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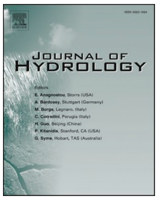

Research papers

Australian non-perennial rivers: Global lessons and research opportunities

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ABSTRACT

Non-perennial rivers are valuable water resources that support millions of humans globally, as well as unique riparian ecosystems. In Australia, the Earth's driest inhabited continent, over 70% of rivers are non-perennial due to a combination of ancient landscape, dry climates, highly variable rainfall regimes, and human interventions that have altered riverine environments. Here, we review Australian non-perennial river research incorporating geomorphology, hydrology, biogeochemistry, ecology, and Indigenous knowledges. The dominant research themes in Australia were drought, floods, salinity, dryland ecology, and water management. Future research will likely follow these themes but must address emerging threats to river systems due to climate change and other anthropogenic impacts. Four high level opportunities for future research are identified, namely: (1) integrating Indigenous and western scientific knowledge; (2) quantifying climate change impacts on hydrological and biological function; (3) clarifying the meaning and measurement of "restoration" of non-perennial systems; and (4) understanding the role of groundwater. These challenges will require inter- and multi-disciplinary efforts supported by technological advances. The evolving body of knowledge about Australian rivers provides a foundation for comparison with other dryland areas globally where recognition of the importance of non-perennial rivers is expanding.

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1. Introduction

The term non-perennial includes ephemeral rivers that flow only for a short time after rainfall events and intermittent rivers that regularly cease to flow for a period of time, leaving behind dry riverbeds and residual water bodies, variably named waterholes (Silcock, 2009; Wallace et al., 2016), lakes (Puckridge et al., 2000; Reid and Puckridge, 1990), pools (Bourke et al., 2020; Lamontagne et al., 2021a; Zhou and Cartwright, 2021), springs (Carey et al., 2021; Chester and Robson, 2011) or billabongs (Hillman, 1986; Hillman and Quinn, 2002). Non-perennial rivers are widespread and diverse features of landscapes across the globe (Shanafield et al., 2021; Stubbington et al., 2017) and are common rather than an exception (Messager et al., 2021). The proportion of non-perennial rivers is increasing as rivers shift from perennial flows due to widespread climate change impacts on temperature and precipitation, surface water use, and groundwater extraction (Datry et al., 2017; Messager et al., 2021).

Although non-perennial rivers exist all over the world (Shanafield et al., 2021), they are especially prevalent in regions with dry climates. In Australia, a combination of ancient geology and dry climate has led to 2.5 million kilometres of non-perennial rivers, which constitutes over 70 % of the country's river network (Bishop-Taylor et al., 2015; Sheldon et al., 2010). These non-perennial rivers span a wide range of climates, including tropical, temperate, alpine, and arid (Fig. 1). There is also an important link between the physical condition, riparian ecosystem, and cultural importance of non-perennials river in Australia, as Australia is home to the longest documented continuous culture in the world, with Indigenous Peoples present for at least 65,000 years (Clarkson et al., 2017). Non-perennial rivers provide drinking water, food resources, places of connection to Country, and are integral to spiritual and creation stories (also referred to as 'songlines' or 'song cycle paths'), where rivers are considered as ancestral being with a right to life (Hartwig et al., 2021; Jackson et al., 2014; Moggridge, 2020; Steward et al., 2012).

Australian non-perennial rivers support large sections of Australia's agricultural and livestock industries, with over $7 billion in irrigated produce in Australia's largest river basin, the Murray Darling River Basin; (Murray Darling Basin Authority (MDBA), 2016). Prior to river regulation, the Murray River itself was non-perennial and many of the tributaries, are currently non-perennial. Protected non-perennial headwaters, often in forested catchments, are also critical water supply catchments to Australia's major cities. Thus, the economic success and food security of Australia is intimately tied to the condition of non-perennial rivers. Australian non-perennial rivers are also important to tourism-based economies in many regions and underpin environmental values, providing surface water and hydrological regimes that support endemic flora and fauna (Chester et al., 2015; Romaní et al., 2017).

Given this disproportionate importance of non-perennial rivers to Australian society, Australian scientists have a long history of pioneering research to understand many aspects of the country's non-perennial river systems (Boulton and Suter, 1986). This research has broadened the global scientific understanding of non-perennial rivers, in particular bringing attention to hydrologic and geomorphic processes in arid zone rivers, the impacts of land clearing on river salinisation, and the links between the wetting and drying cycle and ecosystem function (e.g. Tooth, 2000; Herczeg et al., 2001; Puckridge et al., 1998). There is a

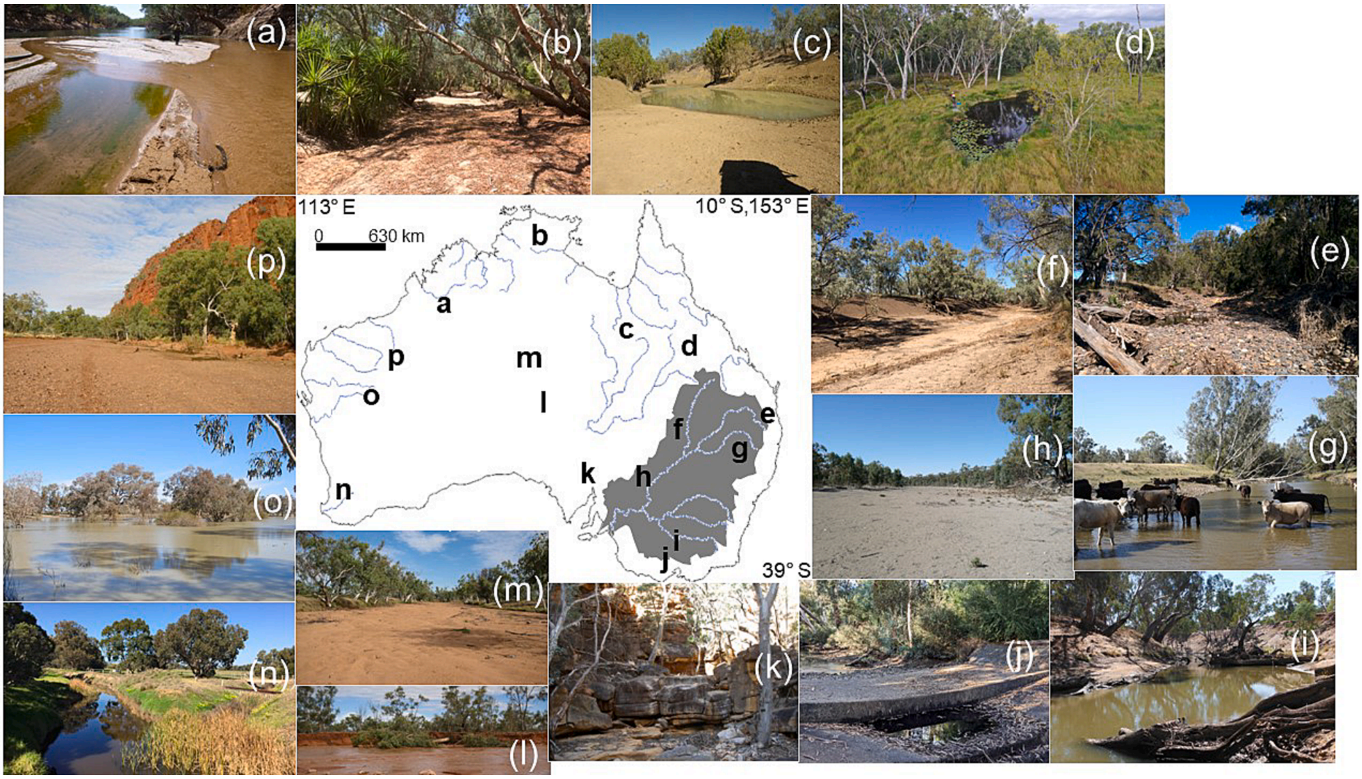

Fig. 1. Non-perennial rivers (shown as blue lines in the centre map) dominate surface water movement across the Australian continent, covering a diversity of climate, geologic, and anthropogenic regimens. Photos here highlight the natural variations in flow, vegetation, and structure of these systems, as well as the increasing human pressure / modifications found particularly in the southeast of the continent (Murray-Darling Basin: f-i). Photos are: a) Fitzroy River (photo: Leah Beasley), b) Magela Creek (photo: Clement Duvert), c) Flinders River (photo: Nathan Waltham), d) Wetland, Bimbah Creek, Doongmabulla Springs Complex, Qld (photo: Eddie Banks), e) Wild Cattle Creek (photo: Ryan Burrows), f) Warrego River (photo: Tim Ralph), g) Maules Creek (photo: Gabriel C. Rau), h) Darling River (photo: Tim Ralph), i) Campaspe River (photo: Nicholas White), j) Loddon River (photo: Kiernan Fowler), k) Edeowie Creek (photo: Jordan Iles), l) Finke River (photo: Eddie Banks), m) Woodforde River (photo: Margaret Shanafield), n) Harvey River (photo: Naomi Wells), o) Bilyuin Pool (photo: Jordan Iles), and, p) Coondiner Creek (photo: Jordan Iles). Sites e, f, h, g, i, and j fall in the Murray-Darling Basin (grey shaded area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

growing body of research on the impacts of drought and the wealth of Indigenous knowledge of river processes. With the current global surge in non-perennial river systems research (Busch et al., 2020), this knowledge provides a rich backdrop to inform current and future multidisciplinary global research on non-perennial rivers.

The objective of this work is to shed light on the accumulated knowledge and areas of uncertainty stemming from extensive research on Australian non-perennial rivers across various scientific disciplines. We commence by elucidating the climatic, geological, and human factors that have not only shaped the landscape but continue to dictate flow patterns. Leveraging a substantial body of scientific literature, we provide concise overviews of pertinent aspects such as hydrology, hydrogeology, ecology, geochemistry, and human impacts on our rivers (although we do not include specific discussion on the impacts of and opportunities for policy, which requires a full analysis on its own). Furthermore, we pinpoint the current gaps in our understanding of river systems and propose priorities for future research and management concerning Australia's non-perennial rivers. It is worth noting that analogous river systems exist worldwide in regions with similar climates and geology. Readers from beyond Australia will find both divergent and convergent aspects in our research and knowledge gaps, offering valuable insights into non-perennial rivers in their own regions.

2. Factors that have shaped Australia's non-perennial rivers

2.1. *An ancient landscape*

Much of the Australian continent has remained tectonically stable since before the breakup of Gondwana more than 150 million years ago, resulting in a deeply weathered low-relief landscape. The climatic trend from wet to arid during the last 66 million years set the scene for non-perennial rivers in the Australian landmass (Habeck-Fardy and Nanson, 2014), in line with general global cooling and drying and Australia's northward drift (Cohen et al., 2011; Wray, 2009). Most of the continent was not glaciated in recent geologic history, which resulted in preservation of the deep regolith. Weathering blanketed the landscape in fine sediments, hard duricrusts, and soft saprolite (Anand, 2005), in places increasing runoff and reducing the infiltration capacity of the soils (Dunkerley, 2011; Wakelin-King, 2022). High evapotranspiration rates and ions leached from weathering profiles resulted in many areas developing saline soil and groundwater (Allison et al., 1990). Where high salinity occurs, the landscapes are highly susceptible to changes in vegetation and land use, as the associated changes to the water balance may mobilise the salt to the surface or into waterways (Lambers, 2003).

Now, around 92 % by length of Australian river channels occur in lowland areas and ∼ 75 % of those regions are semi-arid or arid (Sheldon et al., 2010). Low-relief rivers are often characterised by very low hydraulic gradients (Habeck-Fardy and Nanson, 2014; Knighton and Nanson, 2000), predisposing them to low-energy flows and high transmission losses. Flood pulses may travel long distances, but the combination of topography, variable rainfall (see Section 2.2), and high evaporation rates prevent many streams and rivers from reaching the sea. Instead, they terminate inland in floodouts (*sensu* Tooth, 2000) or ephemeral lakes. Tectonism has further contributed to Australia's wealth of internally-draining catchments. For example, in the Western Plateau, which occupies the western half of the Australian continent, uplift and tilting reorganised the river systems. Catchments that once flowed to the ocean are now ephemeral rivers and chains of infrequently connected playa lakes. In contrast, steep, non-perennial waterways are found in the higher topography regions of Australia's less arid east coast.

These geo-hydrological processes created the iconic Australian riverine landscapes (Fig. 2). The diversity of non-perennial inland waters includes low-angle alluvial fans with distributive drainage networks, anabranching and anastomosing channels, and a variety of water-retaining landforms such as waterholes, lakes, and billabongs (Gibling et al., n.d.; Morón and Amos, 2018). Modern non-perennial systems also occupy the footprint of landforms from previous wetter climates, such as flat plains and lunettes where there were once lakes (Bowler and Magee, 1978), palaeo-river valleys now inhabited by elongate saline playas (Mernagh, 2013) or by small sinuous channels and chains-of-ponds (Hesse et al., 2018; Mould and Fryirs, 2017). In summary, the ancient Australian geology and landscape has led directly to the predominance of non-perennial rivers across the continent.

2.2. *A variable climate*

Australia is a large island, and the climate is strongly influenced by the surrounding oceans. Specifically, the El Niño–Southern Oscillation (ENSO); an irregular periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, the Indian Ocean Dipole (IOD); an irregular oscillation of sea surface temperatures within the Indian Ocean, and the Southern Annular Mode (SAM); the non-seasonal north–south movement of the strong westerly winds that blow almost continuously in the mid- to high-latitudes of the southern hemisphere all play a role in shaping weather patterns across Australia (Bureau of Meteorology, 2022). Over 75 % of Australia is considered arid or semi-arid (Peel et al., 2007) (Fig. 3). However, the interplay between monsoons, tropical depressions, cyclones, trade winds, and westward-moving marine fronts produces a continent that is tropical and subtropical to the north and northeast and temperate to the south and southeast. Most of the continent is hot and dry, especially inland and in the west. The continent's climatic diversity has led to a wide diversity of flow regimes, which are discussed in more detail in Section 3.1.

Annual rainfall varies greatly across most of the continent (Van Etten, 2009), from greater than 2000 mm/yr in isolated mountain pockets along the east coast and in Tasmania and narrow strips of the tropical northern coast, dropping to less than 600 mm/yr 100 km inland, and ultimately to less than 250 mm/yr in the interior. While rainfall in the tropical north is summer dominated (monsoon) and winter dominated in the south, inland rainfall is unpredictable and episodic. Overall, northern Australia has more variability in annual rainfall than southern Australia, and though it has been stated that Australian deserts have greater rainfall variability than elsewhere in the world, they are relatively on par with low-latitudes, summer-dominated regions in other parts of the world (Van Etten, 2009).

Across the country, individual rain events range from ineffective showers to heavy falls that may deliver the annual average (e.g., 200–300 mm) over days to weeks (Acworth et al., 2021; Trewin, 2006). Since 1950, extreme rainfall events over Australia have intensified in general (Contractor et al., 2018). However, due to small-scale rainfall processes (e.g., convective cells), rainfall spatial distributions are commonly heterogeneous even across smaller catchments (Cuthbert et al., 2016). Parts of Australia regularly experience alternating flood and drought, often linked to the ENSO and the IOD (McMahon et al., 2008). Tropical cyclones and ex-tropical low-pressure systems contribute to this high inter-annual rainfall variability, disproportionately driving groundwater recharge, extreme runoff events, and vegetation growth (McGrath et al., 2012; Skrzypek et al., 2019). As few Australian rivers have long-term streamflow data, this high inter-annual variability also complicates river classification, which is usually done based on flow persistence (Verdon-Kidd et al., 2023).

Droughts are common and affect large parts of the continent. For instance, the 'Millennium Drought' lasted from the late 1990 s until 2009 and affected over half a million square kilometres of south-eastern Australia (Van Dijk et al., 2013). During the drought, even Australia's largest river basin, the Murray-Darling, experienced prolonged dry periods (Leblanc et al., 2009). The drought also overlapped with a multi-decade reduction in the occurrence of tropical cyclones crossing north-west and central Australia (McGrath et al., 2012).

The prevalence of non-perennial rivers across Australia is not only due to variable rainfall, but also high potential evapotranspiration rates and the strong seasonality of both (Fig. 3). Potential evaporation is

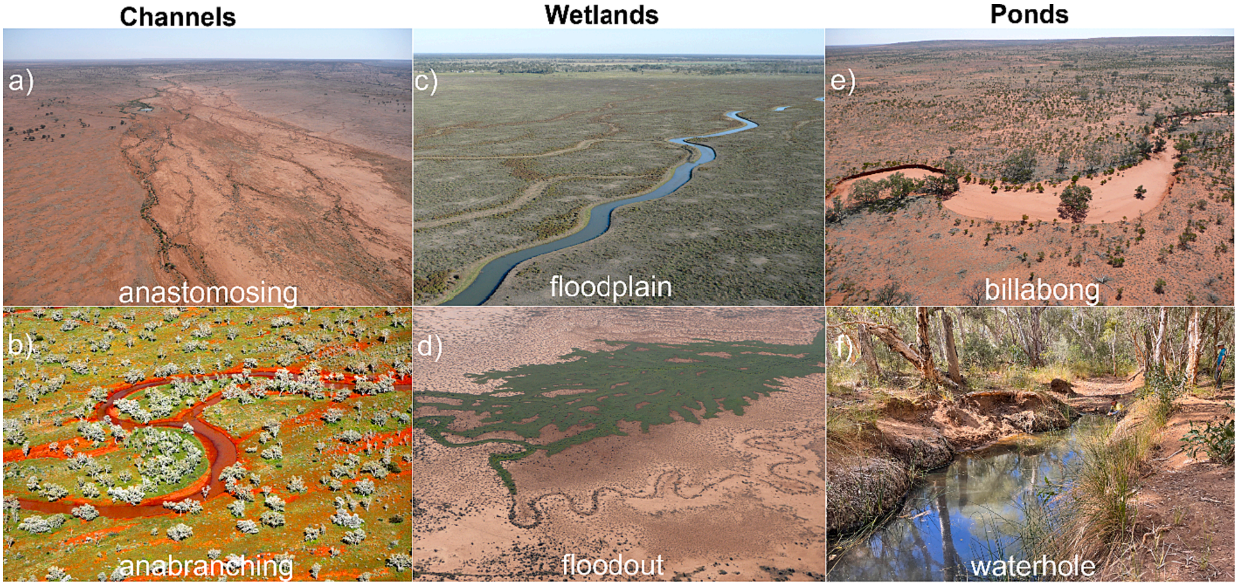

Fig. 2. The low-relief, ancient Australian non-perennial river landscapes create distinctive channels (a, b) and water-retaining (c-f) features. Highlighted here are, a) anastomosing channels of Byers Creek, NSW (photo: Tim Ralph), b) anabranching channels in the Fortescue River, WA (photo: Alexandra Rouillard), c) extensive floodplain wetlands like the Macquarie Marshes, NSW (photo: Tim Ralph), d) floodouts like Acacia Creek, NSW (photo: Tim Ralph), e) billabong lakes formed in disconnected anabranch channels (unnamed feature near Peery Lake, NSW; photo: Tim Ralph), and, f) persistent waterhole in the otherwise dry Beasley River, WA. (photo: Eva Pellegrini).

generally far greater than rainfall (Trewin, 2006), and average annual pan evaporation across the continent is 2000 mm or greater, rising to more than 4000 mm in north central Western Australia (Australian Bureau of Meteorology, 2008). Transpiration rates from the native eucalyptus forests are higher than many other vegetation types (Zolfaghar et al., 2017). In cases where the seasonality of rainfall is out of phase with that of evapotranspiration, this creates highly variable flow regimes (Kennard et al., 2010; Potter et al., 2005). For example, in the south, winter rainfall replenishes many small river systems, which then dry in late spring-summer when precipitation is low and evapotranspiration is high. In the north, more than 90 % of total annual rainfall occurs during summer months, and river channels dry during winter, or exist as a series of isolated waterholes that provide the last remaining refuges for many aquatic species (McJannet et al., 2014; Wallace et al., 2016).

2.3. Human-river relationships

2.3.1. Indigenous relationships

To Australia's Indigenous Peoples, rivers are more than just their physical components; rivers can be considered living beings (RiverOfLife et al., 2020), are significant spiritually and socially, and are integral in shaping human existence and identity (Langton, 2006). This stems from an understanding that not only is water key to survival and a source of life and resources, particularly in arid environments, but that it plays important roles in spiritual and cultural life (Moggridge and Thompson, 2021). In this way, rivers have shaped human communities in providing places of family and community connection, as important food sources, areas to swim, highways for trade, and sites of cultural significance for burials, birthing places and scar trees (Duncan, 2011), with each community uniquely shaped by their local river (Jackson and Barber, 2016; Toussaint, 2008). Conversely, Indigenous connections to rivers also come from shaping riverine environments; that is, the lived experiences of water management that existed pre-colonisation, such as Indigenous damming practices, wetland management and riparian management using fire. In northern Australia, where there are many Indigenous groups that still rely on rivers for sustenance, these experiences continue to shape Indigenous perspectives on water resource development in contemporary contexts as well as Indigenous land management practices (Langton, 2006; Pyke et al., 2021).

Many Indigenous Australian communities and management practices have been irrevocably disrupted by colonisation, resulting in loss of land with river access severely constrained and often exclusion from water resource management (Hartwig et al., 2021). Many groups have been affected by declines in fish and shellfish or concerns over contamination (Noble et al., 2016). Despite these challenges, Indigenous Peoples still maintain strong connections to their rivers, waterholes, and other water features on the land (RiverOfLife et al., 2020; Toussaint et al., 2005). The overarching viewpoint for many Australian communities living with non-perennial streams, is that water, culture, and livelihood cannot be separated (Altman and Branchut, 2018).

Waterholes are important features of non-perennial rivers and hold particular significance to Australia's Indigenous Peoples; knowledge of their locations was key to survival in hot arid conditions (Tolcher, 1986). Each language group has specific creation stories detailing ancestral beings' movement through the landscape creating river channels and springs and explaining connectivity between rain, rivers, billabongs, groundwater and the sea as water moves through the landscape (Weir, 2009). Water quality is also an extremely important part of cultural lore (law). In particular, swimming is discouraged at particular waterholes or springs to maintain drinking water quality; for example, through stories of spirits or serpents that would prey on swimmers (Moggridge, 2020). Water quality in wetlands was improved and managed through management of flow to prolong water movement during the dry season, fire management of riparian zones, and in some cases removal of excessive vegetation in-stream (Pyke et al., 2021).

Indigenous Peoples have histories of active management and shaping of landscapes to enhance aquatic resources. On the River Murray floodplain in south-eastern Australia, the Barapa people lived in wetland villages on mounds on the edges of small riverine and wetland channels. Mounds were formed over generations by piling clay onto existing mounds for cooking. At the base of such mounds, excavated pools retained water after a flow event into the dry season after water levels had dropped. These would have enhanced local aquatic productivity supporting juvenile and small-bodied fish, macroinvertebrates, and waterbirds, and are thought to have involved the use of weirs to harvest

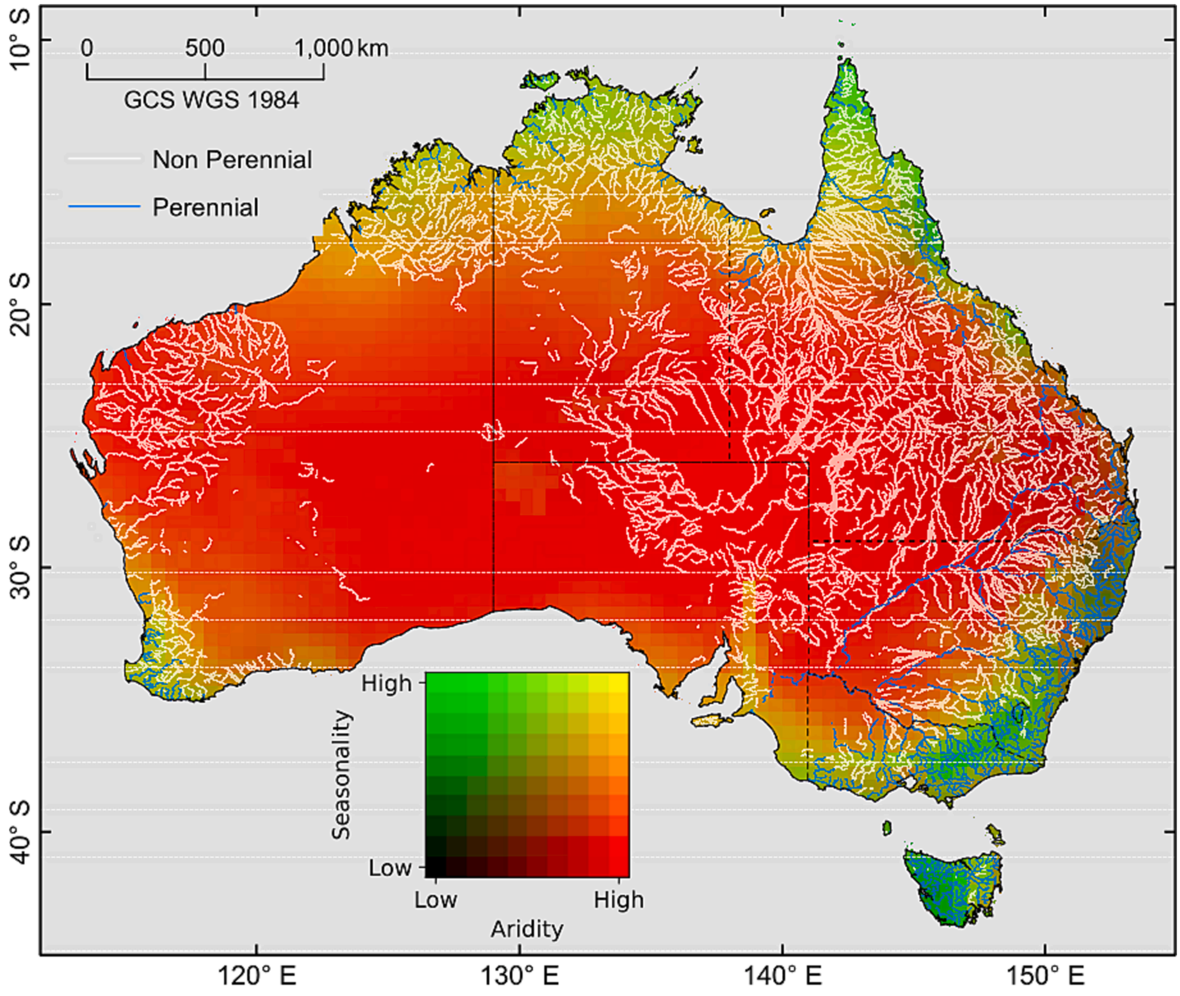

Fig. 3. Map of Australia showing perennial and non-perennial rivers (Geofabric Surface Network by the Australian Bureau of Meteorology; BoM, 2022) on top of the hydroclimate, which is a composite index that merges information on aridity, seasonality, and precipitation as snow (Knoben et al., 2018). The latter is insignificant for Australia and was therefore discarded. River perenniality is from Geoscience Australia's Aushydro database, was last updated in 1988, and is acknowledged to be imperfect.

fish from these ponds (Pardoe and Hutton, 2020).

Another example of aquatic resource management in non-perennial rivers is Biame's Ngunnu, or the Brewarrina Fish Traps, on the Barwon (Darling) River in northern New South Wales. The traps were made by Ngemba people to withstand floods and were shared between multiple tribal groups (DCCEEW, 2021). At Budj Bim, a World Heritage listed site created by the Gunditjmara people at Lake Condah, Victoria, a series of constructed channels and shallow artificial wetlands in an extensive aquaculture system was used to grow eels and other fish for extensive periods over the past 30,000 years (Jackson, 2022). The above examples highlight that in Australia, Indigenous Peoples actively managed, and significantly altered, aquatic ecosystems through their practices as well as their use of resources yet maintained these ecosystems as healthy and highly productive (Balme, 1995; Humphries, 2007).

2.3.2. *Colonial human influences*

Large-scale changes to river shape, flow and water quality have occurred over the past 200 years (Barmuta, 2010). Widespread change in land use has perhaps had the greatest impact on Australian hydrogeology. The clearing of deep-rooted native vegetation for agriculture has caused widespread secondary salinisation in Australia (Allison et al., 1990; Cartwright et al., 2007; Hart et al., 2020). Lowered evapotranspirational demand following vegetation removal led to a rise in the water table, mobilising saline groundwater and soil water (Clarke et al., 2002). For example, more than 65 % of the 30 largest rivers in southwestern Australia are now brackish or saline (Mayer et al., 2005). Ecological impacts of secondary salinisation include the loss of invertebrates and plants (Halse et al., 2003; Nielsen et al., 2003) as well as altered fish assemblages (Beatty et al., 2011; Morgan et al., 1998). The rise in the water table also locally increased the amount and duration of flow in some rivers (Allison et al., 1990).

Decreased vegetation cover due to grazing or clearing, coupled with development of infrastructure (e.g., stock routes and earth dams) also changed the physical character of hillslopes and valleys (Grant, 1994; Muñoz-Robles et al., 2010; Page et al., 2007). Greater volumes and velocity of overland flow triggered erosion, gullying and valley-floor incision (Fanning, 1999), decoupling channels from floodplains and reducing or destroying floodplain productivity and biodiversity (Pringle et al., 2006; Ralph et al., 2012). Vegetation removal also resulted in higher erosion rates that increased sediment loads to rivers (Reid et al., 2007), forming 'sand slugs' that move slowly downstream smothering woody debris, infilling pools, or blocking the river channel (Lind et al., 2009; Prosser et al., 2001). In the Murray Darling Basin (Fig. 1g-i), mathematical modelling estimates that more than 60 % of the river network now experiences more than 20 times the pre-clearing suspended sediment loads (DeRose et al., 2003). Furthermore, a recent study of the Darling-Baarka River indicates that waterholes have shallowed on average by 1.6 m since the late 19th century as a result of sediment accumulation (Pearson et al., 2020). Sediment inputs have also caused many riverine wetlands to shift from clearwater states dominated by macrophytes to turbid states dominated by plankton (Gell and Reid, 2016).

Most Australian rivers are now regulated. Barriers range in size from large reservoirs on major watercourses to hundreds of small farm dams in a single catchment (Stewardson et al., 2017). These flow barriers have disrupted important ecological processes and altered biotic assemblages by preventing flooding of wetlands, changing aquatic vegetation, and reducing populations of birds, fish and invertebrates (Kingsford, 2000; Walker, 1985). One exception to this rule are the ephemeral rivers in the centre of the continent, which only flow following substantial periods of intense rainfall, and are still deemed too challenging and costly to control (Petheram et al., 2008; Warfe et al., 2011).

The development of groundwater resources, especially for irrigated agriculture has also lowered groundwater levels in some catchments and reduced the volume and duration of baseflow to intermittent streams. One such example is reaches of the Namoi River in the Murray Darling Basin where it was demonstrated that groundwater levels decreased below surface water levels due to groundwater drawdown from irrigation (McCallum et al., 2013). Thus, baseflow to the river was lost in the mid-1990 s, which in turn likely prolonged periods of no-flow conditions during the Millenium Drought (Gambastiani et al., 2012; McCallum et al., 2013).

3. Current scientific knowledge

3.1. Hydrological cycle

Australian research has identified a wide gradient of flow regimes, how these flows interact with other components of the water budget across different climates, and how the water cycle governs the ecosystems that inhabit these rivers. Rivers within Australia have been categorised into 12 different classes based on flow regimes ranging from ‘perennial’ to ‘highly ephemeral non-perennial rivers’ (those that only flow very rarely) (Kennard et al., 2010). However, as mentioned in Section 2.2, such classification relies on point data from gauging stations, and gauging stations and long-term data for Australian non-perennial rivers are relatively sparse (Krabbenhoft et al., 2022), and often located in pools with permanent water. The flow regimes of Australian arid zone rivers are of particular note, as they experience extreme hydrologic variability compared to rivers at a global scale (Puckridge et al., 1998). Because most of the country has a semi-arid to arid climate, there is an expectation that a large rainfall threshold that must be exceeded must be exceeded to overcome soil moisture deficits and to create surface runoff and flow within non-perennial rivers. However, at the Fowlers Gap arid zone research station in central New South Wales a rather small rainfall threshold of 10–20 mm was enough to generate streamflow (Acworth et al., 2021). The low threshold is hypothesised to be a combination of poor soils combined with high rainfall intensity of run-off generating storms When rainfall thresholds are exceeded, flows are often quite flashy, with rapid rise and fall of surface water levels. During flow events, water infiltration into the subsurface occurs vertically at time scales of days to weeks, and groundwater flow continues transversally for weeks to months and parallel to the stream for years to decades (Cuthbert et al., 2016). Flashy surface flow is followed by a prolonged period of pooled surface water, while the groundwater level slowly recedes, creating a generic sequence of hydrological regimes unique to non-perennial streams (Rau et al., 2017). Sediment heterogeneity significantly controls the exchange between surface and groundwater (McCallum et al., 2014).

As heavy rainfall events have become more intense since the 1970 s in northern Australia (Ayat et al., 2022; Dowdy, 2020), increasing trends in annual streamflow have also been documented in this part of the country (Zhang et al., 2016). In contrast, many non-perennial rivers in southern Australia have experienced increasing trends in the number of no-flow days (Sauquet et al., 2021). This trend may be reflective of the fact that although the largest floods are sensitive to increases in extreme rainfall intensity, the number of smaller floods are reduced by declining trends in soil moisture (e.g., Wasko et al., 2020). There are also lags in the recovery of river baseflow after multi-year drought for at least some non-perennial rivers (Peterson et al., 2021), possibly indicative of the complexity of relationships between precipitation and shallow groundwater. In southwestern Australia, researchers have found that a 9 % annual reduction in rainfall between 1975 and 2000 and 2000–2012 has contributed to a 51 % reduction in mean annual streamflow (McFarlane et al., 2020). Thus many perennial rivers in the southwest have transitioned to intermittency, and non-perennial rivers have in places disconnected from groundwater, significantly altering total flows and stream chemistry (Kinal and Stoneman, 2012; Petrone et al., 2010). In addition, similar trends have also been observed in eastern Australia after the Millenium Drought (Peterson et al., 2021). For example, in south-east Australia, a year of average rainfall after the multi-year Millennium Drought delivered less streamflow than it did before the drought (Saft et al., 2015), suggesting that in at least some Australian rivers intermittency is increasing and the relative contributions of various hydrological processes to streamflow are changing. A combination of vegetation dynamics, groundwater processes, meteorological forcing and human factors is causing these shifts; the relative contribution of these factors is uncertain (Fowler et al., 2022).

Once rainfall ceases, the duration of flow recession depends on the storage capacity of adjacent water stores (e.g., floodplains, river banks) and their connection to river channels. Return flow from bank and/or alluvial storage can be a major contributor to extending the flow recession and, potentially, to dry season baseflow (Doble et al., 2012; Harrington et al., 2014; Zhou and Cartwright, 2021). Internationally, flow recession mechanisms and characteristics in non-perennial rivers have received relatively less attention from the scientific community, compared to the onset of flow (Price et al. 2023); this is also true in Australia. Ephemeral rivers, characteristic of arid, inland regions, would be expected to generally cease to flow shortly after rainfall ceases (e.g., Villeneuve et al., 2015), while northern, tropical rivers would have shallower groundwater tables that would sustain baseflows for much of the year. However, this may change as groundwater is impacted by an increasing push for primary industry growth in northern Australia (Duvert et al., 2022). Studies in the Daly River in northern Australia, for example, suggest that increased groundwater extraction will result in greater flow intermittency and reduced longitudinal connectivity (Chan et al., 2012; King et al., 2015).

Once surface flows cease, the presence of persistent pools can be attributed to either slow rates of evaporation (where there is no connection to groundwater), return flow from bank storage and/or throughflow of shallow groundwater, or regional groundwater contributions where the streambed intersects the deeper aquifer (Bourke et al., 2020). In practice, it can be difficult to definitively determine which mechanism supports a given pool. A linear rate of water level decline is common where pool presence is controlled by shallow alluvial groundwater levels (Rau et al., 2017; Yu et al., 2022). These shallow, alluvial freshwater stores can be important to sustaining the riparian corridor (Zhou and Cartwright, 2021). For example, lenses of low-salinity alluvial groundwater that are up to several kilometres wide buffer iconic River Red Gum and Box-Ironbark forests on the floodplain from the surrounding highly saline groundwater (Cartwright et al., 2019; Holland et al., 2006; Meredith et al., 2016). Similar low salinity lenses occur around major non-perennial rivers in arid central Australia (Harrington et al., 2002; Vanderzalm et al., 2011). Several studies have indicated that this shallow groundwater is typically only a few years old, even during zero flow periods where the streams consist of disconnected pools (Barua et al., 2022; Cartwright and Morgenstern, 2016).

While there is an intuitive link between non-perennial streamflow and climate (i.e., water availability on the surface), flow and persistence of surface water is also strongly influenced by the subsurface conditions such as streambed sediment characteristics, antecedent soil moisture, depth to groundwater, topography, and the contributing hillslopes’ capacity to generate runoff (Gutiérrez-Jurado et al., 2019; Tooth, 2000). For example, in the Mediterranean climate-type streams characteristic of coastal South Australia, distinct topographical conditions and soil types contribute to patterns of "fast flow" following a rainfall event and sustained "slow flow" that persist throughout the wet season (Gutierrez-Jurado et al., 2021). Although groundwater storage can buffer both climatic and anthropogenic impacts on stream flows, the slow response time (termed "hydraulic memory") can lead to delayed effects that require consideration (Cuthbert et al., 2019).

Finally, given the absence of permanent surface water across much of the continent (Fig. 2), it is important to recognise the important hydrologic role that non-perennial riverbeds play in recharging deeper regional aquifers. Streambed infiltration is especially important in arid regions (Acworth et al., 2021), and infiltration rates have been characterised directly and indirectly in several parts of Australia (e.g., Cartwright et al., 2010; Lamontagne et al., 2021b; Rau et al., 2010; Shanafield and Cook, 2014). For example, studies of the water balance along the Woodforde River, 150 km north of Alice Springs, have shown that evapotranspiration accounts for up to one-third of the volume of its ephemeral flows, while another third slowly infiltrates below the perched aquifer to recharge regional aquifers 40 m below (Villeneuve et al., 2015); this recharge provides much, but not all of the basin's groundwater recharge (Shanafield et al., 2015).

3.2. Aquatic communities

Non-perennial rivers support key aquatic and terrestrial species and communities through mechanisms intimately tied to their hydrological regimes. Of particular importance is the provision of aquatic refuges in times of low and zero flow that are critical for both aquatic and terrestrial organisms (Carey et al., 2021; Rayner et al., 2009; Sánchez-Montoya et al., 2020; Sheldon et al., 2010). As in other ephemeral rivers of the world, large arid-zone, floodplain rivers in Australia traditionally display a 'boom-and-bust' ecology, when seasonal or episodic flooding replenishes rivers with seeds and detached parts of plants, disperses fauna, and connects floodplains to waterways, causing ecological 'booms' (Kingsford et al., 1998; Puckridge et al., 2000). During the 'boom' phase, when the floodplain is inundated, there may be enormous ecological and biological activity including breeding by birds and fishes and movement of sediment and nutrients laterally and longitudinally throughout the catchment (Bunn et al., 2006; Kerezsy et al., 2011).

During the following 'bust' phase, rivers are under extended dry spells, disconnected from floodplains and into a series of isolated pools. Fauna and flora must have a strategy to survive through the periods without surface flow. Some fauna find refuge in persistent waterholes or lay dormant in sediments (Casanova and Brock, 2000; Hay et al., 2018; Hose et al., 2005; Waltham and Schaffer, 2021), though some areas lack the unconsolidated streambed sediments required for this strategy (Carey et al., 2021; Chester and Robson, 2011). Drought is a recurring condition in Australia that can prolong the 'bust' phase, during which remaining waterholes, billabongs, springs, or permanently flowing river reaches act as refuges from drought (Box et al., 2008; Chester et al., 2015; Davis et al., 2013). In Southeast Queensland, recent research has developed statistical models relating surface water extent across river networks to relevant environmental variables in order to complement remote sensing in identifying drought refuges for small rivers (Yu et al., 2019).

Where there is groundwater contribution to disconnected pools, trophic diversity is higher (Siebers et al., 2020a), and localised zones of groundwater discharge may even create distinct ecosystems (Siebers et al., 2020). In contrast, 'reverse' or 'delayed booms' can occur where aquatic macroinvertebrate communities increase in abundance and diversity during inter-flood lentic periods and 'bust' during benthic-scouring, overbank floods and at the drying of pools, particularly where conditions were too harsh to sustain the ecosystem (Blanchette and Pearson, 2012).

The lack of connectivity between water bodies in Australia has led to a diversity of aquatic communities with a high level of endemicity. Approximately 70 % of Australian freshwater fish species are endemic (Pollino and Couch, 2014), with high endemism also evident in surface water species of frogs, crayfish, mussels and invertebrates (Pinder et al., 2010). The spring-fed streams and rivers of central and southwest Australia, in particular, have been influenced by continental-scale biogeographic isolation, and therefore host many endemic fauna species whose habitat is restricted to a small area (Davis et al., 1993; Davies and Stewart, 2013; Razeng et al., 2017). For example, there are only two Hyriidae species in south-western Australia (Vulnerable, IUCN Red List), and populations have declined in response to stream salinisation (Klunzinger et al., 2015).

In the north and northwest of the continent, there is a high diversity of invertebrates and fishes (Pinder et al., 2010; Waltham and Schaffer, 2021). Natural flow regimes have been preserved in most of the rivers in that region thanks to low human population densities, making these some of the few remaining naturally-functioning rivers in the world's wet-dry tropics (Blanchette and Pearson, 2012; Leigh and Sheldon, 2008). Ecosystem function in these rivers is driven by the annual fluctuations between the wet and dry season (Leigh and Sheldon, 2009; Warfe et al., 2011), and those rivers with more predictable annual flow patterns support higher animal diversity (Jardine et al., 2015). Food webs in rivers in the wet-dry tropics may show some similarities with those of arid-zone rivers such as a relatively high dependence of animals on algal production, including on the floodplain (Beesley et al., 2020; Leigh et al., 2010), high mobility of fish during wet periods (Jardine et al., 2012), and the importance of large, perennial refuge pools for faunal persistence (Pusey et al., 2018; Waltham et al., 2013).

3.3. Biogeochemistry (carbon and nutrient cycling)

Flow pulses that reconnect isolated waterholes and their floodplains deliver vital water, terrestrial resources, and floodplain algal production to non-perennial river-floodplain systems (Bunn et al., 2006; Burford et al., 2008; Pettit et al., 2017). Australia's ancient, highly weathered soils tend to be low in all three essential nutrients (C, N, P), leading to generally nutrient-limited surface water ecosystems (Eldridge et al., 2018). Australian riparian plants also tend to contain relatively high concentrations of complex, poorly bioavailable carbon (including secondary metabolites, tannins and phenolic molecules) but little nitrogen (Bunn, 1988; Watson et al., 2011) compared to plants found elsewhere; this further contributes to the Australian continent's nutrient poor, carbon rich waterways (Holland et al., 2018).

Riverine carbon dynamics (inputs and losses) are highly dependent on rainfall (Raymond et al., 2016), and this holds true across the gradients driving the extreme flow fluctuations in Australia's non-perennial rivers. Dissolved organic carbon (DOC) concentrations are high during the initial reconnection of flow (Birkel et al., 2020; Bunn et al., 2003) and first flush events wash terrestrial and/or litter-derived DOC into waterways that can increase microbial respiration (DO consumption) to create anoxic conditions that lead to faunal die back (Hladyz et al., 2011; McCarthy et al., 2014; Whitworth et al., 2012). The risk of extreme 'blackwater events' is higher when both flushing is less frequent, due to higher accumulation of organic matter between events, and flows following rain are low, due to the absence of turbulent mixing with air (Hladyz et al., 2011; Whitworth et al., 2012). River regulation is likely increasing blackwater events in Australia by reducing the occurrence of smaller flood events that regularly flush out floodplain leaf litter and maintain wetlands (Baldwin et al., 2016). Environmental flows to 'top up' flooding across river networks is now recommended to minimise periodic anoxia (Kerr et al., 2013; Watts et al., 2018).

Variation in DOC production and cycling suggests that there are biogeochemical differences across Australian non-perennial rivers (Holland et al., 2018), with the fate of DOC entering these systems varying between climate regimes. In the winter-flow dominated systems of southeast Australia, terrestrial DOC is the important energy and nutrient source (Westhorpe et al., 2010). However, in the drier northern systems, terrestrial DOC accumulates rather than driving growth, and in-stream DOC production instead drives respiration and growth (Fellman et al., 2011; Siebers et al., 2016). The accumulation of leaf litter derived DOC also alters physical nutrient processes (Iles et al., 2022). This divergence is also seen in DO (metabolism), where diurnal DO patterns in the northern wet-dry tropics may be more strongly influenced by the productivity (DO production) of aquatic macrophytes and epiphytic algae (Pettit et al., 2017) than the flow-driven patterns seen elsewhere.

When surface flow ceases, the contraction of Australian non-perennial river systems into disconnected waterholes creates distinct carbon and nutrient supply dynamics. For example, the predominance of sclerophyllous vegetation and warm temperatures combine to produce conditions that make within-system biological production the primary carbon source in many northern Australian rivers (Bunn et al., 1999). In general, extreme flow fluctuations across Australian non-perennial stream networks create locations (refuge pools) and periods (first flush) of high DOC, low pH conditions, which macrofauna must adapt to either through behaviour (remaining dormant until conditions change; (Chester and Robson, 2011) or acquired tolerance (McMaster and Bond, 2008). Waterholes often become anoxic when flow ceases and there is no longer turbulent entrainment of atmospheric oxygen (Burford et al., 2008). Dry periods often coincide with high air temperatures, which also induces water column stratification (Fellows et al., 2009). However, wide variation has been found in the biogeochemical responses to low-flow conditions caused by variation in turbidity, as this regulates light penetration and thus the balance of epiphytic algae, phytoplankton, macrophytes or semi-aquatic vegetation (Blanchette et al., 2014; Faggotter et al., 2013). In particular, high turbidity may limit algal production to a narrow littoral band around the edge of waterholes where light is more available (Bunn et al., 2003; Jardine et al., 2013).

There is also emerging evidence that groundwater contributions play an important role in the biogeochemistry of many non-perennial rivers. For example, groundwater connectivity moderates the evaporative concentration of solutes and influences quantity and composition of dissolved organic matter in disconnected waterholes (Siebers et al., 2016). Groundwater nutrient inputs can play a key role in whole-system productivity because it can contain relatively high nutrient concentrations that stimulate algal growth (Burrows et al., 2020), modulate algal community structure (Iles et al., 2022), and provide bioavailable DOC (Burrows et al., 2018; Mazumder et al., 2019; McDonough et al., 2022). Reductions in groundwater contributions result in both decreased nutrient inputs and longer residence times that could indirectly affect nutrient availability, e.g., by promoting anoxic conditions that favour nitrate removal by denitrification and the progressive release of phosphate (Andersen et al., 2016).

Far less is known about the biogeochemistry of dry channels, although work in this area is growing in response to questions about how non-perennial rivers contribute to global greenhouse gas (carbon dioxide, methane and nitrous oxide) emissions. Global comparison studies confirm that sediments in the dry channels of Australian non-perennial rivers have relatively low nutrients (e.g., organic carbon and nitrogen), relatively high C:N ratios, and experience relatively high temperatures, and go on to show that these attributes are likely to drive relatively low respiration pulses, either upon rewetting of the dry sediments (Schiller et al., 2019) or as measured in-situ under dry conditions (Keller et al., 2020). Likewise, the plant litter and sediments found in Australia's dry river beds tend to leach less organic matter, with a lower labile fraction and less inorganic nitrogen (higher C:N ratio) than other dry rivers around the world (Shumilova et al., 2019).

4. Multi-disciplinary research trends in time and space

4.1. Research trends through time

As described in section 2.3.1, the long history of Australian river science began approximately 65,000 years ago with the knowledge of water regimes and care of water resources developed by Indigenous peoples (Fig. 4). Water science in the century following European colonisation focused on creating consistent freshwater supplies for farms and navigable rivers for transport (Lang, 1944).

The earliest written descriptions of Australia's rivers often reference scenarios where previously large, flowing rivers turned into 'shallow rills' and ceased to 'exist in any shape as a river' (Cunningham, 1832; Mitchell, 1832). These observations evolved into more systematic observations of streamflow responses to rainfall (Wood, 1924). In the early 20th Century, the relationship between land clearing and dryland salinity was identified (Wood, 1924) and reafforestation was trialled to mitigate the impacts (Bell et al., 1990). Forest thinning was trialled in southwestern Australia to increase water yield to large reservoirs supplying Perth and the goldfields in Western Australia (Kinal and Stoneman, 2012). By the mid-20th century, scientists considered not just how water could be delivered most effectively to meet human needs, but also how recent land-use changes were impacting waterways. For instance, several paired-catchment experiments were developed between the 1960 s and 1990 s to assess how streamflow was affected by afforestation and deforestation (Bari et al., 1996; Brown et al., 2005; Ruprecht and Schofield, 1989).

By the 1980s, river research expanded to address the chemistry and ecology of Australia's waterways. This shift was catalysed by evidence that the increasing salinity of Australia's inland waters was affecting potability and suitability for agriculture (Peck, 1978; Turner et al., 1987). The 1980 s and 1990 s also saw a focus on the impact of water quality on ecology and ecosystem function (Boulton and Lake, 1990; Bunn and Arthington, 2002; Hart et al., 1990). Research found that the slow recharge rates of groundwater, coupled with the high evapotranspiration rates, have resulted in groundwater with very high salinities (commonly several thousand mg/L total dissolved solids) in many areas of Australia (e.g. Cartwright et al., 2008; Herczeg et al., 2001). Therefore, much research effort was devoted to understanding the prevalence and processes leading to groundwater discharge into rivers that increased riverine salinity, so that management options could be developed. Concurrently, major advancements in river geomorphology and boom-bust ecology arose from research examining the large ephemeral river systems of inland Australia (Puckridge and Drewien, 1988.; Walker et al., 1995).

The Millennium Drought (late 1990s to 2009) was the worst drought recorded in the instrumental period for south-eastern Australia (Freund et al., 2017; Van Dijk et al., 2013) and re-focussed research towards understanding the impacts of climate change, the capacity of rivers to recover, and management options to reduce stress and/or facilitate recovery. Ecological research during the drought focussed on fish (Bond and Lake, 2005), macroinvertebrates (Lind et al., 2006), and floodplain vegetation (Capon and Reid, 2016; Shilpakar et al., 2021) but also examined freshwater ecosystems more generally (Bond et al., 2008). Frameworks were proposed to identify vulnerable locations and species (Crook et al., 2010). Hydrologic research on the effects of the Millennium Drought also continues, seeking to further our knowledge about the enduring resilience of streams to extreme protracted climatic events (Fowler et al., 2022; Peterson et al., 2021).

Following the drought, the benefits of environmental water were documented (Chester et al., 2014; Ellis et al., 2013; Mackie et al., 2013). Subsequently, research on environmental flows has moved away from simply demonstrating a benefit towards optimising benefits for single taxa (Beesley et al., 2014) and then incorporating more complex interactions between multiple taxa and interacting non-flow factors (Tonkin et al., 2020).

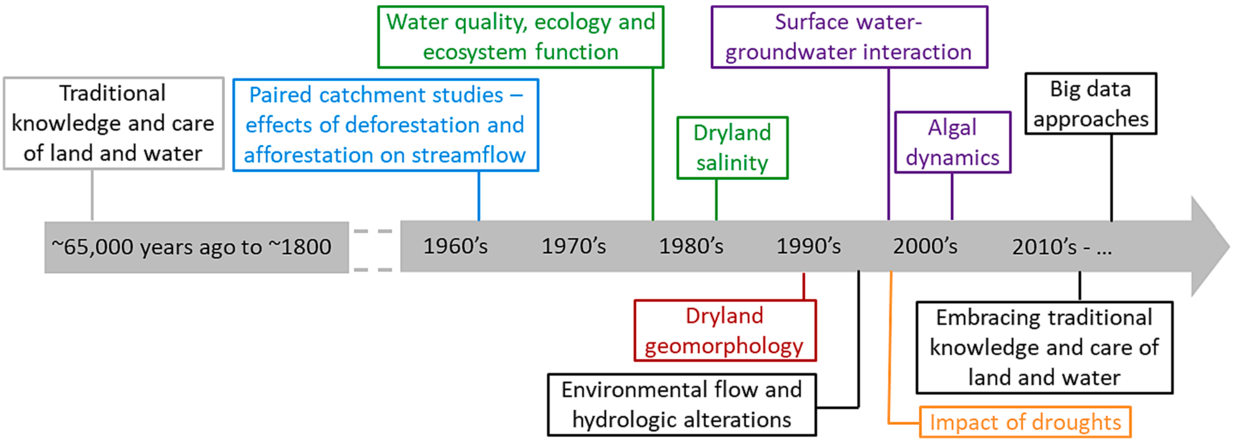

Fig. 4. Timeline of salient multi-year research themes pertaining to Australian non-perennial rivers.

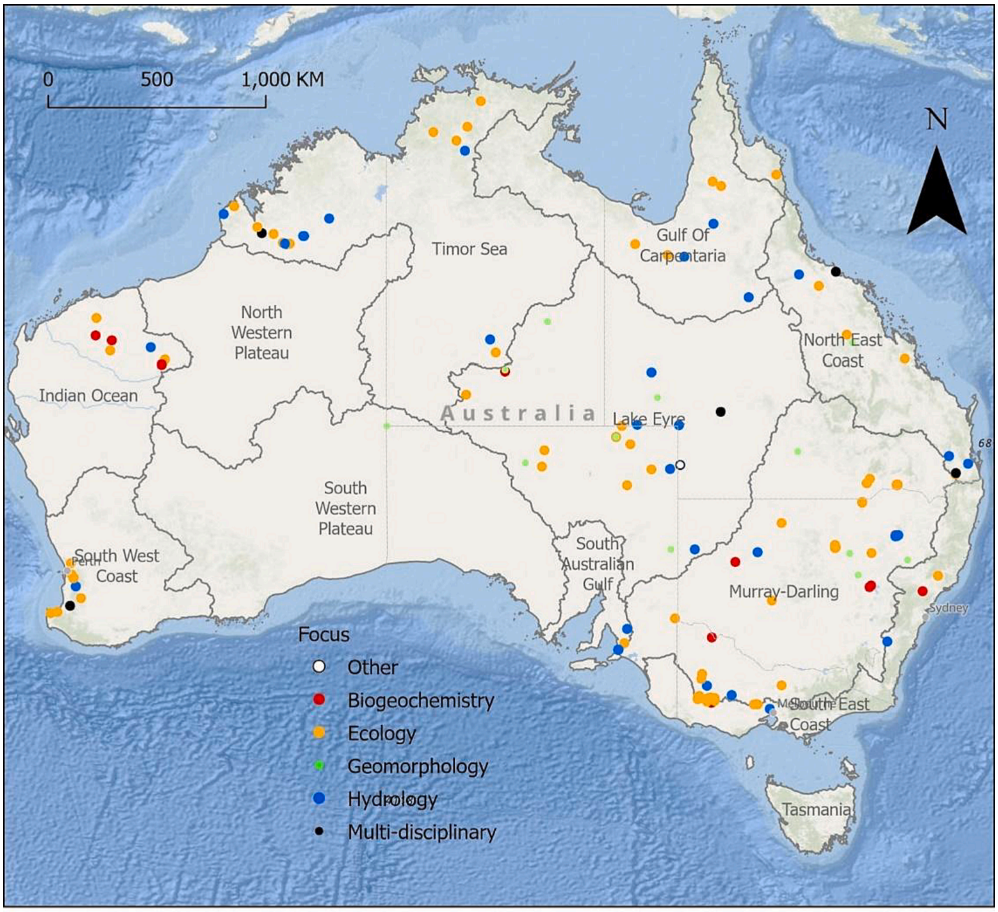

Fig. 5. Locations of known non-perennial river research studies in Australia (n = 184). The dots represent individual studies conducted across multiple spatial scales: 'sites', whole reaches, or across an entire basin (dot at the centre of that basin). Although many studies were multidisciplinary, the primary focus of the study was chosen for illustration. Note that this map is not an exhaustive list of studies, but indicative of research regions over the timeframe discussed in Section 3.1. A spreadsheet bibliography of all points is included as Appendix 1.

4.2. *Geographic research trends*

Across much of the arid, sparsely populated western part of the continent, the sparse presence of rivers (even non-perennial rivers) has meant that research has necessarily focused on coastal areas in the tropical north and Mediterranean southwest. Exploiting, managing, and more recently, restoring, the vast Murray Darling Basin in eastern Australia has produced a large body non-perennial river research (Fig. 5). The main stem of the Murray River is highly regulated and often experiences no-flow periods at the mouth due to heavy withdrawals all along its length (Kingsford et al., 2011). While the hydrology of some rivers in the northern Basin (such as the Warrego and Paroo Rivers) is less regulated, most tributaries are heavily impacted by water extraction, and as a result during severe droughts there are fewer perennial reaches or pools than under natural conditions. For example, the lower Darling River (the lowest point of the northern Basin with extensive tributaries extending into Queensland) used to flow most of the time (Mallen-Cooper and Zampatti, 2020). However, extensive water extraction, combined with repeated dry conditions has led to extensive and repeated drying and water quality issues. These conditions led to three fish kills of tens to millions of fish in the summer of 2018/2019 alone (Sheldon et al., 2022).

Another area that has received research attention is Australia's sparsely populated, remote interior (Fig. 1 l-m; Fig. 5). Early published work in this area was motivated by a fascination with its large saline lakes like Kati Thanda-Lake Eyre (e.g., Whitehouse, 1943), and the possibility of harnessing the floodwaters to convert what was seen as the 'Dead Centre' of the continent into productive agricultural land (Gregory, 1906). The national river flow monitoring scheme that was rolled out in the 1960 s explicitly included rivers in this arid part of the continent (Fleming, 1974). The Lake Eyre Basin (LEB), which occupies > 15 % of the mainland, extends across four states, and consists entirely of ephemeral catchments, has been a particular focus. Research includes ARIDFLO's documentation of hydrology (Costelloe et al., 2003), and interdisciplinary research linking aquatic ecosystems, landscapes and hydrology (Schmarr et al., 2017). The LEB's Diamantina and Cooper catchments provided critical information for the development of metrics to quantify flow variability (Mcmahon, 1979; Mcmahon et al., 1987), and have been central to important advances in fluvial geomorphology and Quaternary climate history (Habeck-Fardy and Nanson, 2014). Increasing use of groundwater in the 21st century has also driven research on inland rivers, as estimates of groundwater recharge through ephemeral riverbeds are crucial for sustainably allocating groundwater for large horticultural schemes (Villeneuve et al., 2015).

The tropical northern areas of the continent have also been the focus of non-perennial river research, particularly in the Gulf of Carpentaria and the Burdekin Catchment in North Queensland and the Ord River and Fitzroy River in Western Australia (Fig. 1 a,c). These sparsely populated regions have been the focus of various failed "nation building" schemes over the decades that attempt to harness their abundant wet season rainfall for human water supply and agricultural schemes (Powell, 1991). Instead of succeeding in 'drought proofing' the nation, these schemes generally failed because the region is too remote and sparsely populated to make these proposals either environmentally or economically viable. Nevertheless, scaled-back plans have resulted in completion of the Burdekin Falls Dam and wider irrigation area (Davis et al., 2014) as well as the Ord River irrigation scheme (Robson et al., 2014). Regardless of infrastructure outcomes, these proposals catalysed decades of research into the intermittently flowing rivers of the wet-dry tropics and their associated floodplains (Douglas et al., 2019; Hart, 2004; King et al., 2015).

5. Opportunities and directions for future research and management

Recent global efforts have highlighted the key research questions emerging in our understanding of the hydrology and ecology of non-perennial rivers (Shanafield et al., 2021; Stubbington et al., 2017). Addressing these discipline-specific questions will be critical to advance our understanding of the dynamic behaviour of non-perennial rivers. Based on our synthesis of the long history of research into the geomorphology, hydrology, and biological function of Australia's ubiquitous non-perennial river systems, addressing the stressors now facing these systems will require a multi-disciplinary approach. To date, interdisciplinary studies on non-perennial rivers are limited. Here we highlight four key multi-disciplinary knowledge gaps for non-perennial river research in Australia that emerged from this collaborative review, which are also critical for non-perennial river research that extends beyond the Australian continent.

1 How can Indigenous Knowledge and western science work together for the best outcomes for our rivers?

For most catchments in Australia there is much work left to do towards effectively including Indigenous stakeholders in decision-making for river management (Moggridge et al., 2022). Historical approaches to water management have prioritised some stakeholders (e.g., agricultural interests) above others, resulting in inequitable distribution of resources as well as reduced environmental health (Jackson and Barber, 2016). Progress toward fair representation is hampered by institutional barriers, power imbalances, and the late-stage involvement of Aboriginal people in decision making processes (Godden et al., 2020). Moreover, it has been difficult to incorporate Indigenous values into water resource management outside of the area of 'cultural heritage' (Jackson and Altman, 2009; Weir, 2009), as Indigenous relationships with their Country are frequently considered only in terms of spiritual beliefs and not their need for healthy ecosystems or their substantial knowledge of local conditions, ecological processes and the likely effects of water management decisions based on previous experiences and intergenerational knowledge (Langton, 2006; Moggridge, 2020). Addressing the collaboration of Indigenous Knowledges and western science requires a multidisciplinary approach, as there are many social factors involved in addition to the physical sciences, which are the focus in this paper. Yet Indigenous ways of caring for Country are inextricably linked to culture and ethical principles and have much to contribute to western management practices (Milgin et al., 2020). It is also acknowledged that it is important for all members of communities to have the opportunity to identify goals for water management to achieve equitable management outcomes.

There are examples of where meeting of Indigenous Knowledges and western science have been successful in Indigenous-led research, such as a Kamilaroi approach which involves community from the very beginning of the project, agreeing on important sites and turning to both science and Indigenous knowledge to identify cultural values such as flow requirements that can be indicators of stream health (Moggridge et al., 2022). Importantly, the cultural knowledge and stories do not necessarily need to be shared outside of the knowledge holders, in this example the knowledge holders within their communities were able to agree on certain indicators or thresholds that are indicative of stream health, based on their own cultural obligations and needs. Additionally, scientific information on river health and potential impacts from management decisions can be shared with the community. Another benefit of this approach is it is tailored to that catchment and is location-specific, which can be more effective for working with communities or even particular ecosystems than a one-size-fits all approach.

Another non-Indigenous led study employed a Multiple Evidence Based framework to share Nyul Nyul and Bardi Jawi peoples' knowledges on wetlands management in northern Australia with western Scientific approaches. This sharing then led to further steps of negotiation, synthesising and applying those approaches (Pyke et al., 2021). Indigenous knowledge holders now remain involved in the ultimate application of their knowledge and the implementation and outcomes, rather than divulging knowledge to external parties with no further involvement or agency over how it is used. In another example, Indigenous Knowledge and scientific knowledge was shared between researchers and Jawoyn, Wardaman, and Wagiman people of the Daly River (Northern Territory) to better understand ecological flow requirements to inform water resource planning. Such collaborations enhance knowledge on both sides (Jackson et al., 2014), and greater collaboration lead not just to better management, but also to a greater understanding of river systems and improved human-river relationships.

There is growing awareness of the need for change in the water management and research space, with a mounting number of champions advocating for collaborative knowledge generation and governance, and the incorporation of different world views on water resources science and management. There are also now many Indigenous river alliances that are actively advocating for a voice for rivers in Australia, including Murray Lower Darling Rivers Indigenous Nations (MLDRIN), Northern Basin Aboriginal Nations (NBAN), Martuwarra Council, and North Australian Indigenous Land and Sea Management Alliance (NAILSMA).

An example of their work is the Cultural Flows project, which developed a series of guidelines on specific water volumes required to support Aboriginal water uses and values in the Murray Darling Basin (Cultural Flows, 2017).

When it comes to consulting with Indigenous peoples for their views, it is imperative that such knowledge generation is equitable and not simply an extraction of Indigenous knowledge to be managed and used by non-Indigenous researchers or government agencies, or to benefit non-Indigenous interests, for example the way that prioritising water for agriculture has benefitted mainly non-Indigenous stakeholders (Jackson and Barber, 2016). This goal is best achieved by engaging with communities from project inception, enabling Indigenous peoples and communities to drive research questions and project outcomes, and continuing these partnerships into ongoing projects that enable communities to have agency over managing their land and waters.

2 What are the effects of global climate change on non-perennial rivers?

There is ample evidence that the length of no-flow periods affects the aquatic communities (Section 4.2) and biogeochemical processes (Section 4.3) of non-perennial rivers. However, the impact of a changing climate on the spatial and temporal variations in wet-dry periods across non-perennial river networks is unclear. Climatic shifts across the Australian continent have been observed since the 1970s, with future projections indicating increasing frequency and intensity of the continent's characteristic drought-flood cycles, overall reduction in soil moisture and water storage, raising air temperatures, and increasing duration and intensity of bushfires (Alexander and Arblaster, 2017; Andrys et al., 2017).

The short period of instrumental records of climate and river flow combined with the highly variable climate makes assessments of potential climate impacts on river flow very uncertain. A recent study has used tree-rings to reconstruct and extend the record of climate extremes to 800 years for the Murray River, in particular the occurrence and severity of droughts (Higgins et al., 2023). These paleo-records show that the Millennium Drought was the most severe during the 800-year reconstruction. The study further used climate models to predict how the occurrence probability of future severe droughts may change. When compared to the 800-year baseline, the driest model forecast shows a significant increase in the likelihood of severe droughts compared to natural variability and the climate models project an increase in future drought severity (Higgins et al., 2023). The impact of these changes on the hydrological and biological functions of Australia's diverse non-perennial rivers is still unclear (Larkin et al., 2017).

Climate warming will increase stream water temperatures (Van Vliet et al., 2013), with yet unknown but potentially detrimental follow-on effects, as temperature controls key hydrological and physiochemical parameters and influences the biogeochemical cycling of nutrients (Ouellet et al., 2020). How non-perennial streams will react to these altered thermal regimes represents a research gap (Zimmer et al., 2022). For example, increases in water temperature reduce dissolved oxygen saturation, affecting biotic respiration and photosynthetic production, along with abiotic oxygen-mediated chemical reactions. Increased water temperatures may exceed thermal tolerance limits of aquatic organisms or alter their range and distribution (Galego de Oliveira et al., 2019; Morash et al., 2021). A changing climate may also affect the quantity and quality of groundwater (McDonough et al., 2020) with consequences for streams when flow and aquatic refuges are supported by groundwater discharge (see knowledge gap 4 for detail). How these complex effects shape the ecology and function of non-perennial rivers in a changing environment is not fully understood.

Other impacts of climate change, such as CO_2 fertilisation (Donohue et al., 2013; Rifai et al., 2022) and effects of invasive insect species (Jactel et al., 2019), are less well understood, making the prediction of future ecosystem conditions of non-perennial rivers challenging. Additionally, these climatic changes are accompanied by on-going anthropogenic alterations to biological community diversity and abundance, surface water and groundwater flows, and nutrient enrichment. This is exemplified by the situation in the 2018/2019 Lower Darling's Menindee Lakes, when the combination of a prolonged drought and intensive agriculture led to stagnant, hot, and nutrient rich water that produced algal blooms that killed ~ 1 million fish (Sheldon et al., 2022). Future-proofing Australia's non-perennial rivers will require understanding how groundwater, landscape, vegetation and land-use in a changing climate control their water, chemistry, and ecology.

3 What is 'effective' restoration of non-perennial rivers and how is it measured?

Measuring restoration success is challenging because it is subjective, variable (Blanchette et al., 2016; Flatley and Markham, 2021), and requires social license (Naiman, 2013; Rogers et al., 2013). In Australian non-perennial rivers, environmental flows are used to either repair the pattern of flow intermittency towards a pre-regulation benchmark or create a novel regime that balances multiple objectives, values, and environmental impacts (Robson and Mitchell, 2010; Tonkin et al., 2020; Webb et al., 2018). It is understood that geomorphological processes (e.g., sediment transport and storage) interact with flow (Bizzi and Lerner, 2012; Henriques et al., 2022), underpinning non-perennial river restoration. Sediment supply and vegetation influence flow at multiple scales and affect channel topography (Singer and Michaelides, 2014). Yet a lack of information on how flood pulses may affect downstream infrastructure has been contentious (Jacobson and Galat, 2008), highlighting the importance of social license in restoring non-perennial rivers (Naiman, 2013; Rogers et al., 2013).

While there is increasing consensus that return to a pre-European river state is undesirable given their multifunctional uses, level of degradation and variable climate (Capon et al., 2018; Chessman and Royal, 2004), setting restoration targets is often fraught with difficulty. Desired targets often differ among stakeholders depending on their world view, roles and expectations (Stoddard et al., 2006; Tedford and Ellison, 2018). Often 'success' is evaluated merely in terms of compliance (i.e., whether actions have been implemented), rather than meaningful ecological improvement. Unfortunately, the long-time frames of recovery and the short time frames of funding mean that few systems are assessed appropriately. Monitoring success in non-perennial rivers is further complicated by the natural seasonal and interannual variability of these systems (Blanchette et al., 2019). New models of monitoring and restoration that capture 'system variability' are emerging (Flatley et al., 2018; Flatley and Markham, 2021), but need to be tested in more non-perennial river systems.

4 How does groundwater contribute to non-perennial rivers?

In both perennial and non-perennial rivers, groundwater inflows impact both the quantity and water quality of streamflows, as well as supporting surface water flows and ecological communities. While it is well established that groundwater inputs are critical to maintaining many non-perennial streams, it remains unclear just *how* critical they are and *when* they are important for ecosystems. Groundwater inflows into non-perennial rivers are variable in both space and time, and often enter the stream channel at relatively low flow rates, making them difficult to accurately quantify. The low volumes of groundwater inflow relative to volumes of flow during floods have also led to the common belief that their contribution is insignificant for ecological processes; however, these inflows may have critical ecological contribution during dry periods – how big, is largely unknown. It is thus difficult to manage groundwater withdrawals to protect groundwater contributions to streamflow, as well as groundwater dependent ecosystems (which are often located along non-perennial river corridors), due to lack of understanding of where and when groundwater plays an important role at the surface (Cook et al., 2022). There is also uncertainty as to the relative importance of shallow riparian groundwater and deeper regional groundwater in sustaining non-perennial rivers. If non-perennial rivers are connected to shallow near-river groundwater stores, they are less susceptible to the impacts of regional groundwater extraction from deeper aquifers; however, because the shallow stores are younger and often have smaller volumes, they are more at risk from short-term variations in climate (Barua et al., 2022; Zhou et al., 2022). Therefore, despite the research on surface water-groundwater interaction described in sections 3 and 4.1, significant knowledge gaps remain regarding the role groundwater plays in contributing to flows in Australian rivers.

Groundwater's significant role in river classification is overlooked in the current surface-focused approach. Intermittent rivers benefit from groundwater baseflow, and bank storage affects the flow duration of ephemeral rivers. To improve river classification, we need comprehensive research on the entire water cycle, including its impact on surface runoff and groundwater recharge, all of which are influenced by climate variability and change.

There is also a dearth of information on how groundwater contributions affect water quality in non-perennial rivers. Changes to catchment hydrology (e.g., via climate change, groundwater abstraction, land-use change or river regulation) may change the length and timing of influxes, the relative contribution of water from regional groundwater discharge, bank storage and hyporheic exchange, subsurface water residence times, and the subsurface processing of carbon and nutrients. A change in catchment hydrology may also lead to changes in redox-conditions and water quality via increasing groundwater tables (reduced conditions) or lowered groundwater tables (oxidising conditions). Such water quality changes and their implications for surface water ecology during the wetting and drying cycles in non-perennial rivers are poorly understood and quantified (Commonwealth of Australia, 2020).

Finally, there remains a paucity of knowledge on how groundwater supports the aquatic ecosystem through the cycling of carbon, nutrients and energy between subsurface and surface. The timing and the magnitude of the dependency of surface water ecosystems on groundwater inputs (Boulton and Hancock, 2006) remains a key knowledge gap. For instance, if sediments underlying or adjacent to the river channel retain water content, they may become important sites for ecological processes (e.g., decomposition of organic matter and mineralisation of nutrients) and refuges for species during periods of surface drying (Burrows et al., 2017; Carey et al., 2021; Chester and Robson, 2011), yet there are few studies elucidating where and when this mechanism is important. It is further unknown whether groundwater provides refuge for microbes responsible for stream respiration and biogeochemical cycling, especially during no flow or periods of the year when streams are reduced to disconnected pool, and how groundwater plays a role in the transfer of microbes in times of streamflow.

6. Conclusion: What comes next?

Australia is globally unique in its spread and diversity of non-perennial rivers spanning climates and landforms; however, most, if not all, of the classes of non-perennial rivers found in Australia also occur in other regions of the world with similar climates and geology. In this review we have identified the prevailing factors that shape the hydrology, ecology, and energy flows in these rivers (Section 2), what decades of research on non-perennial rivers have taught us about them (Section 3), and some of the overarching knowledge gaps that remain (Section 5). The knowledge gaps elucidated here fit within the burgeoning literature on non-perennial river science globally.

Australian non-perennial river research has been driven by the needs of its inhabitants over time and space for survival, agriculture, resource economics, environmental concern and politics. Considering the continent's ancient geological history and its harsh, arid climate, it comes as no surprise that significant attention has been directed toward water resource management during drought periods, the reduction of salinisation, and gaining insights into the intricate dynamics of the transient rivers that are a defining feature of central Australia. The prevalence of prolonged drought periods has also had a marked impact on driving research. Given that increasing trends in hydrological droughts are projected to negatively impact streamflow not just in Australia, but also in South America, southern Africa, and the Mediterranean (Wanders et al., 2015), we anticipate that research in these areas will similarly be driven to understand the impacts of drought and salinisation on the hydrology, ecology, and geochemistry of those regions' rivers. Work is already underway to begin addressing the knowledge gaps identified above. For example, Aboriginal Waterway Assessments are becoming increasingly common practice for waterways within the Murray-Darling Basin, and Traditional Owners views are becoming a greater component of management plans and working towards water entitlements and flow targets that support Indigenous communities (Cultural Flows, 2017; Moggridge et al., 2022; MDBA, 2015) a first step in addressing knowledge gap 1. In addition, frameworks are being established that increase sharing of knowledge between Indigenous communities and western Science to develop contemporary management practices and support Indigenous peoples in managing their lands and waters in culturally appropriate ways (Pyke et al., 2021; Moggridge et al., 2022). Progress is being made in northern Australia, where high Indigenous land ownership increased bargaining power and led to the creation of the Strategic Aboriginal Water Reserve in the Northern Territory in 2017 (Jackson and Barber, 2016). Similarly, in the Murray-Darling Basin, First Nations groups now legally own and manage 'Cultural Flows' which are water entitlements "to improve the spiritual, cultural, environmental, social and economic conditions of Indigenous Nations" (MLDRIN 2008 Echuca Statement). There is a strong push for change elsewhere in Australia (Jackson and Woods, 2021). As we accept that environmental stationarity is no longer an appropriate assumption (Yates et al., 2018), several states are now mandating that climate change must be accounted for in water management plans (knowledge gap 2). In theory, this should increase environmental flows, and thus improve our rivers' resilience to future droughts (knowledge gap 3). However, additional research is required to understand the spatial and temporal connection with groundwater, its influence on stream classification, and the ecological significance of this input at several scales (knowledge gap 4).

Over the long term, future research will continue to be driven by the contemporary demands for resources by society and requirements from environmental legislation. We expect that ongoing technological advances and the increasing prevalence of interdisciplinary collaborations will also have a fundamental impact on how knowledge gaps are addressed. For example, advances in remote sensing are now facilitating ecosystem and surface water resource monitoring in areas difficult to access, providing valuable information about river systems in the most arid and remote parts of Australia (Tayer et al., 2023; Thapa et al., 2020). The advent of LiDAR imagery is further allowing accurate assessments of the flow status of rivers at small catchment scales (Hall et al., 2019). Although such opportunities for using remotely sensed data have increased dramatically over the past two decades and continue to expand, there will always be a need for detailed field studies and verification. The current downward trend in the number of long-term streamflow monitoring stations further complicates effort to complement or ground truth some remotely-sensed data and may mean that citizen science must play a larger role in future research efforts. However, more investment in long-term hydrological monitoring is desperately needed to increase our knowledge so that water management can address the competing water needs of communities, agriculture, mining, and ecosystems in a dry environment.

The increasing availability of advanced data networks across Australia will enhance the ability to develop a multi-disciplinary understanding of river dynamics at many locations. Finally, the growing trend toward cross-institutional and international research networks will play a role in meeting the research needs of an increasingly connected world. We anticipate that changing global water fluxes (Langenbrunner, 2021) and continued groundwater pumping (de Graaf et al., 2019) will cause more of the world's rivers to become non-perennial, leading to growing scientific interest that has the potential to accelerate our understanding of these systems across many disciplines. In turn, a more thorough understanding will help to underpin science-driven management of non-perennial rivers to both meet the needs of a growing Australian population while protecting the integrity of ecological systems.

CRediT authorship contribution statement

Margaret Shanafield: Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Melanie Blanchette:** Conceptualization, Formal analysis, Project administration, Writing – original draft. **Edoardo Daly:** Conceptualization, Writing – original draft, Visualization. **Naomi Wells:** Conceptualization, Methodology, Visualization, Writing – original draft. **Ryan M. Burrows:** Conceptualization, Visualization, Writing – original draft. **Kathryn Korbel:** Conceptualization, Formal analysis, Writing – original draft. **Gabriel C. Rau:** . **Sarah Bourke:** Writing – original draft, Writing – review & editing. **Gresley Wakelin-King:** Writing – original draft, Writing – review & editing. **Aleicia Holland:** Conceptualization, Visualization, Writing – original draft. **Timothy Ralph:** Conceptualization, Writing – original draft. **Gavan McGrath:** Writing – original draft. **Belinda Robson:** Writing – original draft, Writing – review & editing. **Keirnan Fowler:** Writing – original draft. **Martin S. Andersen:** Writing – original draft, Writing – review & editing. **Songyan Yu:** Writing – original draft. **Christopher S. Jones:** Writing – original draft, Writing – review & editing. **Nathan Waltham:** Writing – original draft. **Eddie W. Banks:** . **Alissa Flatley:** Writing – original draft, Writing – review & editing. **Catherine Leigh:** Writing – original draft. **Sally Maxwell:** Writing – original draft. **Andre Siebers:** Writing – original draft. **Nick Bond:** Writing – original draft. **Leah Beesley:** Writing – original draft. **Grant Hose:** Writing – original draft. **Jordan Iles:** Writing – original draft. **Ian Cartwright:** Writing – original draft, Writing – review & editing. **Michael Reid:** Writing – original draft. **Thiaggo de Castro Tayer:** Writing – original draft. **Clément Duvert:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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