent recruitment	
Porochilus argenteus	Silver tandan	All catchments	Spring/summer recruitment, extreme dispersal ability	
Retropinna semoni	Australian smelt	Cooper Creek catchment	Winter recruitment	
Craterocephalus eyresii	Lake Eyre hardyhead	Georgina River catchment (Mulligan R.)	Extreme dispersal, colonises springs opportunistically	
Melanotaenia splendida tatei	Desert rainbowfish	All catchments	Extreme dispersal, continual recruitment, colonises springs opportunistically	
Ambassis sp.	Glassfish	All catchments	Extreme dispersal, continual recruitment, colonises springs opportunistically	
Macquaria sp.	Yellowbelly	All catchments	Conservative dispersal to deeper areas, flow and continuous recruitment	
Amniataba percoides	Barred grunter	Georgina River catchment	Extreme dispersal, continual recruitment, colonises springs opportunistically	
Bidyanus welchi	Welch's grunter	All catchments	Conservative dispersal to deep areas, flow-dependent recruitment	
Leiopotherapon unicolor	Spangled perch	All catchments	Extreme dispersal, continual recruitment, colonises springs opportunistically	
Scortum barcoo	Barcoo grunter	All catchments	Conservative dispersal to deep areas, flow-dependent recruitment.	
Glossogobius aureus	Golden goby	Diamantina–Georgina River catchments	Spring/summer recruitment, conservative dispersal ability	
Hypseleotris sp.	Carp gudgeon	Cooper Creek catchment	Continual recruitment	

Species	Common name	Distribution	Life history	References
Riverine translocated species				
Oxyeleotris lineolata	Sleepy cod	Cooper catchment	Benthic carnivore likely to threaten native species	Kerezsy 2011
Riverine alien species				
Gambusia holbrooki	Gambusia	Cooper catchment	Live-bearer, continuous recruitment, also present in springs (Edgbaston)	Kerezsy 2009
Carassius auratus	Goldfish	Cooper catchment	Widespread but potential effects unknown	
Species of the Great Artesian Basin springs				
Scaturiginichthys vermeilipinnis	Red-finned blue-eye	Barcaldine spring group (Cooper catchment)	Endangered. Present in one naturally occurring and six relocated populations at Edgbaston, threatened by gambusia	Fairfax *et al*. 2007; Fensham *et al*. 2011; Kerezsy and Fensham 2013; Kerezsy 2014; Kerezsy 2015
Chlamydogobius micropterus	Elizabeth Springs goby	Springvale spring group (Diamantina catchment)	Endangered. Small benthic species limited to the Elizabeth Springs complex	
Chlamydogobius squamigenus	Edgbaston goby	Barcaldine spring group (Cooper catchment)	Endangered. Small benthic species limited to springs and bore drains on Edgbaston, Myross and Ravenswood	

Fig. 3.2. The Cooper Creek catfish is known only from the Thomson and Barcoo Rivers and Cooper Creek (Fig. 3.1), and grows to 60 cm.

catchments. It is a common smaller cousin of the Barcoo and Welch's grunters. Similarly, the golden goby is a northern and Indo-Pacific species, but some populations survive in the few permanent waterholes of the Georgina River, and more recently were found in the Diamantina and Mulligan Rivers (Table 3.1).

Our understanding of fish ecology in remote regions of the Lake Eyre Basin remains in its infancy. A good example is the detection of a small schooling species (Lake Eyre hardyhead) in the highly temporary Mulligan River during the wet years 2009–2012 (Kerezsy *et al.* 2013). This was over 300 km away from previous records in Goyder's Lagoon (Costelloe *et al.* 2004; R. Mathwin and D. Schmarr, pers. comm.), and the first time the species had been found in Queensland. These records suggest that this species, previously only recorded from South Australia, can migrate long distances following above-average rainfall and the inundation of usually dry channels.

Fish species of the springs

Three endemic species live in the springs of the Queensland section of the Great Artesian Basin (Fig. 3.1), and a further five fish species are found in Dalhousie Springs in northern South Australia. The Queensland species are listed as either endangered or vulnerable under both state and national legislation.

No endemic fish species are present in springs in the Mulligan group (Fig. 3.1), where desert rainbowfish, glassfish, Lake Eyre hardyhead and spangled perch colonise during floods which briefly connect the springs to the Mulligan River (M. Tischler and A. Kerezsy personal observations 2009–13; Table 3.1). At the Springvale group, south-east of Boulia in the Diamantina catchment, populations of the Elizabeth Springs goby are the only fish present

Fig. 3.3. Great Artesian Basin springs form isolated wetlands that provide habitat for the endangered red-finned blue-eye and Edgbaston goby. These species are significantly affected by competition with the invasive mosquito fish. Trampling by livestock and feral animals and drawdown from water extraction are more general threats to spring complexes (photo, A. Kerezsy).

and are comparatively secure as this spring complex is reserved as a national park and fenced to exclude stock. Cattle, pigs and camels all severely damage and deplete springs through pugging, wallowing and drinking (Fig. 3.3). In addition, the invasive fish species gambusia or mosquitofish has not been recorded in the Diamantina catchment in Queensland.

Two species of endangered and endemic fish occur at Edgbaston in the Barcaldine group (Fig. 3.3), the most ecologically diverse Great Artesian Basin spring complex in Australia. The Edgbaston goby (Fig. 3.4) is a close relative of the Elizabeth Springs goby and three other *Chlamydogobius* species from South Australia and the Northern Territory. All are morphologically similar and their speciation is an artefact of their prolonged isolation and subsequent evolution. The second species, the red-finned blue-eye, is far more curious. It is the only Pseudomugilid fish known from inland Australia; all other species in this family live in coastal-draining rivers in northern and eastern Australia and New Guinea. Discovered in 1990 by fish biogeographer and geneticist Peter Unmack, populations of the species had dwindled to occupy only four of the 40 habitable springs when the conservation not-for-profit organisation Bush Heritage Australia purchased the property in 2008. The red-finned blue-eye was identified by IUCN as among the world's 100 most endangered species of any animal or plant group, and is threatened by gambusia, feral and domestic stock, and aquifer drawdown.

Gambusia probably out-compete red-finned blue eye because the former give birth to live young, meaning new-born juveniles are comparatively large and self-sufficient. In contrast, red-finned blue-eye are egg-layers, and gambusia are known to predate the eggs of

Fig. 3.4. The endemic and endangered Edgbaston goby, with a global population existing in only nine springs at Edgbaston and at two locations on adjacent properties in the Aramac district in central western Queensland (photo, A. Kerezsy).

native Australian fish species. Since 2009, intensive management has focused on recovery of red-finned blue-eye using three control techniques: use of the piscicide rotenone to remove gambusia, relocation of red-finned blue-eye (using a founder populations of 20 individuals) to safe habitats where gambusia have been removed or do not occur, and the installation of barriers around some springs to prevent gambusia colonisation (Kerezsy and Fensham 2013; Kerezsy 2015).

Alien invasions

Unlike the neighbouring and similarly sized Murray–Darling Basin, the Lake Eyre Basin and its rivers remain unregulated, with relatively few alien aquatic species in relatively low numbers (see Chapter 4). Carp (*Cyprinus carpio*), redfin (*Perca fluviatilis*) and various salmonids (trouts and salmon) are absent from the Bulloo, Cooper, Diamantina and Georgina Rivers. Small populations of gambusia and goldfish live throughout Cooper Creek (Table 3.1), although their impacts are largely unknown (with the exception of impacts on the spring species mentioned above). However, several translocated native fish species have established in the Lake Eyre Basin rivers, and they were probably first introduced by government agencies and/or local fishing clubs for recreational fishers or aquaculture. The largest and most iconic Murray–Darling Basin fish, Murray cod (*Maccullochella peelii*) was introduced into the Thomson River at Longreach in the Cooper Creek catchment in the late 1980s and early 1990s; individuals still show up occasionally (A. Emmott, pers. comm.). This fish is a top order predator in rivers where it naturally occurs, and therefore has the potential to negatively impact populations of naïve prey species in rivers where it is translocated. From the 1980s to the early 2000s, far larger numbers of yellowbelly (*Macquaria*

Fig. 3.5. Sleepy cod, naturally occurring in Australia's tropical rivers, is a predator and was first detected in the Thomson River in 2008. The species is now well established throughout the Cooper Creek catchment (photo, A. Emmott).

ambigua) from the Murray–Darling Basin were also introduced across a wide area. The negative effects on local populations of yellowbelly (potentially a separate species) were never considered, and the fate of these stocked fish remains unknown (including potentially breeding with local yellowbelly).

In the 1990s, the large red claw crayfish (*Cherax quadricarinatus*) was also deliberately released, with considerable investment of resources. Red claw are native to north-eastern Australia but not the Lake Eyre Basin. They quickly established in the Cooper Creek, Diamantina and Georgina River catchments. It is assumed that individuals escaped from aquaculture populations and walked into the rivers. Dramatically, red claw exclude and outcompete the locally occurring blue claw yabbies (*Cherax destructor*) (Kerezsy 2010; B. Cockayne and D. Akers, personal communication).

Most recently, the large bottom-dwelling gudgeon, sleepy cod (*Oxyeleotris lineolate*; Fig. 3.5) – also from rivers in Australia's north-east – has become established in the Cooper Creek catchment. The source population of sleepy cod in the Cooper Creek catchment is likely to be specimens that escaped from dams close to Longreach during flooding. The species was first caught in 2008, near Stonehenge on the Thomson River (Kerezsy *et al.* 2014), and is becoming increasingly common during recent fish surveys in the Cooper Creek catchment (B. Cockayne, D. Sternberg personal communications). The concern is that this large (up to 450 mm) and carnivorous species may also have a negative effect on the local food webs within Cooper Creek, particularly as waterholes dry during summer.

Conclusion – now and the future

Our current knowledge of fish communities throughout the Queensland Lake Eyre Basin indicates that native fish populations are in good condition, especially compared to other inland systems regulated by dams and extractions (e.g. the rivers of the Murray–Darling Basin). In stark contrast, the endangered spring communities, particularly those in the easternmost Barcaldine group, are still threatened by alien species (primarily gambusia but also cane toads), spring destruction and degradation due to trampling and disruption by domestic and feral stock, and the threat of aquifer drawdown from extractive industries such as coal mining and coal seam gas.

Governments and communities have rarely attempted to contain or control the impacts of invasive aquatic species in the Queensland section of the Lake Eyre Basin. Exceptions include the concentrated rehabilitation of artesian springs and their fish at Edgbaston by controlling gambusia, and preventing the liberation of other aquatic invaders – a recent goal of government agencies and associated research institutions. The ecological effects of population booms of introduced species (e.g. red claw crayfish and sleepy cod) could be locally catastrophic during dry periods when all species – both native and introduced – concentrate in shrinking waterholes. Unfortunately, our ability to successfully control or mitigate such impacts in the extensive boom and bust systems of the Lake Eyre Basin is limited.

Avoidance of further invasions into catchments where non-native species do not occur should be the priority. This means preventing sleepy cod, Murray cod, goldfish and gambusia reaching the Diamantina and Georgina, and dedicated programs and policies (e.g. community education programs) to reduce the chances of other alien or translocated species entering Lake Eyre Basin watersheds. Carp and various *Tilapia* species, established in the rivers of the Murray–Darling and north-eastern Australia, are currently the biggest potential threats facing the riverine communities of far western Queensland, and every effort should be made to prevent their expansion into the Lake Eyre Basin rivers.

The Lake Eyre Basin rivers occupy an iconic place in Australia's cultural identity and history (Durack 1959; Bowen 1987; Murgatroyd 2002; see Chapters 1, 7 and 8), and are considered to comprise the healthiest and most intact arid-zone aquatic ecosystems worldwide (see Chapters 2, 4 and 7). There are legislative challenges associated with managing such a large area, especially as it is administered by multiple jurisdictions (Queensland, South Australia, Northern Territory and New South Wales), and there are considerable logistical and practical difficulties. Management and research in the Lake Eyre Basin must be approached collaboratively in order to assess threats and adequately monitor river health in these unique systems, because evidence-based policy and sound management of the Lake Eyre Basin rivers and springs are crucial for maintaining dependent biodiversity.

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4

Natural flows drive the 'boom and bust' ecology of fish in Cooper Creek, an arid-zone floodplain river

Angela H. Arthington and Stephen R. Balcombe

Introduction

Why is the Lake Eyre Basin so special and why should we care so much about the future of its rivers and floodplain wetlands? It covers an area of more than 1 million km^2, about one-seventh of Australia (Habeck-Fardy and Nanson 2014), and is one of the world's largest internally draining river basins, meaning its waters never reach the sea. In Cooper Creek, one of the main catchments of the basin, most stream flow is generated by summer monsoon rainfall in the headwaters of the Thomson and Barcoo Rivers and by periodic local rainfall (see Chapter 1). Episodic floods can inundate tens of thousands of square kilometres of floodplain, and reconnect channels, anabranches, and isolated channel and floodplain waterholes (Fig. 4.1), turning a fragmented river network into a mighty floodplain river, occasionally helping to fill Kati Thanda-Lake Eyre, the largest lake in Australia.

Lake Eyre Basin catchments have very high conservation values – high endemic biodiversity, Ramsar wetland listings, range-restricted species (e.g. the Cooper Creek catfish), relatively few alien fish species (i.e. species foreign to Australia) and few translocated species (see Chapter 3). Rivers and floodplain wetlands of the basin are in very good ecological condition relative to most of the world's large developed river basins, and especially compared to the Murray–Darling Basin. Cooper Creek is a largely undeveloped catchment with a near natural and very erratic flow regime (Puckridge *et al.* 1998; see Chapter 2). Aquatic habitats exist for most of the time as isolated waterholes, connected occasionally by channel flows and large overland floods (Fig. 4.1). Rivers of the Channel Country, especially Cooper Creek, have been studied as model arid-zone floodplain systems for understanding the 'boom and bust' ecology of fish and other biota. This chapter demonstrates the importance of flow variability and the boom and bust cycle to fish, and outlines threats associated with changing the natural flow regime, concluding with scientific principles for the conservation and wise use of arid-zone rivers.

Cooper Creek fish

Twelve native fish species in eight families, two translocated species (Murray cod, *Maccullochella peelii*, and sleepy cod, *Oxyeleotris lineolata*) and two alien species (goldfish and mosquitofish) are known from the Cooper Creek catchment (Table 4.1). Both alien species and Murray cod are relatively rare in Cooper Creek, but the sleepy cod is becoming

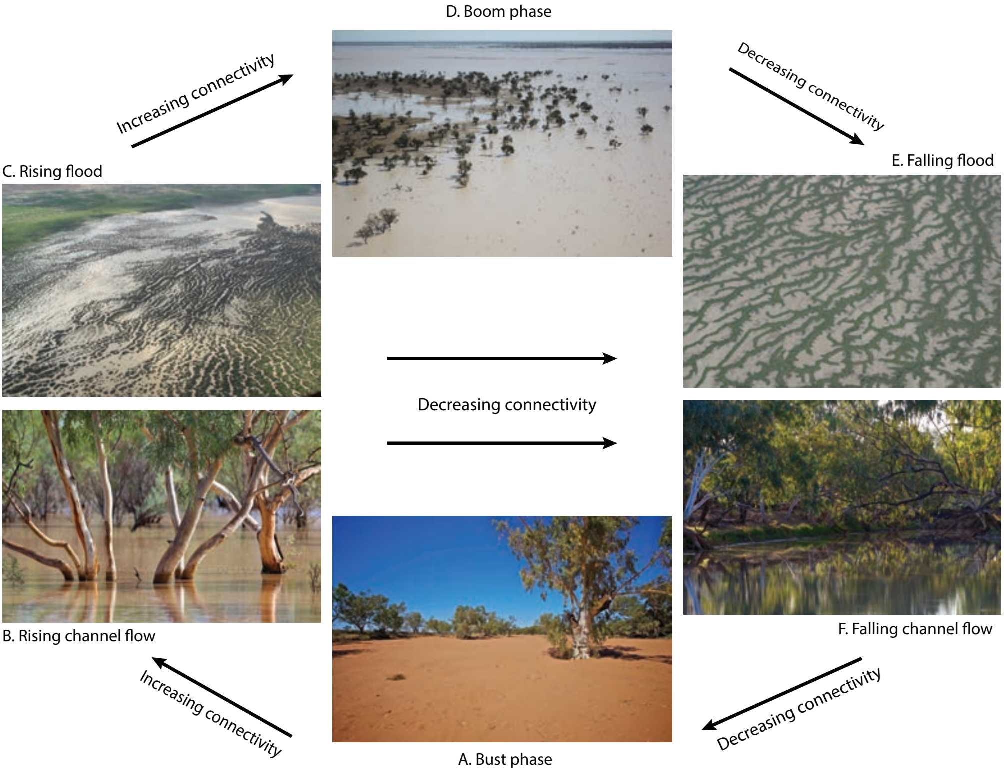

Fig. 4.1. Aquatic habitat conditions associated with the natural hydrological cycle in Cooper Creek, showing: (A) drying waterhole (bust phase, photo, A. Emmott), (B) rising channel flow (photo, A. Emmott), (C) rising flood and breakout onto floodplain (photo, R. T. Kingsford), (D) large flood in October 2016 (boom phase, photo, R.T. Kingsford), (E) falling flood (photo, R. T. Kingsford), (F) falling channel flow (photo, A. Emmott), sparse riparian vegetation, bare banks and exposure of habitat features such as fallen timber. Patterns of increasing and decreasing connectivity are represented. B and F show a rising channel flow becoming a falling channel flow rather than breaking onto the floodplain. C and E show a small flood receding off an inundated floodplain. In both cases connectivity pathways are limited compared to those achieved by a very large flood (D). Figure adapted from Arthington and Balcombe (2011).

more common (B. Cockayne, pers. comm.). The wider distribution patterns of Lake Eyre Basin fishes are also described elsewhere (Kerezsy *et al.* 2014).

The Cooper Creek fish fauna is not rich compared with Queensland's coastal rivers (23–55 species; Pusey *et al.* 2004), but the native fishes are of ecological and conservation significance, and several are valued socially and economically for recreational fishing (e.g. yellowbelly). In 15 waterholes sampled in the Cooper Creek catchment in 2001 using standardised fyke-net sampling (Fig. 4.2), five widespread indigenous species contributed 96% of the total catch (Arthington *et al.* 2005). Proportional abundances were silver tandan (45.5%), north-west ambassis or glassfish (19.9%), spangled perch (12.5%), bony bream (9.7%) and Hyrtl's tandan (8.4%). Seven species contributed the remaining 4% of catch. Sampling in four waterholes of the Windorah reach of Cooper Creek on eight occasions between April 2001 and December 2004 (Balcombe and Arthington 2009) yielded generally similar patterns of abundance: silver tandan (~54% of total catch) and Hyrtl's tandan (-14%), bony bream (-16%), two grunters (Welch's grunter (~8%), Barcoo grunter (~6%)) and yellowbelly (-2%). A typical fish sample may include several of these species, as well as turtles (Fig. 4.3).

Fish ecology during the bust

The fish fauna spans a range of body sizes, physiological tolerances, habitat and dietary preferences, and breeding strategies (Table 4.1). These adaptations equip all species to tolerate the 'bust' conditions in drying waterholes, and to reproduce opportunistically, seasonally or on rising flows and floods, tracking changing habitat conditions and food resources (Fig. 4.1). Although all 12 native species are adapted to survive bust conditions, fish abundances and assemblage composition in waterholes change markedly during dry periods. Individual species suffered 50–100% reduction in numbers per waterhole, and across the entire fish fauna 93% of individuals were lost from 15 drying waterholes between April and September 2001 (Arthington *et al.* 2005). Each species responded to different environmental pressures during this dry period (Arthington *et al.* 2010). For the desert rainbowfish, low physical habitat diversity and susceptibility to decreasing water temperatures drove losses from 11 of 15 waterholes. The yellowbelly was lost from six of 15 waterholes, particularly those on the fringes of the floodplain that are rarely rewetted and reconnected. The Barcoo grunter did not persist in 11 waterholes with low levels of bed, bank and habitat complexity and less cover to protect them from predators. This grunter was also less likely to persist in waterholes on narrow floodplains, possibly because fish coming off narrow floodplains may not have accumulated the body lipids that govern condition, and probably survival, in isolated, drying waterholes (Puckridge *et al.* 2000). These natural pressures drive adaptation to flow variability over successive generations.

The fate of the uncommon Cooper Creek catfish in drying waterholes is particularly interesting. Waterholes that experienced increases in primary production over the dry season were able to sustain this catfish, which is the only species not found on the floodplains of Cooper Creek when they are inundated (Balcombe *et al.* 2007). During dry periods, a conspicuous, shallow 'bathtub ring' of benthic algae forms around the margins of isolated waterholes and this productive food resource sustains the entire fish community (Bunn *et al.* 2003). This is especially important for large species like the Cooper Creek catfish that feed on large-bodied invertebrates (crustaceans and snails), themselves sustained by high levels of algal production (Balcombe *et al.* 2005). However, without an energy subsidy from the food-rich floodplain, the Cooper Creek catfish would be totally reliant on the waterhole food web, and this is not very productive in steep-sided waterholes where the bath-tub ring of algae is usually less well developed (Arthington *et al.* 2010).

Fish ecology during the boom

High fish mortalities during the dry times in Cooper Creek are balanced by episodes of spawning and recruitment. Fish exhibit three main recruitment strategies in Cooper Creek (and other rivers of the Lake Eyre Basin), termed no-flow recruitment, seasonal recruitment, and flow or flood-dependent recruitment (Kerezsy *et al.* 2011). At least six of the 12 native

Table 4.1. Native and alien fish species found in Cooper Creek, showing maximum body length recorded, feeding habits, spawning seasons, spawning cues and life stages (L – larvae, J – juvenile, A – adult).

Data drawn from Balcombe *et al.* (2005), Balcombe *et al.* (2007), Balcombe and Arthington (2009), Kerezsy *et al.* (2011), Cockayne *et al.* (2015).

Family/species	Common name	Maximum body size (S.L. mm)	Feeding habits (common foods eaten)	Spawning season and cues	Life stages using floodplains		
Native species							
Ambassidae							
Ambassis sp.	North-west ambassis	65	Pelago-carnivore (micro-crustacea)	No-flow or flow-related spawning			A
Clupeidae							
Nematalosa erebi	Bony bream	276	Benthivore (algae/detritus)	No-flow spawning, all year	L	J	A
Gobiidae							
Hypseleotris spp.	Carp gudgeons	28	Bentho-carnivore (zooplankton/dipteran larvae)	No-flow spawning, all year		J	A
Melanotaeniidae							
Melanotaenia splendida tatei	Desert rainbowfish	79	Pelago-carnivore (terrestrial insects)	No-flow spawning, all year		J	A
Percichthyidae							
Macquaria sp. B	Lake Eyre golden perch, yellowbelly	398	Pelago-macro-carnivore (large crustaceans)	No flow, seasonal or flow-related spawning	L	J	A
Plotosidae							
Neosiluroides cooperensis	Cooper Creek catfish	468	Bentho-carnivore (gastropods/crustaceans)	Summer spawning			
Neosilurus hyrtlii	Hyrtl's tandan	350	Bentho-carnivore (aquatic insects)	Summer spawning on rising flows and floods	L		A
Porochilus argenteus	Silver tandan	199	Bentho-carnivore (aquatic insects)	Summer spawning	L	J	A

Family/species	Common name	Maximum body size (S.L. mm)	Feeding habits (common foods eaten)	Spawning season and cues	Life stages using floodplains		
Retropinnidae							
Retropinna semoni	Australian smelt	65	Pelago-carnivore (aquatic insects/micro-crustaceans)	Mid-late winter spawning on rising water temperature	L	J	
Terapontidae							
Bidyanus welchi	Welch's grunter	263	Benthivore (molluscs, crustaceans)	Summer spawning on rising flows and floods		J	A
Leiopotherapon unicolor	Spangled perch	193	Pelago-carnivore (aquatic insects /crustaceans)	No flow, seasonal or flow-related spawning	L	J	A
Scortum barcoo	Barcoo grunter	280	Benthivore (molluscs, crustaceans)	Summer spawning on rising flows and floods		J	A
Alien species							
Cyprinidae							
Carassius auratus	Goldfish	132	Pelago-carnivore (micro-crustaceans)	Spring spawning, rising temperature			
Poeciliidae							
Gambusia holbrooki	Mosquitofish	43	Pelago-carnivore (micro-crustaceans, terrestrial invertebrates)	Summer spawning, no or low flows		J	A

Fig. 4.2. Catching fish using fyke nets in a waterhole of the Mulligan River in the Georgina River catchment of the Lake Eyre Basin (photo, A. Kerezsy).

species can complete their life histories within isolated waterholes during dry periods when there are no channel flows; these include yellowbelly, bony bream, spangled perch, carp gudgeons, rainbowfish and glassfish (Table 4.1). These opportunistic species can maintain recruitment or replace their populations in isolated waterholes irrespective of season, channel flows or floods, but if channel flow or flood events occur, new recruits are available to disperse or colonise newly available habitat (Balcombe and Arthington 2009; Kerezsy *et al.* 2011; Cockayne *et al.* 2015). Three fish species have a seasonal recruitment strategy. Australian smelt probably commence spawning in mid to late winter (July–August) in the Cooper Creek catchment when the timing of breeding is linked with seasonal temperature cues rather than flow conditions. Summer-cued recruitment is characteristic of silver tandan and Cooper Creek catfish. These species breed on an annual cycle, with spawning occurring in early summer, and spawning events take place irrespective of antecedent hydrology and flow conditions (Balcombe and Arthington 2009; Kerezsy *et al.* 2011). The remaining species are either dependent on, or heavily influenced by, the occurrence of channel flows or flooding (Hyrtl's tandan, Barcoo grunter and Welch's grunter). Recruitment of Hyrtl's tandan in Cooper Creek and other Lake Eyre Basin rivers is triggered by major flooding (Balcombe and Arthington 2009; Kerezsy *et al.* 2011). Similar recruitment patterns have been reported in populations of Hyrtl's tandan from the Murray–Darling Basin (Balcombe *et al.* 2006). Three members of the Cooper Creek fish fauna (yellowbelly, spangled perch and glassfish) show particularly flexible breeding patterns by spawning when there is no flow as well as demonstrating flow-related recruitment.

Fig. 4.3. In boom phases, the high productivity in waterholes and on floodplains provides opportunities for fish species – such as these spangled perch, Cooper Creek tandan, Lake Eyre golden perch, Barcoo grunter, silver tandan, Hyrtl's tandan – to build up their populations. Fish catches were identified to species, counted, measured and weighed. Turtles and most fish were returned to the water alive (photo, S. Balcombe).

Although their spawning strategies vary, most native species in Cooper Creek benefit from rising channel flows and floods by moving into backwater habitats, flooded channels and floodplains to feed and grow in shallow, food-rich, warm-water habitats (Balcombe *et al.* 2007). Fish use backwaters and flooded areas as larvae, juveniles and adults. All native species other than Australian smelt and Cooper Creek catfish have been caught on the floodplain as adults, and nine species have been collected in the juvenile life stage. Sampling in floodplain habitats has also yielded the late stage larvae of six native species (bony bream, yellowbelly, Hyrtl's tandan, silver tandan, smelt and spangled perch). The Cooper Creek catfish may be the only native species to spend its entire life history within waterholes and channels. Juveniles and mature individuals of the alien mosquitofish have also been recorded from floodplains; however, goldfish captures have been confined to waterholes.

Access to floodplains, feeding on diverse food items and high growth rates allow most Cooper Creek fish to build up large populations and significant biomass (Fig. 4.2). During the 2004 summer flood in Cooper Creek, shallow floodplain areas near Windorah supported high fish biomass in the range of 21–240 kg/ha. These biomass figures are comparable to production from important floodplain fisheries in Bangladesh (50–400 kg/ha), the Mekong (138–175 kg/ha) and the Amazon (24 kg/ha) (Balcombe *et al.* 2007). The global literature records strong relationships between the magnitude and/or duration of the annual flood pulse, floodplain area inundated and fish production in the same or subsequent years (Welcomme *et al.* 2006). Similar relationships have been demonstrated in Cooper Creek after large floods. For example, the February 2000 flood in Cooper Creek flooded nearly 14 000 km^2 of floodplain, and was followed by a boom in fish numbers that remained evident in waterholes sampled 14 months later. The species most responsive to flooding were rainbowfish, silver tandan, spangled perch, yellowbelly and Barcoo grunter (Arthington *et al.* 2005). Similar increases in fish abundance following large floods have been reported in the intermittently flooded Coongie Lakes in the lower Cooper Creek catchment (Puckridge *et al.* 2000) and in other Lake Eyre Basin rivers (Kerezsy *et al.* 2011).

Most species in the Lake Eyre Basin move over considerable distances into the variety of aquatic habitats (Fig. 4.1), using channel flows or flood waters for dispersal and colonisation. Two patterns of movement behaviour identified in native fish from the ephemeral Mulligan River may be the norm for the fauna of the Lake Eyre Basin (Kerezsy *et al.* 2013). Extreme dispersing species (bony bream, spangled perch, silver tandan, desert rainbowfish and glassfish) move widely into intermittently wetted habitats, while conservative dispersing species (Barcoo grunter, Welch's grunter, yellowbelly and Hyrtl's tandan) do not move as far, tending to inhabit deep waterholes within mid-reaches of rivers that are likely to hold water for long periods. For the entire fish assemblage, the capacity to disperse and access periodically flooded habitats is an important life history trait enabling most species to build up sufficient numbers for at least some healthy individuals to persist through the bust period. These temporal population fluctuations and variable recruitment and movement strategies have many parallels in the fishes of other floodplain rivers around the world (Welcomme *et al.* 2006).

Alien species are scattered but not common in arid-zone rivers of the Lake Eyre Basin. The mosquitofish presents the greatest threat to native species (see Chapter 3), particularly small species with a preference for slow-flowing or still water habitats, similar feeding behaviour and no-flow recruitment strategies (e.g. the desert rainbowfish and Lake Eyre hardyhead). The small aggressive mosquitofish could become far more abundant over time, judging by its successful invasion and proliferation in floodplain wetlands of the Murray–Darling Basin (e.g. the Macquarie Marshes), where it often out-numbers small native species (Rayner *et al.* 2009; D. Cruz, pers. comm.). Efforts to eradicate the mosquitofish have focused on isolated springs of the Great Artesian Basin (Kerezsy and Fensham 2013), particularly Edgbaston Springs where extant populations of the endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) are at risk (see Chapter 3).

Implications of changing the natural flow regime

The role of the natural flow regime as an important driver of riverine ecology is spectacularly evident in the boom and bust ecology of fish in arid-zone rivers. Even so, a pronounced capacity to swing between low and high population levels does not imply resilience to human impacts, particularly changes in the flow regimes of arid-zone rivers (Arthington and Balcombe 2011). The fish assemblages of Cooper Creek and other arid-zone rivers are vulnerable to alteration of flow patterns and catchment characteristics in several important ways.

First, the absolute necessity for all fish species to be able to persist in 'refuge' aquatic habitats (e.g. waterholes) during dry periods makes them vulnerable to any process that may accelerate rates of water loss and reduce the number of waterholes that could sustain aquatic organisms over extended dry periods. Several natural factors influence water loss by evaporation; these include waterhole depth and surface area, the effective width for wind action (and evaporation), the degree of incision below levee banks, and the height and width of riparian vegetation (Hamilton *et al.* 2005). As waterholes decrease in depth and volume, prominent features like benches, bars, offtake channels and structural habitat (logs, riparian leaf litter and aquatic plants) become exposed and desiccated. Habitat loss reduces opportunities for fish to rest, feed and shelter from predators, leading to high mortality rates that deplete waterhole fish populations (Arthington *et al.* 2010). Waterholes that maintain depth, volume, habitat diversity and water quality during dry times provide refuges for fish, and their identification and protection from human interference is an essential part of fish conservation and river management during dry periods and drought (Bond *et al.* 2008; Silcock 2009).

Human activities can influence the amount of water in waterhole refugia and the duration of waterhole persistence between flow pulses. Hamilton *et al.* (2005) estimated that most of the named waterholes mapped along Cooper Creek would dry within 22 months if not replenished by channel flows or flooding; after 24 months of no flow, only four of the named waterholes along Cooper Creek would remain wet. However, a broader study identified over 200 waterholes in the Cooper catchment that have not dried in living memory (Silcock 2009). River flows can be altered by upstream impoundments, small-scale diversions for irrigation in the upper catchments or capture of runoff for agricultural use (water harvesting), and water can be withdrawn directly from waterholes during intervals between flows (Thoms and Sheldon 2000). Small impoundments, raised roads, or other disturbances of the geomorphological structure of anabranches can alter river flows through various channels and waterholes (Hamilton *et al.* 2005). Reduced flows, less frequent waterhole replenishment, and increased frequency and degree of waterhole desiccation could have deleterious ecological impacts, including reduction or local extirpation of fish and turtle numbers as well as reduced water availability for riparian trees, floodplain wildlife and livestock (Hamilton *et al.* 2005; Leigh *et al.* 2010; Sheldon *et al.* 2010).

As well as reconnecting, refilling and replenishing isolated waterholes, channel flows can provide cues for fish spawning, movement and dispersal into backwater habitats or anabranches, allowing opportunistic discovery of high quality habitats and rich food resources or avoidance of predators. With the probable exception of Cooper Creek catfish, all members of the Cooper Creek fish community use inundated floodplains for feeding, growth, recruitment and dispersal. Hydrological connectivity between channels and floodplains is vital to these processes (Fig. 4.1). Many of the world's floodplain rivers have lost their natural floodplain and river connections, inhibiting the natural movement patterns of aquatic species and life stages (Tockner *et al.* 2010). Altered catchment configurations (e.g. levee banks, roads and infrastructure) can cut off or impede delivery of flows onto floodplains (Steinfeld and Kingsford 2013), and this reduces connectivity and inhibits fish movements into favourable habitats for feeding and growth. The disruption to connectivity between waterholes and their floodplains has been implicated in recruitment failure of yellowbelly in the upper Murray–Darling Basin (Balcombe *et al.* 2011).

Although flooding is unpredictable in frequency, extent and duration in Cooper Creek, floods underpin similar processes to the predictable annual floods of tropical and subtropical floodplain rivers (Junk *et al.* 1989; Welcomme *et al.* 2006). Floods also enhance recruitment of frogs, turtles and waterbirds and support the high levels of pasture production that underpin the vitality and viability of the pastoral industry in dryland catchments of western Queensland (Morrish 1998; see Chapters 10, 11 and 17). Regulating, dampening or eliminating occasional large floods or smaller channel flows undermines the resilience of arid-zone ecosystems, and has been disastrous for the fisheries of the Aral Sea in Uzbekistan and Kazakhstan, the Mesopotamian Marshes, Lake Mono in California and the Macquarie Marshes in the Murray–Darling Basin, Australia (Kingsford *et al.* 2006).

Conclusion

We have substantially increased our understanding of arid-zone rivers through research and monitoring in Cooper Creek and other rivers of the Lake Eyre Basin. Fish are adapted to the extreme natural flow variability of floodplain rivers in the Australian arid zone, where the natural processes driving population booms and busts are broadly consistent with other studies in dryland floodplain rivers (Welcomme *et al.* 2006). Erratic floods and long dry spells underpin the spectacular boom and bust dynamics so characteristic of Cooper Creek fishes. Maintenance of natural flow variability, sequential flood pulses, complex habitat mosaics, floodplain-channel connectivity and environmental flows for valued species are key management principles for arid-zone rivers (Balcombe *et al.* 2005; Larned *et al.* 2010; Sheldon *et al.* 2010). Challenges for the future are to avoid developments that threaten native fishes, especially alterations to naturally variable flow patterns, habitat diversity, connectivity and water quality. Wise use of these complex, dynamic systems is essential if we wish to conserve their biodiversity and enjoy the benefits of healthy Lake Eyre Basin ecosystems in the future.

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5

Turtles of Cooper Creek – life in the slow lane

Arthur Georges and Fiorenzo Guarino

Introduction

Cooper Creek in central Australia is one of the least likely places to be home to freshwater turtles. When it flows, it flows into one of the largest inland salt lakes in the world, Kati Thanda-Lake Eyre, and on the way fills waterholes, channels and floodplains in the semi-arid and arid regions, with median annual rainfall less than 200 mm/year (Kotwicki 1986). Yet turtles not only survive but thrive in the waterholes and billabongs along Cooper Creek.

Freshwater turtles in Australia are not only faced with a scarcity of water, compared to turtles in North America and Asia, but also the variability of when this water is available, given the considerable unpredictability in rainfall and resultant timing and magnitude of river flow and floodplain inundation. Turtles such as the Cooper Creek turtle (*Emydura macquarii emmottii*; Fig. 5.1), which survives in the driest part of our continent, cope in different ways with periodic drying and unpredictability, timing and duration of floods and dry periods.

Fig. 5.1. The endemic Cooper Creek turtle is a giant of freshwater turtles and a top predator living mainly in the large waterholes of the Cooper Creek catchment (photo, A. Emmott).

The ecology of the Cooper has characteristic boom and bust periods (Kingsford *et al.* 1999; Bunn *et al.* 2006; see Chapter 1). Long dry periods of low productivity ('busts') dominate but are punctuated by widespread floods, usually driven by rainfall high in the catchment ('boom' periods) (Puckridge *et al.* 2000). For the freshwater turtles, the boom comes in two forms. First, when the river runs, the turtles take advantage of foods carried into their waterholes with the floodwaters; they often concentrate around the inflows. These are 'mini-booms' (Bunn *et al.* 2006), occurring with greater frequency than major floods. Second, there are the major floods which dramatically expand available habitat and access to new food sources.

The key message we convey here is how dependent these animals are on flows – on the timing and frequency of river runs, on the frequency, extent and duration of major floods, and on the pattern of floodplain inundation across the landscape, essential to the metapopulation dynamic that sustains the turtles. The hydrology of Cooper Creek has been little affected by water resource development, with the main driver of flow being natural climatic fluctuations that influence rainfall and runoff (Puckridge *et al.* 2000). Although Cooper Creek experiences low-level flows in most years, the discharge rates are extremely variable and episodic (Puckridge *et al.* 1998). One of the greatest threats to natural flow and flooding regimes is the diversion of flows. This water resource development in dryland rivers often decreases the frequency and duration of flow pulses, reducing floods and sometimes elevating base flows (Bunn *et al.* 2006). We argue that it is the alteration of these flow attributes through water resource development and deliberate or inadvertent water diversion in a landscape of very low relief that will be potentially catastrophic for turtle populations, and for other species with similar requirements and dispersal capabilities. We compare the biology of two turtles in the Lake Eyre Basin.

Eastern long-necked turtle

The eastern long-necked turtle (*Chelodina longicollis*; Fig. 5.2) is a carnivore, feeding on slow-moving prey such as macroinvertebrates, tadpoles, terrestrial insects that fall upon the water, and carrion (Georges *et al.* 1986; Kennett *et al.* 2009). It survives dry periods by migrating overland between temporary and permanent water (Roe and Georges 2008; Roe *et al.* 2010). Individuals have adaptations for surviving extended periods on land without access to food and water (Roe *et al.* 2008). During short dry periods, they move onto land and become semi-dormant (aestivate) in the leaf litter and other damp areas or waterholes, emerging when the rains come. They know the landscape well and navigate using the sun and an internal clock (Graham *et al.* 1996). They can maintain their body condition and water balance for up to a year, without access to freestanding water (Roe *et al.* 2008). During more extended dry periods, the turtles migrate from ephemeral swamps and wetlands to permanent water where their densities can reach 400 turtles/ha (Parmenter 1976). When there is insufficient food, the turtles stop growing and reproducing (Kennett and Georges 1990). Large populations in waterholes can enter a form of collective dormancy, waiting out the drought, like some fish and other reptiles. This contrasts with mammals whose populations crash and rebound when the good times return, or birds who move out and return during boom periods.

Fig. 5.2. Eastern long-necked turtles live in the upper reaches of the Lake Eyre Basin, favouring temporary waters and taking advantage of the production boom in invertebrate life when they fill (photo, A. Emmott).

Eastern long-necked turtles live in the Cooper catchment, but only as far south as Lake Dunn, near the town of Aramac. Further south along the Cooper becomes problematic for this species because of the long dry periods between flooding and the distances between waterholes which make overland migration difficult.

Cooper Creek turtle

Surprisingly, the Cooper Creek turtle (Fig. 5.1) survives in Cooper waterholes (Fig. 5.3), all the way down to Innamincka. It also occurs at low densities in the Diamantina River. Unlike the Eastern long-necked turtle, the Cooper Creek turtle must have access to free-standing water at all times to survive. As a subspecies of Murray River turtle (*Emydura macquarii*), the Cooper Creek turtle is catholic in its diet, eating algae, freshwater sponges, flowers, fruits and leaves of terrestrial plants when they become available as litterfall or through inundation, and various sedentary animals, including aquatic and terrestrial insects, crustaceans and carrion. As a short-necked turtle, it lacks the long neck of eastern long-necked turtle, and so is unable to secure moving prey such as fish and some mobile invertebrates (Chessman 1986).

The turtles can move extensively onto the floodplains during floods. For example, one individual moved 20 km between Broadwater billabong on Lochern National Park to

Fig. 5.3. Waterholes along Cooper Creek are deep and critically important aquatic habitat for turtles, which need to survive through prolonged dry periods. They form along the main channel during dry times. These waterholes are vulnerable to reductions in flows resulting from future water resource development (photo, R. T. Kingsford).

Waterloo billabong on Noonbah Station). They were observed walking just in front of a flood on the floodplain of South Galway Station, near Windorah, far from the nearest permanent waterhole (Sandy Kidd, pers. comm.). The turtles probably know the landscape well, and use the floods to move between waterholes and floodplains where there is plentiful food. The food source then concentrates as the boom period ends and floodplains dry out and fish, crustaceans and insects concentrate in the waterholes where the only water remains. Cooper Creek turtles are giants of the turtle world in Australia (Fig. 5.1).

They reach sizes up to 37 cm in shell length (White 2002). It could be that their size reflects these periods of considerable plenty, punctuating the relatively extensive periods of scarcity. Food resources are partitioned between maintaining essential body functions (cellular maintenance and sustenance), body growth and reproduction (Bowden *et al.* 2011). When food is limiting, turtles allocate their resources more tightly. For example, *Emydura macquarii nigra* on Fraser Island partition food resources for maintenance and growth until they are sexually mature, and then they reallocate resources into maintenance and reproduction. Growth slows dramatically at maturity and body sizes are limited by this dynamic partitioning (Georges 1985).

In the boom–bust Cooper Creek, resources bounce between severe depletion and plenty. During the bust times, Cooper Creek turtles direct their resources almost entirely to maintenance, sometimes even surviving in the mud (Fig. 5.4). Similarly, eastern long-necked turtles in wetlands near Jervis Bay in New South Wales partition their resources (Kennett and Georges 1995). In the boom times, there is abundant food, probably allowing Cooper Creek turtles to direct their energy to maintenance, reproduction and growth in a way not possible in more stable systems. This allows them to grow to be giants, albeit sporadically, throughout their lives.

The pressures of booms and busts and these life history tactics mean that populations of Cooper Creek turtles vary in a fascinating way, along the waterholes of Cooper Creek. Juveniles and adult males and females can be distinguished (Georges *et al.* 2006). The

Fig. 5.4. During bust periods, turtles in Cooper Creek can die when waterholes dry up. Some individuals can survive briefly by seeking refuge in the mud, such as this Cooper Creek turtle from Lake Dunn, but they soon die (photo, J. Cann).

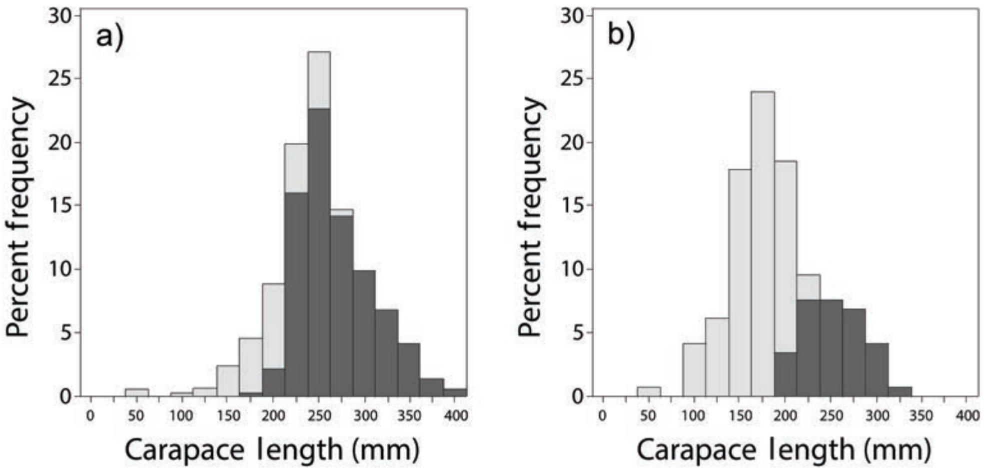

Fig. 5.5. Size distributions of adult (dark grey) and juvenile (light grey) Cooper Creek turtles, measured as carapace length which is a good indication of age from (a) a permanent waterhole on Cooper Creek (Eulbertie Waterhole) compared with (b) a typical waterhole that periodically undergoes complete drying (Tanbar Homestead Waterhole).

permanency of waterholes becomes critical. There are many waterholes of different size and permanency along Cooper Creek (Silcock 2010). Large waterholes with permanent water since European settlement (e.g. Eulbertie Waterhole) are dominated by large mature individuals, with few juveniles and no evidence of recent recruitment (Fig. 5.5a). This represents a climax state where the population has matched the capacity of the waterhole to sustain a turtle population of a certain size. Contrastingly, some waterholes dry completely (e.g. Tanbar Waterhole in 1983; Fig. 5.5b), presumably killing all the turtles. In these waterholes, when they fill up, juveniles, including small individuals, dominate. These waterholes are colonised by a few individuals from more permanent waterholes. They follow an upswing, inevitably followed by a catastrophic decline when the waterhole dries again, perhaps decades later.

There is a dynamic built around the different successional waterholes from some completely dry to others remaining as a chain of small pools (e.g. Fish Billabong and Broadwater Billabong in Lochern National Park) and the permanent ones. Turtle sizes and growth rates track this gradient between ephemeral and permanent waterholes. There is added complexity with the variability of floods and their effects on waterhole permanency. All along the Cooper, there are local extinctions of turtles and climax populations from which recruits then colonise waterholes when they fill. These processes unfold over decades, affecting dynamics in the slow lane, but allowing this water-dependent turtle to persist in the desert rivers of the Lake Eyre Basin.

Turtle sustainability

Natural river flows and flooding have produced healthy but highly dynamic populations of turtles, intricately locked into the dynamics of the rivers. Boom periods are pivotal in their production of widespread flooding, which also produces high productivity of plants and animals (Kingsford *et al.* 2014) as well as cattle (see Chapters 10 and 11). Native fish species cope with this episodic flooding, breeding in large numbers during boom periods and then dispersing across the floodplains (see Chapters 3 and 4). Waterbirds also capitalise on the large feeding areas created by the floods before congregating on lakes in the Lake Eyre Basin or other wetlands in Australia (Kingsford *et al.* 1999).

The freshwater turtles of the Cooper Creek employ different strategies. They can live for a long time (likely more than 100 years, though hard data are difficult to obtain), with their low metabolism and energy needs, allowing them to wait out bleak dry periods. Their success in this difficult environment depends on food delivered by flows into the Cooper waterholes when the river 'runs'. These 'in between' (Bunn *et al.* 2006) flows sustain the waterholes, allowing some to persist, even in the dry times, and then colonising waterholes which may dry out after breeding in the boom times. Abstraction of water from the rivers of the Lake Eyre Basin could have devastating consequences on the Cooper Creek turtle. The eastern long-necked turtle is less susceptible but still threatened. For Cooper Creek turtles, diversion of water from the river may push permanent waterholes to dry out, even if small flows are taken out (Bunn *et al.* 2006). The impacts on turtle populations would be devastating. The climax populations could become locally extinct, not only removing them from the river but also halting the ability of these stable populations to provide juveniles to the waterholes along the Cooper. Ultimately, there could be thresholds exceeded, which might threaten the species with extinction. The key message is that these animals depend on flows – all of them. It is the timing and frequency of river runs, as well as the frequency, extent and duration of major floods and how these floods spread across the floodplain which is critical. Alteration of flows through deliberate or inadvertent water diversion will be catastrophic for Cooper Creek turtles.

Conclusion

It is critical to ensure that natural flow regimes are maintained in this incredibly important river system.

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6

Developing the desert – potential effects on wildlife

Chris Dickman, Aaron Greenville and Glenda Wardle

Introduction

> The dogger and prospector follow the explorer; the survey party follows both and makes record of their findings; and hard upon their heels has been the stockman with his cattle, horses, donkeys, and camels, his sheep and goats and dogs; and the great hosts of the uninvited also – the rabbits, the foxes and the feral cats.
>
> The results of all this are hailed by the statistician and economist as progress, and a net increase in the wealth of the country, but if the devastation which is worked to the flora and fauna could be assessed in terms of the value which future generations will put upon them, it might be found that our wool-clips, and beef and timber trades have been dearly bought. (Finlayson 1935)

Arid regions of Australia cover ~5.5 million km^2 – three-quarters of the continent. This immense area supports a population of ~600 000 people, just under 3% of the overall Australian population (Stafford Smith and Cribb 2009). Pastoralism is the major form of land use and occupies most of the arid land area, but other significant desert enterprises include mining, tourism and conservation, as well as recreation and service industries near major watercourses and centres such as Uluru, Alice Springs and Mt Isa (Dickman *et al.* 2014). Around 300 000 km^2 are designated as Indigenous Protected Areas, occupied by many of the 93 000 people of Aboriginal descent for whom the desert is home (Brown *et al.* 2008).

The vast plains of the interior are often viewed as under-populated and ripe for increased exploitation of their aesthetic, biotic and other natural resources. This has led policy-makers to offer assistance programs (e.g. drought and mining subsidies) to ensure that desert residents remain where they are, and incentives such as start-up packages and tax breaks to attract entrepreneurs to begin new enterprises (Callender *et al.* 2011). This emphasis on financial capital has often overlooked other capital, such as human, social, physical, cultural and natural, essential for maintaining sustainable livelihoods in desert regions (Stafford Smith and Cribb 2009). In the Australian deserts, two further factors are usually also overlooked in discussions about ‘progress’ and economic development: the ‘boom and bust’ nature of the climate, and the vulnerability of some plants, animals and other organisms to environmental change (Finlayson 1935; Dickman and Wardle 2012; Dickman *et al.* 2014; Seddon *et al.* 2016). Native mammals declined dramatically with wide-ranging changes to the environment that accompanied the arrival of European settlers; ~19 species of small and medium-sized rodents and marsupials disappeared from arid Australia, within 150 years of settlement (Morton 1990).

Recent proposals and legislative changes by Australian and Queensland state governments could effect great changes to the environment (see Chapters 20 and 22). For example, the Australian Government has proposed that by 2030 much of northern Australia (areas north of the Tropic of Capricorn) would be transformed into a 'food bowl' that would double the nation's agricultural output (Australian Government 2014). Achieving such a great increase in agricultural productivity, assuming this is even possible, would drastically alter current drainage patterns and floodplain dynamics, and require the development of areas for irrigation. Because the extraction of water from rivers, lakes or groundwater changes an ecosystem well beyond the extraction or irrigation zones, the proposed developments would predictably have serious deleterious impacts on the environment and its organisms (Northern Australia Land and Water Taskforce 2009). Mining, similarly, has more extensive impacts on the environment than is evident at mine sites, owing to the expansive regional development and infrastructure that is needed to support mining activity (Andersen *et al.* 2014).

In Queensland, the *Wild Rivers Act 2005* was repealed in 2014, with river (and land) protection placed under the new *Regional Planning Interests Act 2014* (see Chapters 17, 20 and 21). Although claiming to 'identify areas of Queensland that are of regional interest because they contribute, or are likely to contribute, to Queensland's economic, social and environmental prosperity', there is much concern that the new Act will lead to increased mining, irrigation and other developments that compromise environmental values (see Chapters 19 and 22). Concern is particularly acute in the desert channels environment of south-western Queensland where rivers are currently unregulated; their flood waters cover extensive areas that connect waterholes, lakes and wetlands after heavy rainfall (Kerezsy *et al.* 2013), and the ephemeral pulses of productivity that they generate support livestock grazing (see chapters 10 and 11) and highly diverse native plants, animals and other organisms (Robin *et al.* 2010; see Chapter 1). A coalition of groups fought successfully against plans to introduce irrigated cotton farming to the region in the mid-1990s because of the probable impacts on production and biodiversity values (Kingsford *et al.* 1998). Proposals to increase water extraction for mining and irrigation have continued (see Chapters 19 and 20), with the region potentially less able to resist powerful corporate interests that are well served by the *Regional Planning Interests Act 2014*. The Queensland Government changed in early 2015 but does not have a majority government, making changes to environmental or natural resource legislation difficult.

We consider the potential effects of broad-scale irrigation and mining activity on ecological function in the desert channels environment (Fig. 6.1). We focus particularly on how native mammals and other vertebrates might respond to such developments, as their role as consumers also depends on plants in the food chain. We begin with a description of the boom and bust nature of the desert channels environment as this drives the ebbs and flows of many of our native mammals. We then draw upon a long-term dataset on small native mammals to show how species respond to large rainfall events and to the intervening dry periods, before finally considering how these species might respond to irrigation and mining. Because the magnitude of future development activities is not known, we consider different scenarios.

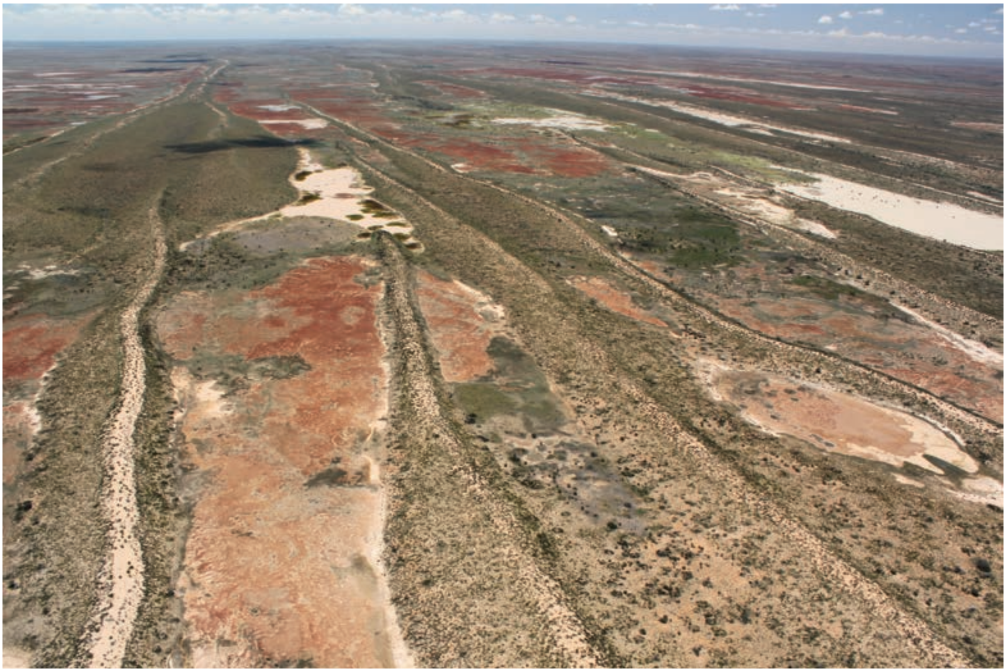

Fig. 6.1. These dunes and channels across the Simpson Desert are part of the desert channels environment, including the Channel Country of Cooper Creek and Georgina–Diamantina Rivers, Mitchell grass downs, desert uplands and Simpson–Strezlecki dunefields. This vast area is biologically highly productive, driven by boom and bust cycles of rainfall and flooding, and it provides habitats for many terrestrial mammals (photo, R. T. Kingsford).

The desert channels environment

This region occupies the north-eastern part of the Lake Eyre Basin in central and western Queensland, and covers over 500 000 km^2 (Dickman 2010). It incorporates parts of seven bioregions, including large tracts of the Channel Country and the Mitchell grass downs, as well as the desert uplands and Simpson–Strzelecki dunefields on the eastern and western boundaries, respectively (Desert Channels Queensland Inc. 2004). The desert channels environment stretches across the catchments of Cooper Creek and the Diamantina and Georgina Rivers (Fig. 6.1), which rise in the north and flow in a southerly direction towards Kati Thanda-Lake Eyre. Rainfall is higher in the north of the region (e.g. annual average for Camooweal = 398.7 mm) than in the south (e.g. 166.9 mm/year at Birdsville and 291.5 mm/year at Windorah), but very heavy rainfalls sometimes punctuate the usually arid conditions (Bureau of Meteorology 2014). Annual rainfalls of ~1000 mm have occurred at both Camooweal and Windorah and more than 540 mm at Birdsville (Bureau of Meteorology 2014); these types of events result in both local filling of river channels and downstream surges that can produce floods covering many thousands of square kilometres (Desert Channels Queensland Inc. 2004). The frequency and magnitude of these extreme rainfall events have increased over the last 100 years, a trend that may continue with climate change (Greenville *et al.* 2012).

Heavy local rains or floods arising from deluges in the northern Desert Channels recharge wetlands and swamps, and sustain the extensive networks of riparian vegetation that line the major watercourses and their braided networks of minor channels (Fig. 6.1). These events provide windows of opportunity for mass flowering and seeding of grasses and herbs, recruitment of perennial shrubs and trees, and surges of vegetative growth (Brock *et al.* 2006; Wardle 2010; Wardle *et al.* 2015). In turn, these pulses of primary productivity drive booms in populations of consumer organisms such as herbivorous insects, many birds (Kingsford *et al.* 1999; Kingsford *et al.* 2004; Kingsford *et al.* 2010) and mammals (Letnic and Dickman 2010). Population booms usually subside within a year unless further rains fall, and give way to bust or dry periods that can last for several years. Organisms can survive these periods by dispersing to wet areas outside the desert, by retreating to refuges within the arid landscape, or by weathering conditions as drought-resistant seeds or eggs (Boulton *et al.* 2006; Brock *et al.* 2006; Robin *et al.* 2010).

Mammals of the desert channels environment

We have monitored vegetation, invertebrates, small vertebrates and weather in the far western part of the desert channels environment since 1990 (Dickman *et al.* 2014). This area in the north-eastern part of the Simpson Desert has long red sand dunes that run in a north-north-westerly to south-south-easterly direction, ~0.5–1.0 km apart. The valleys and sides of the dunes are dominated by hard spinifex (*Triodia basedowii*) with small areas of gidgee (*Acacia georginae*) woodland in patches of heavy clay soil (Wardle *et al.* 2015).

We began catching small animals at Ethabuka Station (now Ethabuka Reserve) in the drought of 1990, using lines of pitfall traps (PVC pipes sunk into the ground). Mammals (and small reptiles) were trapped three to six times a year, usually for three days and nights each time, with captured animals identified, measured, marked and then released (Dickman *et al.* 2014). We have caught more than 40 species of lizard and 14 species of small mammal, with perhaps 30 more species of mammals and reptiles occurring in habitats just outside the sand dune system (Dickman and Wardle 2012). We show how populations of the two most abundant species of native rodent – the spinifex hopping-mouse (*Notomys alexis*, 30 g; Fig. 6.2) and the sandy inland mouse (*Pseudomys hermannsburgensis*, 12 g) – and a common marsupial, the brush-tailed mulgara (*Dasycercus blythi*,100 g; Fig. 6.3), have changed between 1990 and 2012 (Fig. 6.4). The rodents are omnivores, although a large part of their diet comprises seed, whereas the brush-tailed mulgara hunts invertebrates, rodents and other small vertebrates (Chen *et al.* 1998; Murray *et al.* 1999). Their dynamics are represented as catch-per-unit-effort (i.e. a trap-night is one pitfall trap open for one night), standardised as numbers of captures/100 trap-nights.

After a period of prolonged drought in 1990, large rainfall events occurred in the summers of early 1991, 1992, 2000, 2007 and 2010, with other reasonable summer rainfall events in 1995, 1997, 2009 and 2011 (Fig. 6.4a). Spinifex, the dominant vegetation, fluctuated with rainfall, ranging in ground coverage from under 20% during dry periods to over 50% in the months following exceptionally heavy summer rain (Dickman *et al.* 2014; Nguyen *et al.* 2015). Populations of the three mammal species rose and fell with rainfall (Fig. 6.4a–d). Spinifex hopping-mouse populations were often undetectable during periods of

Fig. 6.2. Small mammals such as this spinifex hopping-mouse (*Notomys alexis*) live in the sand dune habitats of the Simpson Desert, feeding on seeds, and go through boom and bust phases that coincide with productive rainfall and dry periods, respectively (photo, A. C. Greenville).

Fig. 6.3. Brush-tailed mulgaras (*Dasycercus blythi*) are predators, feeding on invertebrates, rodents and other small vertebrates, living in the sand dune habitats of the Simpson Desert. Similar to native rodents, mulgara populations go through boom and bust phases that coincide with productive rainfall and dry periods, respectively (photo, A. C. Greenville).

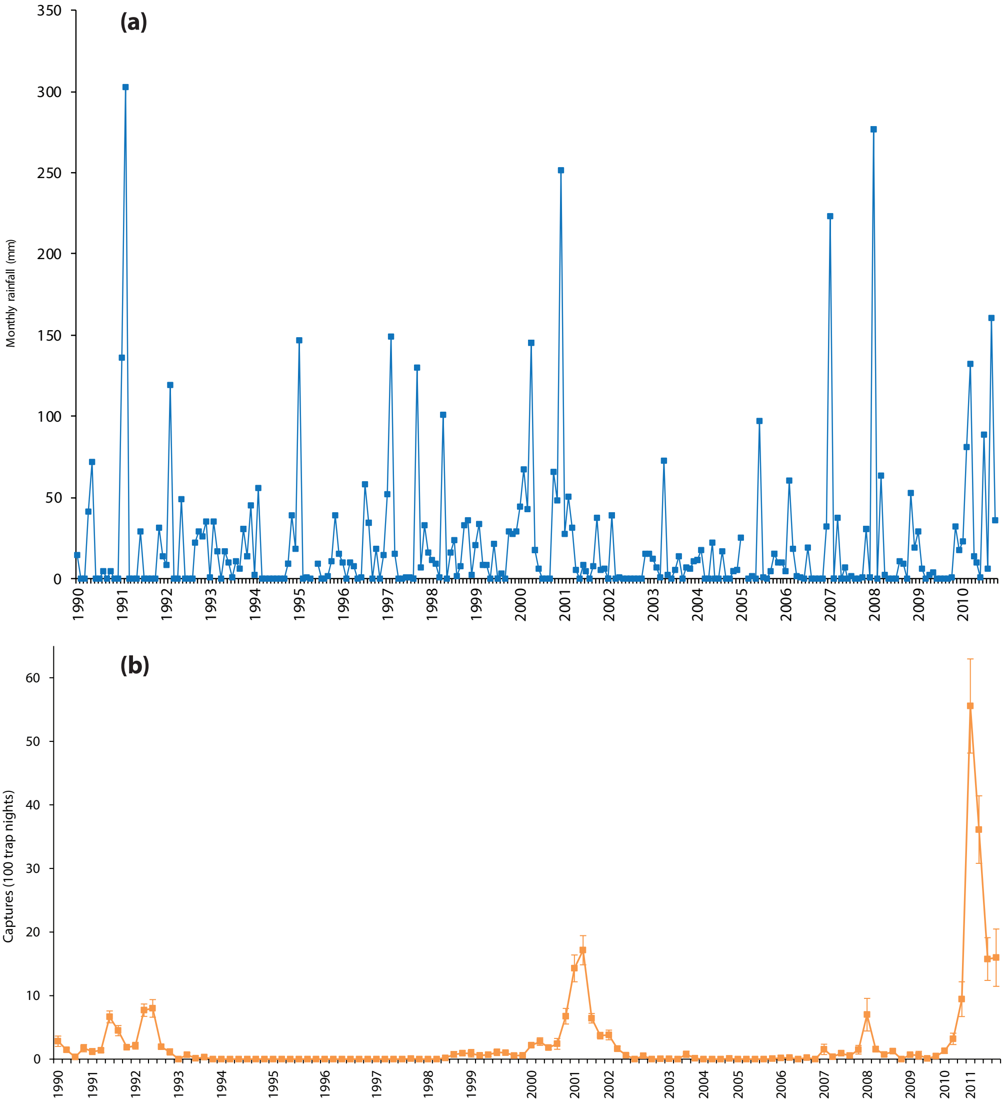

Fig. 6.4. (a) Monthly rainfall (mm) at Ethabuka Reserve, Simpson Desert, western Queensland from 1990 to 2012 (mean annual rainfall for this site is less than 200 mm), and mean capture rates (± s.e.) expressed as captures/100 trap-nights for (b) spinifex hopping-mouse (*Notomys alexis*).

drought, but irrupted within a few months of each of the major rainfall events (Fig. 6.4b). Sandy inland mouse populations were similar but were always detectable, even in dry periods (Fig. 6.4c). This species also showed a small response to moderate rainfall in the summer of 1997, contrasting with the lack of effect on spinifex hopping-mouse populations at that time. These two rodent species had different-sized responses to summer rainfalls, although the highest capture rates were in the most recent irruptions (Fig. 6.4b and c). These population booms were triggered by increases in primary productivity due to rainfall, providing food for breeding (Dickman *et al.* 1999; Breed and Leigh 2011).

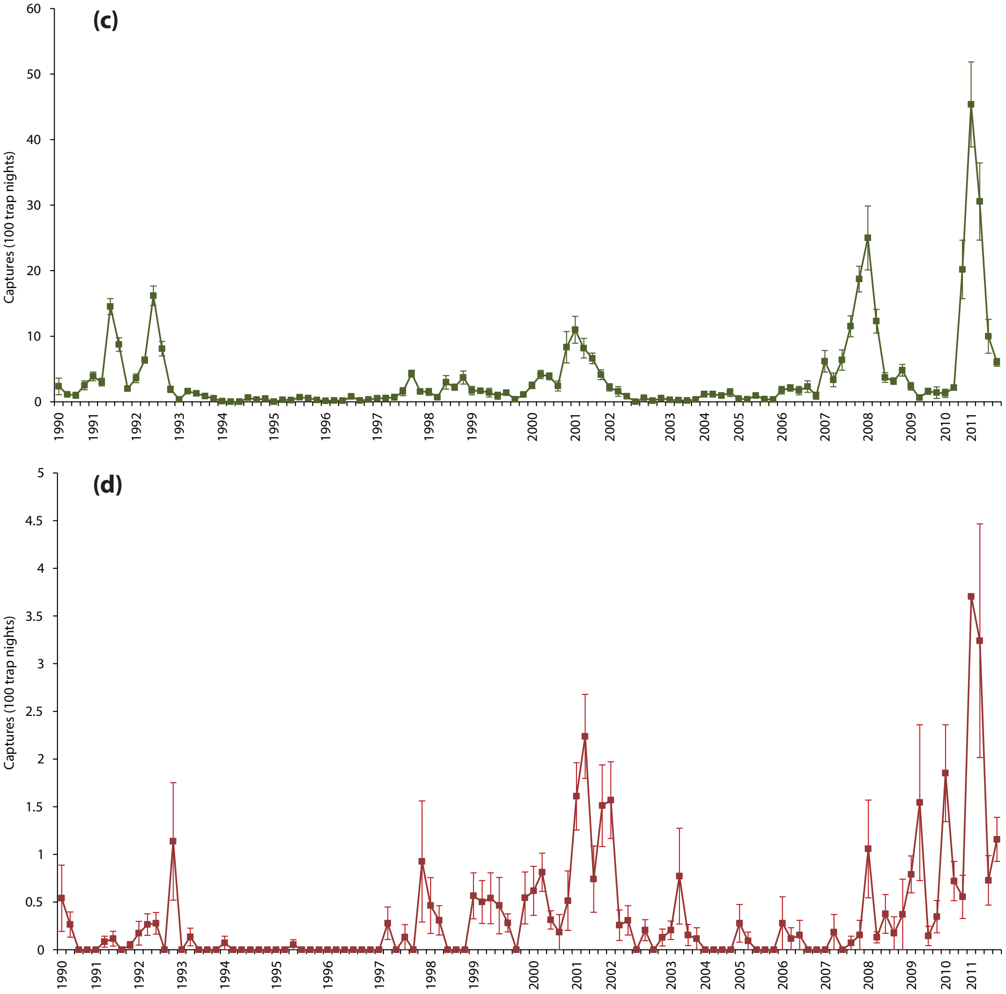

Fig. 6.4. (cont.) (c) sandy inland mouse (*Pseudomys hermannsburgensis*), and (d) brush-tailed mulgara (*Dasycercus blythi*). (Redrawn from Dickman *et al.* 2014).

Brush-tailed mulgara (Fig. 6.3) populations also fluctuated with rainfall, although peaks in the capture rate were usually 9–12 months after heavy summer rain (Fig. 6.4d). Unlike the rodents, this carnivorous marsupial has a fixed breeding time in winter and produces only a single litter. Its delayed response to summer rainfall arises from breeding adults taking advantage of the flush of rodent prey in winter, which improves survival of adults and their young, increasing the population in the following spring (Dickman *et al.* 2001). As dry periods increase, populations of all species fall to low levels (Fig. 6.4), with many retreating to refuges in the landscape where food, shelter and other resources are more consistently and reliably available (Dickman *et al.* 2011; Greenville *et al.* 2013). After 1995, we extended our study to eight other sites in the sand dune environment, using the same methods of trapping, and found very similar changes in populations (Greenville *et al.* 2016). Other, short-term studies from sites in the nearby region describe very similar patterns (Letnic *et al.* 2011; D’Souza *et al.* 2013; Wardle *et al.* 2013).

Populations of waterbirds, flock bronzewings (*Phaps histrionica*), frogs, butterflies, dragonflies and brightly coloured insect pollinators also increased with the rains, often irrupting spectacularly. Increasing populations of plague locusts (*Chortoicetes terminifera*), introduced house mice (*Mus musculus*) and native long-haired rats (*Rattus villosissimus*) exhibited similar patterns, damaging agricultural infrastructure and livestock pastures. This proliferation of prey brings increases in several species of elapid snakes (e.g. western brown snake (*Pseudonaja nuchalis*), ringed brown snake (*P. modesta*) and king brown or mulga snake (*Pseudechis australis*)) that feed on the many mammals and frogs. Feral cats (*Felis catus*), red foxes (*Vulpes vulpes*) and dingoes (*Canis dingo*) also increase in numbers during boom periods (Dickman *et al.* 2014). Heavy rainfall also increases weeds (e.g. buffel grass (*Cenchrus ciliaris*), athel pine (*Tamarix aphylla*)) and other vertebrate pests (e.g. cane toads (*Rhinella marina*), feral pigs (*Sus scrofa*)). With more vegetation growth and spread, fire risk also increases. Fires in the study region are estimated to return to the same patch about every 26 years (Greenville *et al.* 2009), but this may reduce with future climate changes (Low 2011).

Potential consequences of irrigation and mining developments

The boom and bust dynamic that prevails in the desert channels environment and the Lake Eyre Basin more broadly will be affected by developments that destroy habitats and these cycles. For example, coal seam gas contaminates groundwater (Osborne 2012), damaging aquatic animals and potentially polluting surface artesian waters (GABCC 2009). Animals can fall into uncapped drill holes where exploration is unregulated (Pedler 2010), while surface mining activities and their associated infrastructure can remove large tracts of habitat (Andersen *et al.* 2014). More generally, irrigation and mining developments increase human habitation, requiring water and waste disposal operations which can affect populations of plants, animals and other organisms. For example, development of mine sites can artificially inflate predator numbers, change home-range sizes and indirectly affect co-occurring species through changes in levels of predation or competition (Newsome *et al.* 2013; Newsome *et al.* 2015). In addition, increased roads, even if unsealed, and other transport infrastructure increase weeds and feral animals, especially foxes and feral cats that preferably use vehicle tracks (Mahon *et al.* 1998).

We focus on two potential scenarios, assuming current development recommendations (Northern Australia Land and Water Taskforce 2009), which are irrigation developments, mining modification of landscapes with removal of native vegetation for roads and mine infrastructure, and depletion of ground waters and surface water flows. We acknowledge that global environmental change will very likely further alter these scenarios and increase uncertainty in outcomes, both for development options and environmental degradation. This uncertainty emphasises the need to critically evaluate evidence for the success of any proposed scheme before it goes ahead.

Scenario 1: Fixation of boom-period conditions

Increased irrigation will affect natural boom and bust cycles, emulating heavy onsite rainfall or flooding events. Persistent water in the landscape in the form of increased low flows and channels could increase the persistence of introduced house mice, native rodents such as long-haired rats, brown snakes, and many species of mosquitoes and other biting insects. For example, dense populations of the highly venomous eastern brown snake (*Pseudonaja textilis*) use burrows in the banks of irrigation canals in the Murrumbidgee Irrigation Area (Whitaker and Shine 2003), where the snakes feed on house mice, and move over much of the agricultural landscape during warm months of the year. Dense populations of native and introduced species of rodents have also established in irrigated regions of south-east Asia (Aplin *et al.* 2003), damaging crops and livelihoods. Increased reliability of water and concentration of food in cropping areas can also be invasion hubs for feral pigs, cane toads (Letnic *et al.* 2014) and other invasive species (Letnic *et al.* 2015). Irrigation areas could also promote establishment of tropical disease organisms.

Scenario 2: Fixation of bust-period conditions

Depletion of ground and surface waters will prolong dry conditions, reducing opportunities for aquatic organisms to breed (see Chapters 3–5). Vegetation will be stressed; woody plants reliant on deep water will die and the lack of shade and refuge they provide will have flow-on effects for the remaining flora and fauna (Wardle *et al.* 2015). Loss or fragmentation of refuge habitats from surface mining activities will reduce the utility of these habitats as refuges. Over time, reduced numbers of refuge-dependent organisms will lead to losses of their local populations.

Managing the effects of irrigation and mining

Monitoring how irrigation and mining affect animals, plants and other organisms at local and regional scales is essential, if these activities proceed across the Lake Eyre Basin, with clear trigger points identified if any indicators fall outside previously agreed norms. There is, at present, very little indication that regional policy and planning documents understand the importance of such evaluation (e.g. Northern Australia Land and Water Taskforce 2009; Australian Government 2014). Changes in land use would also need to be coordinated across industries. For example, water remoteness is a well-established concept in managing rangeland pastoralism, as it provides relief from grazing pressure (Fensham and Fairfax 2008). Therefore, any new water points or larger irrigated areas arising from development would need to be considered in the landscape context.

We are still discovering the full extent of the dynamics of arid Australia, as witnessed by the extreme years in 2010–11. The intense ‘greening’ in these years led to unprecedented irruptions of small mammals, invertebrates and frog populations, migrations of species outside their known ranges, novel interactions among species, and greatly increased risks of predation and wildfire (Wardle *et al.* 2013). The greening also formed a major carbon sink, with an extraordinary 60% of global carbon being taken up by the growth of vegetation in Australia’s arid interior (Poulter *et al.* 2014). Managing broad-scale developments under such dynamic conditions will not be easy. What we can expect is for the already erratic dynamics of the Lake Eyre Basin to increase due to global climate change (Greenville *et al.* 2012; Greenville *et al.* 2013).

Conclusion

Natural boom and bust cycles driving animal populations in the Lake Eyre Basin potentially will be seriously affected by developments in irrigation and mining. New mining and irrigation developments could have their most serious effects along the rivers and the floodplains of the Lake Eyre Basin (see Chapter 22). There are potentially two broad and contrasting scenarios, affecting the two ends of the cycles. If current environmental conditions (booms or busts) become fixed, or de-coupled from natural boom–bust cycles, we can expect great changes for the organisms and communities that have evolved to survive in a fluctuating environment. It is critical that decisions about the economic development of the rivers of the Lake Eyre Basin account for these potential effects on their natural values and adequately recognise current uses that are often providing economic values or global environmental services. We argue for a precautionary approach. As the visionary naturalist HH Finlayson warned in 1935, we should not bequeath to future generations the knowledge that our decisions have come at costs they cannot bear.

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