The Burdekin River: a review of its ecology, conservation and management

Richard G. Pearson[A,B] , Aaron M. Davis[A] and R. Alastair Birtles[B]

[A]TropWater and [B]College of Science and Engineering, James Cook University, Townsville, Qld 4811, Australia.

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Prepared by Richard Pearson, Aaron Davis and Alastair Birtles

Centre for Tropical Water & Aquatic Ecosystem Research
(TropWATER)
James Cook University
Townsville
Phone : (07) 4781 4262
Email: TropWATER@jcu.edu.au
Web: www.jcu.edu.au/tropwater/

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For further information contact:
Prof. Richard Pearson
Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER),
James Cook University, Townsville, QLD 4811.
Email: richard.pearson@jcu.edu.au

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Cover photo by John Connell

Contents

Summary

We outline current knowledge of the ecology of the streams, rivers and floodplain wetlands of the Burdekin River system, examine the impacts of actual and proposed development, and consider the conservation status of the system and its management. The Burdekin River occupies a large catchment in north-eastern Australia, which overlaps several bioregions and has diverse aquatic habitats and biota. The taxonomic make-up and ecology of the biota is limited, with some patchy detail of invertebrate and fish assemblages and food webs. Water resource development, land clearing, weed invasion, agricultural pollution and climate change are all actual or potential factors negatively affecting the habitats and biota. Effective management needs to integrate multiple uses via governance of activities and interactions of stakeholders, recognising basic hydrogeomorphic, water quality and ecological needs for adequate conservation. While complete ecological protection is impractical amidst current and future water-resource and land-use development, we aim to develop a simple approach to conservation classification of all streams, rivers and associated wetlands, using the Burdekin River as a model system.

1. Introduction

Environmental research on rivers flowing into the Great Barrier Reef (GBR) lagoon has focused on delivery of land-based pollutants to the GBR (e.g., Brodie *et al.* 2012; 2017). While the need for holistic management of linked land- and seascapes is recognised (Brodie and Pearson 2016; Waterhouse *et al.* 2016a), only a few publications have concerned the ecology and values of rivers and wetlands themselves, including a study demonstrating the links between hydrology, land-use and ecological impacts on fresh waters (Davis *et al.* 2017), and a review of the ecology of waterways in the GBR catchment (Pearson *et al.* 2021). Here we review our knowledge of the Burdekin River system, a major contributor of water and contaminants to the GBR, and comment on its conservation and management status, with a view to developing a more holistic approach.

The Burdekin basin (Fig. 1) is a large system with high economic importance and with extensive associated environmental pressures (NQ Dry Tropics 2016a). It has high value for its ecosystem services, including the diversity of its environments and biota (Brizga *et al.* 2006; NQ Dry Tropics 2016a), its Indigenous values (Davis *et al.* 2014) and the importance of its discharge and associated contaminants to the GBR (McCloskey *et al.* 2021). There is moderate (though patchy) scientific knowledge of the system (Connolly *et al.* 2011) and the system is subject to important management activities in the landscape (e.g., Landsberg *et al.* 1998; O'Reagan *et al.* 2005; McIvor 2012; NQ Dry Tropics 2016b). The region is reportedly uniquely positioned for agricultural and water resource expansion (Australian Government 2015), so is potentially threatened with further environmental degradation. However, despite extensive development, important conservation criteria (e.g., naturalness, representativeness, diversity, rarity, linked habitats, migratory species and dispersal of terrestrial species – Dunn 2004) still apply to the Burdekin River (Brizga *et al.* 2006), and all 47 sub-catchments have been rated positively for their aquatic ecosystem and cultural values (Kerr 2013).

Currently, only 6% of the Burdekin catchment area is in protected areas (Table 1), and another 4% is in other low impact areas (e.g., military reserves) (Fig. 1). Protected areas include some rainforest areas and their streams, and some floodplain wetlands, but do not capture the larger rivers, or most of the intermittent streams. The small proportion protected is less than the global 15% (Bastin *et al.* 2019), but similar to the overall Australian situation, where about 8% of streams are in protected areas (Stein and Neville 2011). Elsewhere in Australia, it is often only the smaller streams that are captured: for example, in the Australian Wet Tropics, nearly 50% of the land is in protected areas (GBRMPA 2012), but only headwater streams are well represented, and approximately 80% of freshwater habitat is excluded (Januchowski-Hartley *et al.* 2011). We are working towards a straightforward approach to applying explicit conservation values to whole systems, to which this review contributes (Pearson *et al.* 2022). The review is not intended to be comprehensive, but provides access to further relevant literature through the works cited. We draw attention to many relevant publications available from the websites of TropWATER, NQ Dry Tropics, GBRMPA, CSIRO and Queensland Government.

2. Burdekin catchment landscape setting

Broad biophysical descriptions of the Burdekin River and basin are provided by Water Resource and NRM plans (Brizga *et al.* 2006; NQ Dry Tropics 2016a). The basin is located centrally in the Great Barrier Reef catchment, spanning about 6° of latitude and covering an area of approximately 134,000 km^2, including the floodplain and associated Haughton River (Fig. 1). The catchment is one of the largest in Australia and the river reportedly has the greatest peak (though not median) discharge (Mitchell *et al.* 2007; Inglis and Howell 2009). It drains large parts of three low-rainfall bioregions – the

Einasleigh Uplands, the Desert Uplands and the Brigalow Belt North – and smaller portions of the moist Wet Tropics to the north-east and Central Queensland Coast to the south-east. The largest towns are Ayr (population approximately 8,000) and Home Hill (3,000) coastally and Charters Towers (8,000) inland (Fig. 1). The main regional centre is Townsville (187,000), through which produce from the Burdekin catchment is exported.

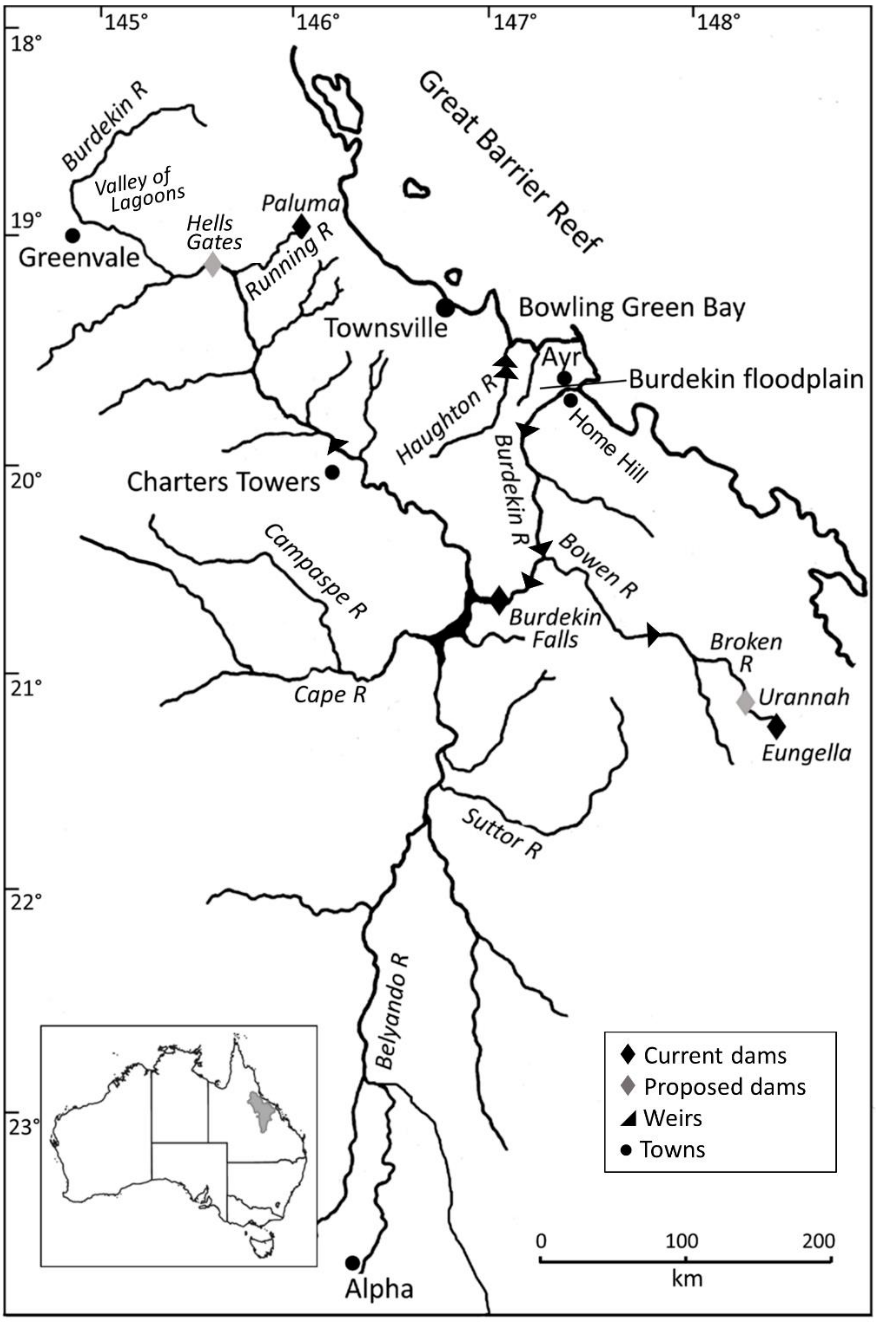

Fig. 1. Map of the Burdekin Basin, including the coastal Haughton River, which delineates the western edge of the floodplain. Locations, rivers and dams referred to in the text are indicated. Proposed impoundments include Hells Gates Dam on the Burdekin River, Urannah Dam on the Broken River, raising the current Burdekin Falls Dam and Big Rocks Weir near Charters Towers (SMEC, 2018; Queensland Government 2021a,b,c). Inset shows the location of the basin in Australia.

Topography includes coastal mountain ranges, extensive inland uplands and plains and the coastal floodplain (Fig. 2). The climate is seasonal tropical (Fig. 3). Native vegetation includes small areas of rainforest in the coastal uplands, open woodland and grassland across the inland plains, and open forests, woodlands and wetland assemblages on the floodplain. The floodplain includes one of the continent's largest concentrations of high-value freshwater, estuarine and marine wetlands (Davis *et al.* 2014). Major industries are agriculture, including cattle grazing (most of the catchment), irrigated sugarcane, horticulture and dryland cropping (Fig. 4, Table 1) (NQ Dry Tropics 2016b); and commercial fishing, mining and tourism. Northern Australia's largest irrigation area is located on the floodplain (NQ Dry Tropics 2016a; Lewis *et al.* 2021). Protected or otherwise lightly used areas are located mainly in the uplands and coastal wetlands. Twenty-five sites are listed in the Australian Directory of Important Wetlands (Environment Australia 2001), including the Ramsar-listed Bowling Green Bay wetlands, Birthday Creek (a tributary of Running River in the Wet Tropics uplands), and wetlands in the upper Burdekin catchment (e.g., Valley of Lagoons).

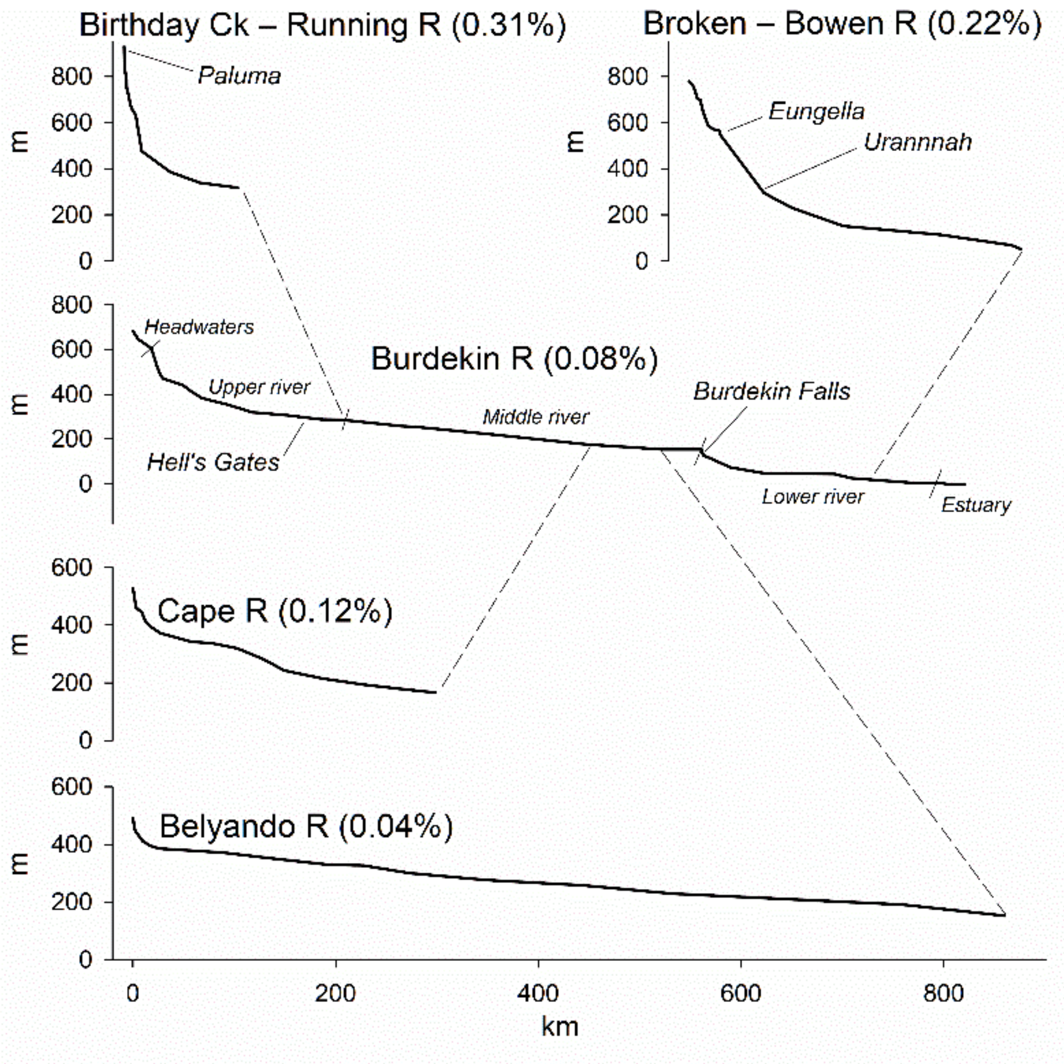

Fig. 2. Longitudinal profiles of the Burdekin River and several tributaries, showing positions of current dams (Paluma, Eungella, Burdekin Falls) proposed dams (Urannah, Hells Gates, raising Burdekin Falls) and main river zones. Dashed lines show junctions between tributaries and the main river. Percentages are gradients of each profile.

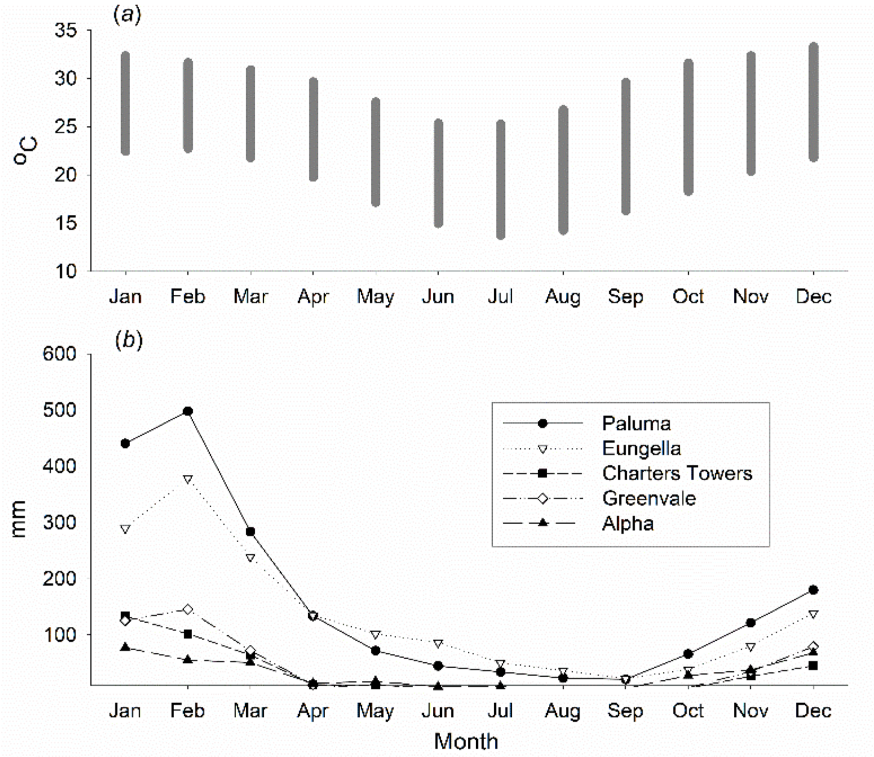

Fig. 3. Monthly temperature range (mean maximum – mean minimum) at Charters Towers (*a*) and mean monthly rainfall at five sites in the Burdekin catchment (*b*). Paluma and Eungella are in the coastal ranges; the others are in the rangelands (Fig. 1). Australian Bureau of Meteorology data.

Table 1. Burdekin River sub-catchments area and percentage land use

Data from NQ Dry Tropics (2016b). *Lower Burdekin includes floodplain and Haughton catchment.**Includes military training area; 6% of total is explicitly protected (GBRMPA 2012)

	Upper Burdekin	Cape/ Campaspe	Belyando	Suttor	Bowen/ Broken, Bogie	Lower Burdekin*	Total
Area km^2	40,499	20,517	35,352	18,230	11,718	7,997	134,313
Area %	30.2	15.3	26.3	13.6	8.7	6.0	100
Grazing %	88	81	94	91	73	73	87
Cropping %				6		12	1.5
Conservation/limited use %	11**	18	4	<1	24	8	10**

The dominant feature of the Burdekin River from water resource and ecological perspectives is the great variability of the hydrosystem within and between years (Fig. 5) (Davis *et al.* 2017), with annual discharges ranging from 530 to over 40,000 GL (Petheram *et al.* 2014), and an annual median value of 2490 GL. Many streams and wetlands in the catchment are non-perennial, but streams that rise in the coastal ranges or are fed by basalt aquifers, and many basaltic and floodplain wetlands, are perennial. The groundwater and flow regimes together determine waterway morphology, wetland extent and duration, connectivity, riparian vegetation, water quality, aquatic habitat, reproductive cues, drinking water availability for terrestrial animals, and supply of sediment, nutrients and organic matter downstream (Brizga *et al.* 2006; Davis *et al.* 2017).

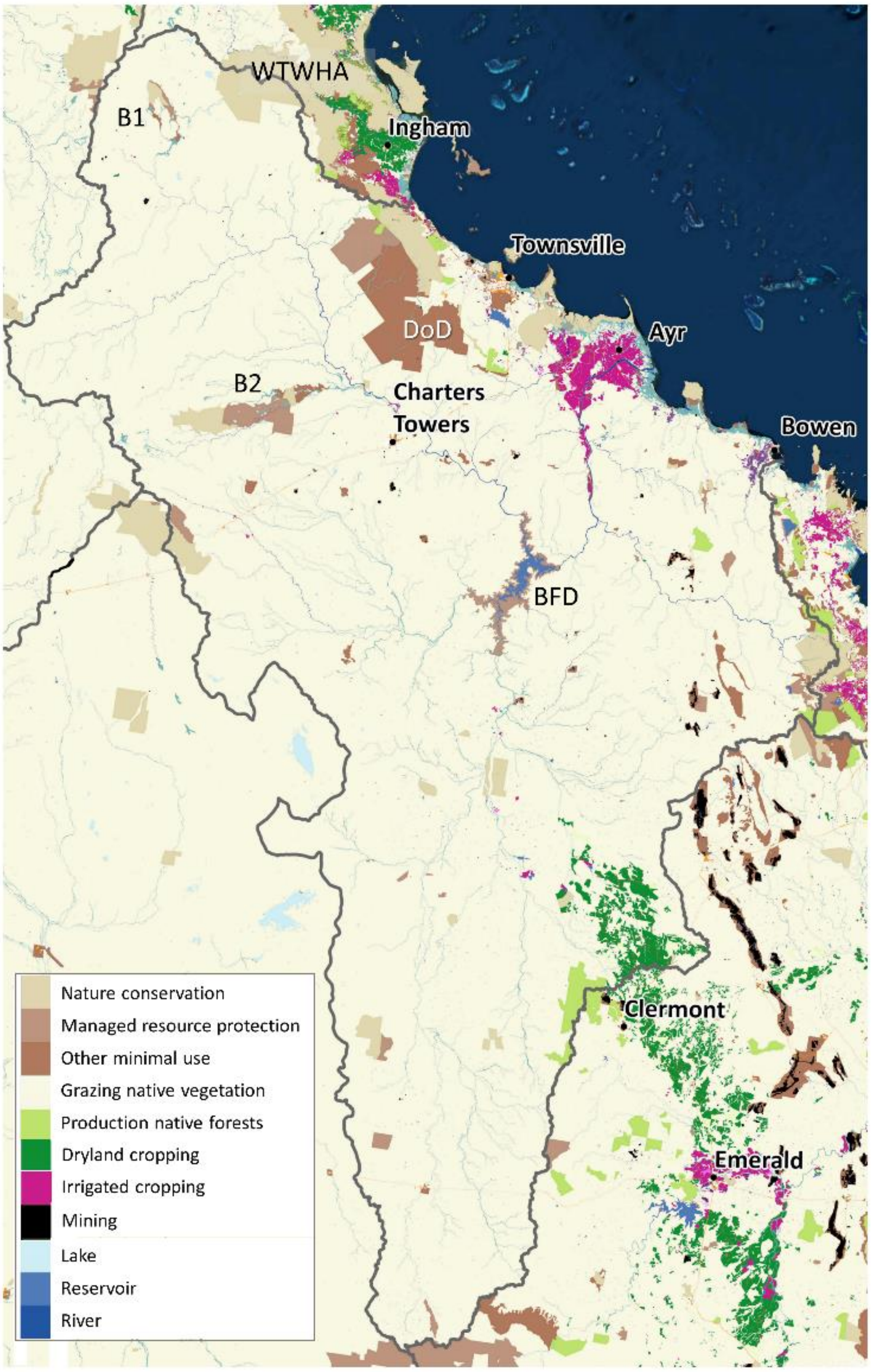

Fig. 4. Land-use in the Burdekin Basin (includes small coastal catchments near Townsville and south-east of Ayr). Abbreviations: B1, B2, areas of surficial basalt; DoD, Department of Defence training area; BFD, Burdekin Falls dam; WTWHA, Wet Tropics World Heritage Area. Modified from Queensland Land-Use Mapping Program (https://www.qld.gov.au/environment/land/management/mapping/).

Current water resource developments in the catchment include dams (Burdekin Falls, 1,860 GL; Paluma, 12 GL; Eungella, 131 GL*)* and several large weirs (Brizga *et al.* 2006) (Fig. 1). Water is used for irrigation on the coastal floodplain, groundwater recharge on the delta, watering of stock and domestic supply. The Burdekin Falls Dam captures about 88% of catchment flow (Lewis *et al.* 2013). The catchment has received much attention from the perspective of GBR management because of its major contributions of freshwater discharge, fine sediments and nutrients into GBR waters (McCloskey *et al.* 2021).

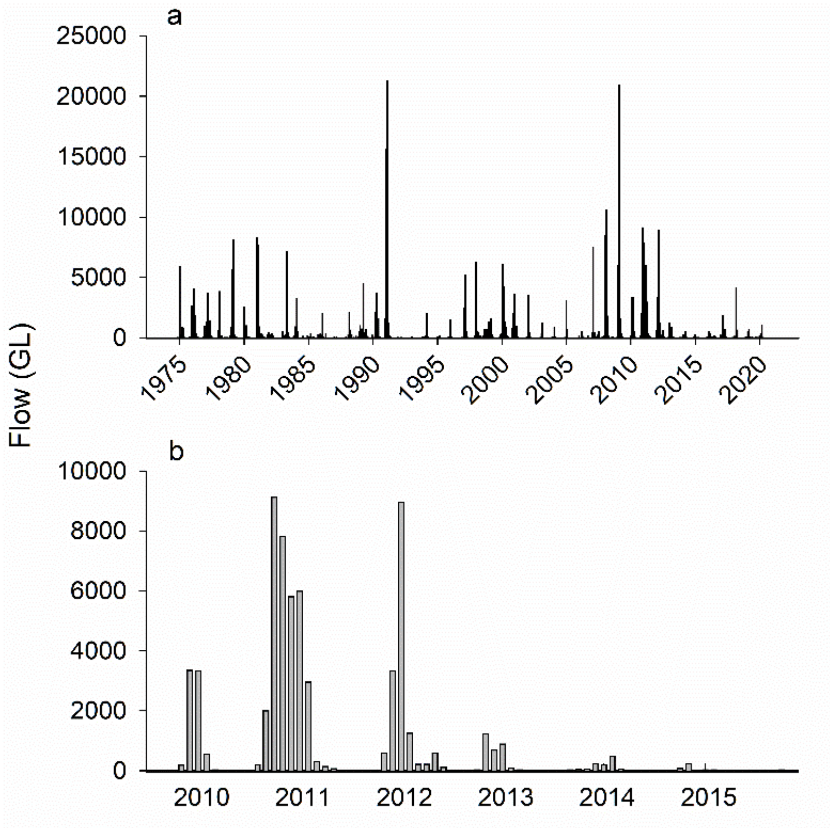

Fig. 5. Monthly flow in the Burdekin River at Clare in (a) 1975-2020 and (b) 2010-2015, showing patterns of monthly and annual variability. Over period of (a) mean = 696 GL and median = 66 GL per month. Queensland Government data (https://water-monitoring.information.qld.gov.au/).

3. Aquatic habitats and ecology

The flow regime comprises four main periods (Davis *et al.* 2017): i) initial "pre-flush" during the dry- to wet-season transition, ii) early wet-season "first flush", iii) peak wet-season floods, and iv) sustained dry-season base flow or progressive disconnection. This cycle is most evident in streams and rivers, but is reflected in lentic waters. Headwaters include springs and rocky or sandy streams, descending to broad plains with low gradient and mostly sandy substrata, eventually converging on the main river (Fig. 2; Fig. 6).

Fig. 6. Burdekin catchment illustrations: (a) Birthday Creek; (b) basalt-fed spring; (c) unnamed intermittent tributary; (d) Running River; (e) Campaspe River permanent lagoon; (f) upper Burdekin River; (g) middle Burdekin River; (h) middle Burdekin River in flood; (i) base flow at same site as (h); (j) Sheepstation Creek on floodplain; (k) coastal wetlands. All photos taken in the dry season, apart from (h). Photos by R. Pearson except (f), J. Connell.

Except when in flood, the river has a meandering channel within a broad sandy bed, occasionally punctuated by rocky outcrops. The Burdekin Falls (now the major dam site) delineates middle and lower river sections. A 45-km rocky gorge downstream of the dam opens up to the sandy lower river and its floodplain. We consider here three major hydrogeomorphic categories: (i) running waters, comprising headwater streams (orders 1 – 3); upper river (mid-sized streams, orders 4 – 5); the main tributaries and middle Burdekin River (order 6-7); and lower river (order 7+) and estuary; (ii) lentic waters, comprising lakes and swamps; and (iii) ground waters.

Several environmental studies address the whole catchment or large parts of it, typically with limited detail, reflecting a lack of available information. They include focus on multiple components (Brizga *et al.* 2006; Inglis and Howell 2009), water quality (Loong *et al.* 2005), riparian condition (Dowe *et al.* 2005; Lymburner and Dowe 2006), wetland condition (Burrows *et al.* 2007), floodplain environmental values and water quality objectives (Lankester *et al.* 2007), and coastal wetlands (Davis *et al.* 2014; GBRMPA 2013; Waltham *et al.* 2019). A government overview of the floodplain, its ecology and its development is available online (Queensland Government 2018). Here we outline ecological knowledge of the Burdekin system, summarised in Table 2.

Headwater streams

Small streams include the perennial forest streams in the north-east and south-east, the ephemeral and intermittent (sensu Busch *et al.* 2020) dryland streams of most of the catchment, and distributary streams on the floodplain. Substantial research has been undertaken at Birthday Creek in the north-east, in the Wet Tropics. It is a perennial rocky stream with moderate gradient (Benson and Pearson 2020) and high diversity of riparian vegetation (Bastian *et al.* 2007) and invertebrates (Pearson *et al.* 2015), with several endemic species (e.g., Christidis and Dean 2005). Biogeography, flow, sediment size and organic matter availability determine invertebrate assemblage composition (Pearson *et al.* 2017). The fauna is highly mobile (Connolly and Pearson 2018) and resilient to disturbance, especially floods (Rosser and Pearson 2018), but also nutrient supplements, sedimentation and hypoxia (Pearson and Connolly 2000; Connolly and Pearson 2007; Connolly *et al.* 2004). Disturbance refugia include epilithic mosses (Wulf and Pearson, 2017), while restricted habitats such as waterfalls sustain a specialised fauna (Clayton and Pearson, 2016).

The abundance and diversity of vertebrates in the headwaters is limited. Of the two species of fish, the eel, *Anguilla reinhardtii*, is becoming locally extinct because the Burdekin Falls Dam prevents migration (Brizga *et al.* 2006). Only two species of stream-dwelling tadpoles remain following local extirpation by fungal disease (Schmidt *et al.* 2019). There are several species of turtle, lizard and snake and two species of kingfisher, but none is abundant. The platypus (*Ornithorhynchus anatinus*) has large home ranges in small forest streams, and native water rats (*Hydromys chrysogaster*) are widespread (unpublished data).

Food webs in the forest streams are largely driven by allochthonous leaf litter, with fungi, bacteria, insect larvae and crayfish important processors of the material (Cheshire *et al.* 2005; Coughlan *et al.* 2010), although algal dietary signatures are also evident (Schmidt *et al.* 2017). Much research has been undertaken on leaf-litter decomposition (e.g., Wootton *et al.* 2019; Benson and Pearson 2020), contributing to global comparisons (e.g., Boyero *et al.* 2011, 2021a,b).

Table 2. Summary of typical biotic characteristics of zones of the Burdekin River and associated rivers and wetlands based on references cited in text

Uncertain characterisation indicated by "?". Abbreviations: CPOM – coarse particulate organic matter (e.g. leaf litter); FPOM – fine particulate organic matter (< 1 mm); both derived locally from leaf litter, macrophyte or algal breakdown, or transported from upstream

Zone/character	Plants	Invertebrates	Fish	Other vertebrates	Food web trophic base*
Headwaters					
Intermittent	Algae	Probably diverse	Occasional	Scarce	Algae, FPOM
Perennial	Limited algae, few macrophytes	Diverse, not abundant	Few species	Reptiles, birds, platypus – low abundance	CPOM, FPOM, some algae
Impounded	Plankton; marginal algae, macrophytes	Not abundant	Few species apart from translocations	Reptiles, birds, platypus – low abundance	Mainly planktonic
Upper river					
Intermittent	Algae	Unknown	Few species	Scarce	Algae, FPOM
Perennial, Interrupted	Algae, abundant macrophytes	Moderately diverse, abundant	Moderately diverse, abundant	Reptiles, birds increasing abundance; platypus?	Algae, some macrophyte, FPOM
Impounded	Algae mainly	Possibly peripherally diverse, abundant	Moderately diverse, abundant	Moderate diversity, abundance	Plankton & peripheral algae
Middle river					
Intermittent	Algae	Occasionally abundant	Moderately diverse	Variable	Algae, FPOM
Perennial	Algae, varying with salinity macrophytes	Not diverse but abundant	Diverse, abundant	Reptiles, birds increasing diversity, abundance	Plankton & algae, FPOM
Impounded	Algae mainly	Possibly peripherally abundant	Moderately diverse & abundant	Moderate diversity, abundance	Plankton & peripheral algae
Lower river					
Perennial	Algae, limited macrophytes	Not diverse but abundant	Diverse & abundant	Birds increasing diversity, abundance	Algae, FPOM
Impounded	Algae mainly	Possibly peripherally abundant	Moderately diverse & abundant	Birds increasing diversity, abundance	?Plankton, peripheral algae

… continued

Table 2 continued

Zone/character	Plants	Invertebrates	Fish	Other vertebrates	Food web trophic base*
Estuary					
	Plankton, algae, mangroves	Plankton, benthic invertebrates abundant	Diverse, abundant	Birds diverse, abundant	Plankton, CPOM, FPOM
Upper floodplain					
Basaltic	Plankton, algae, macrophytes	Unknown diversity, abundant	Unknown diversity, abundance	Birds diverse, abundant	Plankton, macrophytes
Other	Plankton, algae, macrophytes	Unknown	Unknown diversity, abundance	Unknown diversity & abundance	Plankton, macrophytes
Coastal floodplain					
Freshwater	Plankton, algae, macrophytes	Diverse, abundant	Diverse, abundant	Birds diverse, abundant	Plankton, macrophytes
Transient	Varying with salinity	Unknown	Diverse, abundant	Birds diverse, abundant	Plankton
Saline	Plankton, algae, mangroves	Diverse, abundant	Diverse, abundant	Birds diverse, abundant	Plankton, CPOM, FPOM

Intermittent dryland headwater streams have received little attention, although studies on the nearby Townsville coastal plain (Smith and Pearson 1987; Dell *et al.* 2014) and adjacent Fitzroy catchment to the south (Stitz *et al.* 2016, 2017) are relevant. Typically, these streams have shallow gradients and are sandy. Riparian vegetation includes species of *Melaleuca*, *Eucalyptus*, *Corymbia* and *Casuarina* (Pettit 2002), but has lower diversity than rainforests. This vegetation provides important dry-season refugia and dispersal routes for terrestrial fauna (Williams 1994; Bengsen and Pearson 2006). These streams can have diverse invertebrate assemblages and may be important for fish spawning (Orr and Milward 1984). Given the total length of small streams (up to about 85% of total stream length – Januchowski-Hartley *et al.* 2011), the limited information on them is a major gap in our knowledge.

Mid-sized streams

Mid-sized streams and rivers have high banks and intervening flat areas, vegetated with *Melaleuca* and other species, including River red gum (*Eucalyptus camaldulensis*) and some endemics (Brizga *et al.* 2006; Pettit and Dowe 2003). Streams with riparian vegetation in good condition include the upper Burdekin River and tributaries (Keelbottom Creek, Star River and Running River) and the Broken River and tributaries (Lymburner and Dowe 2006). Those fed by basaltic aquifers may be perennial (Preite and Pearson 2017), but otherwise are mostly seasonal, with disconnected waterholes maintained by the water table. Waterholes are typically shaded, with diverse macrophyte, phytoplankton and invertebrate assemblages (Blanchette and Pearson 2012, 2013; Preite and Pearson 2021). Their water quality and biota are influenced by regional lithology, land use and local factors, such as degree of shade and cattle access (Preite and Pearson 2017). Fish diversity is much greater than in smaller streams, and includes endemic taxa such as small-headed grunter (*Scortum parviceps*), softspine catfish (*Neosilurus mollespiculum*) and, in the Running River, a near-extinct rainbowfish (*Melanotaenia* sp.) (Lintermans *et al.* 2020).

Food webs are influenced by removal of aquatic plants and detritus by floods (Pusey *et al.* 2010; Davis *et al.* 2018), and are characterised by omnivory and ontogenetic dietary shifts (Davis *et al.* 2011, 2012). Stable isotope analysis indicates ecological opportunism and variability in basal sources and structure (algae, macrophytes and riparian leaf litter), with sites from the same tributary often as different as sites from other tributaries (Blanchette *et al.* 2014).

Middle river and immediate tributaries

The middle river and larger tributaries have high banks, well vegetated flats alongside the main channel (similar species to upstream), with the wetted area meandering within the channel over a sandy substratum and occasional rocky outcrops. Aquatic macrophytes are not abundant, but algae are prolific on stable sand. Invertebrate diversity is lower than in the headwaters, but abundance is high, with assemblages determined by sediment size, from bedrock to sand (Davis *et al.* 2015). Large crustaceans (Palaemonidae and Atyidae) are abundant, and the red-claw crayfish (Parastacidae: *Cherax quadricarinatus*) has been introduced from northern Australia, with unknown impact on the resident fauna.

The fish fauna comprises about 62 species, comparable with other large rivers in the region, and includes at least 2 endemics, 5 exotics and 6 translocated Australian species (Brizga *et al.* 2006). The Burdekin Falls historically prevented movement of diadromous species. Some piscivorous species have been translocated upstream, with negative effects on the resident species (Pusey *et al.* 2006). Tilapia have invaded the system from unauthorised releases, with unknown ecological impacts (Veitch *et al.* 2006; Burrows *et al.* 2009). Many species are dependent on flow events to initiate spawning (Brizga *et al.* 2006) and within-river movement, and possibly on specific instream habitat features such as riffles, which are regular isolates along the river (Davis *et al.* 2015, 2018). The grunters (Terapontidae) are of great evolutionary interest as they include species that have diversified in their feeding preferences and reflect the marine to freshwater transition (Davis *et al.* 2012).

Other vertebrates include six species of turtle, including one endemic and several that are spatially segregated (Inglis and Powell 2009). The ecology of some species is closely linked to flow and may be compromised by supplemented flows from the Burdekin Falls Dam (Brizga *et al.* 2006). Little is known of the ecology of 5 snake, 3 lizard or 27 frog species (Inglis and Powell 2009). Aquatic or semiaquatic birds include 44 species, with many partly piscivorous species, such as cormorants, herons, egrets, kites and eagles, but their influence in the food web is unknown.

Lower river

There is very limited information on the ecology of the lower river. Many marine/estuarine invertebrate and fish species, as well as freshwater species similar to those of the middle river, occur and at least eight riverine fish species depend on access to estuarine or marine areas for spawning. The fauna includes the estuarine crocodile (*Crocodylus porosus*) and many piscivorous and invertivorous birds.

Estuary

The Burdekin estuary comprises the 1.0-km-wide main river channel and ancillary distributaries, within Australia's largest delta. Dry-season freshwater input is reduced by weirs and sand dams, so estuarine salinity may match or exceed that of normal seawater. While substantial research has been undertaken in estuaries in the region (e.g., Sheaves 2009, 2015; Sheaves and Johnson 2009), the Burdekin estuary itself has received less attention. Like other estuaries in the region, it is expected to be productive, supporting abundant plankton, benthic invertebrates and fishes, including opportunistic marine species, and riverine species that require connectivity between major habitats (Pearson *et al.* 2021). It supplies important inputs for productivity in the coastal commercial and recreational fishery. During times of flooding it may replenish ground waters on the floodplain and delta, thereby sustaining wetlands.

Swamps and lakes

In addition to in-river waterholes, there are numerous perennial and intermittent lentic water bodies in the catchment. In the upper catchment, groundwater sustains perennial wetlands, especially in basaltic parts of the north, where permanent lakes (e.g., Valley of Lagoons) have important fish and bird habitat values (Brizga *et al.* 2006; Pusey *et al.* 2006; Maughan *et al.* 2006), and on tributary floodplains. Natural lakes are not large and ecological information on them is limited. Swamps are most extensive on the coastal floodplain (GBRMPA 2013; Davis *et al.* 2014). They present diverse forms along salinity and hydrological gradients, and often have profuse growth of submerged and emergent plants (Sheaves and Johnston 2008; Connolly *et al.* 2012; Waltham *et al.* 2019). They may be important habitat for fish, such as juvenile barramundi, *Lates calcarifer* (Russell and Garrett, 1985), and waterbirds. The Bowling Green Bay Ramsar site is recognised for its high biodiversity and importance for migratory shorebirds that are subject to international agreements (Commonwealth of Australia 2020, 2021; Weller *et al.* 2020), and for dugongs and turtles (Lankester *et al.* 2007). Many wetlands have been affected by land clearing and irrigated cropping, especially sugarcane, which have reduced riparian vegetation, changed hydrology and groundwater levels, and caused weed invasion and contamination by irrigation tailwater (Davis *et al.* 2014). Despite substantial impact of development (see below), they are regarded as having high ecological value, and even artificial habitats have some value in sustaining fish assemblages (Davis and Moore 2016).

Groundwater

Groundwater sustains the river and wetlands through most of the year, in the absence of surface run-off and irrigation tailwater (e.g., Davis *et al.* 2013). Groundwater is used for irrigation on the delta, requiring careful management of the resource (GBRMPA 2013). Elsewhere on the floodplain, irrigation has raised water tables, so dewatering is required to avoid waterlogging and rising salinity. There is no information on the effects of such management on the groundwater biota and, as elsewhere in the world, knowledge of the ecology of ground waters is scarce. However, Syncaridae, specialised groundwater crustaceans, are diverse (Cook *et al.* 2012).

4. Ecological impacts of 150 years of development

Little of the Burdekin system has escaped the impact of development over the last 150 years, which includes selective logging in the uplands, mining, grazing and cropping on rangelands and floodplains, and water resource developments, including irrigation (Butler *et al.* 2009). We group impacts here as issues concerning land use, water quality and habitat, water flow, and climate, many of which co-occur and probably interact (Pearson *et al.* 2021).

Land use, water quality and habitat

The major land use in the catchment is cattle grazing in wooded and cleared rangelands. Grazing lands are blighted by weed invasion and fire in riparian zones (e.g., Valentine 2006; Valentine *et al.* 2007), and overstocking, leading to substantial erosion and salinity (Williams *et al.* 1997; Wilkinson *et al.* 2018). A huge impact on the river has been increases in suspended sediment and nutrient loads (5 to 10-fold) since the mid-nineteenth century (Lewis *et al.* 2007, 2021; Bartley *et al.* 2014). The Burdekin Falls Dam traps 95% of the coarse sediment from upstream (Lewis *et al.* 2013), possibly affecting coastal processes (Wolanski and Hopper 2022), although substantial supplies still exists in the tributaries of the lower river. Most of the fine sediment is delivered to the coast, with detrimental effects on ecosystems, including coral reefs and seagrass meadows (Bartley *et al.* 2014; Waterhouse *et al.* 2016b; Wooldridge 2017). The impact of perpetually turbid water in the lower river, conveyed from the Burdekin Falls Dam, has not been quantified (Burrows 1999; Burrows and Butler 2007).

Some dryland cropping is practised in the south-east, but cropping is dominated by sugarcane (about 80,000 ha) on the delta and coastal floodplain. Irrigation is supplied by groundwater on the delta and the Burdekin Falls Dam elsewhere, following land clearing in the late 1980s and associated loss of riparian and wetland vegetation and fauna (Davis *et al.* 2014). Irrigated cropping has greatly changed water regimes and water chemistry, creating substantial management challenges for the wetlands, and ultimately the viability of the irrigation area itself (Burrows, 2004; Burrows and Butler 2007; Davis *et al.* 2014; Petheram *et al.* 2014).

Floodplain wetlands have multiple problems associated with water management, loss of riparian vegetation, weed invasion and water quality (GBRMPA 2013; NQ Dry Tropics 2016b). Water-quality stressors such as ammonia, hypoxia and pesticides are major threats to fresh waters during pre-flush or base flows (Davis *et al.* 2017). Hypoxia is caused by prolific growth of exotic weeds and biochemical oxygen demand, which are enhanced by organic and nutrient run-off and loss of riparian shade. Invasive weeds require continuing control measures to maximise ecological values (Waltham *et al.* 2020a, 2020b) – for example, removal of exotic weeds restored fish diversity in wetlands (Perna *et al.* 2012). Invasive grasses exacerbate hot fires in riparian areas, severely reducing remnant riparian vegetation (GBRMPA 2013). Exotic fish species are prevalent in disturbed wetlands, with unknown impact (Brizga *et al.* 2006, Perna *et al.* 2009), while feral pigs damage wetlands across the catchment (Mitchell 2011).

Flow management

The ecological impacts of dams and flow management are generally well understood and include severance of instream and riparian connectivity, reduction of seasonality and major habitat changes upstream and downstream (e.g., Kingsford 2000; Geist 2021; Bower *et al.* 2022). The Burdekin Falls Dam has reduced floods and sediment transport, with possible impacts on coastal processes and wetland integrity (Wolanski and Hopper 2022). Impounded water is delivered downstream in the river channel, supplementing dry-season flow and flooding turtle breeding habitat (Brizga *et al.* 2006). Transfer of water to the irrigation area has changed the flow regime across the floodplain, with multiple effects (Waltham *et al.* 2019, 2020a; Tait 2021), including proliferation of exotic weeds (Connolly *et al.* 2012). Additionally, it is likely that changes in flow negatively affect estuarine fishery production (Robins *et al.* 2005). Such impacts on ecosystems and biodiversity are substantial, not readily mitigated and likely to be exacerbated by further water resource development. Flow management needs to incorporate natural variability because high and low values of variables are usually more important than averages as they have the greatest influence on hydrology, geomorphology and the biota, while changes in averages are less concerning, especially in this highly variable system (e.g., Brizga *et al.* 2006; Naiman *et al.* 2008). We note that current dams do not encompass environmental flows (i.e., supplements or reductions to mirror the natural hydrograph) or fish passage devices to maintain connectivity.

Climate

Climate change presents increasing risk of further environmental degradation (Australian Academy of Science 2021) and predicting its effects on freshwater ecosystems requires understanding of the interactions between ecological and hydrological processes at different scales (Davis *et al.* 2017; John *et al.* 2021). Coastal wetlands are likely to be subject to the combined effects of changing sea level, temperature and hydrology (Grieger *et al.* 2020). The NRM Management Plan (NQ Dry Tropics 2016a) recognises the threat of climate change to agriculture and biodiversity and aims to protect habitat refugia. While the effects of climate on regional flow regimes is uncertain, Barbarossa *et al.* (2021) have estimated a loss of 15% of fish species from the Burdekin River with a 3.2°C increase in global temperature (cf. >50% for some Australian tropical systems). James *et al.* (2017) predict that climate change will extirpate many species in the Burdekin catchment, including fish, crayfish and turtles. Future development proposals need to address possible impacts on climate. For example, wetlands have a role in regulating the global climate (Nahlik and Fennessy 2016) and are important stores of carbon in the GBR catchment (Costa *et al.* 2021). Conversely, tropical reservoirs release methane, offsetting the low-carbon benefits of hydropower (Kemenes *et al.* 2007), and may lead to large outputs of CO_2 (Calamita *et al.* 2021).

5. Proposals for further development

The Australian Government's (2015) White Paper on developing the north highlights the unique ecological values of the rangelands ("the largest intact tropical savanna in the world") and identifies key threats as fire, climate change, coastal development, feral animals, overgrazing, fishing, weeds, land clearing and water quality. An additional threat is loss of Indigenous values and cultural heritage. All are relevant to proposed water resource developments, especially dams, in the Burdekin catchment. These proposals, intended to support agricultural expansion, within the framework of the Water Plan (Burdekin Basin) (Queensland Government 2007), have long been mooted, with substantial public funding to investigate proposals. Current proposals are the 2110-GL Hells Gates Dam on the Burdekin River (SMEC, 2018), the 970-GL Urannah Dam on the Broken River (Queensland Government 2021a), raising the current Burdekin Falls Dam (Queensland Government 2021b) and the 10-GL Big Rocks

Weir near Charters Towers (Queensland Government 2021c) (Fig. 1). Raising of the Burdekin Falls Dam is the most cost-effective development in the whole of northern Australia (Petherham *et al.* 2018), although it may exacerbate current environmental issues (Brizga *et al.* 2006). Nevertheless, other proposals are being strongly promoted. The Hells Gate, Urannah and Big Rocks impoundments would affect extensive sections of the Broken, Bowen and upper-middle Burdekin rivers. These proposals present high risk of substantial degradation of habitats and ecological processes, including migrations by freshwater fish (Burrows 1999; Brizga *et al.* 2006) and coastal fishery production, and may affect sediment transport (Burrows 1999; Wolanski and Hopper 2022).

Further possible developments include extraction of coal seam gas in the southern part of the Burdekin catchment, and water abstraction from the Suttor River for use in the development of coal mining. Both have likely substantial negative local consequences for water flows and quality (and global climate effects), and while the coal-seam gas industry claims that it would have lower impact than agriculture (Zammit and Lee 2015), it would be an additional rather than alternative use.

6. Management and research for mitigation and conservation

Governance and management of a catchment is usually under the auspices of several government departments and agencies, the goals of which may differ and compete. There is a complex of regulations and plans relevant to water management, environmental protection and native title (NQ Dry Tropics 2016b; Queensland Government 2007, 2017). Improvements in land management are promoted and facilitated by the NRM board, which has a whole-of-system approach to land and water management, and is successful in forming partnerships with funding bodies, stakeholders and researchers (NQ Dry Tropics 2016a,b; 2021). The NRM Management Plan (NQ Dry Tropics 2016a) aims to sustain biodiversity, manage invasive species, manage environmental flows for ecosystem health, encourage best land-management practices to reduce nutrient and sediment loads to the GBR, and repair damaged ecosystems, in keeping with the Reef Water Quality Protection Plan and Reef 2050 Plan targets (NQ Dry Tropics 2016b), including reductions in fine sediment, dissolved inorganic nitrogen, particulate nitrogen and herbicides. Adoption by industry of best-practice guidelines has been slow (GBRMPA 2019), with mixed success in restoration of wetlands (Waltham *et al.* 2019).

An early example of the challenges of conflicting agendas of water resource development and conservation management was in the development of the current Burdekin-Haughton Water Supply Scheme. Recommendations to retain riparian vegetation along Barratta Creek, which drained much of the floodplain, were adopted, providing continuous vegetation from source to mouth (Pearson and Thomas 1993). The retention of such significant areas of remnant floodplain habitat in a catchment-to-coast corridor was unprecedented for a government-funded irrigation scheme in Australia. The conservation values remain high, especially given the great loss of such habitat to development on Queensland's east coast (Tait and Veitch 2007). Nevertheless, this apparently holistic approach did not include management of hydrology and water quality, as large volumes of irrigation tailwater are now discharged with apparently little consideration of the effects of tailwater quantity and quality on receiving wetlands, contemporaneously listed as of international importance under the Ramsar Convention. There have been consequential changes to local water tables, stream flows, and water quality (Davis *et al.* 2014), while active management has apparently been limited. Conversely, another floodplain waterway, Sheep Station Creek, which is used as an irrigation distributary of water pumped from the Burdekin River, has been the subject of intensive management of weeds in its large waterholes, and installation of fishways, leading to successful fish rehabilitation over 15 years (Perna *et al.* 2012; Waltham *et al.* 2020a), but requiring continuous mitigation works to sustain ecological values.

The current environmental impact statement (EIS) process, required for new projects, is illustrated by the terms of reference for the Urannah Dam proposal (Queensland Government 2021a). The objectives include assessment of environmental, social and economic impact of the project within the regional and local infrastructure context, and refer specifically to environmental flow objectives, terrestrial impacts, crops to be irrigated, resultant water quality, and long-term protection of aquatic biodiversity and connectivity. The context includes possible cumulative impacts and the need for holistic appraisal, which were not addressed in development of the Burdekin Falls Dam (Day 1989; Moon 1998). However, it is uncertain how these broad-scale issues might be addressed when different practitioners are separately commissioned for studies on individual proposals.

Current conservation status

The Queensland Government increasingly recognises the importance of fresh waters (Queensland Government 2021d) but protected area management is mainly focused on terrestrial and marine systems, with limited explicit conservation of river sections, as elsewhere (Stein and Nevill, 2011; Nogueira *et al.* 2021). Incidental protection may occur in land-based reserves, such as in the Wet Tropics bioregion, a large proportion of which is in the Wet Tropics World Heritage Area, but even there, protection of freshwater habitats is limited (Januchowski-Hartley *et al.* 2011). Some protection to wetlands is afforded by the Bowling Green Bay Ramsar area and declared fish habitats (Connolly *et al.* 2011). The limited extent of protected areas fails to capture the full diversity of freshwater/estuarine environments (Fig. 4). Implicit protection may apply through regulations on water quality or species protection, but may be ineffective – for example, for nesting turtles downstream of the Burdekin Falls Dam. More explicit conservation, especially of rivers, is warranted (Pearson *et al.* 2021) and, given the current extensive development, could be applied to different extents to specified sections (Linke *et al.* 2019). For example, the upper-middle Burdekin river is largely in good condition and warrants special protection, while for the river downstream of the Burdekin Falls Dam, which has been greatly modified, urgent protection of remaining habitat, connectivity and biodiversity values is warranted. A conservation management plan for the whole river and floodplain is required (GBRMPA 2013) to protect against further damage (Reside *et al.* 2017), mitigate predicted species losses (James *et al.* 2017) and rehabilitate damaged systems (Burrows and Butler 2007) from catchment to coast (Waterhouse *et al.* 2016a).

A typology

A first step towards broad-scale conservation is a classification or typology to provide the basis for management of a practicable number of management units. Butler *et al.* (2009) introduced a bottom-up typology for assessment of site-based water quality and ecological processes in the Burdekin River, but in the absence of comprehensive data, a top-down approach may be more tractable for broad conservation zoning. This can involve statistical classification of management units (e.g., Olden *et al.* 2021) but this approach requires substantial data input, which is limited for the Burdekin catchment. Alternatively, generic typologies (e.g., Parsons *et al.* 2004; The Aquatic Ecosystems Task Group 2012) can be adapted as required. In the Burdekin system, a typology would include riverine, estuarine and floodplain habitats, enhanced by land-use and ecological information (Table 3).

Table 3. A simple typology for delineating management zones and linked biotic assemblages in the Burdekin River

"Lentic" division includes floodplain wetlands. Categories within tertiary division to be determined from empirical data – e.g. stream size, conductivity/salinity, vegetation cover. Modifiers and responders may apply to conservation categories (see text)

Primary division	Secondary division	Tertiary division	Potential modifiers and responders
Riverine	Stream size	Headwater, upper river, middle river, lower river, estuary	Modifiers ▪ Catchment – natural, grazing, agriculture etc. ▪ Flow supplemented, reduced or natural ▪ Water quality: suspended sediment, N, P, dissolved oxygen, pesticides ▪ Point source pollution ▪ Riparian integrity ▪ Protection status (national parks, reserves etc. ▪ Invasive weeds ▪ Exotic/translocated animals Responders ▪ Ecological processes: productivity, food webs ▪ Representativeness ▪ Phytoplankton ▪ Macrophytes ▪ Invertebrates ▪ Vertebrates ▪ Endemic species
	Gradient	Steep or shallow	
	Lithology	Basalt, granite or alluvium	
	Substrate	Rock, cobble, sand or silt	
	Flow regime	Perennial, intermittent or interrupted	
		Supplemented or impounded	
		Connectivity/barriers	
	Freshwater	Conductivity	
	Brackish water	Salinity	
	Vegetation	Catchment, riparian & aquatic	
Lentic	Water regime	Permanent or intermittent	
	Area		
	Open water area		
	Depth		
	Connectivity	Occasional or permanent	
	Freshwater	Conductivity	
	Brackish	Salinity	
	Vegetation	Floating, emergent, submerged	

7. Conclusion

In the Burdekin River, there is opportunity to protect against further impact on rivers and wetlands and avoid the mistakes of the past, which have caused loss of ecological values and continuing expensive mitigation. We support the principles of integrated catchment management, adopted in Queensland in 1990, including explicit policy for ecosystem sustainability (Thoms and Sheldon 2000; Davis *et al.* 2014). To be effective, such a framework requires whole-of-catchment consideration of development, as evident in contemporary EIS requirements. It also needs more systematic information gathering and adaptive management, allowing for trade-offs between environmental, economic and social outcomes (Productivity Commission 2021). Governance by a body with jurisdictional authority (which NRMs do not have) is required, especially because of the wide range of relevant regulations and stakeholders (NQ Dry Tropics 2016b; Queensland Government 2007, 2017). Catchments within states should not have the transboundary problems that have beset the Murray-Darling Management Authority (Beasley 2021; Chen *et al.* 2021; Colloff *et al.* 2021).

We advocate holistic conservation categorisation or zoning of systems to protect remaining values while balancing competing demands (Pusey *et al.* 2020), with the major goal of ecological sustainability. It would be wise to broadly apply the precautionary principle in the management of the river and its resources, given its conservation values and the potential impacts of future development and climate change. Our proposed process requires an appropriate plan adopted prior to further development (Productivity Commission 2021). Although the Burdekin basin is notable for its diverse habitats and biota, this is not unusual for a large river or perhaps any stream (Hynes 1975; Poole 2002). However, we suggest that all river sections or wetland sites should be given protection levels commensurate with their explicit values, coordinated appropriately to alleviate future negative change (Finlayson *et al.* 2019). We therefore present this case study as a precursor to developing an approach to assist in this process, as a model for rivers generally, especially those with limited information availability (Pearson *et al.* 2022).

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