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Revisiting Michael Bonell's work on humid tropical rainforest catchments: Isotope tracers reveal seasonal shifts in catchment hydrology

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Abstract

It has been almost 50 years since the foundational work at the Babinda catchments in North Queensland kickstarted the field of tropical hydrology globally. To expand upon this work and build a more generalized hydrological understanding of steep rainforest catchments, we studied the seasonal evolution of hydrological response from two catchments with broadly similar characteristics to the Babinda catchments. Both hydrometric and water stable isotope data were collected at relatively high frequencies during one wet season (Thompson Creek) and a 3-year period (Atika Creek). The longer dataset spans a wide range of environmental conditions experienced in the humid tropics, including events that cover the wetting-up transitional period of the wet season and tropical cyclones (TC). Both catchments displayed a fast streamflow response to rainfall with the shallow upper soil profile responding quickly to rainfall at Atika Creek. New findings from this study include the importance of pre-event water (>50% using the two component hydrograph separation technique) for overall event flows, especially when the catchment was wet. Rainfall, surface runoff and groundwater isotope and specific electrical conductivity (SEC) compositions varied between rainfall events with the most complex bivariate mixing plots observed for multi-peak events that occurred at the start of the wet season and after a dry period within the wet season. Two-tracer, 3 component hydrograph separations did not provide satisfactory results in identifying source water contributions to streamflow. These results highlighted the time-variant and non-conservative behaviour of the rainfall, surface runoff and shallow groundwater source waters over the seasonal timescale, with soil water being an important unidentified source contributor. Our findings highlight the need for high frequency multi-source sampling to accurately interpret catchment behaviour and the importance of soil water contributions to streamflow. We propose a framework to describe the seasonal evolution of streamflow response in steep tropical rainforest catchments experiencing seasonal rainfall activity.

KEYWORDS
seasonal tropical rainfall, steep forest catchments, time-variant endmembers

1 | INTRODUCTION

The work by Michael Bonell and his colleagues in Northeastern Queensland, Australia, represented one of the earliest attempts to examine the streamflow generation processes in humid tropical forest catchments. Over the years, their work combined intensive hydrometric and hydrochemistry monitoring at the hillslope and catchment scale. The catchments, North and South Creek (also known as the Wyvuri or Babinda catchments) were first instrumented in 1969 by the Queensland Forestry Department's rainforest research programme with monitoring maintained by Dr. Don Gilmour and David Cassells. Mike Bonell's involvement started in the mid-1970s and together, their research focused on understanding runoff pathways in the undisturbed tropical rainforest catchment (South Creek) at Babinda. This work extended to other regional rainforest catchments, to investigate the likelihood of similar runoff processes by characterizing soil hydraulic conductivity patterns across the Wet Tropics (Bonell et al., 1983a, 1983b; Bonell & Gilmour, 1978; Cassells et al., 1985; Gilmour & Bonell, 1979; Figure 1). Stable water isotopes and other tracers were used to understand source water contributions (Elsenbeer et al., 1994; Elsenbeer et al., 1995). Hydrologic modelling was also conducted to understand rainfall-runoff response behaviour, particularly the forested South Creek catchment (Barnes & Bonell, 1996, 2012).

FIGURE 1 Infiltration/permeability experiments circa 1976/77 with Mike Bonell featured on the left (photo credit: Don Gilmour)

Both North and South Creek are in the wettest parts of NE Australia with annual rainfall ranging between 2000 and >7000 mm. Rainfall is highly seasonal and depends on monsoonal and tropical cyclone (TC) activity (Petheram et al., 2008). Even though the catchments are forested, they exhibited fast responses to rainfall (Bonell et al., 1998). This 'flashy' catchment response reflected a combination of synoptic climatic conditions, largely associated with the monsoon trough, that result in intense and continuous rainfall during the wet season (Bonell et al., 2004; Bonell & Callaghan, 2009). Anisotropic soils (highly conductive shallow soil layer <0.25 m deep) where a sharp change in saturated soil hydraulic conductivity (Ks), by up to three orders of magnitude (<1 mm/h), encouraged shallow subsurface flow (SSF) in the upper conductive soil layer to occur (top 25 cm). Saturated overland flow (SOF) occurred when the soils became saturated and was highly sensitive to rainfall intensity and soil properties (soil storage in the upper layers, spatial variation in Ks) (Barnes & Bonell, 1996; Bonell et al., 1983a; Elsenbeer et al., 1995; Howard et al., 2010). Water movement into the subsurface was slow, unless aided by preferential pathways (macropores) which recharged and linked the deep groundwater reserves to surface pathways and the stream (Barnes & Bonell, 1996, 2012; Bonell et al., 1981, 1983c, 1998; Bonell & Gilmour, 1978). The importance of surficial flow pathways in both catchments contradicted the prevailing opinion that forested catchments were dominated by subsurface flows (Dunne, 1978; Hewlett & Hibbert, 1967; Kirkby, 1978).

Fast streamflow responses were also observed in other forested tropical catchments outside Australia where climatic conditions and soil hydraulic conditions were similar. Examples include La Cuenca, Peru (Elsenbeer et al., 1995; Hensel & Elsenbeer, 1997), French Guyana (Bonell & Fritsch, 1997), Panama (Barthold et al., 2016; Zimmermann et al., 2014), and Costa Rica (Birkel et al., 2021). Catchments subject to less intense, but continuous rainfall activity displayed a more dampened streamflow response than the Babinda catchments, despite having similar soil characteristics (Chappell et al., 2012, 2017).

The extensive monitoring of individual storm events at the Babinda catchments also provided an important glimpse into seasonal changes in streamflow response. Changing rainfall intensity and catchment wetness conditions affected flow pathways and source water contributions. As the catchments became progressively wetter and more connected during the wet season, intense rainfall caused widespread SSF and SOF. Over 45% (even up to 80%) of the storm hydrograph was made up of new water contributions (Bonell, 1993; Bonell et al., 1998; Elsenbeer et al., 1995). At the end of the wet season, surface runoff pathways declined in importance due to reduced rainfall frequency and intensity. SSF became the dominant pathway for catchment waters reaching the stream (Bonell et al., 1981, 1983c; Bonell & Gilmour, 1978; Cassells et al., 1985). The dynamic changes in source water contributions and runoff pathways presented difficulties in modelling the rainfall–runoff response behaviour, where model parameter values varied between wet and post-wet seasons, highlighting non-stationarity in rainfall–runoff conversion within and between seasons (Barnes & Bonell, 2012).

Within the seasonal timescale, the wetting-up/drying phases (transitional periods) are periods of time when the catchment response behaviour is most non-linear (Ali et al., 2013). This is especially the case for intermittent/ephemeral streams which transition from low/no flow conditions to high flows during the wet season and vice versa in the dry season (Boulton et al., 2017; Shanafield et al., 2020). Yet little is known about how catchments behave during these transitional periods. Rainfall at the start of the wet season was found to recharge deep groundwater reserves via preferential pathways at the South Creek catchment (e.g., macropores, Bonell, 1993). For tropical montane cloud forests in Mexico, the relative contributions of event and pre-event water contributions changed over the wetting-up phase of the wet season (e.g., Muñoz-Villers & McDonnell, 2012). Characterizing the seasonal evolution of streamflow response in terms of runoff pathways and source water contributions improves understanding of the rainfall-runoff behaviour of seasonal tropical catchments, particularly for the purposes of improved water resources and quality management (Messager et al., 2021; Shanafield et al., 2020).

This paper aims to build upon Bonell's work by examining the streamflow responses of forested catchments in the same region with similar catchment characteristics to the Babinda catchments. The catchments chosen for this study experience intermittent flow in comparison to the Babinda catchments which experience perennial flow. We seek to identify common patterns in streamflow response through continuous hydrometric monitoring combined with high frequency analysis of stable water isotopes. The objectives of this paper are to examine:

1. if drier/more seasonal streams of the region behave similarly to the wetter/perennial Babinda streams,
2. the role of rainfall properties and catchment wetness in controlling streamflow response, particularly focusing on the progression through the wet season.

2 | METHODS

2.1 | Study sites

Thompson Creek and Atika Creek are two small, forested catchments in NE Queensland that have intermittent flow characteristics. Both catchments are in the tropical monsoon (Am) climatic zone experiencing dry months where rainfall totals less than 60 mm occur. Thompson Creek is located in the Daintree region, approximately 140 km north of Cairns. Atika Creek is located approximately 15 km north of Cairns. North and South Creek catchments experience a tropical rainforest climate (Af) according to the Köppen-Geiger climate classification system, with rainfall throughout the year with a minimum of 60 mm of rainfall in any month (Kottek et al., 2006). Rainfall in this region is generated by convection storms during the early wet season. Monsoon and TC rainfall dominate rainfall activity as the wet season progresses (Bonell & Callaghan, 2008). Rainfall activity outside the wet season is mostly from moist onshore rainfall due to the southeast trade winds (McJannet et al., 2007). The hydrological year starts in November and finishes at the end of October the following year. The wet season starts from November and finishes at the end of March. The dry season commences at the beginning of April and finishes at the end of October.

Both Thompson and Atika Creek catchments have similar physical characteristics which are summarized in Table 1. The Thompson Creek catchment is located in relatively undisturbed mesophyll vine forest while the Atika Creek catchment is covered by tropical rainforest transversed by numerous mountain bike trails which may act as overland flow pathways transporting water to the drainage network during storm events. The soils of both catchments are dermosols developed over rock (Atika) or have a significant number of rocks mixed with the soil (Thompson Creek) (Paul Nelson, personnel communication). Saturated hydraulic conductivities (Ks) were not measured for the study sites but display the same trend as the Babinda catchments where a highly conductive shallow soil occurs above less conductive soils (Cassells, personnel communication). An estimate of the Ks values for Atika Creek are presented here, based on an extensive study of soil hydraulic properties conducted by the CSIRO Division of Soils that incorporated the major soil groups of the region. The site with soil properties most similar to Atika Creek has the following Ks values for the different depth ranges: 12.89–170.76 m/day (0–0.1 m), 2.8–24.69 m/day (0.1–0.2 m), 0.068–0.51 m/day (0.5–0.5 m), and 0.036–0.16 m/day (0.5–1.0 m) (Bonell et al., 1983a; Cassells et al., 1985).

2.2 | Hydrometric monitoring

This paper presents data from 2019 to 2021 for Atika Creek, which has a more complete dataset of the two catchments. Monitoring started at Atika Creek in January 2019 and soil moisture monitoring was added in November 2020 until July 2021. Thompson Creek has a more limited dataset, which spans the 2016/2017 wet season and stopped in July 2017 after the streamflow sensor was washed away in a storm event. As a result, most of the data and analysis presented in this paper focuses on Atika Creek.

Rainfall was monitored using a Hobo RG3-M tipping bucket rain gauge (Atika Creek). A Nylex rainfall sampler was used to measure rainfall for Thompson Creek. This meant that rainfall information for Thompson Creek was only available at the daily timestep and calculations of short-term maximum rainfall intensity (e.g., 6 min) was not possible for this site. Streamflow was monitored using a Unidata Starflow ultrasonic doppler instrument at both sites, at a 10-min frequency. Although the Starflow Doppler instrument measured both water depth and velocity, a rating curve showing the relationship between water depth and discharge was developed. Velocity measurements were conducted using the velocity-area method with a current meter and dilution gauging with salt to cover the range of flows

TABLE 1 Catchment properties for Atika and Thompson Creek catchments relative to the Babinda catchments (North, South Creek)

	Thompson Creek (Daintree National Park)[a]	Atika Creek[b]	North/South Creek[c]
Catchment area (km^2)	1.7	1.57	0.183 0.257
Highest elevation (m asl)	875	508	118 199
Annual rainfall (mm)	4900[a]	1992[b]	4259[c] (Max 7040)
Wet season rainfall (% of annual total)	79[d]	85[e]	75[f]
Climate (Köppen-Geiger)	Am (tropical monsoon)	Am (tropical monsoon)	Af (tropical rainforest)
Streamflow	Intermittent	Intermittent	Perennial
Geology	Metamorphics and Granite	Metamorphics (Hodgkinson Formation)	Metamorphics
Slope (°)	Up to 40° (at the ridgelines) Approx. 8.5° (at monitoring site)	25–30°	6.4° 16.5°
Soils	Acidic, dystrophic, brown Dermosol with 20%–50% stone and cobbles throughout the soil profile	Brown and red demosols	Kaolin dominated silty clay loam to clay soils
Vegetation	Complex mesophyll vine forest	Pristine rainforest, open eucalypt forest on steep slopes and ridgelines	Regenerated forest/mesophyll vine forest disturbed by cyclone activity

[a] Bass et al. (2011).
[b] Bass et al. (2014).
[c] Bonell et al. (1998).
[d] Based on data from 2017–2021.
[e] Based on data from 2019–2021.
[f] Based on data from 1911–2020 (*Source*: http://www.longpaddock.qld.gov.au/silo).

experienced by both catchments. Discharge values were obtained using the rating curve.

At Atika Creek, shallow soil water content was measured using TOMST TMS-4 soil moisture sensors that measure volumetric soil moisture in the top 14 cm of the soil profile at 15-min intervals at two locations. Site 1 is located further up the catchment while Site 2 is located closer to the streamflow monitoring site (Figure 2). Each location has two soil moisture sensors installed. The two sensors at Site 1 were located at the top and bottom of a short hillslope while the sensors were spaced approximately 10 m apart at Site 2 which was located on relatively flat topography at the bottom of a short hillslope, located close to the stream. Surface runoff was collected from the hillslopes near Site 2 using a 50 cm wide metal trough with the uphill facing lip placed flat on the ground. A receiving bottle was connected to the deepest point of the trough and included an airlock tube so only the initial flow was sampled.

2.3 | Water sampling for isotope and geochemical tracers

Water sampling occurs over the same time as hydrometric monitoring activities for both catchments. Water sampling at Thompson Creek was limited to rainfall, streamflow, and groundwater samples. The Atika Creek site had additional samples taken from the soil profile and surface runoff.

Streamflow samples were collected over the course of rainfall events using an automatic water sampler for both catchments (Model 3700, Teledyne ISCO Inc.). Sampling varied from 30 min to 2 h depending on the predicted rainfall and likely streamflow response behaviour. For example, a 2-h sampling interval was chosen for a long-duration event in order to capture both rising and recession limb of the storm hydrograph. Manual grab samples were taken during non-event flows on a weekly basis.

Soil samples were only collected from Atika Creek, from the top 14 cm of the soil profile at Sites 1 and 2 for stable water isotope analysis using a shovel (November 2020, January, February, April and June 2021). The term ‘shallow soil water content (SWC)’ in this paper refers to the volumetric soil water content (%) for the top 14 cm of the soil profile.

Groundwater samples were collected from two bores, located on the James Cook University Cairns campus, Bore A is 42 m deep, and Bore B is 65 m deep and are referred to as GW_A and GW_B, respectively.

Rainfall samples were collected daily at approximately 9 AM (after rainfall) using a Palmex rainfall sampler RS1 and represent rainfall isotope composition for the past 24-h period (http://www.rainsampler.com/).

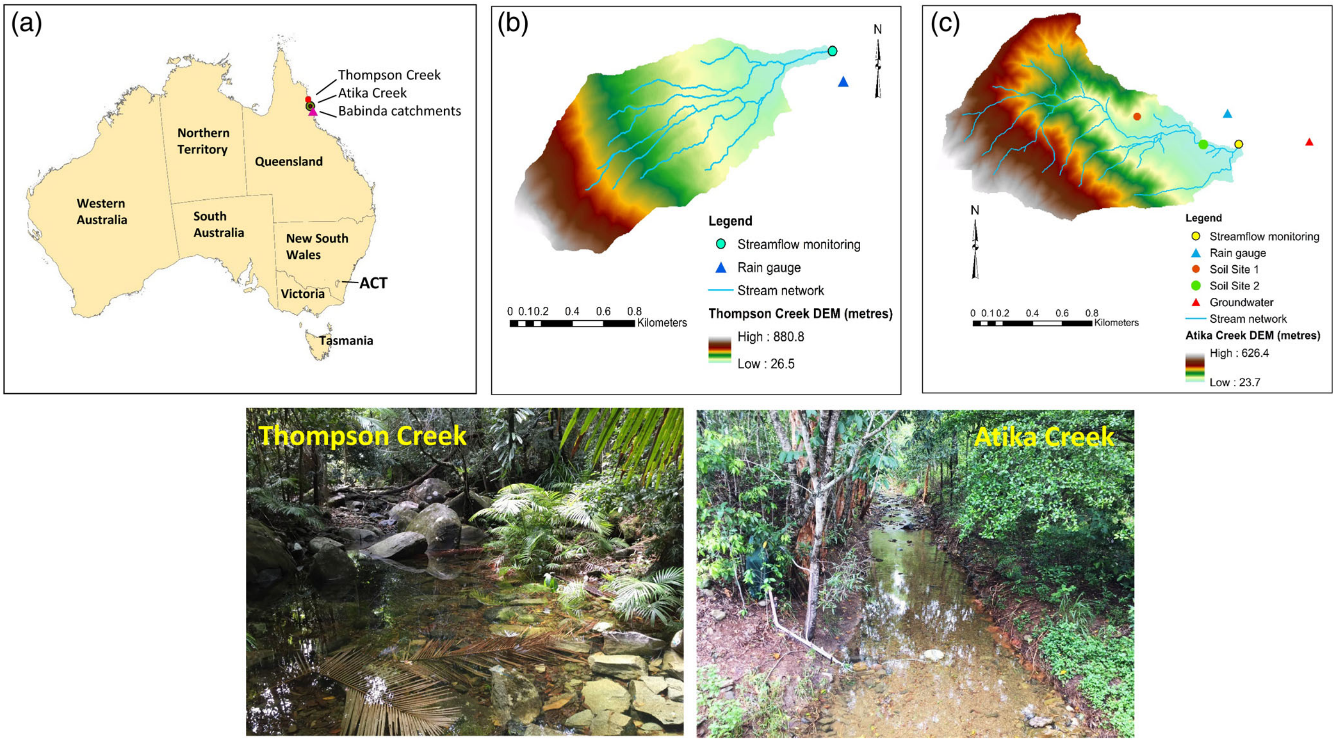


FIGURE 2 (a) Location of catchments relative to each other in NE Queensland, (b) Thompson Creek catchment and (c) Atika Creek catchment

Surface runoff were collected from Site 2 for several events that occurred between December 2020 and April 2021. All samples were collected within 24 h after the event occurred.

All water samples were stored in dark brown glass bottles at laboratory room temperature prior to stable water isotope analysis. Measurements of specific electrical conductivity was conducted as soon as the sample was collected.

2.4 | Isotope analysis of water samples

Oxygen (δ^{18}O) and hydrogen (δ^{2}H) isotope analysis was carried out on discrete water samples using a Picarro L2130i isotope spectrometer connected to a diffusion sampling device and autosampler (Munksgaard et al., 2011). Isotope measurements are reported as per mil (‰) deviations from the VSMOW2-VSLAP2 scale. Precision was typically ±0.1‰ and ± 0.5 ‰ for δ^{18}O and δ^{2}H, respectively (1σ standard deviation).

The Liquid-Vapour Equilibration Laser Spectroscopy method of Wassenaar et al. (2008) was adopted to measure the δ^{2}H and δ^{18}O concentrations in soil pore water. Briefly, approximately 10 ml of soil samples were equilibrated in doubled 1 L zip-lock plastic bags inflated with dry air. After an equilibration time of 30 min, the vapour was analysed by connecting the bags to the analyser via a syringe and tube. Calibration was carried out by analysis of water standards using the same system under identical conditions.

2.5 | Analysis of hydrometric data

Flow duration curves for both catchments were analysed using the HYDRO OFFICE software (FDC 2.1 software, https://hydrooffice.org/Tool/FDC). Graphs of cumulative rainfall and streamflow were obtained by summing up the consecutive amounts of each variable over the course of the 2020/21 hydrological year for Atika Creek. The change in depth equivalent soil water (top 14 cm) was calculated using the method after Farrick and Branfireun (2014a) which is obtained from:

$$\text{Depth equivalent soil water} = \left(\frac{\text{VWC}}{100} \times 140\right), \qquad (1)$$

where, VWC is volumetric water content (%) and 140 refers to the top 140 mm of soil water content measured using the TOMST sensors.

2.6 | Isotope hydrograph separation

With the available data collected in this study, streamflow was separated using two separation methods: a two-component and three-component separation of Ogunkoya and Jenkins (1993). Both methods are based on the mass balance approach initially introduced by Pinder and Jones (1969), which rely on the endmembers used in the hydrograph separation to have distinct compositions. The endmember composition should be both time and space invariant (Klaus & McDonnell, 1993; Sklash & Farvolden, 1979).

For the two-component hydrograph separation, event hydrographs are separated into new (event water, direct input into the catchment due to rainfall) and old water (pre-event water stored in the catchment prior to rainfall occurring) using the δ^{18}O tracer:

$$Q_s = Q_p + Q_n, \tag{2}$$

$$Q_s C_s = Q_p C_p + Q_n C_n, \tag{3}$$

where, Q and C represent streamflow and the tracer concentration, respectively. The subscripts, n, p, s represent the event, pre-event and streamflow values. The event water contribution is calculated using the following:

$$Q_n = Q_s \frac{(\delta_s - \delta_o)}{(\delta_n - \delta_o)}, \tag{4}$$

where, δ_n, δ_o and δ_s represent the δ^{18}O isotopic composition of event, pre-event and streamflow water. Rainfall isotopic composition represented the event water component. Pre-event water is low-flow samples taken before each hydrograph rise. The proportion of event water to streamflow was calculated for (a) the duration of time when stable water isotope samples from the stream were available, reflecting the total event water contributions for the event (Q_{tot}) and (b) at the time peak discharge (Q_p) occurred. This method assumes that contributions from the vadose zone (soil water) are similar to groundwater and that surface storage contributions to streamflow are minimal (Klaus & McDonnell, 1993).

To characterize the relative contributions of sampled endmembers, Ogunkoya and Jenkins (1993)'s two-tracer, 3-component hydrograph separation method is included, using an additional tracer in the form of specific electrical conductivity (SEC). The equations for the two tracer, 3-component hydrograph separation are an extension of Equations (1) and (2) (modified from Elsenbeer et al., 1995):

$$f_1 + f_2 + f_3 = 1, \tag{5}$$

$$(\mathrm{SEC})_1 f_1 + (\mathrm{SEC})_2 f_2 + (\mathrm{SEC})_3 f_3 = (\mathrm{SEC})_Q, \tag{6}$$

$$(\delta^{18}\mathrm{O})_1 f_1 + (\delta^{18}\mathrm{O})_2 f_2 + (\delta^{18}\mathrm{O})_3 f_3 = (\delta^{18}\mathrm{O})_Q, \tag{7}$$

where, f is the fraction of each endmember contributing to streamflow (subscript, Q). SEC and δ^{18}O represent the two tracers used in the separation analysis and the subscripts 1, 2, and 3 represent rainfall, surface runoff, and shallow groundwater. The equations are solved for each stream sample taken.

Bivariate endmember mixing plots (δ^{18}O-SEC) are plotted to examine streamflow chemistry relative to potential source water contributions for each rainfall event. Streamflow composition was assumed to be a mixture of three endmembers: direct rainfall, surface runoff and groundwater. We hypothesised that soil water would be an important endmember, but the method used did not allow SEC measurements to be made, so this endmember was not included in the mixing plots. For each event, the δ^{18}O value and SEC values of the endmembers were obtained from one rainfall and surface runoff sample collected for that event. Groundwater values were taken from samples taken closest to the event in question.

3 | RESULTS

3.1 | Rainfall characteristics and hydrological response

Three TCs and two tropical lows occurred during the monitoring period (2017, 2019–2021). Annual rainfall varied between 1759 and 4968 mm over the monitoring period for Atika Creek and Thompson Creek, respectively. The wet-season rainfall accounted for 70%–91% of annual rainfall. Thompson Creek had higher rainfall totals than Atika Creek (Table 2, Figure S1a). Both study catchments, however, received lower (Atika Creek) or are at the lower end (Thompson Creek) of annual average rainfall received at the Babinda catchments (4000–8000 mm). The seasonal evolution of rainfall activity differed between years; cumulative rainfall increased gradually over the 2020/21 wet season. More pulsed rainfall activity occurred for the same period for the 2018–19 and 2019–20 wet seasons. Even though rainfall totals were different between the catchments, short-term maximum rainfall intensity at the Atika Creek catchment, using the maximum 6-min rainfall intensities (I_6), were similar to those measured at the Babinda catchments in the 1970s for the wet and post-wet season (Atika Creek: 16.5–185.9 mm/h, Babinda catchments: wet: 70–150 mm/h, post-wet: 25–65 mm/h, Cassells et al., 1985; Howard, 1993 cited in Bonell & Callaghan, 2008).

Streamflow response for Atika Creek reflects seasonal rainfall variability, with flow occurring for approximately 55% (2020) to 72% of the year (2021) (Figure S1b). The annual runoff coefficients for Atika Creek (14.7%–38.7%) is lower than the Babinda catchments (>45%, Bonell, 1993).

3.2 | Isotopic characteristics of catchment source waters

The paper will only present δ^{18}O results since the source waters and streamflow are (almost exclusively) unevaporated and therefore δ^2H and δ^{18}O values are strongly correlated along the local meteoric water line (Figures 3b and 4b).

a. Atika Creek

The δ^{18}O composition of sampled source waters and streamflow varied on an inter-annual and seasonal basis. Rainfall had the most variable δ^{18}O composition, followed by soil water and then surface runoff (Figure 3a,b). Streamflow isotope values were highly responsive

TABLE 2 Summary of rainfall properties and streamflow response characteristics for Atika and Thompson Creeks

	Atika Creek			Thompson Creek[a]			
	2018/19	2019/20	2020/21	2016/17	2018/19	2019/20	2020/21
Rainfall properties							
Annual RF (mm)[b]	2695	1759	2340	1877	1992	3629	4968
Wet season (% of annual total)	2354 (87.3)	1363 (77.5)	2131 (91.0)	2775 (76.5)	4269 (85.9)	1971 (69.8)	3973 (84.7)
Dry season	342	396	210	854	699	851	719
I_6 (mm/h)							
Wet	140.8	113.6	119.8	-	-	-	-
Dry	71.5	51.6	70.2	-	-	-	-
Streamflow properties							
Annual streamflow (mm)[c]	697.5	250.8	905.2	-	-	-	-
Annual runoff coefficient (%)	25.9	14.3	38.7	-	-	-	-
Peak discharge, Q_p (mm/s)[d]	0.0029	0.0040	0.0035	0.161	-	-	-
Q_{10} (mm/s)	8.29×10^{-5}	2.82×10^{-5}	9.03×10^{-5}	3.49×10^{-4}	-	-	-
Q_{50} (mm/s)	2.77×10^{-6}	3.45×10^{-6}	4.00×10^{-5}	3.00×10^{-5}	-	-	-
Q_{90} (mm/s)	0	0	0	6.74×10^{-6}	-	-	-
No of no flow days (%)[e]	-	119.5 (32.7)	150 (41.1)	-	-	-	-

[a] Only daily rainfall data are available for Thompson Creek.

[b] Annual rainfall is calculated from 1 November to 31 October the following year.

[c] Annual streamflow is expressed in depth units (mm) after dividing discharge by catchment area.

[d] At Atika Creek, annual Q_p occurred consistently in January for the 3-year monitoring period. For Thompson Creek, annual Q_p was recorded in March 2017.

[e] Flow monitoring at Atika Creek started 9/1/2019 so it is not possible to calculate the number of no flow days for the 2018/2020 hydrological year.

to rainfall inputs and exhibited inter-annual variability, similar to rainfall. Surface runoff samples were the most ^{18}O depleted (mean δ^{18}Owet = −8.3 ± 2.9‰, δ^{18}Odry no sample, Figure 3c). Groundwater was the least variable hydrograph component, with deep groundwater exhibiting an almost constant isotopic component over the 3-year monitoring period. Both bores have relatively similar δ^{18}O values; Bore A (δ^{18}O: −6.2‰ to −5.3‰), Bore B (δ^{18}O: −6.3‰ to −5.2‰).

Soil water and surface runoff samples from the 2020/21 wet season revealed distinct seasonal variability in δ^{18}O composition, with the wet season generally having more variable and more depleted δ^{18}O values (Figure 3c). Shallow soil moisture exhibited a strong seasonal signal (mean δ^{18}Owet = −5.8 ± 4.7‰, δ^{18}Odry = −2.9 ± 2.0‰). Isotope fractionation via evaporation was evident for almost all samples, especially during the late dry (September) and early wet season (January, Figure 3b insert).

a. Thompson Creek

The δ^{18}O composition of the various hydrological components showed distinct seasonal variability; rainfall (mean δ^{18}Owet = −4.1 ± 2.8‰, δ^{18}Odry = −2.4 ± 0.6‰) and streamflow (mean δ^{18}Owet = −3.9 ± 0.3‰, δ^{18}Odry = −3.6 ± 0.1‰) (Figure 4). A seasonal signal was observed for soil moisture data from 2014 where both shallow (50 cm) and deep (150 cm) (mean Shallow: δ^{18}Owet = −7.4 ± 7.4‰, δ^{18}Odry = −3.2 ± 1.5‰, Deep: δ^{18}Owet = −4.6 ± 0.7‰, δ^{18}Odry = −3.4 ± 1.1‰). Soil moisture did not show a strong evaporative influence, except for the April sample (Figure 4b,c).

3.3 | Seasonal evolution of hydrological response behaviour: Atika Creek (2020/21)

The seasonal evolution of hydrological response is examined using the 2020–21 wet season, which had the most complete dataset including soil water and surface runoff. Significant periods of rainfall occurred from early January to mid-April due to TC and monsoon rainfall activity, respectively (Figure 5). Soil moisture at Site 2 increased at a faster rate and remained wetter than Site 1. The maximum volumetric soil water content attained during the wet season was 48.2% (Site 1) and 56.2% (Site 2), representing saturated conditions (Paul Nelson, personnel communication). Consistent streamflow commenced on 25 December 2020 and ceased on 29 August 2021.

Four rainfall events with different rainfall characteristics (TC, monsoon) and catchment antecedent conditions reflect the wetting-up and early wet (January), wet (February, March) and post-wet (April) phases of seasonal rainfall activity (Figure 5c). Three of these rainfall events were impacted indirectly by TC activity with the eye passing approximately 95–160 km away (Table 3).

a. Wetting-up and early wet: Events AC1a, b, c (4–6 January 2021)

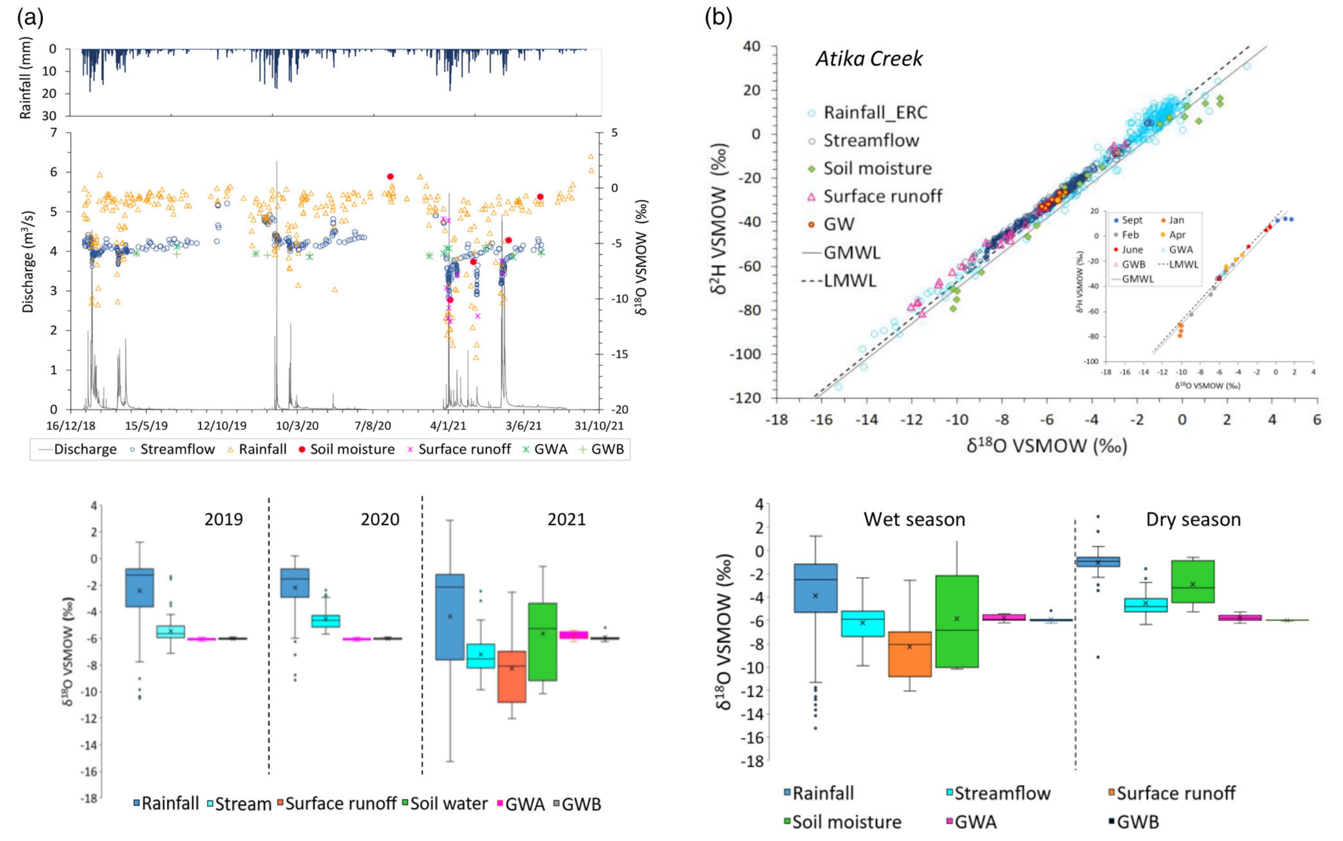


FIGURE 3 (a) Timeseries of rainfall, streamflow and isotope $\delta^{18}O$ values for different source waters, 2019–2021 Atika Creek, (b) dual isotope plot ($\delta^{18}O$, $\delta^{2}H$), (c) boxplots of catchment source waters on an annual timescale, (d) boxplots of catchment source waters for wet and dry season. Inset of (b) shows showing evaporative fractionation of shallow soil moisture (e.g., January, September, 0–14 cm depth). Samples were collected between September 2020 and June 2021. Groundwater samples are plotted for reference to the isotope composition of deeper subsurface water sources

The wetting up behaviour is described for the period when streamflow commenced (25 December 2020) to 4 January 2021 when three closely spaced events occurred due to TC Imogen. The stream and rainfall $\delta^{18}O$ values were similar when streamflow commenced but the stream $\delta^{18}O$ values approached those of groundwater (31 December 2020) and decreased further with time as $\delta^{18}O$ depleted TC rainfall continued to wet the catchment (Figure 6a).

Events AC1 (a, b, c) occurred approximately 9 days after Atika Creek started flowing. Rainfall totals and intensity were high (109–120 mm/h) and the catchment had been wetted by previous rainfall events (ADP_7 = 177 mm, SWC = 26.7%, Table 3). Event AC1c had the highest peak discharge for the 2020–21 wet season due to a combination of high rainfall intensity and wet soils (I_6 = 120 mm/h, SWC = 29.3%, Table 3). However, total event flow (7.7–17.5 mm) and runoff coefficients (12.4%–26.7%) were low at this point in the wet season (Table 3).

Both streamflow (70–130 min) and soil moisture (15–30 min) responses to rainfall were rapid during event AC1 (Table 3). The hillslope site (Site 1) showed pulsed increases in soil water content in direct response to rainfall whereas the lower elevation, flatter site (Site 2) likely reached saturation (Figure 6a).

a. Wet season: Events AC2 (20–21 January) and AC3 (1–2 March 2021)

Compared to Event AC1 (a, b, c), both Events AC2 and AC3 experienced less intense rainfall (I_6: 16.5–37.2 mm/h) but occurred at a time in the wet season where catchment soils were wetter (SWC: 34.6%–36.3%, Table 3). As a result, both events had a lower Q_p and longer hydrograph response (970–1030 min) for the stream to achieve Q_p than event AC1 (Figures S2 and S3).

a. Early post-wet: Events AC4a, b (18–23 April 2021)

Event AC4 consisted of two events with multiple peaks from rainfall associated with a monsoon trough in the Coral Sea and occurred after a period of relatively low rainfall. Over 500 mm of relatively high intensity rainfall (I_6 > 50 mm/h, ADP7 = 18 mm) occurred, which essentially constituted a new wetting-up phase in the post-wet season (Table 3). Soil water content before Event 4a occurred was only 23% but increased to 35.1% (Event AC4b), which was comparable to the events sampled during the wettest part of the 2020/21 wet season (Events AC2, 3, Table 3). Both events resulted in rapid responses within the shallow soil profile, with Site 2 likely attaining saturation

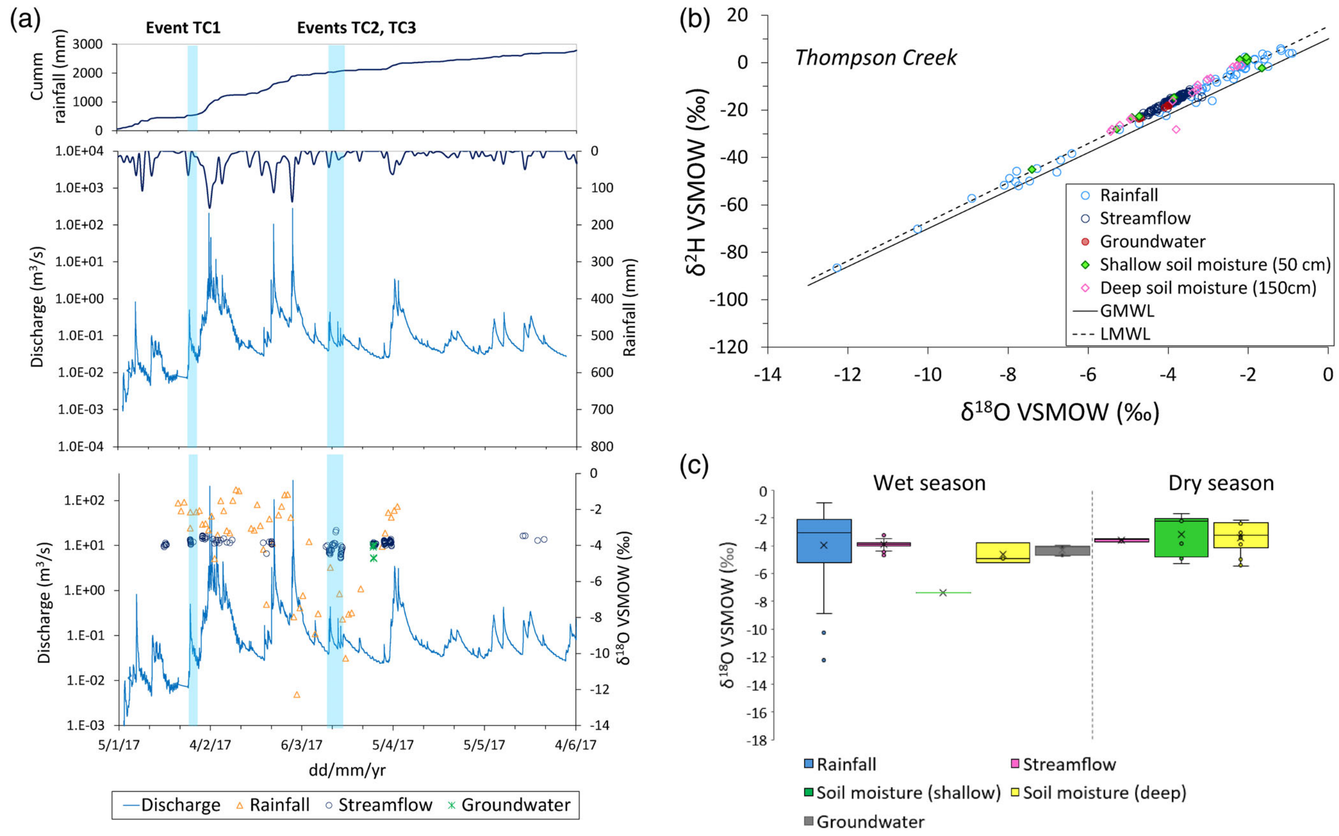


FIGURE 4 (a) Timeseries plots of stream discharge and δ^{18}O values for various hydrological catchment components, (b) dual isotope plot (δ^{18}O, δ^{2}H), (c) boxplots of δ^{18}O values for different components of the hydrological cycle sampled in 2017, Thompson Creek. Soil moisture data were sampled during the 2014 dry season from April to June (shallow: 50 cm, deep: 150 cm, Buckton et al., 2019), for general comparison to the other source waters

and maintaining that condition throughout the duration of the event (Figure S4a). Despite the relatively dry conditions prior to this event, the high rainfall input wetted up the catchment sufficiently such that Q_p was the second highest after event AC1c. Total runoff (134.9–169.7 mm) and runoff coefficients (31.1%–58.6%) for this event were also the highest of the events presented in this section (Table 3).

3.4 | Seasonal evolution of hydrological response behaviour: Thompson Creek (2016/17)

The analysis for Thompson Creek is limited to a basic description of hydrograph and stream δ^{18}O response patterns for three events during the 2017 wet season due to the limited data available for rainfall (daily) and source water samples.

At Thompson Creek, the rainfall δ^{18}O values were highly variable over the course of the 2017 wet season (δ^{18}O: −12.3‰ to −0.91‰) (Figure 4). Rainfall was relatively ^{18}O depleted in March compared to the earlier part of the wet season. Streamflow δ^{18}O variability was less, fluctuating around an average value of −3.9‰ (range: −4.7‰ to −3.2‰).

a. Wet: Event TC1 (28–30 January 2017)

This event (72.7 mm) occurred when approximately 14.2% of annual rainfall had already fallen on the catchment (527 mm) (Table 4, Figure S5a).

a. Late wet: Events TC 2, 3 (14–19 March 2017)

By the time both events occurred, stream discharge was higher due to wetter catchment conditions (>50% of annual rainfall had already fallen on the catchment), despite the relatively low rainfall inputs for both events (TC2: 44.1 mm, TC 3: 17.3 mm, Table 4). The hydrograph response for both rainfall events was fast; approximately 1 h for discharge to increase from pre-event values to peak flows (Figure S5b).

3.5 | Hydrograph separation and source water contributions

For Atika Creek, the two-component hydrograph separations revealed increasing event water contributions to the storm hydrograph over the course of the wet season (Table 3). For events occurring during the wetting-up phase (Event AC1), event water contributions when Q_p occurred (9.9%–48.6%) and for Q_{tot} (3.3%–23.2%) were low

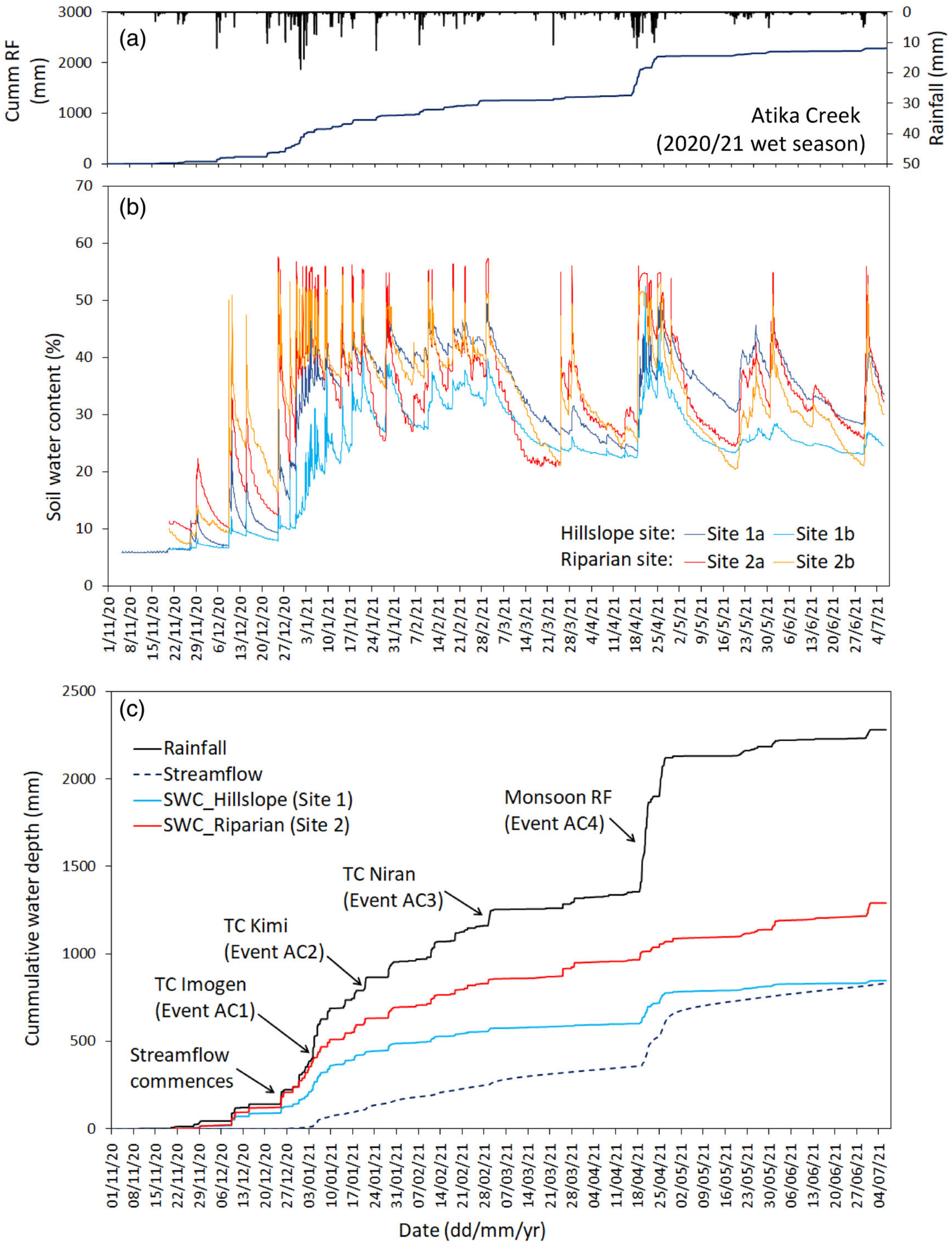


FIGURE 5 (a) Cumulative rainfall, (b) soil water content, and (c) cumulative change in water depth for rainfall, streamflow and depth equivalent soil water (for top 14 cm) from November 2020 to early July 2021 when soil monitoring ended, Atika Creek

compared to subsequent events (Figure 6c). As the wet season progressed, event water contributions to Q_p (AC2: 48.6%, AC3: 95%) and the entire event (AC2: 11.4%, AC3: 84.1%) increased (Figures S2c and S3c). By the time Event AC4 occurred at the start of the post-wet season, sufficient rainfall inputs resulted in high event water contributions to Q_p (AC4a: 70.6%, AC4b, 55.1%) and Q_{tot} (AC4a: 49.5%, AC4b, 34.7%), even though the catchment experienced some drying prior to this rainfall event (Figure S4c). Pre-event contributions appeared to increase over the course of Events 4a and 4b (Table 3).

At Thompson Creek, the monitored storm hydrographs appear to be dominated by pre-event contributions, with very low Q_n contributions for Q_p (TC1: 31.8%, TC2: 24.5%–41.7%) and Q_{tot} (TC1: 6.1%, TC2: 4.7%–9.9%) (Table 4).

TABLE 3 Rainfall and streamflow response characteristics for events monitored during the 2020/21 wet season, Atika Creek

	Early wet (wetting up)			Wet		Post-wet	
	1a	1b	1c	2	3	4a	4b
Rainfall properties							
Rainfall system	TC Imogen			TC Kimi	Severe TC Niran	Monsoon rainfall	
Dates	4–6 January			20–21 January	1–2 March	18–23 April	
TC eye proximity to catchment (km)	160			95	120	-	
Event RF	62	69.2	65.5	76.0	92.1	545.4	230.2
I_6 (mm/h)	109.4	185.9	119.8	37.2	16.5	70.2	55.8
Storm duration (min)	160	520	220	1650	1250	6280	2900
ADP7 (mm)[a]	177.2	239.2	291.8	100.6	24.78	17.8	500.1
Cumm RF since 1/11/20	407.4	463.6	534.6	791.3	1162.2	1355.3	1902.3
Streamflow response							
Q_{tot} (mm)[a]	7.7	15.3	17.5	30.0	37.2	169.7	134.9
Runoff coefficient (%)[a]	12.4	22.1	26.7	39.5	40.4	31.1	58.6
Q_p (mm/s)[a]	0.0023	0.0018	0.0035	0.00064	0.00038	0.0031	0.0023
Time to Q_p from baseflow (min)[a]	50	42	40	970	1030	1400	530
Time to Q_p from RF initiation (min)[a]	130	76	70	1073	1067	1400	587
% event water at Q_p	44.3	9.9	48.6	95.0	33.0	70.6	55.1
% event water for Q_{tot}	23.2	3.3	11.4	84.1	8.47	49.5	34.7
Soil moisture content, SMC (%): Site 1 (hillslope)							
At start of event	26.7	29.4	29.3	34.6	36.3	23.0	35.1
End of event	31.8	30.6	31.7	38.3	42.6	38.4	41.9
Change in SMC	5.1	1.2	2.4	3.6	6.2	15.4	6.8
Response time (min)	30	15	15	45	60	60	15
Site 2 (bottom of hillslope, near stream)							
At start of event	41.7	50.1	41.2	38.4	38.0	26.8	41.8
End of event	53.4	53.8	51.9	42.6	53.9	51.9	49.9
Change in SMC	11.7	3.6	10.7	4.2	15.9	25.1	8.1
Response time (min)	15	15	15	15	15	15	15

Note: Q_{tot} refers to streamflow depth for each rainfall event and is calculated from the initial rise in hydrograph to when discharge returns to pre-event values or until the next event occurs. Runoff coefficient is calculated as Q_{tot}/Event rainfall. Q_p refers to peak discharge (mm/s).

[a] ADP7 refers to the total amount of rainfall that fell on the catchment 7 days prior to the event in question.

The bivariate mixing plots, available only for Atika Creek, revealed complex source water contributions for storm events occurring in close succession at the wetting-up phase of the wet season (Event AC1). Many stream samples plotted outside the triangle bounded by the rainfall, surface runoff and shallow groundwater endmembers (Figure 7). With Event AC4, the streamflow chemistry was initially outside the mixing triangle but became more constrained by the three endmembers with continuous rainfall input. Streamflow chemistry was well constrained by the above three endmembers for the individual TC-induced storm events (Events AC2, AC3). For both events, streamflow δ^{18}O values became more like pre-event waters at the end of the event, signalling a return to pre-storm conditions (Figure 7). The hysteresis loops of streamflow δ^{18}O-SEC relationship were tight and almost linear for these two events whereas complex hysteresis loops were observed for the multi-peak events (AC1, AC4). The surface runoff endmember is likely a mixture of rainfall and subsurface sources of varying proportions at different times of the wet season. Rainfall contributions was likely dominant for Events AC1 and AC2, whereas subsurface sources are likely dominant for Event AC3 (Figure 7). The groundwater endmember, GW_A, was most similar to streamflow only during the wetting-up phase of the 2020/21 wet season and pre-event samples for Event AC1 (Figures 6 and 7).

The endmember δ^{18}O-SEC values varied between the events with rainfall and surface runoff displaying shifts in δ^{18}O values (Figure 8). The groundwater endmember (both GW_A and GW_B), displayed greater variability in SEC values over the course of the 4 events, indicating possible groundwater recharge during the wet season. The two-tracer three-component hydrograph separation did not result in source contributions well constrained by the rainfall, surface runoff and shallow groundwater endmember, with proportions adding up to >1 for all four 4 events

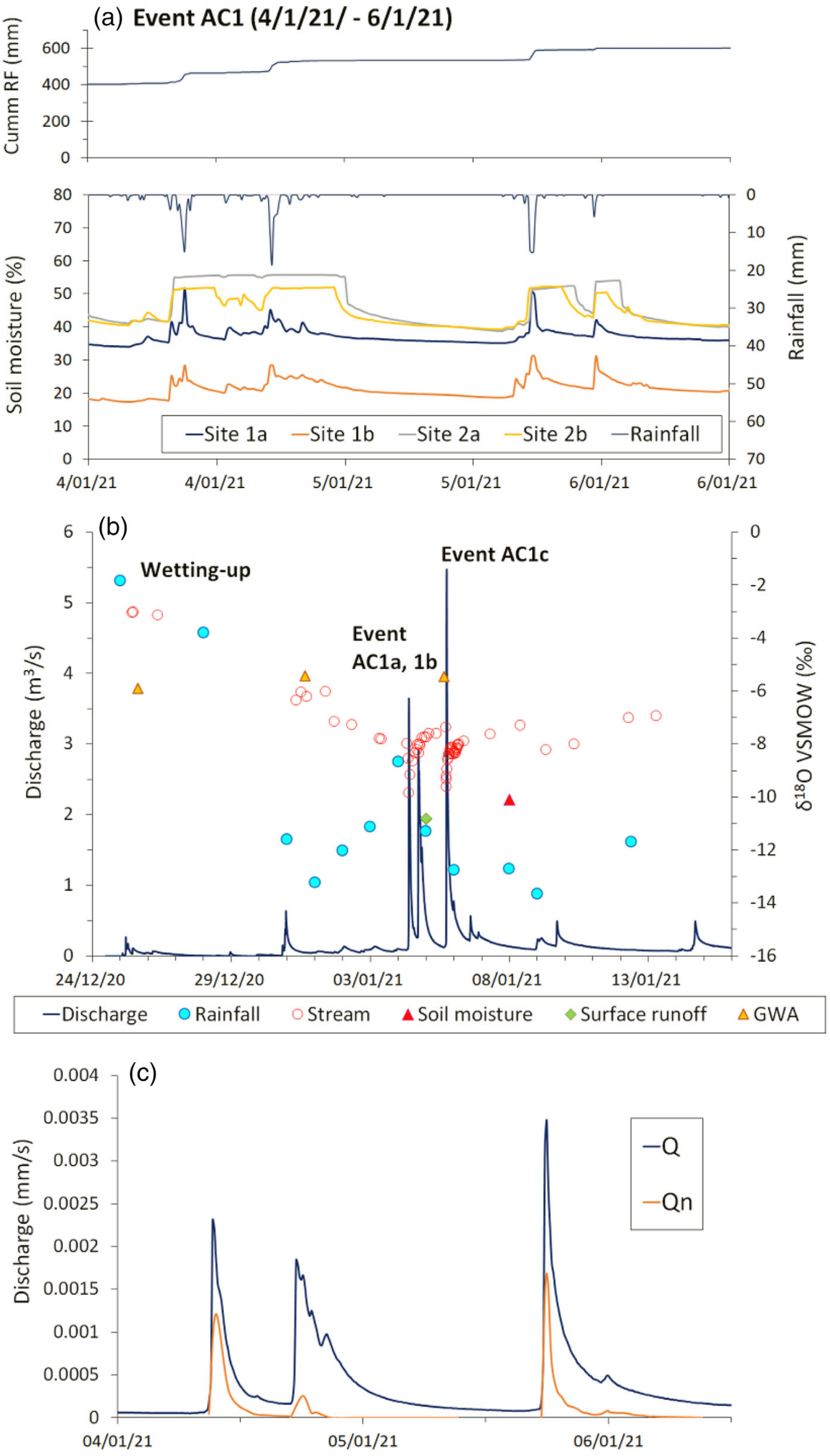


FIGURE 6 Event AC1, (a) cumulative rainfall, event rainfall, stream discharge, (b) stream $\delta^{18}O$ event variability, and (c) proportion of event water (Q_n), Atika Creek 2020/21 wet season

monitored for Atika Creek. These results suggest that the assumptions around the source water endmembers (distinct composition, conservative nature, and linear mixing processes) are not applicable in this catchment for the monitored events for the events monitored during the wet and post-wet season and that other endmembers are likely important contributors to streamflow.

TABLE 4 Rainfall and streamflow response characteristics for events monitored during the 2016/17 wet season, Thompson Creek

Events	TC1 28/1/2017	TC2 15/3/2017	TC3 18/3/2017
Rainfall properties			
Event RF	72.7	44.1	17.3
I_6 (mm/h)	-	-	-
Storm duration	-	-	-
ADP7[a]	11.5	58.4	59
Cumm RF since 1/11/2016[a]	771.6	2297.8	2342.1
Streamflow response			
Q_{total} (mm)	5.48	11.6	2.21
RC (%)	8.2	29.7	15.3
Q_p (mm/s)	0.00028	0.00024	0.00009
Time to Q_p from baseflow (min)	302	590	60
% event water at Q_p	31.8	41.7	24.5
% event water	6.1	4.7	9.9

Note: Q_{total} refers to streamflow depth for each rainfall event and is calculated from the initial rise in hydrograph to when discharge returns to pre-event values or until the next event occurs.

[a] ADP7 refers to the total amount of rainfall that fell on the catchment 7 days prior to the event in question.

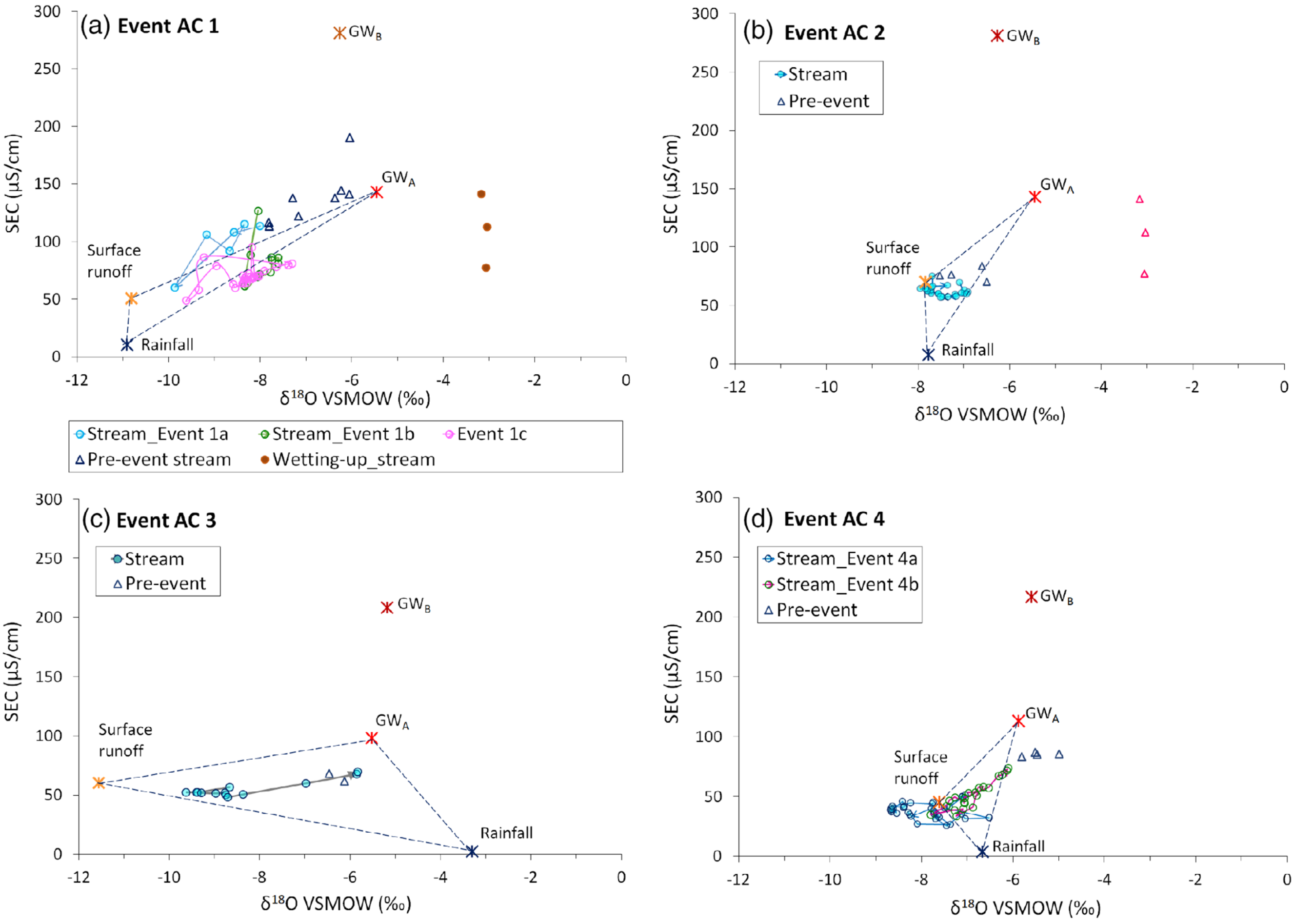


FIGURE 7 Bivariate mixing plots of δ^{18}O-SEC relationship for streamflow and source water endmembers; rainfall, surface runoff, groundwater (GWA, GWB), 2020/21 wet season, Atika Creek

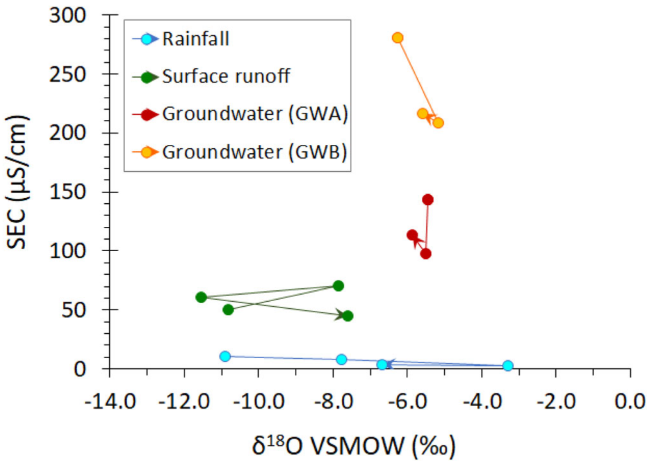


FIGURE 8 $\delta^{18}O$ and SEC endmember values for the four events (AC1–AC4), Atika Creek, 2020/21 wet season. The arrows show the direction of progression of storm events (Events AC1–AC4)

4 | DISCUSSION

4.1 | Catchment runoff response for NE Queensland catchments

Both Atika and Thompson Creeks displayed fast streamflow responses to rainfall due to their steep catchment topography and intense wet season rainfall activity. The rainfall events monitored at both catchments were mostly >50 mm (I_6: 16.5–185.9 mm/h) and caused by large-scale weather events that included TCs and the influence of the monsoon trough. These rainfall amounts and short-term intensities are comparable to events reported for the Babinda catchments, resulting in similarly fast streamflow response (Bonell & Callaghan, 2009; Howard et al., 2010). The shortest streamflow response time to attain Q_p was 40 min (Event AC1c), comparable to 30 min reported for the Babinda catchments (Bonell et al., 1998; Bonell & Gilmour, 1978). Lower rainfall intensities (Events AC 2 and 3) and multiple pulses in rainfall resulted in slower streamflow responses (Events AC 2, 3, TC1, 2).

At Atika Creek, the surficial soil layer, at all sites, responded quickly to rainfall inputs (between 15 and 60 min). For the flatter riparian location (Site 2a, 2b), multiple peak events likely caused saturation to occur as the soil water content curve flattens at values ranging between 50% and 60% for all events. At the hillslope site (Site 1a, b), saturation occurred but was short-lived, likely due to the fast translation of surficial soil water downslope due to the steeper topography at these sites. Similarly, at the South Creek catchment, the shallow subsurface soil layers also responded quickly to rainfall, where SOF can develop within 6 min of rainfall occurrence and accompanied by large volumes of shallow subsurface and SOF runoff (Bonell et al., 1983a; Bonell & Gilmour, 1978; Cassells et al., 1985; Gilmour & Bonell, 1979).

For Atika Creek and the Babinda catchments, rainfall intensity and amount are crucial factors determining streamflow response during the wet season, regardless of soil moisture. The highest rainfall intensities experienced at Atika Creek resulted in the highest Q_p of the 2020/21 wet season (Event AC1c), an event that occurred at a time when the catchment was wetting up (Event AC1c, Figure 6b). Likewise, short-term rainfall intensity controlled the initiation of SOF and Q_p response for all seasons (wet, post-wet, dry) for the South Creek catchment (Bonell & Callaghan, 2009; Howard et al., 2010).

The way antecedent catchment wetness controlled streamflow response varied over the course of the wet season. For Atika Creek, antecedent catchment wetness played a supporting role to rainfall amount and intensity in determining Q_p, Q_{tot} and RCs of individual events, especially for large multi-peak events (Events AC1c, AC4b, rainfall >100 mm). At the South Creek catchment, a large rainfall event (>500 mm, TC Joy) that occurred at the start of the wet season (December 1990) did not have a significant impact on Q_p since most of the rainfall infiltrated into the soil, recharging the deep groundwater store (Bonell, 1993). However, streamflow response was determined by the interplay between rainfall amount, duration, and catchment wetness for events in the main part of the 1993 wet season (Elsenbeer et al., 1995).

4.2 | Catchment source water contributions

For both Atika and Thompson Creeks, event water contributions was more important for Q_p (AC: mostly >33%, TC: 25%–42%) than Q_{tot} (AC: 3.3%–84%, TC: 4.7%–9.9%, Tables 3 and 4). Pre-event water was an important contributor to Q_{tot}, particularly for Thompson Creek (>90%, Events TC1, TC2) and more variable for Atika Creek (15.9%–96.7%). Differences in the event water contributions to Q_p and the entire event for Events AC2 (Q_n > 80%) and AC3 (<33%) may be due to the release of stored catchment water that expresses itself as pre-event water in the case of Event AC3, given the reasonably similar rainfall characteristics and antecedent wetness conditions of both events (Table 3). At South Creek catchment, this pre-event water contribution was identified as hillslope groundwater or deep groundwater contributions (Barnes & Bonell, 1996, 2012; Bonell et al., 1998; Elsenbeer et al., 1995). At Atika Creek, the soil moisture data and bivariate plots suggest that soil water or shallow groundwater may be important sources of pre-event water.

For the Babinda catchments, hydrograph separations showed almost equal contributions of pre-event (53%) and event water (47%). Event water contributions increased to >80% for large intense rainfall events over South Creek (e.g., Gilmour, 1977; Howard et al., 2010). Pre-event contributions became more important on the recession limb or in the latter event in a series of closely spaced events (February events 1991, 1993) (Barnes & Bonell, 2012; Bonell et al., 1998; Elsenbeer et al., 1995; Gilmour, 1977). Our results are broadly similar to those of South Creek but show more variability in event water contributions for both Q_p and Q_{tot}, partly due to the wider range of storms sampled across the wet season. The pre-event water contributions from Atika and Thompson Creeks are also within the range reported for other tropical sites including high Andean grassland catchments (71%–94%, Correa et al., 2017; Mosquera et al., 2016), montane dry forest (35%–95%, Muñoz-Villers & McDonnell, 2012) and tropical dry forests (72%–97%, Farrick & Branfireun, 2015).

The fast responses observed for the Atika Creek catchment is likely due to surficial contributions, also observed at the Babinda catchments (see Elsenbeer et al., 1995). We postulate that soil water is an important source contributing to streamflow at Atika Creek. The fast soil water response and ability to maintain wet conditions for longer periods of time at the level narrow riparian site (Site 2) suggests that the upper soil profile was closely linked to surface runoff and the stream via SOF during the wet season. Furthermore, SOF may be a mixture of rainfall, soil water, with the relative proportions changing depending on rainfall intensity and catchment wetness over the course of the wet season (Figure 7).

In the Babinda catchments, particularly the South Creek, streamflow was partitioned into five source waters that include saturation excess overland flow (SOF), SSF, soil water, upper groundwater and deep well-mixed groundwater (Bonell & Fritsch, 1997). Macropores linked surficial flow pathways to groundwater (Barnes & Bonell, 1996, 2012; Bonell et al., 1981). At Atika Creek, streamflow δ^{18}O-SEC chemistry for single events (AC2, AC3) was constrained by the sampled source waters (rainfall, surface runoff and the groundwater endmember, GW_A). The hysteresis loops of streamflow δ^{18}O-SEC relationship indicated mixing of source water endmembers (e.g., Inamdar et al., 2013). For more complex, multi-peak events (Events AC1, AC4), occurring when the catchment was wetting up, streamflow was not constrained by the measured source waters, revealing highly complex evolution of streamflow δ^{18}O-SEC patterns over the course of both events (complex hysteresis loops, see Barthold et al., 2016; Inamdar et al., 2013). The absence of soil water and shallow groundwater endmember information for Atika Creek is likely the main reason behind the inability of the two-tracer, three component analysis to provide satisfactory hydrograph separations using the rainfall, surface runoff and shallow groundwater endmembers. However, the available dataset revealed aspects of the endmember behaviour that include mixing and activation of additional source waters over the wet season. Source water mixing is likely during multi-peak events or when the catchment is wetting up, making endmembers indistinguishable (e.g., Barthold et al., 2010, 2016; Inamdar et al., 2013; Jacobs et al., 2018; James & Roulet, 2006). Additional source waters become activated when different catchment elements become connected over the wet season (e.g., Correa et al., 2017). Source water composition may also change over the wet season due to leaching processes in the soil (e.g., Barthold et al., 2010). Future sampling at Atika Creek includes soil water and shallow groundwater monitoring and sampling in the narrow riparian zone and on hillslopes using suction lysimeters to better characterize shallow subsurface water chemistry, given the potentially important role of soil water at Babinda, Atika Creek and other tropical catchments (e.g., Birkel et al., 2021; Elsenbeer & Lack, 1996; Farrick & Branfireun, 2014a; Jacobs et al., 2018; Mosquera et al., 2020).

4.3 | Dynamic and transient catchments

For intermittent streams such as Atika and Thompson Creeks, streamflow initiation at the start of the wet season occurs when threshold conditions are exceeded. Approximately 118–150 mm of rainfall was needed to fill catchment storage deficits of Atika Creek (2019–2021 data). Drier areas, such as dry forests in Mexico required higher rainfall inputs before continuous streamflow was generated (e.g., 176–191 mm, Farrick & Branfireun, 2014b, 2015). Once consistent streamflow was established for the 2020/21 wet season, Q_{tot} and RC increased gradually over the wet season. In the early post-wet season, Atika Creek still produced significant peak flows and event runoff totals, with runoff coefficients exceeding 50%, even though the catchment dried to conditions like the start of the wet season. The runoff coefficients for both Atika and Thompson Creek catchments were very similar to steep tropical montane cloud forests dominated by overland flow and SSFs in Mexico (11%–54%, Muñoz-Villers & McDonnell, 2012) which suggests that at least 50% of event rainfall is stored in these catchments.

The extent of dynamism experienced within and between the wet/dry seasons depends on the relationship between rainfall properties (e.g., rainfall intensity, wet season rainfall distribution) and catchment wetness, which can vary between years (e.g., Farrick & Branfireun, 2015; Muñoz-Villers & McDonnell, 2012). The δ^{18}O signature for rainfall, streamflow and soil water at Atika Creek showed distinct seasonal variability, reflecting changing source water contributions and runoff pathways over the wet and post-wet season, which was also observed at the Babinda catchments (Bonell et al., 1981; Bonell & Gilmour, 1978; Elsenbeer & Lack, 1996). The changes in the δ^{18}O and SEC values of rainfall, surface runoff and groundwater endmembers at different points over the wet and post-wet seasons highlight the time-variant nature of these endmembers which was also reported elsewhere for a tropical catchment (e.g., Barthold et al., 2016). Elsewhere, source waters were more distinguishable during dry periods when compared with the wet season due to changes in connectivity between source waters and pathways (e.g., Barthold et al., 2010; Elsenbeer et al., 1995; Inamdar et al., 2013; Muñoz-Villers & McDonnell, 2012). These dynamic changes presented difficulties in modelling the seasonal catchment response behaviour using one parameter set that is applied to the entire year, rather than parameter sets that differ for the wet/dry seasons, respectively (Barnes & Bonell, 2012) and for source water identification using hydrograph separation techniques, for the Atika and Babinda catchments (Bonell et al., 1998). A useful approach to understand these dynamic changes is to divide the seasonal timeseries into different hydrological regimes, each characterized by their rainfall properties and catchment wetness conditions, to identify endmembers that operate in different parts of the wet/dry seasons (e.g., Ali et al., 2010).

4.4 | A framework to characterize seasonal catchment rainfall-runoff response

Bonell's work highlighted the fast responses and importance of new water to streamflow via shallow and surface runoff contributions for humid tropical forested catchments This study presents catchments with more seasonal flow regime, using a variety of storm events that included transitional periods for the wet season. Our results highlight the complex streamflow response behaviour for the wetting-up periods at the start of the wet season and early post-wet season. For steep forested catchments, such as Babinda and our study catchments, large and intense rainfall events (>100 mm, even >500 mm) due to synoptic climate conditions play a dominant role in the fast and very dynamic streamflow response behaviour for catchments with shallow conductive soil. Both hydrometric and source water sampling reveal the importance of shallow subsurface and surface flow pathways, which vary with changing rainfall and antecedent catchment wetness over the seasonal timescale, resulting in event waters contributing at least 50% of runoff during storm events. For the Babinda catchments, deep groundwater (pre-event water), recharged via vertical preferential pathways, contributes to streamflow during the latter part of the wet season and early post-wet season periods. There is some indication to suggest that deep groundwater is recharged over the wet season and that soil water is an important source contributor to streamflow at Atika Creek. Similar runoff processes and responses were reported for other steep forested tropical catchments (Barthold et al., 2016; Elsenbeer & Lack, 1996).

More recent work in other tropical catchments report changes in connectivity within catchment elements (e.g., riparian zones, floodplains, and hillslopes) (e.g., Correa et al., 2017; Duvert et al., 2020; Farrick & Branfireun, 2014a; Zimmermann et al., 2014), changes in dominant flow pathways (e.g., Barthold et al., 2016; Blume, Zehe, & Bronstert, 2008; Blume, Zehe, Reusser, et al., 2008; Blume et al., 2009; Goller et al., 2005; Muñoz-Villers & McDonnell, 2012) and source water contributions at different points in the wet season (e.g., Correa et al., 2017; Elsenbeer & Lack, 1996; Muñoz-Villers & McDonnell, 2012). Table 5 provides a summary of these key findings. Using collective evidence available from the North Queensland catchments and other tropical catchments, we propose a conceptual framework that describes streamflow response to seasonal rainfall for wet/dry tropical catchments (Figure 9). This framework focuses on the general patterns of streamflow response on a seasonal timescale, rather than on specific runoff processes or pathways, which makes the framework more applicable for other seasonal tropical catchments.

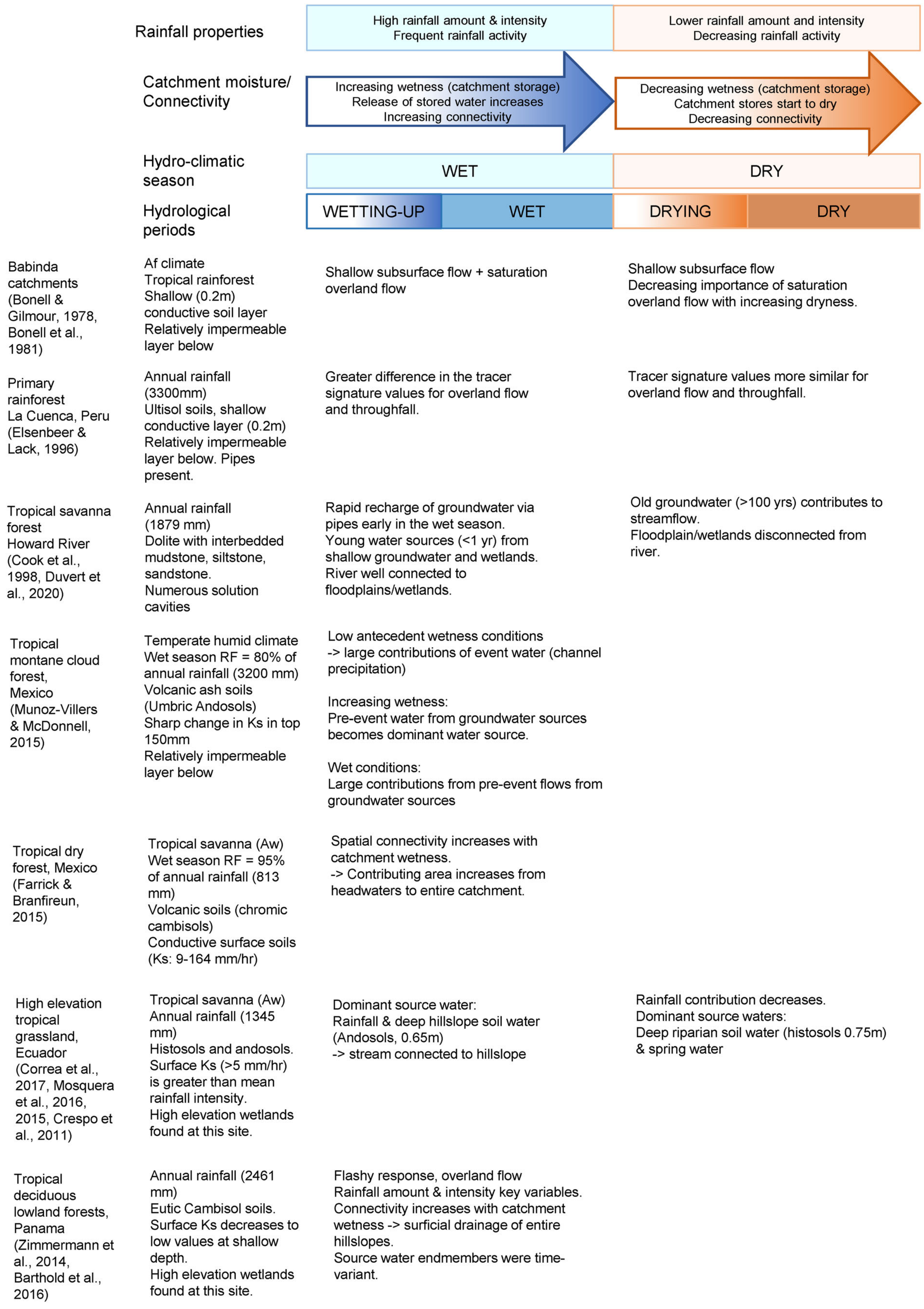
For intermittent streams, the change from no flow to continuous flow at the start of the wet season shows highly non-linear catchment-specific behaviour. This emergent feature is reported not only for humid temperate, arid, snow and permafrost catchments (refer to Ali et al., 2013; Shanafield et al., 2020; Ross et al., 2021), but also seasonal tropical catchments (e.g., Farrick & Branfireun, 2014a; Zimmermann et al., 2014), including Atika Creek. Threshold conditions must be exceeded before source waters, flow paths and the stream become connected, initiating consistent streamflow (Ali et al., 2013; McDonnell et al., 2021; Zehe & Sivapalan, 2009). The opposite occurs when the catchment dries. The storage threshold is often represented by cumulative rainfall or soil moisture deficits (e.g., Farrick & Branfireun, 2015; Penna et al., 2011; Ross et al., 2021; Saffarpour et al., 2016; Spence, 2010).

The relationship between rainfall inputs, catchment storage and hydrologic connectivity determine the nature of streamflow response over the seasonal timescale. Hydrological connectivity is both temporally and spatially variable within and between seasons, due to changing rainfall and catchment wetness conditions, and their respective interactions with each other. The nature of these relationships is catchment-specific, depending on the unique biophysical characteristics (geology, soil, depth to groundwater) and climatic conditions, whether rainfall events are caused by large-scale synoptic weather conditions or localized convective events (Bonell & Callaghan, 2009; Chappell et al., 2012, 2017; Gutiérrez-Jurado et al., 2019). Increasing connectivity during the wetting-up phase results in higher RCs and pre-event water contributions, observed at Atika Creek and elsewhere (e.g., Muñoz-Villers & McDonnell, 2012). Highest runoff production occurs in the peak of the wet season when catchment storage and connectivity are greatest with the fill and spill mechanism most likely occurring at the maximum rate and extent (McDonnell et al., 2021; Tromp-Van Meerveld & McDonnell, 2006).

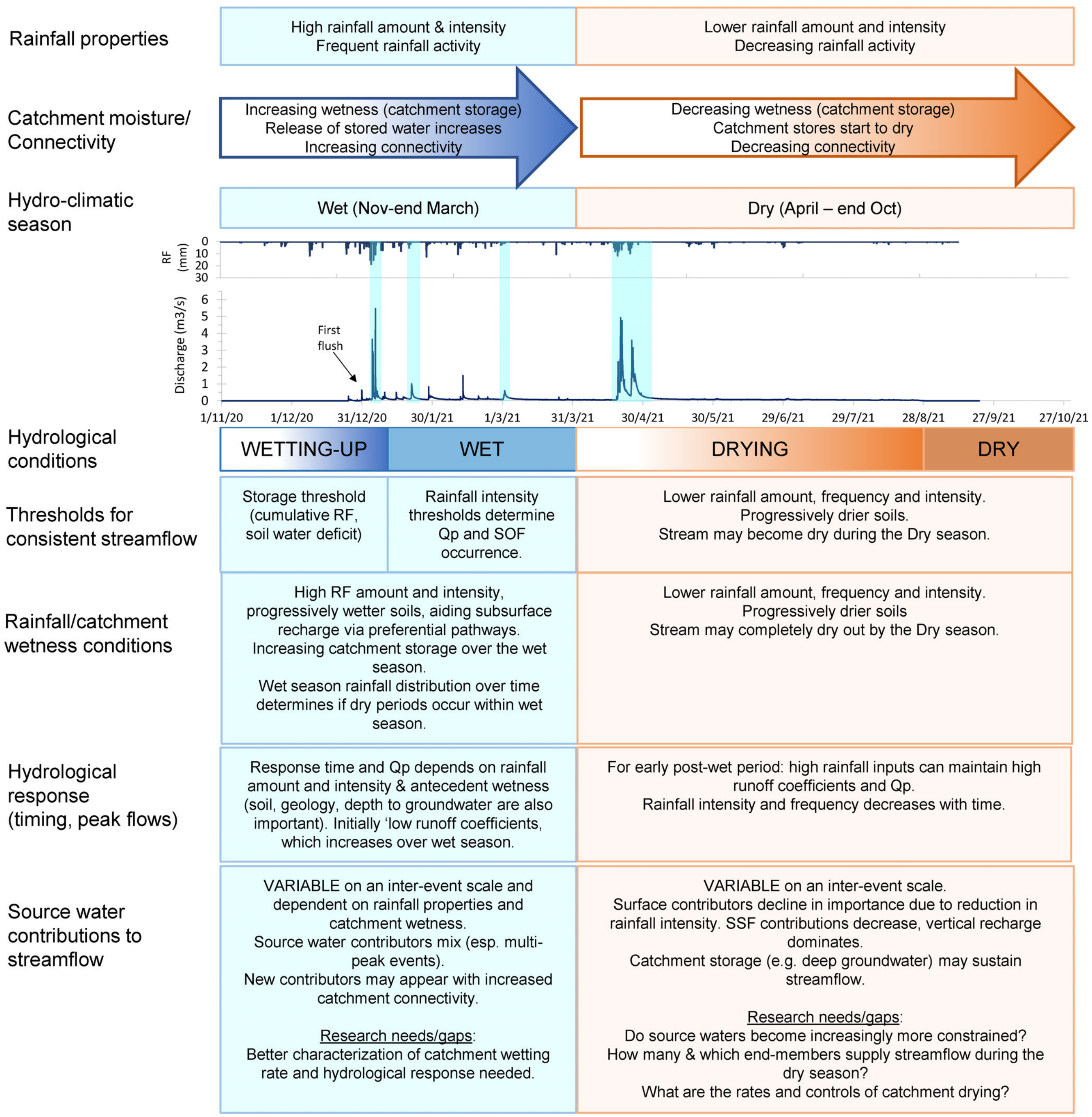
Changes in the duration and spatial extent of connectivity, determine the source waters, runoff flow paths and landscape elements contributing to streamflow (e.g., Blume et al., 2009; Cook et al., 1998; Correa et al., 2017; Farrick & Branfireun, 2014b; Zimmermann et al., 2014). During the wettest part of the wet season, source waters may mix and/or additional source waters may be switched on and contribute to streamflow (e.g., Barthold et al., 2016; Correa et al., 2017; Inamdar et al., 2013). For small catchments such as the North Queensland catchments and other tropical catchments, connectivity may be between the stream, riparian zones and hillslopes (e.g., Correa et al., 2017; Elsenbeer et al., 1995; Farrick & Branfireun, 2014a). For larger flat catchments, typical of most of northern Australia, the spatial extent and duration of connectivity between the rivers and floodplains modulates the seasonal hydrological behaviour of the catchment and associated material transport (e.g., Duvert et al., 2020).

Dry periods may occur within the wet season, disconnecting catchment elements and pathways. Connectivity may be re-established when rainfall occurs, resulting in catchment re-wetting. It is possible that source water contributions during the wetting-up phases occurring later in the wet season or early post-wet season may be different from that occurring at the start of the wet season because of contributions from catchment stored water that accumulated over the wet season from rainfall recharge (Bonell, 1993). As the catchment progresses into the dry season, reductions in rainfall intensity generally decreases surficial contributions which are replaced by subsurface contributions. The number of source water endmembers will likely decrease as the catchment becomes increasingly more disconnected over time (Boulton et al., 2017). We know much less about the way catchments transition from wet to dry conditions, highlighting an important gap in the understanding of seasonal catchment response behaviour. For example, the nature of wetting-up and drying may be greater for catchments with intermittent flow (Atika Creek, Thompson Creek) as compared to those with perennial flow (e.g., Babinda). Important questions around threshold conditions when

TABLE 5 Streamflow response and runoff generation mechanisms for the wet and dry seasons of wet/dry tropical catchments



	Rainfall properties	High rainfall amount & intensity Frequent rainfall activity	Lower rainfall amount and intensity Decreasing rainfall activity
	Catchment moisture/ Connectivity	Increasing wetness (catchment storage) Release of stored water increases Increasing connectivity	Decreasing wetness (catchment storage) Catchment stores start to dry Decreasing connectivity
	Hydro-climatic season	WET	DRY
	Hydrological periods	WETTING-UP WET	DRYING DRY
Babinda catchments (Bonell & Gilmour, 1978, Bonell et al., 1981)	Af climate Tropical rainforest Shallow (0.2m) conductive soil layer Relatively impermeable layer below	Shallow subsurface flow + saturation overland flow	Shallow subsurface flow Decreasing importance of saturation overland flow with increasing dryness.
Primary rainforest La Cuenca, Peru (Elsenbeer & Lack, 1996)	Annual rainfall (3300mm) Ultisol soils, shallow conductive layer (0.2m) Relatively impermeable layer below. Pipes present.	Greater difference in the tracer signature values for overland flow and throughfall.	Tracer signature values more similar for overland flow and throughfall.
Tropical savanna forest Howard River (Cook et al., 1998, Duvert et al., 2020)	Annual rainfall (1879 mm) Dolite with interbedded mudstone, siltstone, sandstone. Numerous solution cavities	Rapid recharge of groundwater via pipes early in the wet season. Young water sources (<1 yr) from shallow groundwater and wetlands. River well connected to floodplains/wetlands.	Old groundwater (>100 yrs) contributes to streamflow. Floodplain/wetlands disconnected from river.
Tropical montane cloud forest, Mexico (Munoz-Villers & McDonnell, 2015)	Temperate humid climate Wet season RF = 80% of annual rainfall (3200 mm) Volcanic ash soils (Umbric Andosols) Sharp change in Ks in top 150mm Relatively impermeable layer below	Low antecedent wetness conditions -> large contributions of event water (channel precipitation) Increasing wetness: Pre-event water from groundwater sources becomes dominant water source. Wet conditions: Large contributions from pre-event flows from groundwater sources	
Tropical dry forest, Mexico (Farrick & Branfireun, 2015)	Tropical savanna (Aw) Wet season RF = 95% of annual rainfall (813 mm) Volcanic soils (chromic cambisols) Conductive surface soils (Ks: 9-164 mm/hr)	Spatial connectivity increases with catchment wetness. -> Contributing area increases from headwaters to entire catchment.	
High elevation tropical grassland, Ecuador (Correa et al., 2017, Mosquera et al., 2016, 2015, Crespo et al., 2011)	Tropical savanna (Aw) Annual rainfall (1345 mm) Histosols and andosols. Surface Ks (>5 mm/hr) is greater than mean rainfall intensity. High elevation wetlands found at this site.	Dominant source water: Rainfall & deep hillslope soil water (Andosols, 0.65m) -> stream connected to hillslope	Rainfall contribution decreases. Dominant source waters: Deep riparian soil water (histosols 0.75m) & spring water
Tropical deciduous lowland forests, Panama (Zimmermann et al., 2014, Barthold et al., 2016)	Annual rainfall (2461 mm) Eutic Cambisol soils. Surface Ks decreases to low values at shallow depth. High elevation wetlands found at this site.	Flashy response, overland flow Rainfall amount & intensity key variables. Connectivity increases with catchment wetness -> surficial drainage of entire hillslopes. Source water endmembers were time-variant.	



Rainfall properties	High rainfall amount & intensity Frequent rainfall activity		Lower rainfall amount and intensity Decreasing rainfall activity	
Catchment moisture/ Connectivity	Increasing wetness (catchment storage) Release of stored water increases Increasing connectivity		Decreasing wetness (catchment storage) Catchment stores start to dry Decreasing connectivity	
Hydro-climatic season	Wet (Nov-end March)		Dry (April – end Oct)	
Hydrological conditions	WETTING-UP	WET	DRYING	DRY
Thresholds for consistent streamflow	Storage threshold (cumulative RF, soil water deficit)	Rainfall intensity thresholds determine Qp and SOF occurrence.	Lower rainfall amount, frequency and intensity. Progressively drier soils. Stream may become dry during the Dry season.	
Rainfall/catchment wetness conditions	High RF amount and intensity, progressively wetter soils, aiding subsurface recharge via preferential pathways. Increasing catchment storage over the wet season. Wet season rainfall distribution over time determines if dry periods occur within wet season.		Lower rainfall amount, frequency and intensity. Progressively drier soils Stream may completely dry out by the Dry season.	
Hydrological response (timing, peak flows)	Response time and Qp depends on rainfall amount and intensity & antecedent wetness (soil, geology, depth to groundwater are also important). Initially 'low runoff coefficients, which increases over wet season.		For early post-wet period: high rainfall inputs can maintain high runoff coefficients and Qp. Rainfall intensity and frequency decreases with time.	
Source water contributions to streamflow	VARIABLE on an inter-event scale and dependent on rainfall properties and catchment wetness. Source water contributors mix (esp. multi-peak events). New contributors may appear with increased catchment connectivity. Research needs/gaps: Better characterization of catchment wetting rate and hydrological response needed.		VARIABLE on an inter-event scale. Surface contributors decline in importance due to reduction in rainfall intensity. SSF contributions decrease, vertical recharge dominates. Catchment storage (e.g. deep groundwater) may sustain streamflow. Research needs/gaps: Do source waters become increasingly more constrained? How many & which end-members supply streamflow during the dry season? What are the rates and controls of catchment drying?	

FIGURE 9 Conceptual framework for the seasonal evolution of streamflow responses for steep seasonal tropical catchments (refer to Table 5). For NE Queensland catchments, the different hydrological conditions follow the general timeline: Wetting-up/wet (Dec/Jan to Mar/Apr), drying/post-wet (March/April to mid-June) and dry (mid-June to Sept/Oct), pre-wet (Oct to early December) (after Bonell & Callaghan, 2009; Howard et al., 2010). SOF, saturation overland flow; SSF, shallow subsurface flows

streamflow cessation occurs, rate of catchment drying and associated changes in dominant source waters and if the drying transition periods are mirrors of the wetting-up periods, remain to be discovered for seasonal tropical catchments as they continue to face challenges associated with human activity (landuse change, water abstraction, and flow regulation) and climate change (Messager et al., 2021; Shanafield et al., 2020).

5 | CONCLUSIONS

Using a range of events that span the wet season, this paper showed that both Atika and Thompson Creek catchments have fast streamflow responses to high, intense, and frequent rainfall activity caused by TC or monsoon rainfall activity, similar to the Babinda catchments despite their slightly more seasonal flow regime. The Atika Creek catchment also displayed fast shallow soil water responses similar to the Babinda catchments, suggesting that steep forest catchments in humid tropical Australia behave similarly in response to seasonal synoptic rainfall activity. While event water contributions to streamflow was important for the Babinda catchments, the results of this study showed that event water dominated during peak flows (9.9%–70.6%) but total event flows were generally dominated by pre-event water (>50%), especially when the catchments were wetter. Threshold conditions exist for streamflow generation and transitional periods (at the start and after a dry period within the wet season). These periods present the most difficult conditions for identifying endmember contributions to streamflow and hydrograph separations especially for multi-peak events due to changes in catchment connectivity. An important finding relates to the time-variant nature of the measured source water endmembers given the seasonal rainfall-runoff response behaviour of our study catchments and the Babinda catchments. Our results also highlight the need for high frequency multi-source sampling, incorporating soil water and shallow groundwater, to accurately interpret hydrological response behaviour on the event and seasonal timescales. We present a conceptual framework that describes the seasonal evolution of streamflow for seasonal tropical catchments based on the findings from the North Queensland catchments and other tropical catchments.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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