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Hydrological processes in tropical Australia: Historical perspective and the need for a catchment observatory network to address future development

Clément Duvert[a,b,*], Han-She Lim[c], Dylan J. Irvine[a,b], Michael I. Bird[c], Adrian M. Bass[d], Sarah O. Tweed[e], Lindsay B. Hutley[a], Niels C. Munksgaard[c]

[a] Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Australia
[b] National Centre for Groundwater Research and Training, Adelaide, Australia
[c] College of Science and Engineering, James Cook University, Cairns, Australia
[d] School of Geographical and Earth Sciences, University of Glasgow, Glasgow, Scotland, UK
[e] Institut de Recherche pour le Développement, UMR G-EAU, Montpellier, France

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ABSTRACT

Study region: Tropical Australia.
Study focus: Streams and rivers of the Australian tropics have been the subject of substantial hydrological process research spanning the last 50 years. In this review, we highlight initial efforts to understand the hydrological response of forested ecosystems in the humid tropics, and how this has been more recently followed by work in savannas of the seasonal tropics. We describe recent findings from modelling and tracer studies and derive a framework of dominant hydrological processes for the region. We also detail five critical knowledge gaps that will require further attention with climate change and ongoing interest in development in the region.
New hydrological insights for the region: We outline the diversity of runoff generation mechanisms that prevail in the region and emphasise the role of connected wetlands and floodplains in catchment response. We discuss the prominence of focused, episodic recharge in the replenishment of groundwater stores across the region. We also review how climate change and potential water resource development projects may alter the hydrology of northern Australian catchments. Future research should focus on improving our physical understanding of key hydrological processes, as well as anticipate the likely effects of development and climate change on these processes. Intensive and long-term studies of experimental observatories, which capture the diversity in landscapes and climates of the region, will help frame sustainable water development policies in northern Australia.

1. Introduction

Stretching from the Kimberley in Western Australia (WA) to the Cape York Peninsula in Queensland (QLD), about 25% of Australia's land mass is characterised by a tropical climate (Fig. 1). Here we loosely define the Australian tropics as all land north of latitude ~21°S, approximately corresponding to the transition between the seasonal, semi-arid tropics and more arid areas to the south

* Corresponding author at: Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Australia.
E-mail address: clem.duvert@cdu.edu.au (C. Duvert).

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(Beck et al., 2018). This land, which has a strong cultural value to Indigenous Australians, is sparsely populated and has been subject to relatively limited water resource development to date. Less than 2% of the area is used for forestry, cropping or mining, with the remaining land either supporting extensive cattle grazing or reserved as conservation areas (ABARES, 2021). The relatively undisturbed landscapes of tropical Australia generate a disproportionate amount of the continent's surface runoff (Petheram et al., 2010), with many rivers in the region having retained a natural flow regime (Warfe et al., 2011). This situation contrasts with most other tropical regions of the world that are often affected by large-scale deforestation (Gibbs et al., 2010; Lambin et al., 2003) and river impoundment (Zarfl et al., 2015). The relatively intact state of northern Australia, combined with its diverse range of landscapes and sub-climates, and political stability relative to other tropical countries, provides unique opportunities to develop a solid knowledge base of natural hydrological processes in the tropics. Further, the renewed commitment from all levels of government to enable economic development in northern Australia (Commonwealth of Australia, 2015; Hart et al., 2020; Watson et al., 2021) is likely to drive an expansion of primary industries across the region, including irrigated agriculture (Ash et al., 2017), aquaculture (Cobcroft et al., 2020) and extractive industries (Knudsen et al., 2019). There is therefore an urgent need for research that assesses the response of Australian tropical catchments to projected water resource development as well as climate change.

While the humid tropics have been the subject of important research on fine-scale hydrological process understanding since the

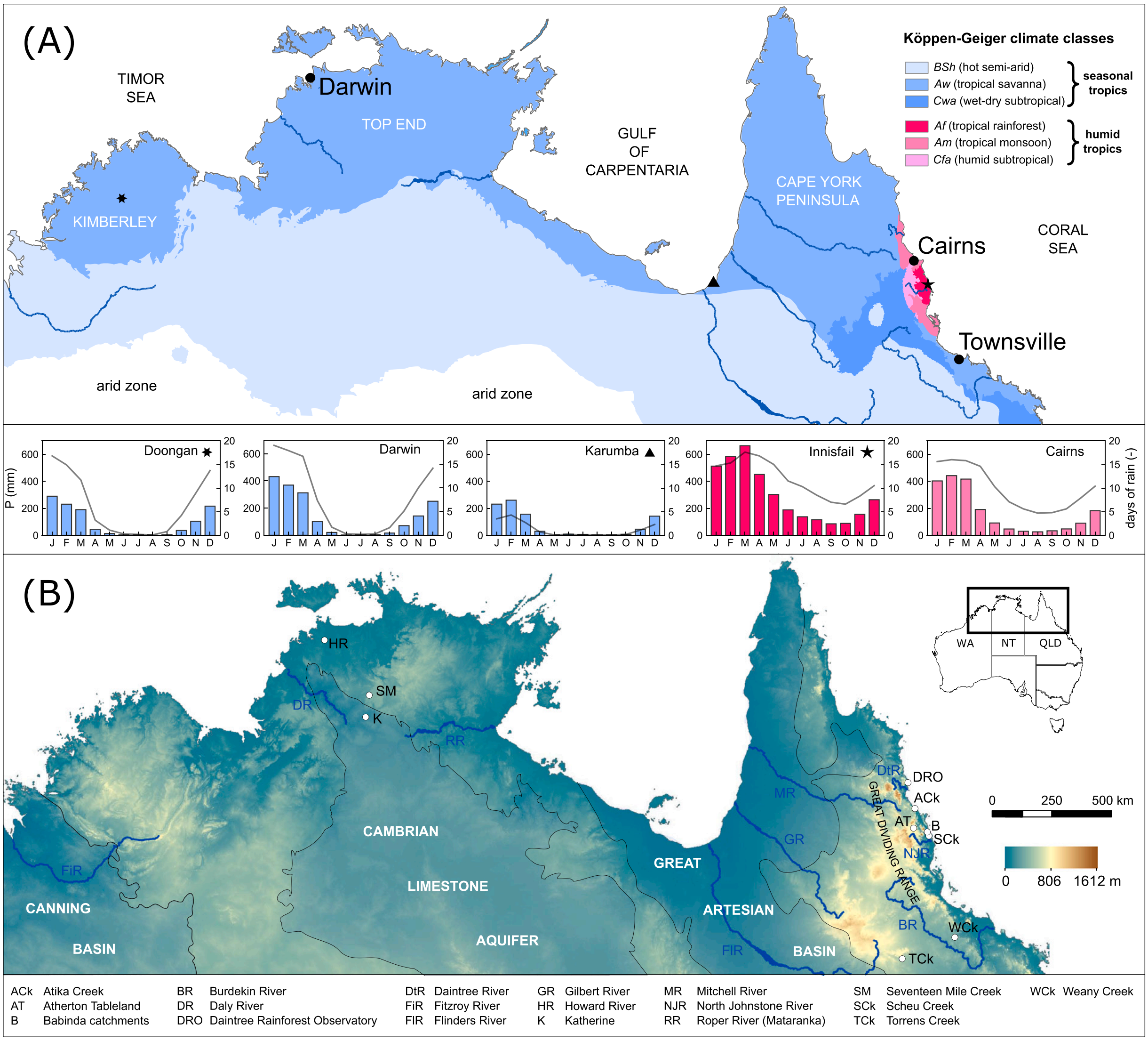

Fig. 1. (a) Map of northern Australia with Köppen-Geiger climate classification corresponding to the seasonal and humid tropics. Plots show the long-term average monthly rainfall and number of rainy days for three locations across the seasonal tropics (Doongan, Darwin, Karumba) and two locations of the humid tropics (Cairns, Innisfail). (b) Elevation map of northern Australia with location of the study sites and large river systems presented in this review. Shaded areas depict the spatial extent of three regional aquifer systems (Canning Basin in WA, which includes the Grant Group and Poole Sandstone aquifers, Cambrian Limestone Aquifer in the NT, and northern part of the Great Artesian Basin in QLD).

1970 s and 1980 s (e.g. Bonell and Gilmour, 1978; Bonell et al., 1981; Cassells et al., 1985; Elsenbeer et al., 1995), the seasonal (or wet-dry) tropics have received comparatively less attention (e.g. Cook et al., 1998), even though the latter occupy a much larger area of the Australian tropics (Fig. 1). Despite recent efforts to collect field data from understudied areas, the research coverage has been spatially uneven, and observations remain limited across much of tropical Australia (Petheram et al., 2012a). The disparate nature and limited number of field studies has precluded development of a robust conceptual framework for understanding the key hydrological processes at play in the region. In this article, we first describe the diversity of landscapes and climates across the region (Section 2). We then provide a historical perspective of the work carried out to understand the hydrological response of forested ecosystems in the humid tropics (Section 3) and outline the more recent interest in hydrological process understanding across the seasonal tropics (Section 4). Through several recent examples, we show how the collection of isotopic, and other, data has provided new insight into the response of these highly dynamic systems to monsoonal rainfall pulses (Section 5). We then draw on these examples to propose a framework of dominant processes for the region. In Section 6, we discuss how current hydrological functions may be affected by climate change and potential water resource development. Lastly, we highlight some of the remaining knowledge gaps in Australia's tropical hydrology in the face of future development and climate change (Section 7).

This review synthesises the processes that control the hydrological response of catchments across the Australian tropics, and as such, there are topics that are outside of the scope of this paper. We do not review the numerous hydrological and hydrogeological assessments conducted by state agencies and research organisations since the 1950 s (e.g. water budgets of specific regions; groundwater recharge estimates; etc.), unless these studies have expanded our understanding of key hydrological processes. Likewise, we do not review studies that investigate other aspects of the critical zone, such as aquatic biogeochemistry, nutrient and sediment fluxes through rivers, as each of these topics could be the focus of review papers in their own right.

2. Landscape and climate drivers of streamflow in the Australian tropics

The Australian tropics are broadly made up of two bioclimatic zones, the humid tropics and the seasonal (or wet-dry) tropics, the latter covering most (>99%) of tropical Australia (Fig. 1a). The humid tropics, defined here as the area that falls under climate classes *Af*, *Am* and *Cfa* of the Köppen-Geiger classification (Beck et al., 2018), are a region of rugged rainforest terrain along the eastern flanks of the Great Dividing Range (Fig. 1b), with confined valleys and narrow coastal plains that support pasture and cropland. The geology of the humid tropics comprises of ancient (e.g. Palaeozoic) metamorphic and granitic formations partially overlain, in places, by more recent (e.g. Cainozoic) lava flows and ash deposits, while thick colluvial and alluvial deposits extend along the coastal plains (Jell, 2013).

The seasonal tropics, defined here as the area that falls under climate classes *Aw*, *BSh* and *Cwa* of the Köppen-Geiger classification, comprise highly weathered landscapes of generally low topography (Fig. 1b) that support mixed savanna woodland/grassland. A diverse range of geological settings occur across the seasonal tropics, for instance, sedimentary siliciclastic rocks in much of the Kimberley and Top End; igneous and metamorphic rocks in the headwaters of the Flinders, Gilbert and Mitchell catchments in QLD; but also sedimentary carbonate rocks occurring sporadically across the Daly and Roper catchments in the Northern Territory (NT) as well as Gulf of Carpentaria region (Ahmad and Munson, 2013; Groves et al., 1994; Jell, 2013). In places, the surface geology overlies large sedimentary basins that can contain highly permeable carbonate (e.g. the Cambrian Limestone Aquifer in the NT) or siliciclastic

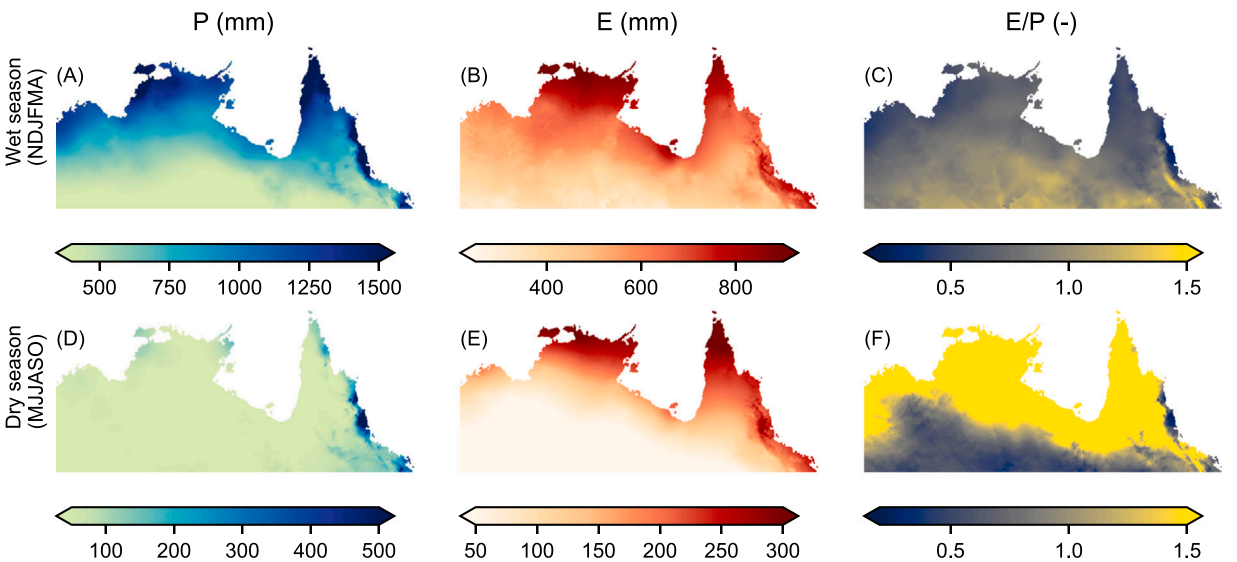

Fig. 2. Spatial visualisation of long-term mean precipitation (P), evaporation (E) and evaporative ratio (E/P) for the wet (November to April; top) and dry (May to October; bottom) seasons. Data obtained from BoM at a 0.05 degrees grid. E is averaged between 1961 and 1990 and P is averaged between 1981 and 2010. Note that the colour shadings are not the same for the dry and wet seasons, except for E/P.

formations (e.g. Grant Group and Poole Sandstone aquifers in WA; northern parts of the Great Artesian Basin in QLD) (Fig. 1b). The seasonal tropic region also includes wide alluvial floodplains associated with meandering rivers and extensive wetlands that form during the wet season. Much of the land surface has been subjected to intense chemical weathering, leading to widespread laterite formation. Another feature of the seasonal tropics are the numerous low-lying islands off the Top End coast, in the Gulf of Carpentaria and along the Coral Sea and Timor Sea coastlines (Fig. 1). These islands are often inhabited by Indigenous Australians, hence have important water security considerations.

Rainfall in both the wet and seasonal tropics is primarily driven by the southward migration of the intertropical convergence zone during the summer months (Davidson et al., 1984; Troup, 1961). While early wet season events (from November to December) involve relatively short lived, intense convective storms, the shift to equatorial westerly winds around December brings large scale monsoonal conditions until April (Troup, 1961; Wheeler and McBride, 2005). During this second part of the wet season, monsoonal bursts can last between a few days to a week or more, and are characterised by convective cells that yield lower intensity but higher magnitude rainfall relative to early storms (Wheeler and McBride, 2005). Tropical cyclones can also occasionally form in the vicinity of monsoonal depressions, bringing more intense rainfall. Rainfall regimes during the wet season are broadly similar across the humid and seasonal tropics, with 1000–3000 mm falling along the northern and eastern coast between November and April (Fig. 2a). A substantial rainfall gradient occurs from north to south in the seasonal tropics, with semi-arid tropical regions receiving lower rainfall amounts (<500 mm) during the wet season.

In the drier months (May to October), the two bioclimatic zones experience distinctly different rainfall patterns (Fig. 2d). Rain in the seasonal tropics ceases almost completely for four to five months, making the region one of the global hotspots for extreme rainfall seasonality (Feng et al., 2013). In the humid tropics, however, the presence of the Great Dividing Range enables south-easterly winds to bring orographic rainfall to the region even during the austral winter, ensuring rainfall of between 300 and 1000 mm between May and October. Both regions experience high rates of evaporation year-round ('evaporation' here refers to the bulk flux of water, including transpiration, following Miralles et al., 2020), with the highest rates during the wet season when precipitation and temperature are highest (Fig. 2b; 2e). As a result, the ratio between evaporation and rainfall (or evaporative index) is < 1 in high rainfall areas during the wet season (i.e. no rainfall deficit; Fig. 2c), but > 1 during the dry season—except for the humid tropics, where rainfall occurs year-round, and for the semi-arid inland areas to the south, where evaporation is negligible given the lack of rainfall and low vegetation cover (Fig. 2f).

This diversity in landscape and climate drivers results in significant differences in the hydrological regime of streams and rivers across the region (Fig. 3). Rivers of the humid tropics tend to flow year-round, with rainfall during the drier months ensuring regular

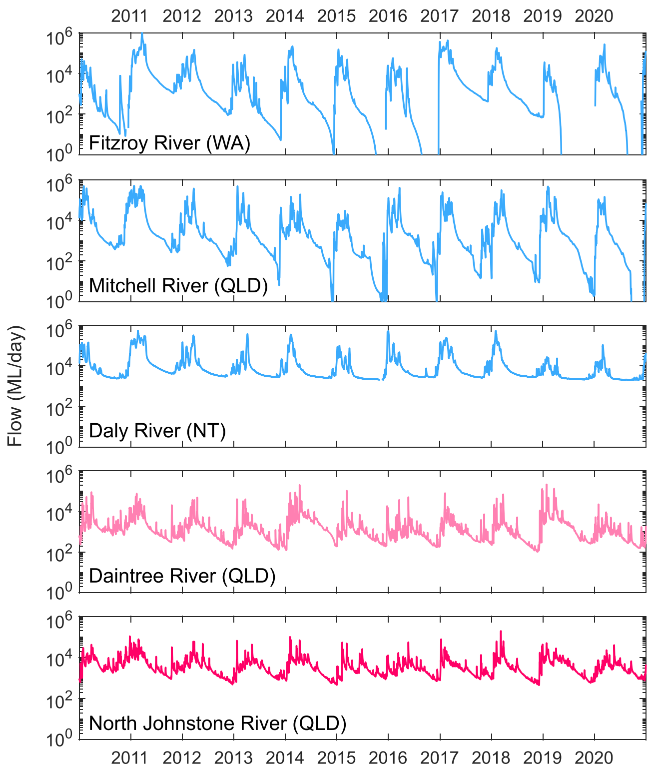

Fig. 3. Illustration of the seasonality and interannual variability in river flow. Daily discharge for the period 2010–2020 in three rivers of the seasonal tropics: Fitzroy River (WA gauging station 802008), Mitchell River (QLD gauging station 919009B), Daly River (NT gauging station G8140040) and two rivers of the humid tropics: Daintree River (QLD gauging station 108002 A) and North Johnstone River (QLD gauging station 112004A). Colours correspond to the respective climate zones as per Fig. 1.

replenishment of groundwater stores and sustained discharge to rivers (e.g. Daintree and North Johnstone Rivers in Fig. 3). In contrast, many rivers of the seasonal tropics cease to flow during the prolonged dry season (e.g. Fitzroy River in Fig. 3), unless they are connected to large groundwater systems that sustain surface water flow via baseflow contributions (e.g. Daly River in Fig. 3; associated with the Cambrian Limestone Aquifer). Because rainfall can be particularly irregular from year to year, rivers of the seasonal tropics are also subject to considerable interannual variations in their flow regime (Petheram et al., 2008b).

3. Humid tropics: a legacy of research on stormflow generation

Hydrological research in tropical Australia began in the 1970 s in the steep forested region of northeast QLD, with the establishment of a hydrological observatory in one of the most humid areas of Australia, near Babinda, south of Cairns (B in Fig. 1b), where annual precipitation averages 4500 mm. In what is often referred to as the "Babinda catchments", a wide range of experimental approaches were applied to examine the response of streams to rainfall and the impact of logging on this response. The site comprised two paired sub-catchments, namely South Creek, supporting intact rainforest, and North Creek, which had been logged. From the 1970 s to the late 1990 s, the Babinda observatory became one of the most intensely studied sites in the tropics (e.g. Bonell et al., 1998; Bonell and Gilmour, 1978; Bonell et al., 1981; Cassells et al., 1985; Elsenbeer et al., 1995; Elsenbeer et al., 1994). These studies generated significant new understandings of storm runoff generation in the humid tropics, as briefly detailed below.

Early work in Babinda showed that tropical rainforest catchments can be highly responsive to rainfall, and capable of generating overland flow (Bonell and Gilmour, 1978). This finding contradicted the then prevailing view that forested catchments were dominated by subsurface stormflow. In both South and North Creek, highly transmissive surface soil layers were underlain by a low-permeability layer at 0.2 m depth, which, under high antecedent wetness and intense rainfall, could result in saturation-excess overland flow as a perched water table formed in the upper soil (Bonell et al., 1983, 1981; Bonell and Gilmour, 1978; Cassells et al., 1985). Subsurface stormflow was also observed and occurred mostly via preferential pathways along large root systems (Bonell and Gilmour, 1978), while stemflow contributed substantially to overland flow via branches that quickly funnelled rainfall to the ground (Herwitz, 1986).

In the 1980 s, research in the Babinda catchments contributed significantly to the emerging debate over the contributions of 'old' (or pre-event) and 'new' (or event) water sources to the storm hydrograph. Under wet antecedent conditions and monsoon-type rainfall, event water dominated the runoff response (Elsenbeer et al., 1995), yet under lower-intensity rainfall less favourable to the generation of saturation-excess overland flow, large contributions from pre-event water were observed both in South Creek (Elsenbeer et al., 1995) and North Creek (Barnes and Bonell, 1996). It was also established that as the region transitioned to the drier season, streamflow became dominated by older groundwater sources (Bonell et al., 1998, 1983, 1981). Recognising the necessary distinction between celerities (pressure wave) and velocities (mass movement) to characterise catchment response, Barnes and Bonell (1996) were the first to incorporate isotopic tracers into a hydrological model—a study that paved the way for a better integration of water transit times in catchment studies and for a widespread use of tracer time-series in hydrology (Hrachowitz et al., 2016; McDonnell and Beven, 2014; McGuire and McDonnell, 2006; Sprenger et al., 2019). Overall, the breadth of research conducted in the humid tropics of Australia during that period inspired hydrological research in other tropical regions of the world (e.g. Elsenbeer and Lack, 1996; Muñoz-Villers and McDonnell, 2012; Noguchi et al., 1997; Schellekens et al., 2004), at a time when hydrological process understanding was predominantly focused on temperate regions.

4. Seasonal tropics: recent scrutiny with the push to "develop the North"

While hydrological monitoring and assessments in the seasonal tropics of Australia have been conducted by state agencies since the 1960 s, interest in small-scale hydrological process understanding was relatively limited until the 2000 s. Among the few research studies undertaken in the 1970 s and 1980 s, Bonell and Williams (1986) examined runoff patterns in an undisturbed savanna hillslope near Torrens Creek (central north QLD; TCk in Fig. 1b). They found that infiltration-excess overland flow developed during high intensity rainfall events on bare soil surfaces. However, over 95% of this runoff was redistributed and subsequently infiltrated a short distance downslope as a result of high soil hydraulic conductivity (Bonell and Williams, 1986). In another study in the Burdekin River catchment (BR in Fig. 1b), Holt et al. (1996) partly attributed the higher infiltration rates they observed in a lightly grazed savanna (relative to an overgrazed site) to higher termite activity within the topsoil. These early findings suggest that both the extent of savanna vegetation cover and soil properties, including soil fauna, may be important determinants of runoff generation processes in the Australian seasonal tropics.

With severe droughts impacting southern Australian catchments, northern catchments have been scrutinised since the mid-2000 s for potential development of primary industries (Commonwealth of Australia, 2015). Several programs were launched that gave impetus to new research on the rivers of the region. These programs (e.g. Tropical Rivers and Coastal Knowledge, established in 2007; Northern Australia Sustainable Yields Project, launched in 2008; Northern Australia Environmental Resources Hub, established in 2012; Northern Australia Water Resource Assessment, launched in 2015) fostered transdisciplinary research that delivered critical information on the extreme variability of flow regimes (Petheram et al., 2008b, 2012a) and the effect of flow seasonality on riverine ecosystems (e.g. Douglas et al., 2005; Jardine et al., 2015; Leigh and Sheldon, 2008; Warfe et al., 2011). Because groundwater development would potentially impact the continuity of dry-season surface flow, the role of intermediate- to regional-scale groundwater systems in maintaining baseflow to rivers was also investigated in detail across the region (Cook et al., 2003, 1998; Gardner et al., 2011; Jolly et al., 2013; Leblanc et al., 2015; Smerdon et al., 2012). Return flow from bank storage was identified as an important process that can contribute significant proportions of baseflow to large rivers (Batlle-Aguilar et al., 2014; Doble et al., 2012). Another focus of these programs was to examine ecohydrological processes during the dry season, with several studies demonstrating the reliance of riparian trees on groundwater (Cook and O'Grady, 2006; Lamontagne et al., 2005; O'Grady et al., 2006).

Overall, we now have access to much-needed baseline information on the biophysical environment of the seasonal tropics. Detailed investigations of hydrological processes specific to the region, however, have been limited until recently. Catchment functioning is likely to be fundamentally different in the tropics compared to temperate regions (Wohl et al., 2012; Wright et al., 2018), yet our understanding of processes such as runoff generation, sources and pathways of stormflow, and groundwater contributions to surface flow remains fragmented for the seasonal tropics of Australia. Recent efforts, including modelling and observations based on environmental tracers (e.g. water stable isotopes, radioisotopes), have helped clarify some of these processes, as outlined in Section 5.

5. New insights from isotopic studies: towards a baseline hydrological framework

The use of environmental tracers has underlain key advances in the conceptual understanding of catchment processes (Kendall and McDonnell, 1998). In Australia, Bonell and colleagues were pivotal in the development of tracer techniques as tools to unravel runoff generation processes (e.g. Barnes and Bonell, 1996; Bonell et al., 1998; Bonell et al., 1983; Elsenbeer et al., 1995; Hensel and Elsenbeer, 1997). While these early investigations relied on a low number of measurements, the advent of infrared isotope spectroscopy is now enabling high resolution observations at time scales that match those of fundamental hydrological drivers (Birkel et al., 2012; von Freyberg et al., 2017). The ability to acquire high resolution isotopic data (both oxygen, $^{18}O/^{16}O$ or $\delta^{18}O$ and hydrogen, $^{2}H/^{1}H$ or δD) is particularly important in tropical regions, where stormflow events can be intense and short lived, and where the isotopic composition of rainfall can be highly variable at sub-hourly time scales (Munksgaard et al., 2012, 2020).

Over the last decade or so, isotopic studies focussed on streams and rivers in tropical Australia have advanced our understanding of the hydrological response of these systems to hydroclimatic drivers (e.g. Birkel et al., 2020; Lamontagne et al., 2021; Smerdon et al., 2012; Tweed et al., 2016). Here we summarise the main findings from these and other studies and propose a broad framework of hydrological functioning for the region.

5.1. Hydrological responses to monsoonal rain

Recent research has shown that wet season rainfall can have distinct isotopic compositions over the course of the season, largely dependent on cloud generation dynamics and their transport trajectories (Zwart et al., 2016, 2018). The large-scale monsoonal convective systems that occur at the peak of the wet season are characterised by highly depleted δD and $\delta^{18}O$ compared to earlier storms and to storms that occur between monsoonal bursts (Munksgaard et al., 2020; Zwart et al., 2016, 2018). Furthermore, tropical cyclones can bring rainfall with even more negative δD and $\delta^{18}O$ values (Munksgaard et al., 2015). Such temporal variations in the isotopic composition of rainfall offer the opportunity to assess the response of Australian tropical streams and rivers to different hydroclimatic drivers and their associated spatial and temporal patterns.

Research has shown that runoff generation mechanisms in tropical Australian catchments vary over the course of the wet season, as a result of rainfall intensity and changing antecedent wetness conditions (e.g. soil moisture and groundwater states). Analysing the hydrological response of Seventeen Mile Creek (SM in Fig. 1b), a river north of Katherine (seasonal tropics), Montanari et al. (2006) found that saturation-excess overland flow occurred during the wettest months and after sustained monsoonal events. This was despite high storage capacity within the catchment and a predominance of subsurface inflows during storms. Saturation-excess can be attributed to the subdued topography and high soil permeability that may together induce optimal infiltration and ponding via a rise of the water table above the ground surface. In the Upper Burdekin catchment (BR in Fig. 1b), Jarihani et al. (2017) also attributed wet-season overland flow to the filling and spilling of shallow soil storage. These authors showed that infiltration-excess was more likely to occur in the drier months, due to high rainfall intensities and lower water tables. To assess the relative proportions of different water sources to high flow events, Duvert et al. (2020) developed mixing models adjusted to $\delta^{18}O$, electrical conductivity and tritium measurements in the Howard River, a monsoon-driven lowland system near Darwin (HR in Fig. 1b). Under high flow conditions, most streamflow originated from the slow drainage of wetland and floodplain stores, as well as from shallow groundwater discharge. Birkel et al. (2020) used a semi-distributed model based on δD and $\delta^{18}O$ time-series to simulate both water and solute movement in the same river system. These authors confirmed the role of seasonal wetlands as receivers and temporary stores of shallow subsurface contributions during the wet season.

Steeper catchments of the humid tropics are characterised by a wide range of hydrological responses, although subsurface stormflow seems to be the prevailing mechanism in these systems. Bass et al. (2014) measured the isotopic ratio of dissolved inorganic carbon ($^{13}C/^{12}C$, $\delta^{13}C$) in combination with $\delta^{18}O$ and δD at a high-resolution during a stormflow event in Atika Creek, a pristine forested stream (ACk in Fig. 1b). Isotopic values showed an initial period of significant overland flow contribution, but as streamflow peaked and receded, the system rapidly switched to an almost entirely subsurface contribution. Subsurface stormflow has also been observed in cleared areas of the humid tropics. Tweed et al. (2016) reported significant changes in $\delta^{18}O$ and δD at peak flow in Scheu Creek, an agricultural catchment south of Cairns (SCk in Fig. 1b), which they interpreted as enhanced discharge of shallow groundwater from saturated areas along the stream via translatory flow of pre-event water. Under particularly high antecedent wetness conditions and intense rainfall, however, overland flow was found to dominate the response in forested catchments, likely a result of the generally low permeability of the subsoil in certain areas (Bonell and Gilmour, 1978; Elsenbeer et al., 1995; Herwitz, 1986).

While surface and shallow subsurface water sources tend to prevail during stormflow events, deeper groundwater inflows can also play a key role in the hydrological response of Australian tropical catchments. Despite the rapid flow response and the dominance of shallow sources in the Howard River, Birkel et al. (2020) found that deep groundwater upwelling led to overall relatively old (>1 year) streamflow even during monsoonal bursts. Similarly, large contributions from 'old' groundwater to peak flow were detected in early work by Barnes and Bonell (1996) during low-intensity rainfall events. Groundwater discharging from fractured rock aquifers in upland areas of the humid tropics was also found to contribute the bulk of streamflow, even under high-flow conditions (Cook et al., 2001).

5.2. Recharge pathways

Evidence shows the importance of riverbanks and alluvial deposits in storing monsoonal rainfall. This process is particularly important in large, low-gradient rivers of the seasonal tropics and typically occurs through overbank flooding (Doble et al., 2012; Jolly et al., 2013; Taylor et al., 2018a). The increase in river stage at the peak of the wet season can be very substantial, with the width of inundation potentially exceeding 30 km in the lower Fitzroy River (Karim et al., 2018). Groundwater recharge from overbank flooding occurs across much of the seasonal tropics, and is likely to be the dominant recharge mechanism to alluvial aquifers in the more arid inland areas (e.g. the *BSh* climate zone).

Other localised recharge mechanisms are likely to occur across the region, in part because of intense chemical weathering of the land surface, which has resulted in large heterogeneities in the hydraulic conductivity of near surface materials. For instance, shallow lateritic horizons can contain solution cavities and macropores (Cook et al., 1998; Doyle, 2001; Hutley et al., 2000), while in areas underlain by carbonate rocks, karstification has created complex networks of sinkholes, conduits and caves (Karp, 2008; Tickell, 2011). Such heterogeneous structures in the subsurface are likely to lead to preferential flow and recharge pathways, which can represent a disproportionate contribution to aquifer recharge. Turnadge et al. (2018) showed that recharged waters to a dolostone aquifer of the NT were not subject to evaporative fractionation. This was inferred to be due to the bulk of recharge occurring via relatively fast, localised pathways such as buried sinkholes. This work was followed up by Enemark et al. (2020) who confirmed via model testing that depressions in the landscape likely act as conduits for preferential recharge. But these mechanisms are not limited to carbonate systems. For instance, sandy paleochannels in upland outcrop areas of the Mitchell catchment (QLD) have also been identified as key recharge zones (Taylor et al., 2018b).

Inter-aquifer flow can also be an important recharge process for lowland aquifer systems receiving limited diffuse recharge. The fractured rock aquifers in upland areas of the Great Dividing Range contribute to recharging alluvial and other sedimentary formations in the drier areas to the west, such as the Flinders and Gilbert catchments (Jolly et al., 2013). Further work is needed to better quantify mountain front recharge and inter-aquifer linkages across such areas. Overall, the role of landscape and geological heterogeneities in controlling groundwater recharge and the contribution of preferential recharge and overbank flood recharge relative to diffuse recharge remain largely unknown across much of tropical Australia.

5.3. Dry season water sources

Differences in the amplitude of rainfall seasonality strongly modulate the flow regimes of streams and rivers across the Australian tropics (Petheram et al., 2008b) (Fig. 3). After rainfall has largely ceased in the seasonal tropics, the magnitude and duration of flow recession is a function of the storage capacity of adjacent temporary stores (wetlands, floodplains, alluvial deposits, riverbanks) and of their state of connection with the channel (Fig. 3). Duvert et al. (2020) and Birkel et al. (2020) showed that the slow drainage of waters previously stored in connected floodplains maintains surface flows in the Howard River several months after the last rains. In larger rivers, return flow from bank and alluvial storage can be a major contributor to flow recession and, potentially, to dry season baseflow (e.g. Batlle-Aguilar et al., 2014; Jolly et al., 2013). Using simple numerical simulations based on cross sections of the Fitzroy River in the Kimberley (FR in Fig. 1b), Doble et al. (2012) demonstrated that after a major high flow event, several years may be required for all water stored in riverbanks to return to the river.

After shallow water sources have been depleted, the connection with larger, deeper groundwater stores becomes an important determinant of the dry season flow regime in the seasonal tropics. Where and when surface systems are not connected to regional groundwater, channels tend to break up into a series of discrete pools (Fig. 3). Using long-term hydrological records and modelling, Cresswell et al. (2009) suggested that intermittent streams and rivers are far more common than perennial systems across tropical Australia. This is often also the case in low-lying islands, where groundwater storage potential is very limited (but see Banks et al., 2021). After surface flow has ceased, subsurface flow often persists in the sandy deposits that underlie channels (Shanafield et al., 2021). Alternatively, perennial surface flow occurs in areas where regional aquifer systems discharge into surface water systems (Fig. 3), such as in the Cambrian Limestone Aquifer (e.g. Cook et al., 2003; Lamontagne et al., 2021; Smerdon et al., 2012), the Grant Group and Poole Sandstone aquifers (e.g. Gardner et al., 2011; Harrington et al., 2011; Taylor et al., 2018c) or other sedimentary or fractured rock aquifers (e.g. Jolly et al., 2013; Leblanc et al., 2015). Where surface flow is perennial, geological faults often provide preferential pathways for groundwater discharge (Harrington et al., 2011). Based on terrigenous helium-4 analyses, Gardner et al. (2011) and Smerdon et al. (2012) estimated that the baseflow of the Fitzroy and Daly Rivers (Fig. 1b; 3) had residence times of up to 1000 and 10,000 years, respectively. A major spring complex that feeds the Roper River (RR in Fig. 1b) also had long residence times associated with the Cambrian Limestone Aquifer, with possibly even older contributions from formations underlying the Cambrian Limestone Aquifer (Lamontagne et al., 2021). Late dry season streamflow in the Howard River, which is connected to a less extensive carbonate aquifer, was $>$ 100 years old (Duvert et al., 2020).

In more humid regions, shallow groundwater stores are likely to be replenished even during the drier months as a result of dry season storms, providing abundant baseflow to rivers all year round (Fig. 3). Cook et al. (2001) showed that groundwater inflows made up the main source of streamflow in areas of the Atherton Tableland (QLD; AT in Fig. 1b) underlain by fractured basalt lava flows, with isotopic evidence that young (<30 years) groundwater contained in the basalt discharged to streams throughout the year. In upland areas where forest cover has remained intact, McJannet et al. (2007) demonstrated the role of cloud interception as an important source of baseflow for streams during the drier months.

5.4. Uptake by vegetation

Due to the seasonal cycle in rainfall, most vegetation communities across tropical Australia are water-limited during the dry season, with evaporation rates as high as or higher than rainfall rates ($E/P \geq 1$; Fig. 2). An exception to this situation is for the rainforests of the humid tropics, where $E/P < 1$ even during the drier months (McJannet et al., 2007). Yet, despite the near absence of dry-season rain in the seasonal tropics, not all ecosystems of the region are limited by water availability. This is because water can occur in underground stores (e.g. deep soil horizons or capillary fringe of the water table) which support steady rates of overstorey evaporation through the dry season. Examples of this are the coastal savannas of the Top End in the NT (Hutley et al., 2000, 2001; Whitley et al., 2011), but also riparian corridors and other groundwater-dependent ecosystems scattered throughout the region (e.g. Canham et al., 2021; Drake and Franks, 2003; Duvert et al., 2022; Lamontagne et al., 2005). Several studies have examined the extent to which riparian trees may be reliant on groundwater. By comparing the isotopic composition (both $\delta^{18}O$ and δD) of potential tree water sources (soil water at different depths, groundwater) to that of xylem water, studies have shown that riparian trees tend to use shallow groundwater stores at the end of the dry season (Canham et al., 2021; Cook and O'Grady, 2006; Duvert et al., 2022; Lamontagne et al., 2005; O'Grady et al., 2006). Although few species used groundwater exclusively, these findings highlight the importance of alluvial and bank storage replenishment during the wet season. In contrast, savanna trees extract soil water from deep soil horizons, suggesting little to no groundwater dependence (Hutley et al., 2000; Kelley et al., 2007). However, the studies by Hutley et al. (2001) and Kelley et al. (2007) were conducted in high rainfall coastal savannas and little is known about the patterns of tree water uptake in lower rainfall inland areas, where savanna vegetation may be more vulnerable to changes in rainfall (Fig. 2).

As a complement to isotopic approaches, remote sensing techniques can offer opportunities to assess evaporation fluxes at broader, but also coarser, scales. Using MODIS products at a 250-m resolution, Crosbie and Rachakonda (2021) identified one area in the Roper River catchment (near Mataranka, NT; RR in Fig. 1b) where evaporation largely exceeds rainfall ($E/P > >1$)—a likely indication of groundwater dependence. Despite the challenge of modelling savanna evaporation due to the different water use patterns of trees and grasses, recent modelling efforts have enabled improved estimates of the seasonal variations in the evaporation flux across the seasonal tropics (Zhuang et al., 2020). More field observations are now needed to advance our understanding of the sources and temporal dynamics of root water uptake at both local and larger scales, and how this uptake may affect other components of the water cycle such as recharge and runoff. Remotely-sensed evaporation data have potential to improve streamflow modelling (Herman et al., 2018; Rajib et al., 2018), and we believe that finer estimates of evaporation fluxes will also improve hydrological understanding and modelling at small catchment scales.

6. Anticipating hydrological responses to climate change and future development

6.1. Interannual flow variability and unknown effects of climate change

Interannual variability in rainfall is ~40% higher in tropical Australia compared to other tropical regions of the world with similar mean annual rainfall (Petheram et al., 2008b). This variability can be explained by the influence of large-scale atmospheric patterns such as the El Niño Southern Oscillation (ENSO; Nicholls et al., 1997), Interdecadal Pacific Oscillation (Power et al., 1999), and by the episodic impact of cyclones across northern Australia. The effect of ENSO on rainfall can in turn drive significant interannual changes in river flow (Chiew and McMahon, 2002), as exemplified with the Mitchell River (Fig. 3). This interannual variability is particularly extreme in more arid, inland areas of the Australian tropics (Petheram et al., 2008b), where it is the rarer, larger rainfall events that tend to generate aquifer recharge. Recent isotopic investigations suggest that the passage of tropical cyclones is key to replenishing groundwater stores in lower rainfall areas of the region (Meredith et al., 2018; Skrzypek et al., 2019).

Climate models project an increase in the frequency and intensity of extreme rainfall in tropical Australia (Alexander and Arblaster, 2017; Jourdain et al., 2013), although large uncertainties remain (Dey et al., 2019). The effect of these expected changes on hydrological regimes are also uncertain, with projections ranging from decreases (by up to 26%) to increases (by up to 29%) in mean annual runoff across the Australian tropics (Petheram et al., 2012b). Because runoff generation and flow duration are highly dependent on the timing and intensity of rainfall, changes in rainfall may exacerbate river flow variability. Modelling by Karim et al. (2016) indicates that the connectivity between wetlands and rivers could last up to 20% less in a drier climate than under the current climate, while the connectivity could be 5% longer under a wetter climate. An increase in potential evaporation rates can also be expected in tropical Australia (Pan et al., 2015), likely driven by changes in rainfall, temperature and increased atmospheric CO_2—noting there remains uncertainty around other key variables such as wind speed. While we lack data to constrain the uncertainties in these processes, it is possible that altered potential evaporation rates during key hydrological periods may alter the response of catchments, particularly during "shoulder" seasons (e.g. delayed wetting-up or early drying-out), and potentially contribute to increased flow intermittency. In addition, the expected increase in cyclone intensity (Knutson et al., 2015) might induce increased runoff and recharge in drier areas of the region. Obviously, the above statements are speculative given the current lack of knowledge, and further research investigating the effects of changing rainfall and evaporation patterns on the hydrological response of Australian tropical streams and rivers is needed.

6.2. Development will alter hydrological partitioning and flow regimes

Agricultural development in the humid tropics of Australia has occurred since the middle of the 19th century, with land cleared for sugarcane production and pasture development for dairy and beef cattle (Harding, 1972; Kemp et al., 2007). Large-scale deforestation, particularly on the coastal plains, has likely led to important changes in the hydrological response of catchments of the region, some of which have been investigated in detail (see Section 3). In contrast, the seasonal tropics have been historically less affected by land disturbance, with much of the land used for extensive cattle grazing on improved and native savanna vegetation (ABARES, 2021). However, since the 2000 s the Federal, state and local governments have focused on opportunities presented by the vast area and abundant water resources of the seasonal tropics (see Section 4). In recent years there has been a renewed push for development of primary industries in the seasonal tropics. Some of the policy initiatives responding to this push are the White Paper on *Developing Northern Australia* (Commonwealth of Australia, 2015) and the establishment of a $1B National Water Infrastructure Development fund in 2018, with $200 M committed to northern Australia (Hart et al., 2020; Watson et al., 2021). The current desire to expand irrigated agriculture in the region is accompanied by an interest to develop shale gas extraction in several sedimentary basins including the Beetaloo Sub-basin (Knudsen et al., 2019), which underlies parts of the Cambrian Limestone Aquifer (Fig. 1). While these potential developments are likely to affect streamflow and groundwater dynamics, considerable uncertainty remains as to how surface and groundwater systems will respond to these changes across the region.

Some of the expected impacts are directly associated with land disturbance. For instance, in the few places where dryland cropping is viable and where savanna woodland will be replaced by cropland, increases in storm runoff and decreases in infiltration can be anticipated. An early study by Ive et al. (1976) near Katherine in the NT (K in Fig. 1b) found that almost 40% of rainfall occurring on grassland was translated downslope as infiltration-excess overland stormflow. At a research farm in the Daly River area, Dilshad and Peel (1994) showed that tillage and low vegetation cover resulted in nearly twice as much overland flow relative to cropping soil under zero till. Conversely, Bartley et al. (2014) found that increased ground cover in the semi-arid tropics of the Upper Burdekin catchment resulted in lower hillslope runoff coefficients during early wet season events. However, the expected decreases in infiltration rates following soil disturbance may be counterbalanced by a decrease in evaporation resulting from the replacement of native vegetation by shallow-rooted pasture or cropland. Groundwater level rise and waterlogging following land clearing has been a common observation in the southern parts of the country (e.g. Allison et al., 1990; Sharma et al., 1987), and could eventuate in areas of the tropics where the water table is already shallow. Despite lacking detailed investigations, these early results suggest that local modifications to the land cover and soil structure of tropical savannas may have considerable impacts on the partitioning between runoff and recharge in those areas.

Aside from the direct effects of land use change, which will likely be restricted to a small proportion of the landscape, important questions arise from the potential impacts of water resource development projects. First and foremost, groundwater abstraction for irrigation and the mining industry may have important effects on flow regimes and groundwater-dependent ecosystems. Modelling results reported by Chan et al. (2012) suggest that groundwater development may significantly alter the natural flow regime of the Daly River (NT) in the dry season by increasing flow intermittency and reducing lateral (river–floodplain) and longitudinal (upstream–downstream) connectivity. Because the regional groundwater that discharges into rivers can be very old (see Section 5.3), the effects of groundwater abstraction on river baseflow may occur long after development started, as was modelled for the Roper River in the NT (Bruwer and Tickell, 2015). Furthermore, there is broad consensus from isotopic studies that riparian trees in the seasonal tropics tend to use shallow groundwater stores at the end of the dry season (Canham et al., 2021; Cook and O'Grady, 2006; Duvert et al., 2022; Lamontagne et al., 2005; O'Grady et al., 2006), indicating that a lowering of the water table due to groundwater development may alter the composition and abundance of some riparian ecosystems.

Apart from impacts linked to groundwater abstraction, unconventional gas mining operations may further alter natural groundwater flow processes. Hydraulic fracturing for shale gas extraction has the potential to increase the connectivity between exploited aquifers and deeper formations via preferential flow through faults or fractures (Myers, 2012). Of interest in the northern Australian context are the possible vertical connections between the Cambrian Limestone Aquifer and underlying formations containing high salinity water (Frery et al., 2022; Lamontagne et al., 2021).

The construction of dams for irrigation is also likely to affect the hydrological functioning of streams and rivers in northern Australia. Dam release during the dry season means that some intermittent streams can become permanent (e.g. Bunn et al., 2006), with potentially important ecological consequences (Close et al., 2012; Rolls and Bond, 2017). Another dam-related impact is the possible reduction of downstream flooding due to the storage and capture of flood waters during the wet season. Karim et al. (2015) estimated that the construction of large dams in the Flinders and Gilbert catchments would have a relatively small impact on river–floodplain connectivity, but Nielsen et al. (2020) found that the inundated area of floodplains in the lower reaches of the Mitchell River could potentially be reduced by $> 50\%$ following dam construction. While this has not been examined in detail, the decrease in flooding extent and duration may also result in decreasing rates of overbank flood recharge, a key recharge process in much of the region. Another effect of dams and irrigation could be the rising of water tables and increasing salinity in shallow aquifers, as was observed in the lower Burdekin catchment in QLD (Petheram et al., 2008a). While small-scale water harvesting is the more likely type of development in northern Australia, it is necessary to anticipate the hydrological impacts of the few large dams that might be built across the region (Petheram et al., 2018).

Overall, there remains important unknowns surrounding how future land use change and water resource development will impact the hydrology of northern Australian streams, rivers and aquifers, as well as their associated ecosystems. While basic hydrological assessments and modelling are certainly needed to address these unknowns and anticipate future change, there is an equally important need for research programs that generate new data, examine hydrological processes at different scales and the way these respond to different forcing, and advance our conceptual understanding of catchment functioning in tropical Australia. We believe this should be achieved through intensive and long-term studies of experimental catchment observatories that capture the diversity in landscapes and climates of the region, as detailed in Section 7.

7. A research agenda for hydrological science in tropical Australia

Despite improved understanding over recent decades, our knowledge of key hydrological processes in the Australian tropics remains incomplete. Limited observations across this vast and diverse tropical region prevent a more detailed description of the role of heterogeneities in both landscape and meteorological factors in modulating hydrological responses. In addition to new observations, we also need new cross-disciplinary initiatives centred on the understanding of the critical zone (i.e. the near-surface environment from treetops to the water table) as an integrated system made of interacting components and processes. Improved coordination among hydrological subdisciplines and with other disciplines can facilitate the development of hydrological theory and prediction of hydrological functioning across time and space (Brooks et al., 2015). Through the utilisation of multiple disciplines, we can develop a baseline understanding of how tropical streams and rivers function at present, against which to assess the effects of future development and climate change (Wright et al., 2018). In the following, we propose five broad research areas that we believe should be priorities for future hydrological research in northern Australia. These areas relate to (1) stormflow response, (2) groundwater recharge, (3) interactions with vegetation, (4) groundwater discharge, and (5) hydrological (dis)connectivity. For each research area we outline the need for improved mechanistic understanding as well as implications in the context of future development and climate change. We conclude by discussing the needs to build a network of experimental observatories across the tropics and to better integrate Indigenous perspectives into hydrological science and management.

7.1. Stormflow response

Can we improve our conceptual understanding of the dominant runoff processes across the region, and develop spatialised estimates of the partitioning between runoff and infiltration? In lowland areas of the Australian tropics, saturation-excess overland flow may be the dominant runoff mechanism. But more observations are needed to evaluate the exact role of saturated areas along streams and rivers in generating runoff during the wetter months. Only by understanding how streamflow is generated across the landscape can we then predict the likely impacts of development on these processes. Additionally, the potential occurrence of preferential flow pathways through macropores in shallow lateritic horizons, as observed in other settings (Cuthbert and Tindimugaya, 2010; Ruprecht and Schofield, 1993), needs further examination in the northern Australian context, particularly in relation to how macropores contribute to the hydrological response of catchments under monsoonal conditions. One other key question is related to the way land disturbance (whether it is clearing for agriculture, change in fire management regimes or weed infestation) may impact the partitioning between runoff and infiltration. For example, an important component of land use in the seasonal tropics is extensive livestock grazing (ABARES, 2021). Grazing can significantly reduce infiltration rates due to soil compaction and erosion (Gifford and Hawkins, 1978; Greenwood and McKenzie, 2001) and decreased termite activity (Holt et al., 1996). Likewise, post-logging changes in soil properties and vegetation cover have led to decreased infiltration and increased overland flow during stormflow events in both the humid (Bonell, 1993; Cassells et al., 1985) and seasonal tropics (Ive et al., 1976). We need new field studies that assess the effect of both land clearing and changed grazing intensity on infiltration and recharge rates for contrasting areas of the Australian tropics. Importantly, changes in rainfall patterns due to climate change will be superimposed over any impacts from land use change. Studies that combine both these driving factors will provide key information to resource managers and decision makers.

7.2. Recharge

What are the relative contributions of overbank flood recharge and other preferential recharge pathways across the Australian tropics? Overbank flooding likely plays a major role in recharging the alluvial and underlying aquifers of large, low-gradient rivers (Doble et al., 2012; Jolly et al., 2013; Taylor et al., 2018a). However, there has been little effort to accurately quantify this recharge pathway and to highlight its importance in replenishing groundwater systems of the seasonal tropics relative to diffuse recharge. This is much needed information, especially if we are to predict the effect of dam construction and/or groundwater abstraction on the loss of downstream river–floodplain connectivity and, in turn, on recharge rates. Other recharge pathways also need more research. The typically heterogeneous subsurface in tropical Australia, resulting from intense weathering and tectonic deformation, indicates that much of the unsaturated and saturated flow may occur via preferential pathways (e.g. Enemark et al., 2020; Jolly et al., 2013; Taylor et al., 2018b). Despite its importance, the role of structural heterogeneities in controlling groundwater recharge as well as vertical connectivity remains unclear in the region. New studies should focus on assessing the contribution of preferential flow as a recharge pathway to underlying aquifers relative to diffuse recharge and overbank flood recharge. Imaging the structures of the subsurface via geophysical measurements is a promising avenue for the delineation of preferential pathways. For instance, airborne electromagnetic surveys have been successfully used to map geomorphologic features relevant to hydrological processes (Christensen et al., 2017; Jiang et al., 2019; Parsekian et al., 2015). Ultimately, these data will enable better management and protection of the areas identified as key recharge zones and ensure long-term, more sustainable use of groundwater resources.

7.3. Plant water uptake

What is the role of vegetation in partitioning water fluxes, and can we predict the vulnerability of different vegetation communities to change? Water uptake by vegetation plays a central role in the hydrological cycle, as it partitions rainfall into evaporation and recharge. From a hydrological point of view, accurate understanding of the mechanisms and patterns of plant water uptake is vital to successfully simulate catchment flow processes (Knighton et al., 2020; Kuppel et al., 2020; Sprenger et al., 2019; Yang et al., 2016). In tropical Australia, most studies have focused on identifying groundwater use by riparian trees in the dry season (e.g. Canham et al., 2021; Lamontagne et al., 2005; O'Grady et al., 2006), but many questions remain regarding both temporal and cross-ecosystem variations in plant water use. For instance, little is known about the sources and patterns of water uptake for different vegetation types (savanna, rainforest, riparian corridors), and how these vary under different wetness conditions. In-situ isotope measurements, although still in their infancy, can be particularly useful to fingerprint the sources of water extracted by vegetation and changes over time (Kühnhammer et al., 2022; Seeger and Weiler, 2021). Spot measurements of stable isotopes can also add important information, although questions currently arising around the potential biases associated with water extraction techniques should not be ignored (Allen and Kirchner, 2022; Barbeta et al., 2022; Chen et al., 2020). Because plant water uptake and productivity are also controlled by the structure of the subsurface, particularly in water-limited environments, geophysical methods can provide additional insights into where plants obtain water (Brooks et al., 2015; Parsekian et al., 2015). A solid understanding of plant water uptake at local and regional scales is a critical step towards addressing the potential impacts of water resource development on vegetation communities. Key questions remain on the condition and abundance of groundwater-dependent ecosystems, how these may change under different types of development, and whether species can adapt in response to changes in water table depth, particularly in the dry season. While clear advances have been made to predict the ecological responses of riverine ecosystems to changes in surface water flow (e.g. Pettit et al., 2017; Warfe et al., 2011), much more needs to be done to understand how groundwater-dependent vegetation may respond to human-induced and climate change impacts.

7.4. Groundwater discharge

How old and vulnerable are groundwater and spring systems across the Australian tropics? Compared to the detailed investigations of springs in the arid zone of Australia (e.g. Flook et al., 2020; Keppel et al., 2012; Love et al., 2013), there is limited information on flow pathways and water ages of spring systems in the tropics. Groundwater contained in the large sedimentary basins of northern Australia can be extremely old (e.g. Harrington et al., 2011 reported groundwater from the Grant Group and Pool Sandstone aquifers over 30,000 years old), and it has been shown that several spring-fed rivers of the region are sustained by deep, old groundwater sources (Gardner et al., 2011; Lamontagne et al., 2021; Smerdon et al., 2012). However, an inventory and assessment of the origins of spring water, their age and yield for northern Australia is currently lacking. This information is key to understanding the vulnerability of tropical springs to future development—for instance, the effect of groundwater abstraction on river baseflow and/or spring yields may not be experienced for several decades or centuries because of the lags inherent to old, regional groundwater systems. All three major aquifer systems (Fig. 1b) have extensive unconventional gas reserves, and the availability of water for hydraulic fracturing is a contentious issue for local communities. Given the cultural and environmental significance of springs in northern Australia, it is essential that the best available science is used to assess vulnerability prior to project approvals where spring flow may be affected. The approval of the Carmichael Coal Mine in QLD is a high profile example where this was not the case (Currell et al., 2020). Furthermore, there is limited data on the importance of groundwater discharge into other aquifers (i.e. inter-aquifer flow), although this may be an important pathway in areas located downgradient of upland fractured rock aquifers (Jolly et al., 2013). As water allocation policy in Australia seeks to avoid double allocation, future research should aim to quantify these inter-aquifer linkages.

7.5. Flow intermittency

Can we anticipate how flow regimes and hydrological connectivity will be affected by climate change and development? There is a clear need to assess the security of water supply in the Australian tropics under future climate and development scenarios. While climate models generally project an increase in the intensity (and possibly frequency) of extreme rainfall events in tropical Australia, the effect of these changes on hydrological regimes have been rarely considered. The impact of potential changes to rainfall patterns requires further investigation, but uncertainties in climate model predictions present challenges. For example, simulations across northern Australia under a 1 °C warming scenario resulted in an increase in runoff for half the global climate models tested and in a decrease for the other half (Petheram et al., 2012b). One possible scenario is that shifts in flow regimes due to changes in rainfall and evapotranspiration will exacerbate the duration and frequency of dry phases (Döll and Schmied, 2012). A recent study suggests that flow intermittency has increased in Australia in the past few decades (Sauquet et al., 2021), although there was no clear trend for tropical rivers. Because increased intermittency would have large implications for riverine ecosystem health (Datry et al., 2016; Rolls and Bond, 2017), the mechanisms by which climate change may exacerbate or reduce flow intermittency require further examination. Non-perennial river systems are governed by distinctive and complex hydrological processes that have not yet been fully described (Shanafield et al., 2021). Better understanding these processes in the northern Australian context is imperative for anticipating the potential consequences of altered flow regimes across the region. Also important is the potential effect of water resource development (dam construction and/or groundwater abstraction), with dam construction likely to suppress flow intermittency (Bunn et al., 2006) and groundwater abstraction likely to increase flow intermittency and reduce connectivity (Chan et al., 2012; King et al., 2015;

McCallum et al., 2013). The few studies that have modelled the impacts of development scenarios in northern Australia suggest that reductions in flow connectivity may occur (e.g. Nielsen et al., 2020). We now need further research that underpins an ability to predict the responses of tropical streams and rivers to future climate and development scenarios.

7.6. Towards a network of observatories

As illustrated by the pioneering work carried out in the Babinda catchments, long-term and intensive monitoring of experimental sites is essential to advance our understanding of the hydrological cycle. Burt and McDonnell (2015) highlight that the hydrological community needs long-term experimental catchments in the tropics, where observations remain scarce and process understanding is lacking. In the seasonal tropics in particular, the lack of high-resolution and long-term hydrological data continues to limit our hydrological understanding as well as the robustness of water resource assessments and thereby water allocation policy (Petheram et al., 2012a). Observations are required not only to unravel the processes of streamflow generation, recharge pathways and ecohydrological interactions, but also to develop and test predictive models, and ultimately to provide an evidence base for informed decision making (Tetzlaff et al., 2017). There are established networks of experimental catchments in North America (e.g. White et al., 2015) and in Europe (e.g. Bogena et al., 2016; Gaillardet et al., 2018), and the emerging Australian Critical Zone Observatory Network (OZCZO; funded through the Australian Research Council) represents a step forward in integrating below- and above-ground environmental processes, but at this stage focuses mostly on the soil and groundwater compartments of the critical zone. Similarly, the newly established, $15 million long-term groundwater monitoring network (Groundwater Super Science; funded through the National Collaborative Research Infrastructure Strategy) does not include any sites in the tropics. Working towards the establishment of a network of research observatories across tropical Australia should be a priority, and to this end, the Daintree Rainforest Observatory (DRO) in the humid tropics (Bass et al., 2011; DRO in Fig. 1b) could be paired with representative catchments of the seasonal tropics such as the Weany Creek long-term monitoring site (Bartley et al., 2006, 2014; Koci et al., 2020; WCk in Fig. 1b). In addition to the acquisition of high-resolution data, a key focus of these observatories should be the extrapolation and upscaling from small experimental catchments to larger, regional river and groundwater systems. Cross-site comparisons can help with identifying mechanisms that are generalisable across space and time (Brooks et al., 2015). Experimental sites will contribute to accurate and long-term quantification of water and energy fluxes at the regional scale, which will in turn assist management and policy decisions. Such evidence base is particularly needed in the northern Australian context, with the predicted effects of climate change and the ongoing push by the Federal and state governments for the development of primary and mining industries.

7.7. Integrating Indigenous perspectives

Indigenous people make up a large proportion of the population in northern Australia, and almost two thirds of remote Indigenous communities rely primarily on groundwater for their main source of drinking water (Australian Bureau of Statistics, 2006). Many of these communities are facing increasingly pressing issues that undermine their water security, including groundwater depletion and heavy metal contamination (Howey and Grealy, 2021). To address these water security issues, both local and regional scale assessments of surface and groundwater systems are urgently needed across remote areas of northern Australia. More generally, water governance in Australia has largely overlooked the interests and perspectives of Indigenous Australians until recently (Jackson et al., 2015; O'Donnell et al., 2022). Greater involvement of Indigenous organisations will be key to the success of future water resource development projects across the north. Research aimed at integrating and translating Indigenous knowledge of hydrological systems into Western science is necessary to not only improve understanding of Indigenous water resource use, but also to inform water management activities (Robinson et al., 2016; Woodward et al., 2012).

CRediT authorship contribution statement

Clément Duvert: Conceptualization, Writing – original draft. **Han-She Lim**: Conceptualization, Writing – review & editing. **Dylan J. Irvine**: Conceptualization, Writing – review & editing. **Michael I. Bird**: Conceptualization, Writing – review & editing. **Adrian M. Bass**: Conceptualization, Writing – review & editing. **Sarah O. Tweed**: Conceptualization, Writing – review & editing. **Lindsay B. Hutley**: Conceptualization, Writing – review & editing. **Niels C. Munksgaard**: Conceptualization, Writing – review & editing.

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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