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Hydrology of the Great Barrier Reef catchment area along a latitudinal gradient: Implications for estimating discharge

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ABSTRACT

Study region: Great Barrier Reef catchment, north-eastern Australia
Study Focus: The Great Barrier Reef (GBR) catchment of north-eastern Australia contains 35 separate river basins comprising an area of 423,000 km^2. This study compiled flow data for 49 gauging stations to elucidate drivers of hydrologic patterns across the GBR catchment. We compare different methods to upscale annual flow volumes recorded at individual gauging stations to total end of system volumes for the GBR catchment. Accurate estimates of total basin discharge are essential for pinpointing sources of pollution and focussing land management strategies within the GBR.
New hydrological insights for the region: Our spatial analysis revealed distinct north-south gradients in the discharge data largely related to rainfall/climate variability. The northern basins generally have higher stream discharge per unit area, lower coefficients of variation for both inter- and intra-annual discharge, higher runoff to rainfall ratios, higher baseflow contributions and fewer zero-flow days relative to basins in the south. River basins deviated from the north-south gradient due to location-specific factors such as basin size, rainfall variability and anthropogenic modification to flow regimes. We provide recommendations on the most appropriate factors to use when scaling up the gauged discharge data to represent total basin discharge. Our study systematically assesses the spatial variability in river discharge statistics across a north-south latitudinal gradient and provides insights on key drivers of hydrological processes.

1. Introduction

Knowledge of stream discharge variability is critical for water planning and allocation, instream ecological assessments, understanding anthropogenic impacts, and quantifying the magnitude, duration and extent of influence on receiving ecosystems (Puckridge et al., 1998; Dettinger and Diaz, 2000; Vörösmarty and Sahagian, 2000; Bunn and Arthington, 2002; Milliman et al., 2008; Petheram et al., 2008; Kemp et al., 2016; Davis et al., 2017; Hughes and Croke, 2017; Baird et al., 2021; Duvert et al., 2022). On broader spatial scales covering multiple river basins, analysis of streamflow data provide insights on the factors controlling hydrology such as catchment area and morphology, rainfall/climate, vegetation, land use and water resource development (i.e. dams and groundwater extraction) (e.g. Moliere et al., 2009; Rustomji et al., 2009; Kennard et al., 2010a; Waterhouse et al., 2016; Fowler et al., 2022). Indeed,

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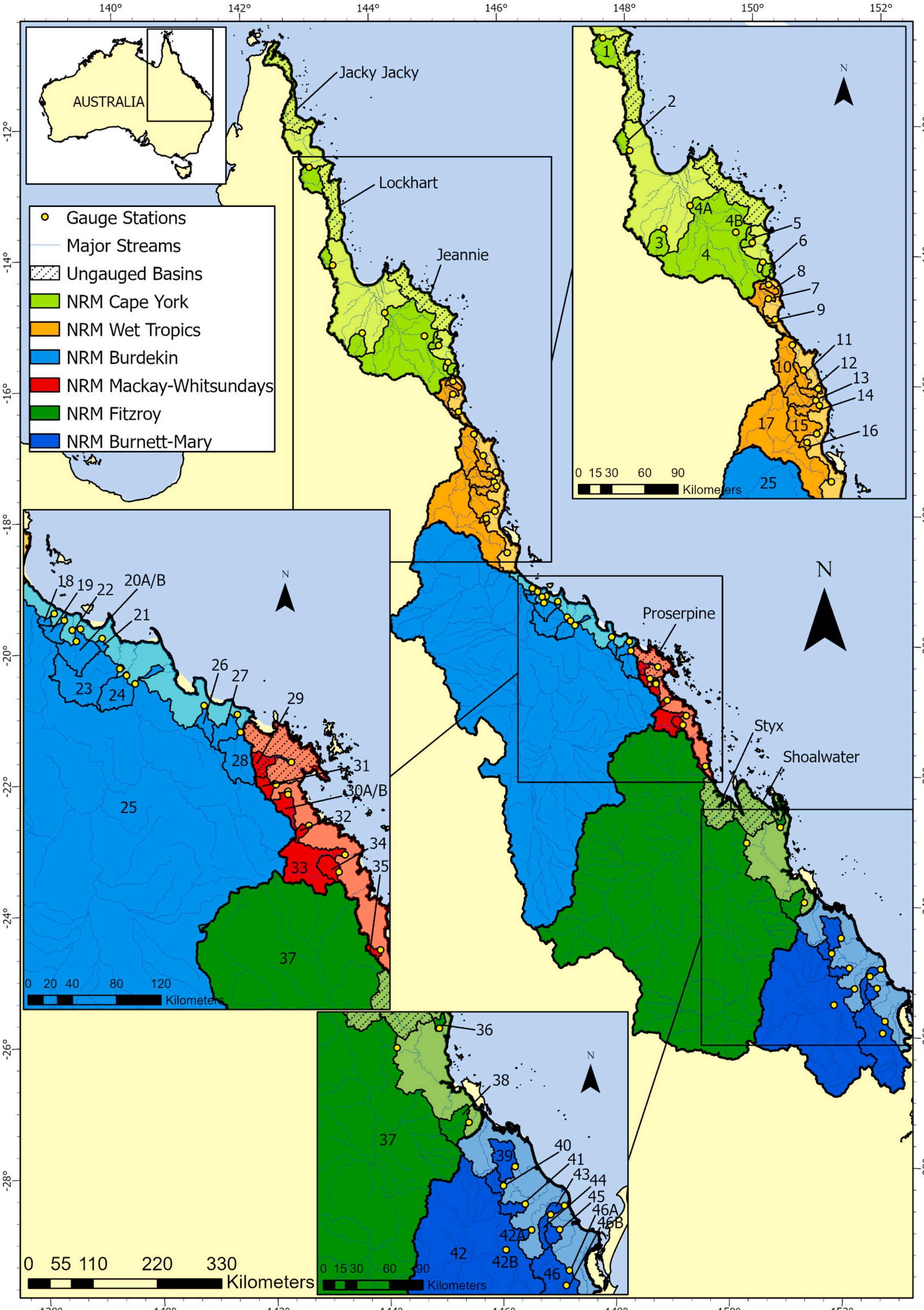

Fig. 1. Map of gauging stations (yellow dots: see Table 1 for names of gauging stations) used in the GBR catchment area. The ungauged basins are labelled with a hashed pattern. The coloured shaded areas represent the NRM regions for the GBR and the lighter shades highlight the areas below the streamflow gauge.

most hydrological classification studies on a regional to country-wide scale employ multivariate statistics to highlight spatial differences in flow regimes that are often linked to key climatic drivers such as the El Niño Southern Oscillation, the Pacific Decadal Oscillation and the Antarctic Oscillation (Redmond and Koch, 1991; Dettinger and Diaz, 2000; Verdon et al., 2004; Rubio-Alvarez and McPhee, 2010). Understanding the climatic drivers of hydrologic variability allows changes to freshwater discharge to be assessed

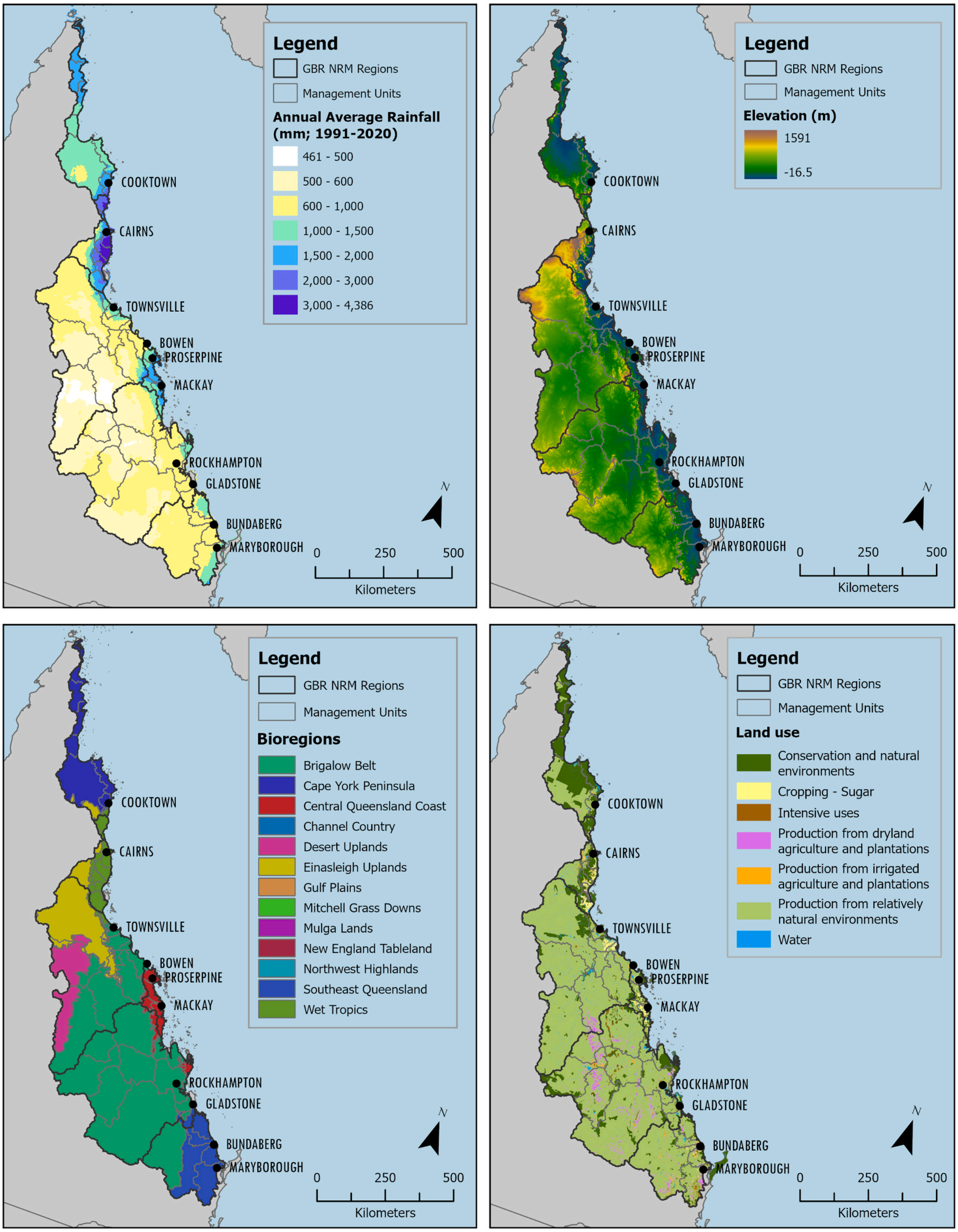

Fig. 2. Maps of the GBR catchment area for mean annual rainfall, topography, bioregions and land use.

under future climate scenarios (Zheng et al., 2024).

Fundamental research from the tropics of northern Australia across a range of spatial and temporal scales have considerably advanced our understanding of hydrological processes in tropical locations including the quantification of baseflow and event flow contributions and establishing intra- and inter-annual variability of streamflows (reviewed in Duvert et al., 2022). Hydrological classifications of northern and eastern Australia reveal several distinct groupings that are broadly related to perennial and intermittent systems, their intra- and inter-annual variability and the flora and fauna based ecosystems they support (Verdon et al., 2004; Petheram et al., 2008; Rustomji et al., 2009; Moliere et al., 2009; Kennard et al., 2010a; Davis et al., 2017). These classifications provide the fundamental description of the hydrological processes that underpin the structure and functioning of freshwater ecosystems (Bunn and Arthington, 2002; Davis et al., 2017) and are also highly relevant to the management of receiving marine ecosystems such as the Great Barrier Reef (GBR). The 35 river basins of the GBR catchment area, north-eastern Australia (Fig. 1) cover ~ 14.5 degrees of latitude, stretch across wet and dry tropical climates, contain different land uses and have basin areas ranging from 473 km^2 (Mossman) to 143, 000 km^2 (Fitzroy) (Furnas, 2003; Lewis et al., 2021). Despite the availability of relatively long-term stream gauging records (> 30 years) and the large variability in geography and climate in the region, there has been no recent evaluation of hydrologic patterns across basins in the GBR catchment (but see Pusey and Arthington, 1996; Furnas, 2003). From 2010 the basins of the GBR have experienced historically large discharge events interspersed with periods of very low streamflow (Gruber et al., 2024). An updated statistical summary with flow descriptors calculated from contemporary flow data would provide valuable insights on the hydrological variability of the river basins of the GBR and the factors that drive freshwater discharge to the GBR. We focus on a 30-year period (1990/91 – 2019/20 water years) which maximised the number of stream gauges included and also incorporates recent hydrologic extremes.

Of the 35 basins that drain to the GBR, 29 have at least one continuously operating gauging station which cover the most recent 30 year climate period (1990/91–2019/20). However, the locations of the gauges in most instances are upstream of the river mouth and capture varying proportions of the total basin area (Fig. 1). Hence, the gauge flow volume data in their current form cannot be directly compared across basins. For example, the Daintree and Barron Basins within the Wet Tropics NRM region contain a similar area (2100–2200 km^2); however, the most downstream flow gauge on the Daintree River (Bairds gauge) only measures 43 % of the Daintree Basin while the Barron River at Myola gauge captures 89 % of the Barron Basin (Fig. 1; Supplementary Table 1). As the Barron Basin covers more than double the area compared to the gauge on the Daintree Basin a 'scaling factor' is required on these data so that total catchment discharges (and constituent loads) can be directly compared across basins and broader management regions. The development of a scaling factor would also allow basin discharge contributions to the GBR to be more accurately resolved and compared over longer temporal scales. In instances where a basin does not have a currently operating gauging station, a gauging station from a neighboring basin could be used as a proxy to estimate discharge.

The GBR faces several catchment issues, primarily related to declining water quality due to land-based runoff and modifications in land use (Brodie et al., 2012; Lewis et al., 2021). These issues are directly linked to changes in hydrology, such as altered river flow patterns and increased sediment and nutrient transport to receiving ecosystems. Effective water quality management requires understanding of key hydrological processes within the catchments and confident estimates of total discharge essential for pinpointing sources of pollution and focussing land management strategies. The objectives of the present study are to: 1) Systematically analyse the spatial variability in river discharge statistics across the north-south latitudinal gradient of the GBR catchments, providing insights on the key drivers of hydrological processes in the tropics of north-eastern Australia; 2) Identify the most suitable approach for each GBR catchment to up-scaling hydrological data to represent the total basin discharge. For the latter we developed five upscaling factors based on the outputs from two hydrological models used extensively across the GBR: the Source Catchments (Queensland Government) and the Grid to Grid hydrological model (Australian Bureau of Meteorology) along with the gauged flow data over their common period to resolve the most appropriate scaling correction factor for each basin. These scaling factors were then applied to highlight the variability in total GBR catchment area discharge over the most recent 30-year climate period. The paper strictly covers the spatial variability of the GBR catchment area region where a longer-term temporal analysis of the data is beyond this contribution. This contribution serves to benchmark key hydrology statistics for river basins of the GBR catchment area so that it may be used to inform responses to past and future trends in climate, water infrastructure development and land management.

2. Study area

The GBR catchment area covers a large section of north-eastern Australia (423,000 km^2) and contains a high diversity of geomorphology, soil types, vegetation and climate which can be separated into seven distinct bioregions. These bioregions include Cape York, Wet Tropics, Einasleigh Uplands, Desert Uplands, Brigalow Belt, Central Queensland Coast and South East Queensland (Furnas, 2003) (Fig. 2). The diverse range of vegetation communities include *Eucalyptus*-dominated woodlands and open forests, tropical and sub-tropical rainforest, *Melaleuca* forests, *Acacia*-dominated woodlands and *Corymbia* woodlands (Furnas, 2003). For management purposes, the GBR catchment has been divided into six Natural Resource Management (NRM) regions: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary (Fig. 1).

The average annual rainfall of the GBR catchment area ranges from less than 500 $mm.y^{-1}$ at its inland, semiarid boundaries to 8200 $mm.y^{-1}$ in the Wet Tropics (Petheram et al., 2008; Davis et al., 2017; Fig. 2). In general, most (~ 90 %) of the annual rainfall is concentrated during the summer wet season between November and April (Davis et al., 2017). Rainfall drivers in the GBR catchment area have been summarised by Furnas (2003) and include a decreasing north-south influence of the northern Australian/Asian monsoon which shapes the observed latitudinal gradient in both rainfall and discharge. A strong coastal-inland rainfall gradient results in lower mean annual rainfall for the larger catchments such as the Normanby, Herbert, Burdekin, Fitzroy and Burnett Basins which host a considerable 'inland area' behind the wetter coastal ranges, compared to their coastal catchment counterparts at similar latitudes. Furthermore, the mountain ranges that form the headwaters of GBR catchments from south of the Daintree have peak elevations $\sim >$ 800 m above sea level which promote orographic uplift of warm humid air from the Coral Sea - consequently these catchments have much higher mean annual rainfalls (Fig. 2). Inter-annual variability of rainfall in the GBR catchment area is governed by the strength of the monsoon, the seasonal variability and unpredictable movement of tropical cyclones, the strength of the El Niño Southern Oscillation and the strength of the Pacific Decadal Oscillation (Furnas, 2003; Petheram et al., 2008; Davis et al., 2017).

3. Materials and methods

3.1. Streamflow data

Key gauges within the 29 gauged basins were identified which included the most downstream site (where multiple gauges exist on a stream) as well as to capture additional streams within the basin that discharge to a separate area of the coast (Table 1; Fig. 1; Supplementary Table 1). Streamflow data and gauging station information were obtained from the Water Monitoring Information Portal (WMIP: Queensland Government information.qld.gov.au) (Department of Regional Development, Manufacturing and Water 2021). The records preferably contained a continuous record of the most recent 30 year climate period (1990/91–2019/20 water years) (water year = 1st October to 30th September). For the streamflow data that did not fully cover this period but covered a period $>$ 15 years, an alternative upstream gauge with a complete 30 year period was identified and statistics on both records were calculated. For basins with no streamflow gauge data (i.e. Jacky Jacky, Lockhart, Jeannie, Proserpine, Styx, Shoalwater: Fig. 1), the most suitable 'nearest neighbour' gauge was identified and used to estimate basin volume discharge against the hydrological model outputs for these basins.

Due to a lack of continuous flow data that covered a large area of the Ross Basin, additional water level data from 2002 to 2020 were collated from the Bureau of Meteorology for the Ross River at Aplins Weir (Bureau of Meteorology, 2020). This site captures $\sim$ 48 % of the Ross Basin. Water level was converted to flow using an exponential relationship between the measured (historical) streamflow data from Gleeson's Weir ($\sim$ 4.5 km upstream of Aplins Weir with only minor streams entering in the area between the two sites) and the water level height at Aplins Weir for an overlapping period between 1950 and 1953 that contained levels between 0 m and 3.09 m above the weir level. This relationship was applied to the 2001/02 – 2019/20 dataset to estimate daily and peak discharge for this site.

Overall, the data from 49 gauging stations were analysed over a latitudinal gradient across the GBR catchment area. The latitude at the gauging station was used to examine the flow metric variability over the north-south gradient as part of our spatial analysis. The compilation of streamflow data and the choice of statistical metrics have been informed from several previous studies which have demonstrated the importance of considering the length of record (minimum of 15 years, preferably >30 years) and the type of information that can be obtained through more detailed statistical analyses (e.g. Olden and Poff, 2003; Kennard et al., 2010b).

3.2. Streamflow data infilling

Multiple streamflow datasets downloaded from the WMIP website included temporal data gaps which can affect the accuracy of the results. The River Analysis Package (RAP) (Marsh et al., 2003) was used to interpolate the gaps for incomplete streamflow records. Interpolation was only performed when the gaps were less than one month in length and the periods when the influence on total discharge would be negligible (i.e. dry season periods). In most instances, the gaps in flow data records occurred during the dry season and were less than 3 days in length.

3.3. Rainfall data for the upstream area above gauge

To examine the runoff-rainfall relationships for each gauge record, the annual (water year) area average rainfall was calculated for the corresponding catchment area upstream of each gauge following the methodology of Jarihani et al. (2017). Rainfall data were downloaded from the Long Paddock website, hosted by the Scientific Information for Land Owners (SILO) website (Stone et al., 2019). Long Paddock's historical monthly rainfall records are available as spatial grids constructed by mathematical interpolation techniques (Scientific Information for Land Owers, 2021). The gridded rainfall data were assigned to each upstream gauge catchment area and the historical monthly and annual rainfall in millimetres (with 1σ standard deviation) for the corresponding gauged period (1990/91–2019/20 water years) extracted. Finally, to determine the runoff coefficient, the annual stream discharge was divided by the corresponding annual total rainfall from above each respective gauge site.

$$Runoff\ coefficient = \frac{Runoff(mm)}{Rainfall(mm)} \tag{1}$$

3.4. Statistical analysis: flow data

Peak hourly discharge, monthly discharge volume, mean total annual (i.e. water year) discharge and the minimum and maximum annual discharge over the most recent 30-year period (i.e. 1990/91–2019/20 water years) were compiled for each streamflow dataset. Relevant gauges that contained between 11 and 23 years of data over this period were also compiled to provide support for the longer-

Table 1
Compilation of the streamflow data of the most recent 30 years (1990/91–2019/20) for the selected GBR catchment area gauges. Raw streamflow data were sourced from the Water Monitoring Information Portal (WMIP: Queensland Government https://water-monitoring.information.qld.gov.au/) and the Bureau of Meteorology and the rainfall data sourced from the Long Paddock website (https://www.longpaddock.qld.gov.au/).

NRM Region	Basin	Gauge(s)	Period of record (yrs)	Peak hourly discharge (ML.d-1)	Mean annual discharge (ML)	Minimum annual discharge (ML)	Maximum annual discharge (ML)	Inter-annual COV	Mean Intra-annual COV	Maximum Intra-annual COV	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)	% Runoff
Cape York	Olive-Pascoe	Pascoe at Garraway Creek (1)	30	300,000 (2018/19)	1200,000	9200 (1990/91)	3,000,000 (2005/06)	60 %	160 %	230 % (2002/03)	1661 ± 380	949 ± 570	54 ± 23 %
	Stewart	Stewart at Telegraph Road (2)	30	130,000 (2005/06)	200,000	14,000 (1991/92)	540,000 (2018/19)	69 %	194 %	267 % (1994/95)	1220 ± 348	422 ± 290	32 ± 15 %
	Normanby	Hann at Sandy Creek (3)	30	33000 (2010/11)	130,000	9700 (1992/93)	560,000 (2010/11)	97 %	153 %	192 % (2006/07)	1045 ± 244	130 ± 126	11 ± 8 %
		Normanby at Battle Camp (4 A)	30	230,000 (2018/19)	720,000	19,000 (2002/03)	2400,000 (2018/19)	70 %	204 %	284 % (1994/95)	1341 ± 379	313 ± 219	21 ± 10 %
		Normanby at Kalpowar Crossing (4B)	14 (2006/07–2019/20)	190,000 (2018/19)	2700,000	1100,000 (2011/12)	6400,000 (2018/19)	60 %	191 %	276 % (2014/15)	1127 ± 286	208 ± 125	16 ± 6 %
	Endeavour	Endeavour at Flaggy (5)	30	110,000 (2003/04)	150,000	2200 (2002/03)	340,000 (2005/06)	62 %	177 %	330 % (2002/03)	1584 ± 492	434 ± 271	25 ± 11 %
		Annan at Beesbike (6)	30	170,000 (1998/99)	310,000	49,000 (2001/02)	710,000 (2018/19)	53 %	126 %	183 % (2003/04)	2163 ± 620	1248 ± 667	54 ± 17 %
Wet Tropics	Daintree	Daintree at Bairds (7)	30	360,000 (2018/19)	930,000	110,000 (2001/02)	2900,000 (2018/19)	64 %	117 %	206 % (1995/96)	2200 ± 599	1019 ± 648	43 ± 18 %
		Bloomfield at China Camp (8)	30	210,000 (2018/19)	530,000	160,000 (2001/02)	1100,000 (1999/00)	43 %	101 %	174 % (1995/96)	3131 ± 827	2021 ± 872	62 ± 14 %
	Mossman	Mossman at Mossman (9)	30	120,000 (2013/14)	290,000	110,000 (1991/92)	520,000 (2018/19)	34 %	88 %	171 % (1995/96)	2336 ± 586	2736 ± 937	115 ± 20 %
	Barron	Barron at Myola (10)	30	340,000 (1998/99)	670,000	110,000 (2002/03)	1900,000 (2010/11)	76 %	148 %	247 % (2017/18)	1361 ± 357	349 ± 256	23 ± 12 %
	Mulgrave-Russell	Mulgrave at Peets Bridge (11)	30	250,000 (1998/99)	780,000	180,000 (1991/92)	1600,000 (2010/11)	46 %	102 %	175 % (2007/08)	2853 ± 720	1492 ± 682	50 ± 12 %
		Russell at Bucklands (12)	30	76,000 (1998/99)	1100,000	410,000 (1991/92)	2000,000 (1999/00)	33 %	93 %	125 % (2003/04)	4034 ± 898	3473 ± 1149	84 ± 13 %
	Johnstone	North Johnstone at Tung Oil (13)	30	420,000 (1998/99)	1800,000	620,000 (1991/92)	3500,000 (2010/11)	37 %	90 %	149 % (2017/18)	2834 ± 672	1976 ± 731	68 ± 12 %
		South Johnstone at Upstream Central Mill (14)	30	150,000 (1993/94)	790,000	260,000 (1991/92)	1600,000 (2010/11)	40 %	86 %	138 % (2017/18)	2926 ± 739	2006 ± 786	65 ± 14 %
	Tully	Tully at Euramo (15)	30	91,000 (1998/99)	3100,000	1100,000 (1991/92)	6000,000 (2010/11)	36 %	82 %	117 % (2017/18)	2586 ± 646	2110 ± 764	80 ± 15 %
	Murray	Murray at Upper Murray (16)	30	58,000 (1997/98)	180,000	37,000 (2002/03)	600,000 (2010/11)	64 %	127 %	181 % (1990/91)	1714 ± 518	1164 ± 745	63 ± 25 %
	Herbert	Herbert at Ingham (17)	30	940,000 (1990/91)	3400,000	690,000 (2002/03)	11,100,000 (2010/11)	78 %	158 %	243 % (2008/09)	1119 ± 338	402 ± 295	32 ± 15 %
Burdekin	Black	Black at Bruce Highway (18)	30	190,000 (1997/98)	100,000	750 (1994/95)	350,000 (2010/11)	99 %	241 %	343 % (1992/93)	1186 ± 576	406 ± 402	27 ± 19 %
		Bluewater at Bluewater (19)	30	120,000 (1997/98)	63,000	1900 (1994/95)	230,000 (2018/19)	95 %	222 %	317 % (2004/05)	1297 ± 597	738 ± 703	46 ± 28 %

(*continued on next page*)

Table 1 (*continued*)

NRM Region	Basin	Gauge(s)	Period of record (yrs)	Peak hourly discharge (ML.d-1)	Mean annual discharge (ML)	Minimum annual discharge (ML)	Maximum annual discharge (ML)	Inter-annual COV	Mean Intra-annual COV	Maximum Intra-annual COV	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)	% Runoff
	Ross	Ross at Dam Headwater (20)	11 (1990/91–2000/01)	35,000 (1990/91)	120,000	0 (1991/92–1995/96, 2001/02–2002/03 & 2005/06)	1100,000 (1990/91)	170 %	230 %	256 % (1996/97)	1105 ± 506	238 ± 352	16 ± 19 %
		Ross at Aplins Weir (20)	18 (2001/02–2018/19)	200,000 (2018/19)	180,000	150 (2003/04)	1100,000 (2018/19)		250 %	339 % (2006/07)			
		Alligator at Allendale (21)	30	43,000 (2013/14)	42,000	4200 (1991/92)	160,000 (2008/09)	98 %	194 %	292 % (2001/02)	1251 ± 581	607 ± 573	40 ± 23 %
		Bohle at Harvey Range Road (22)	22 (1990/91–2011/12)	76,000 (1997/98)	110,000	4400 (1992/93)	310,000 (2010/11)	91 %	228 %	318 % (1995/96)	1117 ± 539	782 ± 710	57 ± 35 %
Burdekin	Haughton	Haughton at Powerline (23)	30	380,000 (2007/08)	450,000	42,000 (1991/92)	1800,000 (1990/91)	101 %	171 %	286 % (2006/07)	890 ± 425	254 ± 255	23 ± 14 %
		Barratta at Northcote (24)	30	150,000 (2007/08)	190,000	24,000 (1992/93)	600,000 (2010/11)	88 %	190 %	269 % (1995/96)	779 ± 356	252 ± 223	28 ± 13 %
	Burdekin	Burdekin at Clare (25)	30	2600,000 (1990/91)	9000,000	530,000 (1991/92)	40,000,000 (1990/91)	119 %	182 %	276 % (2018/19)	597 ± 203	69 ± 82	9 ± 9 %
	Don	Elliot at Guthalungra (26)	30	120,000 (2007/08)	64,000	2200 (1991/92)	330,000 (1990/91)	110 %	258 %	344 % (2004/05)	718 ± 313	234 ± 258	27 ± 17 %
		Euri at Koonandah (27)	21 (1999/00–2019/20)	85,000 (2006/07)	180,000	37,000 (2014/15)	580,000 (2010/11)	91 %	252 %	346 % (2001/02)	733 ± 269	427 ± 391	50 ± 29 %
		Don at Reeves (28)	30	390,000 (2007/08)	170,000	23,000 (1993/94)	1100,000 (1990/91)	141 %	229 %	336 % (2004/05)	830 ± 376	170 ± 239	16 ± 12 %
Mackay-Whitsundays	Proserpine	Proserpine at Proserpine (29)	22 (1991/92–2012/13)	18,000 (2006/07)	48,000	7600 (1991/92)	350,000 (2010/11)	134 %	160 %	265 % (1992/93)	1238 ± 486	133 ± 198	9 ± 7 %
	OConnell	O'Connell at Caping Siding (30)	15 (1990/91–2004/05)	220,000 (1990/91)	150,000	3600 (1991/92)	790,000 (1990/91)	101 %	214 %	308 % (2004/05)	1473 ± 575	511 ± 493	28 ± 17 %
		O'Connell at Staffords Crossing (30)	15 (2005/06–2019/20)	240,000 (2007/08)	200,000	22,000 (2014/15)	560,000 (2010/11)		197 %	260 % (2014/15)			
		Andromache at Jochheims (31)	30	150,000 (2007/08)	93,000	5100 (1991/92)	460,000 (1990/91)	126 %	189 %	310 % (2004/05)	1223 ± 501	404 ± 510	25 ± 22 %
		St Helens at Calen (32)	30	100,000 (2006/07)	131,000	10,000 (1991/92)	410,000 (1990/91)	77 %	167 %	247 % (2004/05)	1816 ± 757	1110 ± 860	53 ± 23 %
	Pioneer	Pioneer at Mirani Weir TW (33)	16 (1990/91–2005/06)	350,000 (1990/91)	500,000	36,000 (1991/92)	2800,000 (1990/91)	106 %	174 %	288 % (2004/05)	1474 ± 625	545 ± 582	29 ± 20 %
		Pioneer at Dumbleton Weir HW (33)	14 (2006/07–2019/20)	440,000 (2016/17)	1000,000	120,000 (2014/15)	3300,000 (2010/11)		171 %	225 % (2008/09)			
	Plane	Sandy at Homebush (34)	30	170,000 (2016/17)	180,000	6300 (2005/06)	910,000 (1990/91)	109 %	215 %	324 % (2004/05)	1422 ± 619	558 ± 606	31 ± 20 %
		Carmila at Carmila (35)	30	88,000 (2016/17)	42,000	790 (2001/02)	180,000 (1990/91)	93 %	208 %	328 % (1992/93)	1344 ± 482	497 ± 462	31 ± 20 %

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Table 1 (*continued*)

NRM Region	Basin	Gauge(s)	Period of record (yrs)	Peak hourly discharge (ML.d-1)	Mean annual discharge (ML)	Minimum annual discharge (ML)	Maximum annual discharge (ML)	Inter-annual COV	Mean Intra-annual COV	Maximum Intra-annual COV	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)	% Runoff
Fitzroy	Waterpark	Waterpark at Byfield (36)	30	53,000 (2012/13)	95,000	7900 (2003/04)	330,000 (2012/13)	88 %	158 %	254 % (2007/08)	1398 ± 368	449 ± 397	29 ± 18 %
	Fitzroy	Fitzroy at The Gap (37)	30	1300,000 (1990/91)	5100,000	350,000 (1994/95)	38,000,000 (2010/11)	154 %	209 %	316 % (1993/94)	606 ± 161	37 ± 58	5 ± 6 %
	Calliope	Calliope at Castlehope (38)	30	280,000 (2012/13)	150,000	1400 (1994/95)	920,000 (2012/13)	128 %	225 %	328 % (2002/03)	783 ± 237	120 ± 153	12 ± 12 %
Burnett-Mary	Baffle	Baffle at Mimdale (39)	30	400,000 (2012/13)	280,000	550 (2018/19)	1300,000 (2012/13)	123 %	228 %	293 % (2006/07)	1028 ± 310	199 ± 245	16 ± 15 %
	Kolan	Kolan at Springfield (40)	30	260,000 (2012/13)	70,000	0 (2006/07)	430,000 (2012/13)	154 %	253 %	346 % (1994/95, 2004/05 & 2005/06)	888 ± 271	132 ± 198	11 ± 14 %
		Gin Gin at Brushy Creek (41)	30	290,000 (2012/13)	55,000	330 (2006/07)	410,000 (2012/13)	163 %	227 %	309 % (2015/16)	808 ± 224	104 ± 170	10 ± 14 %
	Burnett	Burnett at Figtree Creek (42 A)	23 (1997/98–2019/20)	1400,000 (2012/13)	1000,000	17,000 (2007/08)	8600,000 (2010/11)	212 %	173 %	276 % (2014/15)	676 ± 165	33 ± 71	3 ± 6 %
		Burnett at Mount Lawless (42B)	30 (2019/20)	1400,000 (2012/13)	800,000	4900 (2006/07)	8300,000 (2010/11)	226 %	196 %	269 % (2019/20)	658 ± 167	27 ± 61	4 ± 7 %
	Burrum	Gregory at Isis Highway (43)	30	86,000 (2012/13)	45,000	420 (1990/91)	260,000 (2010/11)	155 %	238 %	323 % (1990/91)	864 ± 242	99 ± 154	9 ± 11 %
		Isis at Bruce Highway (44)	30	140,000 (2012/13)	49,000	1400 (1992/93)	230,000 (1991/92)	141 %	224 %	328 % (2019/20)	862 ± 249	110 ± 156	10 ± 12 %
		Elliott at Dr Mays Crossing (45)	30	65,000 (2012/13)	19,000	270 (1997/98)	100,000 (2012/13)	142 %	143 %	282 % (1997/98)	860 ± 275	77 ± 110	7 ± 8 %
	Mary	Mary at Home Park (46 A)	30	800,000 (2012/13)	1300,000	90,000 (2001/02)	6200,000 (2010/11)	118 %	176 %	265 % (1994/95)	1002 ± 267	184 ± 219	15 ± 13 %
		Mary at Miva (46B)	30	650,000 (2012/13)	1000,000	76,000 (2001/02)	5000,000 (2010/11)	120 %	173 %	260 % (1994/95)	1059 ± 291	220 ± 263	17 ± 15 %

HW = Headwater; TW = Tailwater; ML = Mega litre; COV = coefficient of variation term gauge records as well as to provide an indication for some basins with shorter records. The coefficient of variation (COV) in the annual total discharge (i.e. the inter-annual COV) and the mean and maximum COVs in the monthly discharge volumes (i.e. the intra-annual COVs) were calculated to assess the variability in streamflow between and within years over the 30-year streamflow records.

$$COV(\%) = \frac{Standard\ Deviation}{Mean} * 100 \quad (2)$$

3.5. Statistical analysis: baseflow data and zero flow days

Baseflow refers to the contribution of groundwater and delayed sources to river runoff (Smakhtin, 2001; Marsh et al., 2003; Ladson et al., 2013; Beck et al., 2013; Singh et al., 2019). It is defined as the portion of streamflow which is sustained in the absence of direct runoff. The GBR catchment region includes perennial and intermittent streams which have high variability in terms of their baseflow volumes. The baseflow contribution to streamflow was measured using a Baseflow Index (BFI) as the ratio of mean baseflow volume to total streamflow volume over a specified period (see Eq. 3). The annual (i.e. water year) BFI for each stream gauge was calculated using daily discharge data across the most recent 30-year period and the default parameters ($\alpha = 0.975$) within the RAP software. RAP uses the recursive Lyne & Hollick digital filter to separate baseflow from total streamflow. This is recognised as a robust technique for characterising differences between catchments (Lyne and Hollick, 1979; Ladson et al., 2013). Low values of BFI (0.2) are mostly characteristic of impermeable catchments with a flashy flow regime, and higher values (to 0.95) are typical for more stable hydrographs in high-storage-capacity catchments (WMO, 2008).

$$Base\ Flow\ Index = \frac{Base\ Flow\ Volume}{Total\ Flow\ Volume} \quad (3)$$

Daily discharge data were also used to calculate the mean number of zero flow days for each year of record to describe the permanency of flow at each gauging station.

3.6. Basin models

The Queensland Government Department of Environment, Tourism, Science and Innovation (DETSI) and the Bureau of Meteorology have both developed independent models to calculate discharge for the basins of the GBR. The Source Catchments model (DETSI) applies the Sacramento rainfall runoff model, which has been shown to provide reliable outputs for the GBR catchment area (e.g. Wilkinson et al., 2014; Zhang et al., 2013), to generate streamflow data and determine constituent loads exported to the GBR from each basin (McCloskey et al., 2021a, 20021b). Daily discharge data were generated for the 1990/91–2019/20 water years for each of the 35 basins using the Source Catchments modelling framework with model parameterization as described by Zhang et al. (2013). From these data, annual (water year) basin discharges were determined.

The Bureau of Meteorology have developed the Grid to Grid “G2G” 1 km^2 gridded hydrological model to simulate hourly flows for streams in the GBR catchment area (Khan et al., 2018, 2019; Wells et al., 2019). The G2G model has been used amongst other applications to inform the GBR marine hydrodynamic model within the eReefs modelling suite (Baird et al., 2021). We obtained hourly discharge data from the Bureau of Meteorology’s G2G model for the period 1st January 2007 (model outputs are not available prior to this) to 1st November 2020 from 47 relevant ‘end of stream’ points. The model does not include the Jacky Jacky, Olive-Pascoe, Lockhart and Stewart Basins in the Cape York NRM region and certain ‘end of stream’ points needed to be summed to produce a basin total. From these hourly data, annual (water year) basin discharges were determined.

While both models are calibrated using the available streamflow gauging data and both account for irrigation and other water offtakes, considerable differences exist in the parameterization (e.g. catchment areas) and input data (e.g. rainfall data, time periods). In that regard, there is a need to compare the model outputs and determine the most suitable scaling factors to provide reliable estimates of total discharge to the GBR.

Table 2
Summary of the five scaling factors used to examine how to upscale the measured gauge streamflow to represent the total basin discharge to the GBR.

Scaling factor (SF)	Description
SF1 (Area correction factor)	Divide the total basin area by the total gauged area of the basin
SF2 (G2G model mean)	Divide mean annual water year basin discharges from the G2G model by the corresponding (i.e. over the same period) mean derived from the available streamflow gauged data
SF3 (G2G model linear relationship)	Establish the linear relationship between the annual (water year) discharge produced by the G2G model (y axis) against the corresponding streamflow gauge data (x axis). Apply strength of the linear relationship (r^2 value) to determine confidence of this factor (> 0.95 = excellent; 0.7–0.95 = good; 0.5–0.7 = fair; < 0.5 = poor)
SF4 (Source Catchments mean)	Divide mean annual water year basin discharges from the Source Catchments model by the corresponding (i.e. over the same period) mean derived from the available streamflow gauged data
SF5 (Source Catchments linear relationship)	Establish the linear relationship between the annual (water year) discharge produced by the Source Catchments model (y axis) against the corresponding streamflow gauge data (x axis). Apply strength of the linear relationship (r^2 value) to determine confidence of this factor (> 0.95 = excellent; 0.7–0.95 = good; 0.5–0.7 = fair; < 0.5 = poor)

3.7. Scaling factors to calculate total basin discharge

The calculation of total annual water year discharge for the individual basins of the GBR, NRM regions and the GBR catchment area requires the application of scaling factors to the streamflow gauge measurements. Five scaling factors were calculated for each basin based on gauged data (and in some cases the sum of multiple gauges within the basin), the proportional gauged area of the basin and the modelled discharge outputs from the Source Catchments and G2G models (Table 2).

Based on the agreement between the different scaling factors as well as the strength of the linear model r^2, we provide a qualitative assessment on the confidence of each recommended basin scaling factor which include low confidence (poor agreement between the scaling factors and/or model r^2), medium confidence (reasonable agreement) and high confidence (high agreement; generally for basins that have a high proportion of the area gauged) (see Table 2). The recommended upscaling factor was then applied to the streamflow gauge dataset to produce a 30 year annual (water year) total GBR discharge and to calculate an annual mean discharge for each basin.

4. Results and discussion

4.1. Spatial variability in river discharge

Streamflow patterns across the GBR catchments are highly variable, reflecting variation in size of the gauged catchment areas,

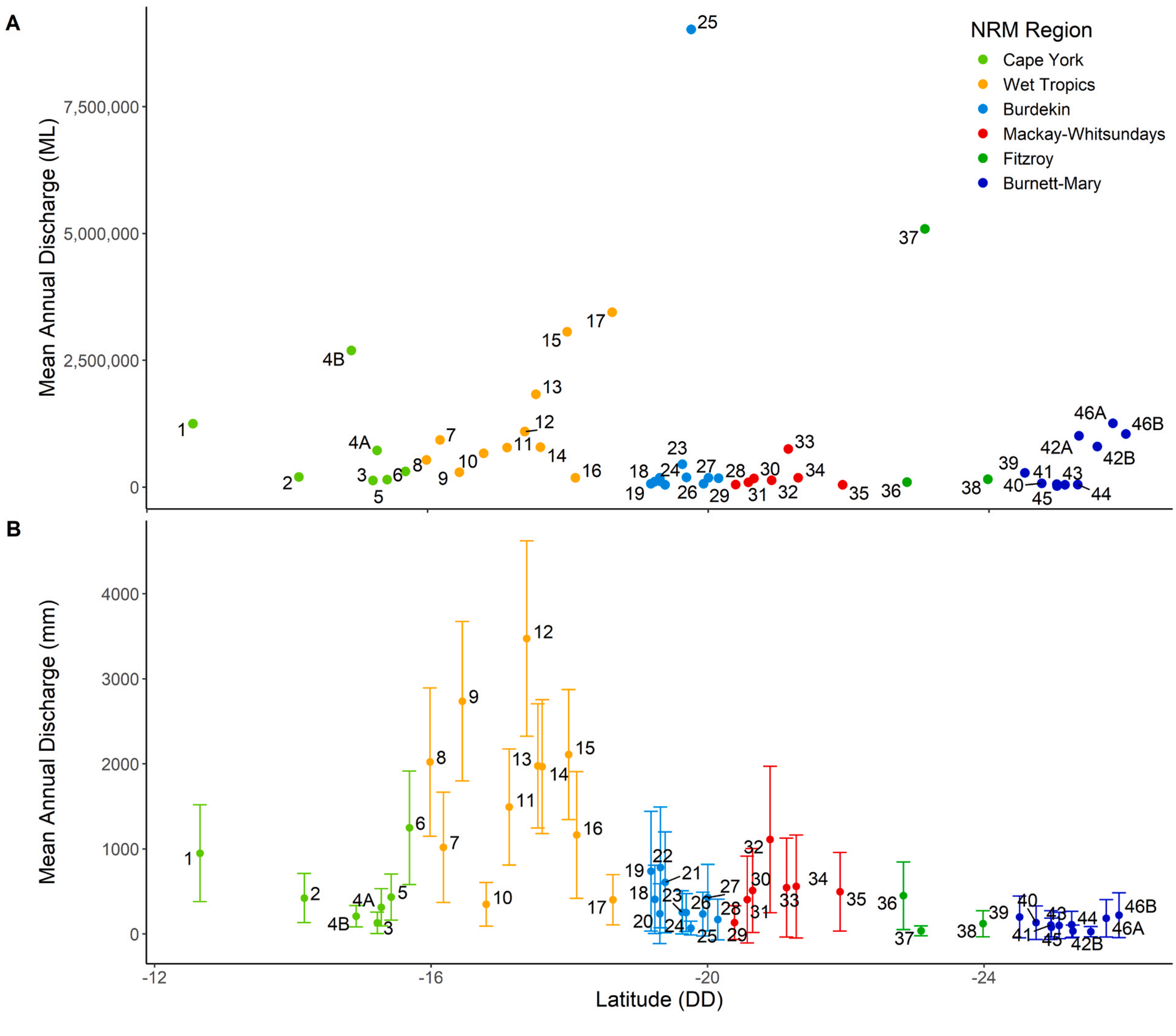

Fig. 3. (A) Mean annual discharge (ML) versus latitude and (B) mean annual discharge (mm) standardised by catchment area versus latitude for 49 gauging stations within the GBR catchment area for the water years 1990/91–2019/20. Numbers adjacent to points relate to gauges in Table 1 and locations are plotted on Fig. 1.

rainfall/climate variability and groundwater inputs (Table 1). The measured peak hourly discharge varies from 18,000 ML.d^{-1} (Proserpine River at Proserpine 2006/07) to 2600,000 ML.d^{-1} (Burdekin River at Clare 1990/91). Mean annual discharge ranges from 19,000 ML (Elliott River at Dr Mays Crossing: Burrum Basin) to 9000,000 ML (Burdekin River at Clare). The Burdekin River at Clare recorded the largest annual discharge range from 530,000 ML (1991/92) to 40,000,000 ML (1990/91) (Table 1; Fig. 3a). Indeed, these low and high discharge statistics are skewed between the gauges which drain the relatively smaller and larger catchment areas, respectively. When the mean annual discharge is normalised to the gauged catchment area, the range falls between 27 mm.y^{-1} (Burnett River at Mount Lawless) and 3473 mm.y^{-1} (Russell River at Bucklands). The wetter areas (i.e. Wet Tropics and Mackay Whitsunday NRM regions) have a higher runoff coefficient relative to the drier areas (Fig. 3b). This result is also closely reflected in the mean annual rainfall in the catchment area upstream of the gauge which ranges from 597 mm.y^{-1} (Burdekin River at Clare) to 4034 mm.y^{-1} (Russell River at Bucklands) (Fig. 4a; Table 1).

A close relationship exists between rainfall and surface stream discharge ($r^2 = 0.87$) for the GBR catchment area which demonstrates that the stream discharge is predominantly driven by rainfall-runoff events; however, the data for some streams deviate considerably from the trend line which suggests that other factors such as evapotranspiration, water resource development and inter-basin transfers can also influence catchment runoff (Fig. 4b). The Bohle River plots above the trend line which suggests that there is considerably more runoff than expected for its mean annual rainfall; this may be partially explained by the release of approximately 1 ML.d^{-1} from the Condon Sewage Treatment Plant into the river (GHD, 2007). In comparison, the Proserpine River falls well below the trend line and this discrepancy is explained by Peter Faust Dam, which captures flow from 74 % of the upstream catchment area above the gauge. Other basins which deviate from the trend line are more difficult to explain but are likely related to evapotranspiration processes which influence antecedent catchment wetness and rainfall infiltration (Furnas, 2003). Alternatively, there may be uncertainty in the calculated rainfall or runoff data. Furnas (2003) provides similar basin-level data for the earlier 1968–1994 period

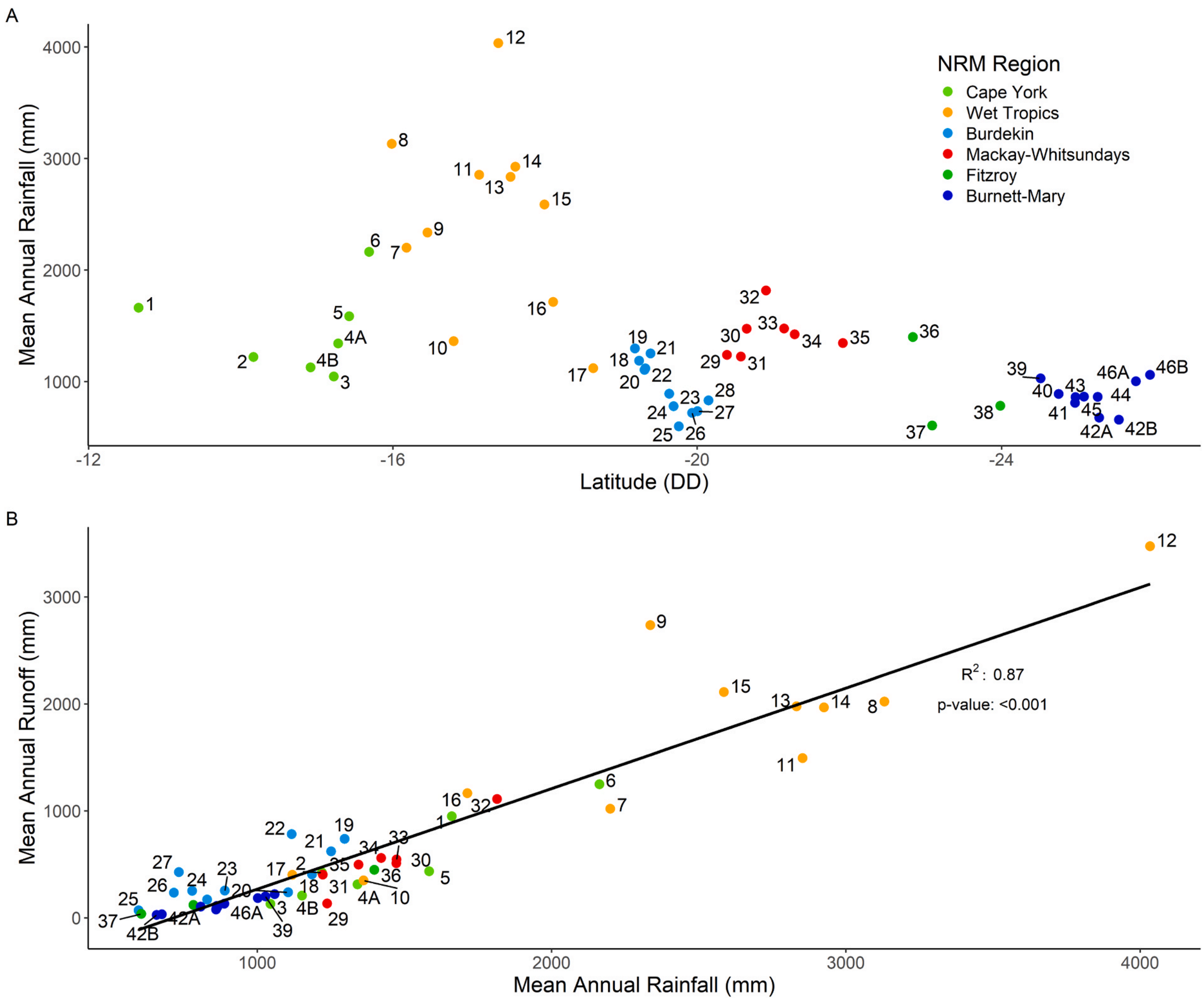

Fig. 4. (A) Mean annual rainfall (mm) for the catchment area above the streamflow gauge versus latitude and (B) mean annual runoff (mm) versus mean annual rainfall (mm) for 49 gauging stations within the GBR catchment area for the water years 1990/91–2019/20. Numbers adjacent to points relate to gauges in Table 1 and locations are plotted on Fig. 1.

that allows a point of comparison to derive insights on the confidence for the rainfall and runoff data. While the 1 σ standard deviations of our calculated runoff coefficients mostly fall within the values presented in Furnas (2003), some notable discrepancies occur including streams in the Daintree, Mossman, Proserpine, Pioneer and Waterpark basins. The runoff values for the Daintree and Mossman Rivers reported in our study are much higher than those in Furnas (2003). Discrepancies for the Proserpine and Pioneer Rivers may relate to the construction and operation of dams in each catchment in the 1990s. Indeed, the influence of the construction of dams and water infrastructure developments (i.e. inter-basin transfers, water supplementation) on river hydrology have been well documented in the literature (e.g. Vörösmarty, and Sahagian, 2000; Magilligan and Nislow, 2005; Graf, 2006). Finally, the difference in the Waterpark basin may be more reflective of the smaller catchment size analysed in our study (i.e. above the gauge) compared to the basin-wide analysis by Furnas (2003).

Importantly, there was little variability in the key statistics (i.e. inter-annual and intra-annual COVs) for basins with multiple gauges or for gauges within a basin that did not contain a full 30 year record. For example, the Normanby River at Kalpowar which encompasses a much larger area (12,930 km^2) had similar statistics in terms of inter- and intra-annual COV and % runoff to the upstream gauge (Normanby at Battle Camp: 2302 km^2) (Table 1; Figs. 5 and 6). This result highlights that the shorter record (14 years) for the downstream gauge still captured the hydrological variability across the catchment area. Indeed, the gauges which were either decommissioned or relocated over the 30-year period (e.g. Ross River, O'Connell River, Pioneer River, Burnett River) show high consistency in the flow statistics across different time periods and/or locations (Table 1). This finding provides confidence that these statistics can be combined to characterise river basin hydrology.

The inter-annual COV for the river gauges increased with increasing latitude (i.e., from north to south across the GBR catchment

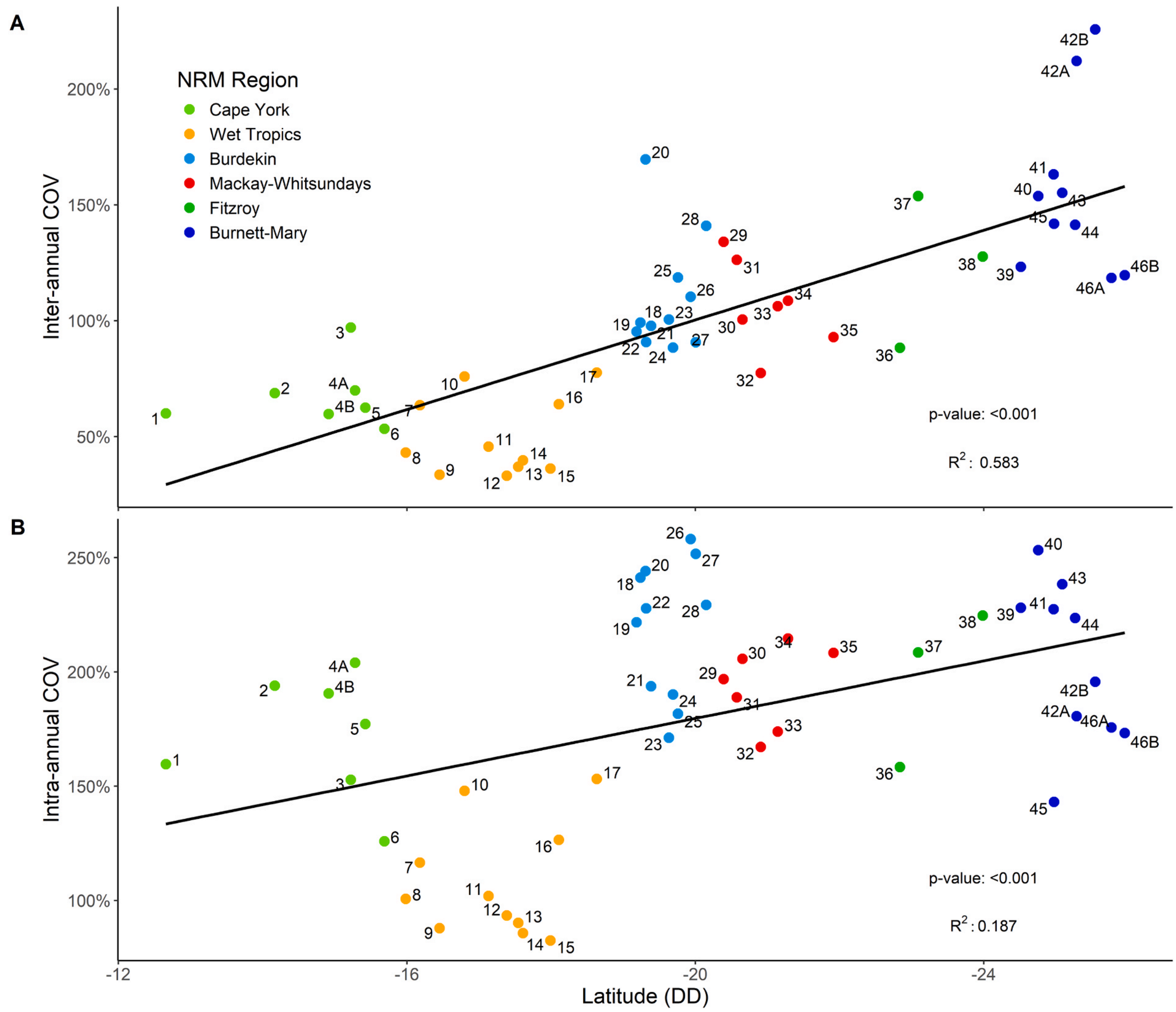

Fig. 5. Changes in (A) Inter-annual variability of total annual discharge across GBR catchment area streams; (B) Intra-annual variability of daily discharge across GBR catchment area streams along a latitudinal gradient. Numbers adjacent to points relate to flow gauges identified in Table 1 and locations are plotted on Fig. 1.

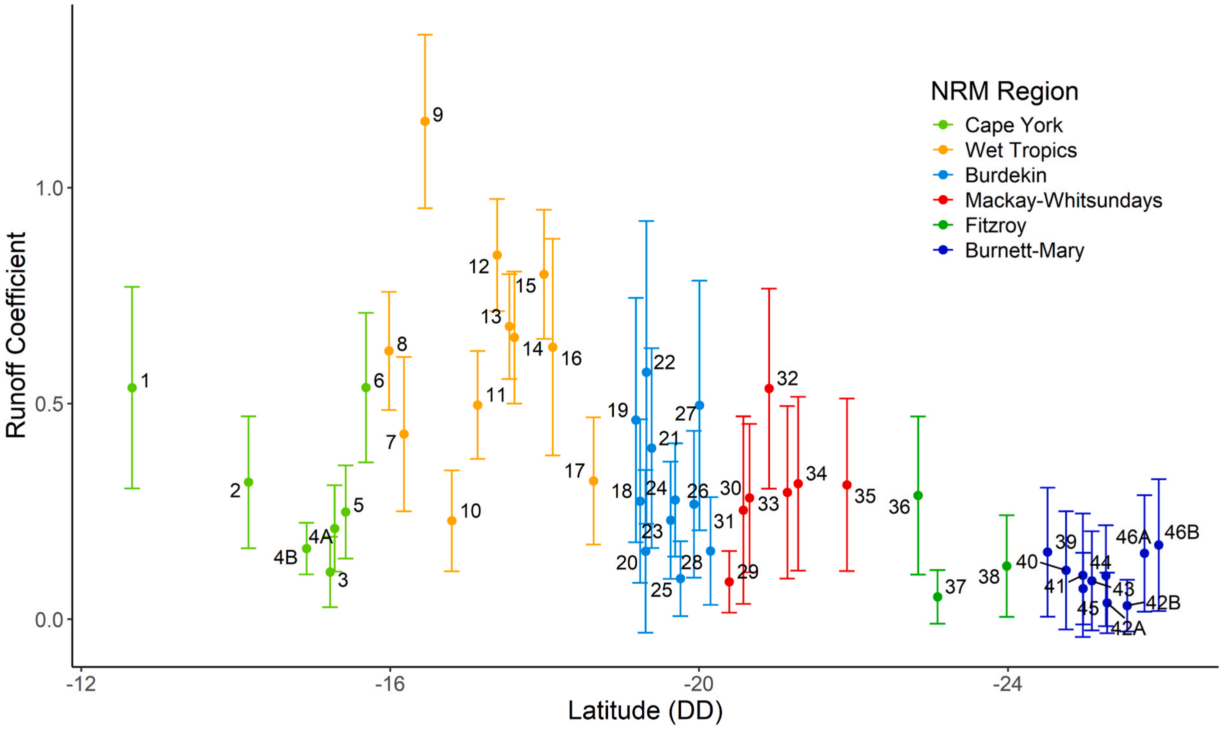

Fig. 6. Changes in the runoff coefficient with corresponding standard deviations across the selected GBR catchment area streams along a latitudinal gradient. Numbers adjacent to points relate to flow gauges identified in Table 1 and locations are plotted on Fig. 1.

area – Fig. 5a). The inter-annual COV ranges from 33 % for the Russell River at Bucklands to 226 % for the Burnett River at Mt Lawless. Several of the streams in the Wet Tropics NRM region have an inter-annual COV < 50 % while all streams in this NRM region were < 100 %. Streams within the Cape York NRM region have inter-annual COVs which range between 50 % and 100 % while most of the streams situated in the dry tropics of the southern catchments (Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary NRM regions) have COVs > 100 %. In fact, several streams in the Burnett Mary NRM region have inter-annual COVs that exceed 150 %, which highlight the more extreme year-to-year flow variability in the southern parts of the GBR catchment area (Fig. 5a; Pusey and Arthington, 1996). This variability reflects the decreasing monsoonal and orographic rainfall influence on the southern catchments as well as the relative orientation of the coastline to capture the moisture from the prevailing south easterly winds.

The intra-annual COV also shows that the streams in the Wet Tropics NRM region were generally less variable compared to the other regions. The north-south trend observed was less pronounced for the intra-annual COV compared to the inter-annual COV (Fig. 5b). In general, the intra-annual COVs for most streams in the Wet Tropics NRM region were < 130 % (with exception of the Barron and Herbert Rivers) whilst for streams in the other NRM regions the COVs were mostly > 150 %. The intra-annual COV ranges from 82 % for the Tully River at Euramo to 258 % for the Elliot River at Guthalungra (Don Basin).

The annual runoff coefficient for each gauge demonstrated a general declining north-south trend towards the drier areas of the GBR catchment area (Fig. 6). The majority of the streams in the Wet Tropics NRM region had mean annual runoff coefficients of 0.50 or higher with two exceptions being the Daintree (0.43 ± 0.18) and the Barron (0.23 ± 0.12) basins, while the streams of the Burnett Mary NRM region all had mean ratios < 0.20. The annual runoff coefficients ranged from 0.03 ± 0.06 for the Burnett River at Figtree Creek to 1.15 ± 0.20 for the Mossman River at Mossman. The value for the Mossman River likely reflects an overestimation of the runoff (gauge) estimates. While this gauge discharge record contained several gaps which needed considerable interpolation, a similar runoff coefficient was obtained (1.20 ± 0.17) when only the periods without data interpolation were analysed. When the values reported for the whole basin by Furnas (2003) were compared with our data, we find that the rainfall estimates were similar (Furnas 2003: 2208 mm versus 2336 ± 586 mm in our study, although note different time periods analysed) but the runoff had considerably different values (Furnas 2003: 1265 mm versus 2736 ± 937 mm in our study). We recommend a thorough examination of the hydrology at this site to resolve these discrepancies.

The streams of the GBR catchment area are characterised by high variability in flow and the data presented here are consistent with the classification of Kennard et al. (2010a) (see also Pusey and Arthington 1996 for a similar analysis on the Burdekin). Indeed, the north-south gradients along the GBR catchment area are captured by the following parameters: discharge per unit area (Fig. 3b), mean rainfall in the catchment above the gauge (Fig. 4a), the inter-annual and intra-annual COV (Fig. 5) and the runoff coefficient (Fig. 6) which generally separate the streams of the Cape York and Wet Tropic NRM regions from the southern regions. This outcome supports Kennard et al.'s (2010a) classifications of 'Predictable summer highly intermittent' and 'Unpredictable summer highly intermittent' for these areas, respectively. Clearly, this classification is driven by the inherent climate/rainfall regime across the GBR catchment area with declining monsoonal influence further south (e.g. Furnas, 2003; Petheram et al., 2008) with most streams in the Wet Tropics region receiving considerably more rainfall than the other regions (Table 1).

Variability in streamflows across the GBR catchment is largely driven by rainfall patterns (i.e. rainfall predominately delivered in the summer months) and the size of the catchment areas. Rainfall variability is determined in part by catchment morphology with higher rainfall associated with those catchments which have elevated mountainous areas near the coast that promote orographic uplift (e.g. Russell-Mulgrave, Johnstone, Tully, Pioneer Basins) (Bonell and Gilrnour, 1980). This relationship has been well documented in studies around the world (Bookhagen and Strecker, 2008; Malby et al., 2007) and in the GBR catchment (Furnas, 2003). The summer monsoon 'wet season' (November to April) influences the intra-annual flow variability, while the strength of the El Niño Southern Oscillation and the Pacific Decadal Oscillation influences the inter-annual flow variability (Lough, 1994; Furnas, 2003).

4.2. Spatial variability in baseflows

The median of the annual baseflow indexes for the streams of the GBR catchment area ranged from 0.00 (Bohle River at Hervey Range Road: Ross Basin) to 0.51 (South Johnstone River at Upstream Central Mill and Tully River at Euramo) (Table 3). The streams within the Cape York and Wet Tropics NRM regions commonly had much higher annual baseflow indexes (mostly > 0.3) than the streams further south (mostly < 0.2), except for the Elliott River at Dr Mays Crossing (0.3) (Fig. 7). In terms of total baseflow volumes,

Table 3
Summary of low flow statistics for the gauging stations. "The median of the mean" represent the median value of the annual means in baseflow over a 30 year period while the mean zero flow days represent the annual mean over the 30 year record. Raw streamflow data were sourced from the Water Monitoring Information Portal (WMIP: Queensland Government https://water-monitoring.information.qld.gov.au/) and the Bureau of Meteorology.

Stream	Median Baseflow Index	Median of the Mean Daily Baseflow Volume (ML/day)	Mean 0 Flow Days
Pascoe	0.21	561	8.2
Stewart	0.12	50	108.8
Normanby (4 A)	0.12	204	59.2
Hann	0.26	56	0.0
Endeavour	0.21	89	36.8
Annan	0.31	248	0.0
Daintree	0.36	765	0.3
Bloomfield	0.39	524	0.0
Mossman	0.47	377	2.2
Barron	0.30	386	0.0
Mulgrave	0.41	801	0.0
Russell	0.42	1220	0.0
North Johnstone	0.48	2169	0.0
South Johnstone	0.51	1044	0.0
Tully	0.51	4062	0.0
Murray	0.38	165	0.0
Herbert	0.29	2094	0.0
Black	0.07	11	149.8
Bluewater	0.09	11	101.8
Ross	0.05	3	296.0
Alligator	0.12	12	145.9
Bohle	0.00	0	295.2
Haughton	0.18	118	0.5
Barratta	0.14	43	0.1
Burdekin	0.20	2340	0.0
Elliot	0.01	1	242.7
Euri	0.01	6	178.8
Don	0.05	9	115.4
Proserpine	0.17	14	16.6
OConnell	0.11	43	68.5
Andromache	0.21	22	0.9
St Helens	0.20	60	12.3
Pioneer	0.16	200	6.0
Sandy	0.06	27	16.2
Carmila	0.08	7	125.5
Waterpark	0.20	37	1.2
Fitzroy	0.11	501	98.2
Calliope	0.07	15	47.7
Baffle	0.06	28	64.5
Kolan	0.07	5	141.2
Gin Gin Creek	0.06	4	157.1
Burnett (41B)	0.11	67	13.9
Gregory	0.04	2	100.7
Isis	0.04	2	107.7
Elliott	0.30	7	51.0
Mary (45 A)	0.16	265	1.4

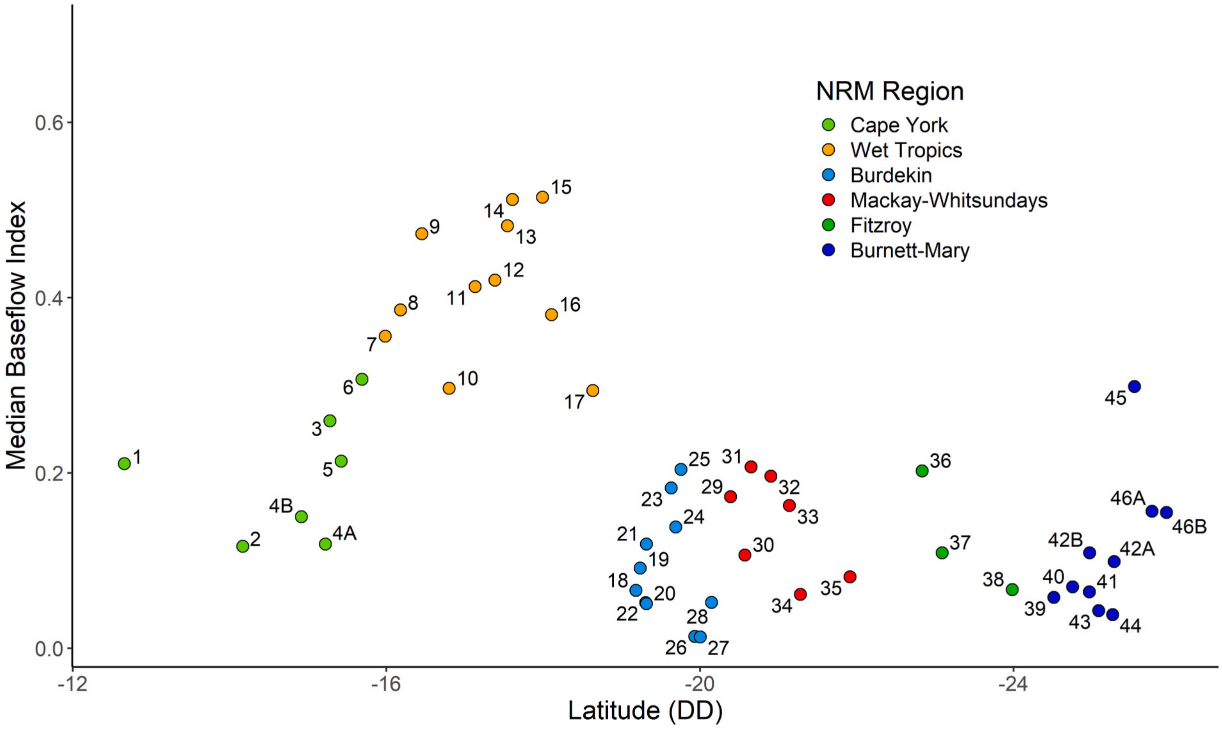

Fig. 7. Annual changes in Baseflow Index for the stream gauges of the GBR catchment area along a latitudinal gradient. Numbers adjacent to points relate to flow gauges identified in Table 1 and locations are plotted on Fig. 1.

only some streams of the Wet Tropics region (Russell River, Johnstone River, Tully River and Herbert River) and the Burdekin River had daily baseflows exceeding 1000 ML.d^{-1} (Table 3).

All the streams of the Wet Tropics NRM region (with the exception of the Mossman River at Mossman), Hann River at Sandy Creek, Annan River at Beesbike, Haughton River at Powerline, Barratta Creek at Northcote, Burdekin at Clare and the Andromache River at

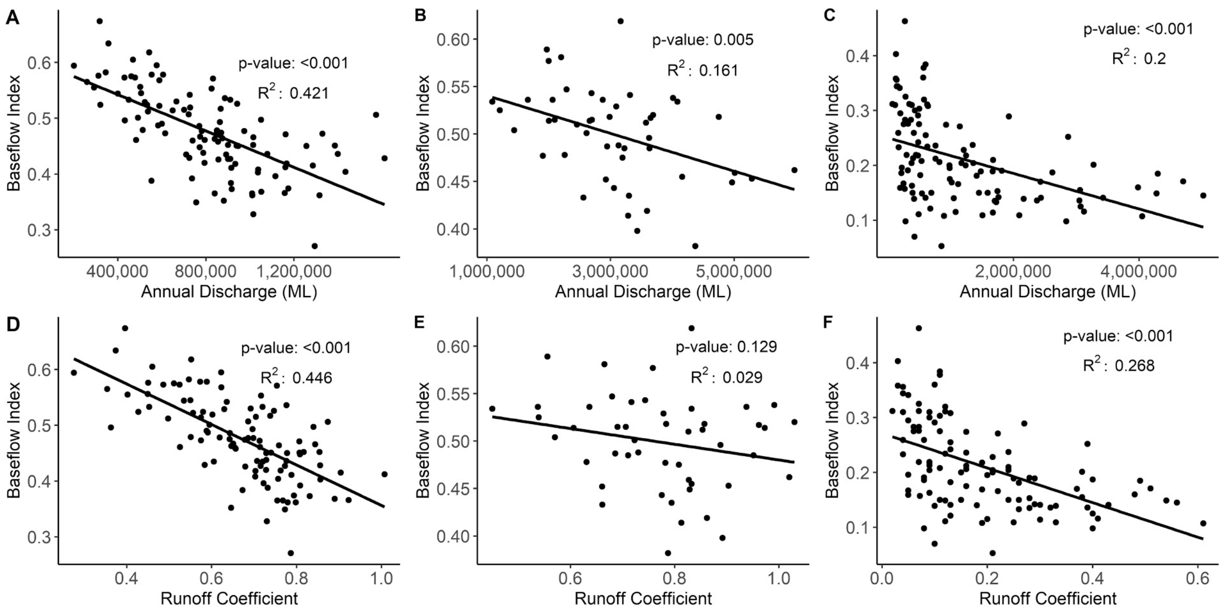

Fig. 8. (A) Total annual discharge and (D) percent runoff coefficient against the BFI for the South Johnstone River at Upstream Central Mill (1928–2019; no. 14); (B) Total annual discharge and (E) percent runoff coefficient against the BFI for the Tully River at Euramo (1972–2019; no. 15); (C) Total annual discharge and (F) percent runoff coefficient against the BFI for the Mary River at Miva (1910–2019; no. 46B).

Jochheims were perennial over the 30 year record. In contrast, many of the streams in the drier basins such as the Black, Ross, Don, Kolan and Burrum Basins had mean annual zero flow days exceeding 100 days per water year (Table 3).

The zero-flow day statistics clearly separate the intermittent and perennial streams, particularly differentiating between wet and dry-tropical climatic zones (Table 3). The zero flow day metric also highlights the influence of flow supplementation from the Burdekin Falls Dam to supply the Burdekin-Haughton Irrigation Area for the historically intermittent streams such as the Burdekin and Haughton Rivers and Barratta Creek (Table 3). Indeed, not unexpectedly, the baseflow index reveals the influences of dam releases and irrigation tailwater runoff during the dry season, but effects can be subtle (Davis et al., 2014). For example, the baseflow index for several streams of the Wet Tropics have been calculated as > 0.4 (Table 3) which imply that the groundwater contribution is over 40 % (on average) of the total discharge. It would be logical to assume that with increasing annual runoff and total discharge (due to a 'wetter year') there would be a corresponding decrease in the annual baseflow index. This predicted and significant decreasing trend of baseflow contribution in higher runoff years occurs when long-term data records are plotted for the wet tropical South Johnstone River

Table 4

Summary of gauges used to upscale flow for river basins of the GBR. The five correction factors provided are based on proportional differences in basin and gauge area, the proportional differences in the means of the models to the total gauge flows and the linear relationship between the models and the total gauge flows.

NRM Region	Basin	AWRC No.	Basin area (km^2)	G2G basin area (km^2)	Source Catchments basin area (km^2)	Total gauged area (km^2)	Relevant gauges	Percentage of Basin covered by key gauges	Annual average gauge flow (2007/08 - 2018/19)	Annual average gauge flow (1990/91 - 2019/20)	G2G mean annual discharge (2007/08 - 2018/19)	Source Catchments mean annual discharge (1990/91 - 2019/20)	Area correction factor	G2G correction factor**	Source correction factor**	Recommended correction factor	Justification
Cape York	Jacky Jacky Creek	101	2,963	N/A	2,990	N/A	Jardine River at Monument*	0%	1,900,000	2,000,000	N/A	2,900,000	1.2	N/A	1.4 (1.1x + 557,000)	1.1x + 560,000[2]	Good fit SC (use area correction as between SC outputs)
	Olive Pascoe River	102	4,180	N/A	4,172	1,313	Pascoe River at Garraway Creek	31%	1,200,000	1,200,000	N/A	3,800,000	3.2	N/A	3.1 (1.6x + 1,860,000)	3.1[2]	Good fit SC (use SC mean)
	Lockhart River	103	2,883	N/A	2,873	N/A	Pascoe River at Garraway Creek*	0%	1,200,000	1,200,000	N/A	1,900,000	2.2	N/A	1.5 (1.2x + 438,000)	1.5[2]	Good fit SC (use SC mean as between other two)
	Stewart River	104	2,743	N/A	2,770	470	Stewart River at Telegraph Road	17%	190,000	200,000	N/A	1,100,000	5.8	N/A	5.6 (4.6x + 211,000)	5.6[2]	Good fit SC (use SC mean as between other two)
	Normanby River	105	24,399	20,023	24,380	13,914	Normanby River at Kalpowar Crossing + Hann River at Sandy Creek (from 2005/06). Previous upscale period uses Normanby at Battle Camp + Hann River gauges with factor of 4.7	57%	2,900,000	3,300,000	5,300,000	4,000,000	1.8	1.8 (1.5x + 776,000)	1.5 (1.8x + 1,100,000)	1.8[1]	Excellent fits G2G and SC (use G2G mean and SC slope as same as area correction)
	Jeannie River	106	3,638	2,038	3,637	N/A	Endeavour River at Flaggy + Annan at Beesbike	0%	520,000	460,000	930,000	1,500,000	6.2	1.8 (2.6x + 484,000)	3.2 (9.2x + 108,000)	3.2[3]	Poor fit G2G; good SC (use SC mean value)
	Endeavour River	107	2,182	2,611	2,186	584	Endeavour River at Flaggy + Annan at Beesbike	27%	520,000	460,000	1,700,000	1,600,000	3.7	3.3 (2.3x + 508,000)	3.6 (3.5x + 20,800)	3.5x + 21,000[1]	Good fit G2G and excellent SC (stronger r2 in SC use slope)
Wet Tropics	Daintree River	108	2,107	2,019	2,105	1,175	Daintree River at Bairds + Bloomfield River at China Camp	56%	1,800,000	1,500,000	2,800,000	3,000,000	1.8	1.6 (1.3x + 485,000)	2.0 (1.6x + 548,000)	1.6[1]	Excellent fit G2G; good fit SC (use G2G mean)
	Mossman River	109	473	604	477	106	Mossman River at Mossman	22%	330,000	290,000	750,000	530,000	4.5	2.3 (2.5x – 73,400)	1.8 (2.0x – 55,000)	2.3[2]	Good fits G2G and SC (use G2G mean)
	Barron River	110	2,188	2,213	2,188	1,945	Barron River at Myola	89%	780,000	660,000	1,000,000	920,000	1.1	1.3 (1.1x + 119.000)	1.4 (1.2x + 128,000)	1.3[1]	Excellent fit G2G; good fit SC (Use G2G mean)
	Mulgrave-Russell River	111	1,983	1,843	1,975	835	Mulgrave River at Peets Bridge + Russell River at Bucklands	42%	2,000,000	1,900,000	3,100,000	4,300,000	2.4	1.5 (1.5x + 75,600)	2.3 (2.0x + 451,000)	2.0x + 450,000[2]	Excellent fits G2G and SC (Use SC slope)
	Johnstone River	112	2,325	2,252	2,317	1,325	South Johnstone River at Upstream Central Mill + North Johnstone at Tung Oil	57%	2,800,000	2,600,000	3,900,000	4,700,000	1.8	1.4 (1.3x + 210,000)	1.8 (1.6x + 536,000)	1.6x + 540,000[1]	Good fit G2G and SC (use SC slope)
	Tully River	113	1,683	1,572	1,125	1,450	Tully River at Euramo	86%	3,300,000	3,100,000	3,500,000	3,500,000	1.2	1.0 (1.0x + 59,300)	1.1 (0.9x + 618,000)	1.1[1]	Excellent fit G2G; good fit SC (use 1.1 to capture extra area below gauge)
	Murray River	114	1,107	1,386	1,668	156	Murray River at Upper Murray	14%	220,000	180,000	890,000	1,500,000	7.1	4.1 (1.7x + 511,000)	8.3 (5. 0x + 599,000)	5.0x + 600,000[3]	Poor fit G2G, good fit SC (use SC slope)
	Herbert River	116	9,844	9,792	9,852	8,581	Herbert River at Ingham	87%	4,500,000	3,400,000	5,200,000	5,100,000	1.1	1.2 (1.1x + 404,000)	1.4 (1.0x + 1,390,000)	1.2[1]	Excellent fits G2G and SC (use G2G slope)
Burdekin	Black River	117	1,057	1,057	1,057	342	Black River at Bruce Highway + Bluewater Creek at Bluewater	32%	230,000	160,000	550,000	760,000	3.1	2.4 (1.9x + 131,000)	4.5 (3.6x + 160,000)	3.1[2]	Excellent fits G2G and SC (use area correction and between both models)
	Ross River	118	1,707	1,578	1,707	880	Ross River at Aplins Weir + Alligator Creek at Allendale (from 2001/02). Previous upscale period uses Ross River Dam HW + Bohle at Hervey Range Rd + Alligator Creek with factor of 1.9	52%	300,000	220,000	500,000	560,000	1.9	1.7 (0.8x + 265,000)	2.7 (1.9x + 160,000)	1.9x + 160,000[2]	Fair fit G2G; good fit SC (use SC slope)
	Haughton River	119	4,051	3,849	4,051	2,526	Haughton River at Powerline + Barratta at Northcote	62%	820,000	640,000	990,000	1,100,000	1.6	1.2 (1.2x + 51,500)	1.7 (1.8x – 21,300)	1.6[1]	Excellent fit G2G and SC (use area correction as in between two models)
	Burdekin River	120	130,120	131,728	130,120	129,900	Burdekin River at Clare	100%	13,000,000	9,000,000	13,000,000	9,100,000	1.0	1.0 (1.0x + 114,000)	1.0 (1.0x – 61,400)	1.0[1]	Excellent fits G2G and SC (use all)
	Don River	121	3,736	2,827	3,736	1,718	Don River at Reeves + Elliot River at Guthalungra + Euri Creek at Koonandah (from 1999/00). Previous upscale period uses Don + Elliot gauges with factor of 3.3	46%	540,000	370,000	700,000	850,000	2.2	1.3 (1.2x + 58,600)	2.0 (1.5x + 209,000)	1.5x + 210,000[1]	Excellent fit G2G, good fit SC (use SC slope)
Mackay Whitsunday	Proserpine River	122	2,494	2,373	2,513	N/A	O'Connell River at Staffords Crossing + Andromache River at Jochheims + St Helens Creek at Calen	0%	480,000	390,000	740,000	2,100,000	3.6	6.3 (1.0x + 269,000)	5.3 (3.3x + 791,000)	3.6[3]	Good fits G2G and SC (use SC slope)
	O'Connell River	124	2,387	2,340	2,305	690	O'Connell River at Staffords Crossing + Andromache River at Jochheims + St Helens Creek at Calen	29%	480,000	390,000	910,000	1,700,000	3.5	2.2 (1.8x + 194,000)	4.3 (3.7x + 266,000)	3.5[2]	Excellent fit G2G, good fit SC (use area correction as in between two models)
	Pioneer River	125	1,572	1,632	1,664	1,488	Pioneer River at Dumbleton Weir TW	95%	1,100,000	750,000	1,200,000	930,000	1.1	1.0 (1.0x + 22,800)	1.2 (1.2x + 65,400)	1.1[1]	Excellent fits G2G and SC (use area correction as in between both models)
	Plane Creek	126	2,539	2,495	2,547	410	Sandy Creek at Homebush + Carmila Creek at Carmila	16%	290,000	220,000	690,000	1,500,000	6.2	2.4 (1.3x + 299,000)	6.5 (5.6x + 208,000)	5.6x + 210,000[3]	Good fit G2G, excellent fit SC (use SC slope)
Fitzroy	Styx River	127	3,013	3,127	2,997	N/A	Waterpark Creek at Byfield*	0%	160,000	100,000	330,000	810,000	14.2	2.1 (1.2x + 134,000)	8.5 (5.7x + 263,000)	5.7x + 260,000[3]	Fair fit G2G, poor fit SC (use SC slope)
	Shoalwater Creek	128	3,601	3,655	3,614	N/A	Waterpark Creek at Byfield*	0%	160,000	100,000	370,000	930,000	17.0	2.3 (1.4x + 145,000)	9.8 (6.6x + 302,000)	6.6x + 300,000[3]	Good fit G2G, fair fit SC (use SC slope)
	Waterpark Creek	129	1,836	1,574	1,846	212	Waterpark Creek at Byfield	12%	160,000	100,000	370,000	560,000	8.7	2.3 (1.1x + 195,000)	5.9 (5.4x + 42,500)	5.4x + 43,000[3]	Good fits G2G and SC (use SC slope)
	Fitzroy River	130	142,552	142,614	142,144	135,800	Fitzroy River at The Gap	95%	8,100,000	5,100,000	9,000,000	5,700,000	1.0	1.1 (1.0x + 899,000)	1.1 (0.9x + 887,000)	1.1[1]	Excellent fits G2G and SC (good model agreement)
	Calliope River	132	2,241	3,004	2,416	1,288	Calliope River at Castlehope	57%	260,000	150,000	180,000	380,000	1.7	0.7 (0.2x + 126,000)	2.4 (1.9x + 94,700)	1.9x + 95,000[2]	Poor fit G2G; excellent fit SC (use SC slope)
	Boyne River	133	2,496	2,342	2,498	N/A	Calliope River at Castlehope*	0%	260,000	150,000	150,000	320,000	1.9	0.6 (0.0x + 147,000)	2.1 (2.3x – 37,000)	2.1[3]	Poor fit G2G; good fit SC (use SC mean)
Burnett-Mary	Baffle Creek	134	4,085	3,894	4,101	1,402	Baffle Creek at Mimdale	34%	430,000	280,000	810,000	770,000	2.9	1.9 (1.3x + 168,000)	2.8 (2.4x + 95,200)	2.4x + 95,000[2]	Excellent fits G2G and SC (Use SC slope)
	Kolan River	135	2,901	2,973	2,891	1,082	Kolan River at Springfield + Gin Gin Creek at Brushy Creek	37%	230,000	130,000	320,000	320,000	2.7	1.3 (1.0x + 74,300)	2.5 (2.4x + 18,700)	2.4x + 19,000[2]	Excellent fit G2G; good fit SC (use SC slope)
	Burnett River	136	33,207	33,073	33,274	30,670	Burnett River at Figtree Ck (from 1996/97). Previous upscale period uses Burnett River at Mount Lawless with factor of 1.3	92%	1,600,000	800,000	1,800,000	1,000,000	1.1	1.1 (1.0x + 99,900)	1.3 (1.2x + 84,400)	1.1[1]	Excellent fits G2G and SC (good model agreement)
	Burrum River	137	3,362	4,117	3,346	1,332	Gregory River at Leesons + Elliott River at Dr Mays Crossing + Isis River at Bruce Highway	40%	190,000	110,000	880,000	360,000	2.5	5.8 (1.7x + 308,000)	3.2 (3.0x + 26,600)	3.0x + 27,000[2]	Good fit G2G, excellent fit SC (use SC slope)
	Mary River	138	9,466	9,330	9,420	6,845	Mary River at Home Park	72%	1,900,000	1,300,000	2,400,000	2,600,000	1.4	1.3 (1.2x + 210,000)	2.1 (1.2x + 1,120,000)	1.4[1]	Excellent fits G2G and SC (use G2G mean)
Total GBR	**GBR catchment area**		**423,122**	**405,619**	**422,961**	**348,439**		**82%**	**54,000,000**	**43,000,000**	**64,000,000**	**73,000,000**	**1.2**	**1.2 (1.1x + 7,100,000)**	**1.7 (1.3x + 20,700,000)**	**1.2[1]**	**Excellent fits G2G and SC (good model agreement)**

AWRC = Australian Water Resources Council drainage basin number.
†Data sourced from Lewis et al# (2021)
*Gauges in neighbouring catchments.
**Scaling factor based on the mean (linear relationship)
[1]High confidence correction factor; [2]Medium confidence correction factor; [3]Low confidence correction factor

at Upstream Central Mill (1928–2019) (average baseflow index 0.51), and also the dry-tropical Mary River at Miva (1910–2019) (average baseflow index 0.16; Fig. 8), two systems with unregulated flows (Fig. 8). However, when the annual runoff coefficient and total annual discharge is plotted against the baseflow index for the Tully River at Euramo (1972–2019) (adjacent to the South Johnstone River catchment), no such trend is apparent in the ca. 50 year dataset (Fig. 8). In this case, flow regime changes associated with operation of the Kareeya hydro power station upstream of the gauge may result in an artificially elevated baseflow index (0.51), even in wetter years. An elevated baseflow index potentially has implications for the allocation of pollutant loads contributed from baseflow compared to flood flow (Binns and Waters, 2018). In any case, the ~ 6 fold difference in total annual flows for the South Johnstone discharge do not result in a corresponding order of magnitude change in the baseflow index (Fig. 8). Indeed, the discrepancy in the magnitude of change between increased runoff and baseflow contribution may also reflect the increased throughflow in the basin as a result of increasing rainfall. It is suggested that the calculation of baseflow be further investigated for the Wet Tropics streams to have greater confidence in the method, and better quantification of impacts of flow regulation on baseflow behaviour.

4.3. Upscaling gauge data to calculate total annual discharge to the Great Barrier Reef

The total gauged proportion of the GBR catchment area is 82 % (Table 4). While several smaller basins in the GBR catchment area are ungauged, together the six largest basins (Fitzroy, Burdekin, Burnett, Normanby, Herbert and Mary) cover ~ 83 % of the GBR catchment area. These large basins are mostly well represented by gauging stations including the Fitzroy (gauging station captures 95 % of total basin area), Burdekin (99.8 %), Burnett (92 %), Normanby (53 %), Herbert (87 %) and Mary (72 %) basins (Table 4). The different scaling factors calculated for these basins as well as for other basins that have a relatively high proportion of the area gauged (> 70 %) show a high level of agreement (Table 4). Hence the recommended correction factors have high confidence (Table 4). However, the scaling factors calculated for basins which are not well-covered by flow gauges, show much greater variability across the various scaling factors and thus the recommended correction factors for these basins have relatively lower confidence (Table 4).

For example, the Waterpark Creek Basin has a scaling factor based on area of 8.7 (i.e. only 12 % of this basin is gauged). This scaling factor is much higher than the scaling factors using the G2G model for mean (2.3) and the linear relationship (1.1x + 195,000) as well as the Source Catchments model for mean (5.9) and linear relationship (5.4x + 42,500). Part of the discrepancy between the two models may relate to the basin area where the Source Catchments model area (1846 km^2) is higher than the G2G model (1574 km^2); the basin area reported here is 1836 km^2 (Table 4) which is based on the Geofabric surface basin boundaries (Bureau of Metrology, 2015). The considerable variability in these reported catchment areas reflects the challenges in delineating catchment boundaries particularly in flat terrain. In this case, we recommend a correction factor in line with the linear relationship with the Source Catchments model (5.4x + 42,500) as there was a good r^2 (0.91) in the relationship between the gauging data and Source Catchments model for annual discharge. This scaling factor also appeared reasonable given the relatively small area that was gauged in this basin.

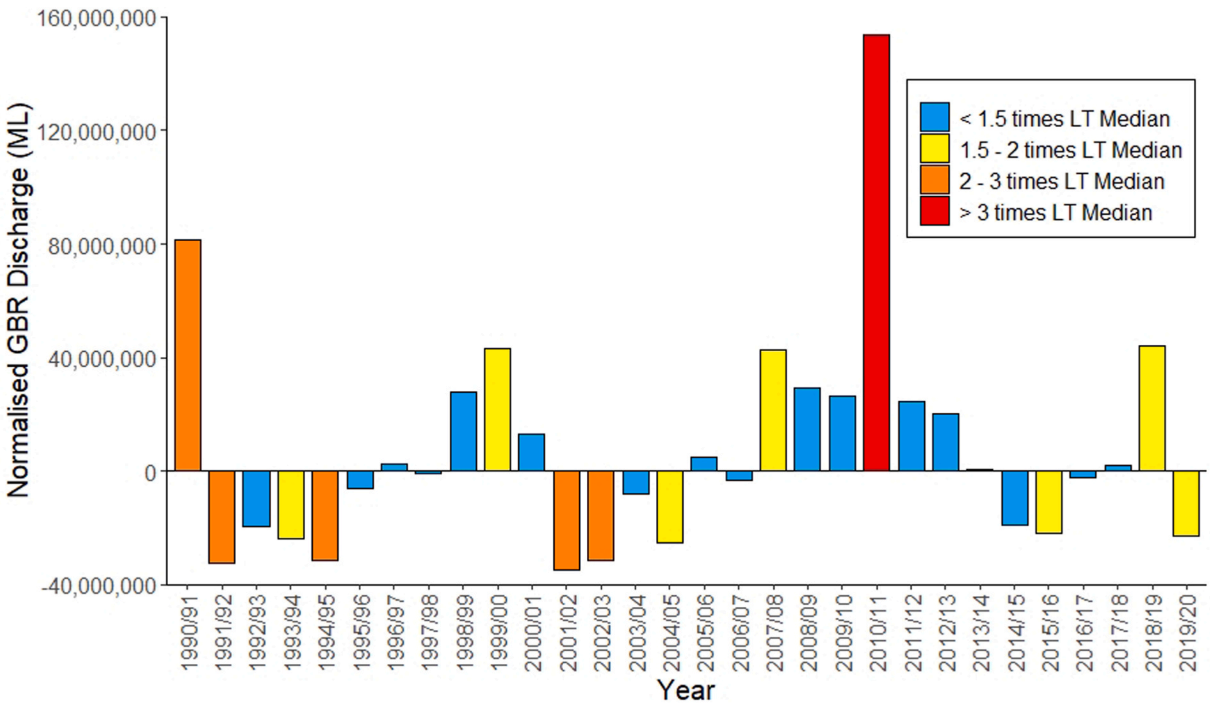

Fig. 9. Annual total discharge to the GBR (i.e. sum of all 35 river basins) over the 30 year period (1990/91–2019/20 water years). Red bars represent discharge more than 3 times above the 30 year long term median (LTM), orange bars are 2–3 times the LTM, yellow bars are 1.5–2 times the LTM and blue bars are less than 1.5 times the LTM.

Similar issues/trends between the models appeared for the neighbouring ungauged basins (i.e. Styx and Shoalwater basins) where the Waterpark Creek gauge was used as a proxy for flow data (Table 4). Another example of our approach is the Mossman Basin where the scaling factor based on area is 4.5 which is much greater than the scaling factors using the G2G model for mean (2.3) and the linear relationship (2.5x – 73,400) as well as the Source Catchments model for mean (1.8) and linear relationship (2.0x – 55,000). Here we recommend the G2G model based on the mean (2.3) as it sits between the models and is closer to the area factor than the Source Catchments model (Table 4). As the model scaling factors were similar, we consider that this recommended correction factor has a medium confidence. While large outliers in the different scaling factors were evident for some basins, these were exclusively from the smaller basins that contribute relatively negligible flow volumes to the total discharge at the NRM and total GBR catchment area scales. Hence, we can be confident that our correction factors provide reasonable estimates of total discharge for most GBR basins with much higher confidence for NRM regions and total GBR discharge (Table 4).

The annual water year discharge to the GBR over the most recent 30 year period (1990/91–2019/20) highlight the high inter-annual variability with one extreme year (2010/11) which discharged more than three (3.5) times the long term median over the 30 year period. The 1990/91 flood was another very large discharge year to the GBR with 2.4 times the long term median discharge while on another five occasions annual discharge to the GBR exceeded 1.5 times the long term median (Fig. 9).

Our scaling factors provide the best available mean and median end of system discharge estimates for individual basins, NRM regions and GBR catchment area for the most recent 1990/91–2019/20 climate period (Table 5). Our calculations compare reasonably

Table 5

Summary of mean and median discharge for each GBR basin, NRM region and total catchment area produced using the correction/scaling factors developed in our study. Raw streamflow data were sourced from the Water Monitoring Information Portal (WMIP: Queensland Government https://water-monitoring.information.qld.gov.au/) and the Bureau of Meteorology.

Basin	Furnas (2003) 1968/69–1994/95	McCloskey et al. (2021a) 1986/87–2013/14	G2G 2007/08–2018/19	Mean 1990/91–2019/20	Median 1990/91–2019/20
Jacky Jacky Creek	1560,000	2890,000	N/A	2740,000	2470,000
Olive Pascoe River	3710,000	3790,000	N/A	3860,000	3180,000
Lockhart River	1940,000	1900,000	N/A	1870,000	1540,000
Stewart River	1210,000	1160,000	N/A	1050,000	758,000
Normanby River	4950,000	3710,000	5270,000	4260,000	3860,000
Jeannie River	1540,000	1430,000	925,000	1430,000	1430,000
Endeavour River	1820,000	1530,000	1700,000	1590,000	1580,000
Cape York NRM	**16,700,000**	**16,400,000**	**N/A**	**16,800,000**	**14,900,000**
Daintree River	1260,000	2890,000	2760,000	2300,000	1920,000
Mossman River	590,000	505,000	748,000	648,000	605,000
Barron River	810,000	879,000	999,000	865,000	622,000
Mulgrave-Russell River	3640,000	4240,000	3080,000	4120,000	4220,000
Johnstone River	4670,000	4820,000	3910,000	4720,000	4800,000
Tully River	3290,000	3530,000	3500,000	3330,000	3390,000
Murray River	1060,000	1540,000	889,000	1510,000	1480,000
Herbert River	4010,000	5080,000	5230,000	4420,000	3830,000
Wet Tropics NRM	**19,300,000**	**23,500,000**	**21,100,000**	**21,900,000**	**20,700,000**
Black River	380,000	735,000	553,000	514,000	294,000
Ross River	490,000	543,000	503,000	583,000	279,000
Haughton River	740,000	1220,000	991,000	1020,000	559,000
Burdekin River	10,300,000	9230,000	12,700,000	9000,000	4410,000
Don River	750,000	993,000	697,000	844,000	496,000
Burdekin NRM	**12,700,000**	**12,700,000**	**15,500,000**	**12,000,000**	**5970,000**
Proserpine River	1080,000	2150,000	742,000	1420,000	859,000
O'Connell River	1540,000	1770,000	911,000	1380,000	835,000
Pioneer River	1190,000	1010,000	1160,000	825,000	616,000
Plane Creek	1490,000	1260,000	691,000	1460,000	1060,000
Mackay-Whitsunday NRM	**5300,000**	**6200,000**	**3500,000**	**5090,000**	**3010,000**
Styx River	1580,000	851,000	327,000	801,000	629,000
Shoalwater Creek	1830,000	996,000	371,000	927,000	727,000
Waterpark Creek	1110,000	632,000	366,000	556,000	393,000
Fitzroy River	6080,000	6020,000	9040,000	5600,000	2880,000
Calliope River	300,000	412,000	179,000	388,000	257,000
Boyne River	290,000	316,000	145,000	324,000	179,000
Fitzroy NRM	**11,200,000**	**9230,000**	**10,400,000**	**8590,000**	**5240,000**
Baffle Creek	780,000	797,000	807,000	718,000	347,000
Kolan River	410,000	312,000	316,000	316,000	116,000
Burnett River	1150,000	1080,000	1790,000	955,000	264,000
Burrum River	550,000	379,000	882,000	318,000	131,000
Mary River	2720,000	2890,000	2420,000	1800,000	909,000
Burnett-Mary NRM	**5610,000**	**5460,000**	**6210,000**	**4110,000**	**1980,000**
GBR Total	**70,800,000**	**73,500,000**	**N/A**	**68,500,000**	**60,700,000**

well with the previous estimates of Furnas (2003) which covers the 1968–1994 period and from the latest Source Catchments model which covers the mean discharge for the 1986/87–2013/14 financial years (McCloskey et al., 2021a). The Bureau of Meteorology's G2G model which incorporates a much shorter 12 year period (2007/08–2018/19) shows reasonable agreement with the other available methods for most basins. However, some differences in the discharge estimates were apparent between certain basins and NRM regions and in particular for the three most southern NRM regions (i.e. Mackay Whitsunday, Fitzroy and Burnett-Mary). Specifically, our data suggest mean discharge for several of these basins (and corresponding NRM regions) are considerably lower than previously thought; our estimated total mean GBR discharge is also ~ 2000,000 to 5000,000 ML lower than the previous calculations (Table 5). Some of these discrepancies could relate to the different time periods analysed (i.e. wetter or drier periods), but they also likely relate to the non-gauged or poorly-gauged catchments where considerable differences in total discharge exist across the methods (e.g. Styx and Shoalwater basins). Our scaling factors do not account for situations where water is extracted for irrigation purposes downstream of the gauging station, most notably the Proserpine and Burnett Basins. The recommended correction factor for the Proserpine Basin has low confidence and so the uncertainty within this basin has already been acknowledged. In the case of the Burnett Basin, the extracted water may be of significance in the lower discharge years, although it would likely represent a minor proportion (i.e. < 10 % of the total discharge) in average to above average years. Nevertheless, our scaling correction factors are based on the quantified relationships using the Source Catchments and G2G models, both of which take into account irrigation water offtake. Similar scaling factors have been attempted as part of the Marine Monitoring Program which is tasked to provide annual estimates of GBR basin/NRM region discharge from the most recent water year (e.g. Gruber et al., 2024). This study has built on this approach by incorporating the latest and best available stream gauging data, and producing a series of scaling factors based on area differences and the latest Source Catchments and G2G modelling data. Indeed, the two models display inconsistencies including differences in catchment area and discharge for some basins and these should be investigated further to better refine our estimates of discharge to the GBR. Reliable estimates of basin discharge are critical to calculate constituent loads from each basin of the GBR (McCloskey et al., 2021a, 2021b) and to inform the hydrodynamic model (i.e. extent of flood plumes) and catchment load-based impacts within the eReefs marine modelling suite (Baird et al., 2021).

The 30 year record of total discharge to the GBR shows that there were seven above average events with flows more than 1.5 times the long term median, a return interval of approximately 1 in 4 years. However, flows greater than 2 times the long term median only occurred twice over the same period (i.e. return interval 1 in 15 years). Annual river discharge for the Burdekin Basin, the largest river in terms of discharge in the GBR catchment area, has been reconstructed for the past 363 years (1648–2011) using luminescent lines preserved within coral cores (Lough et al., 2015). This long-term proxy dataset suggest that these two floods in our most recent 30 year record (1990/91 and 2010/11) were among the largest recorded over the past 360 years (see Lough et al., 2015). Indeed, the coral luminescence records of discharge to the GBR (Lough, 2007; Lough et al., 2015) and tree ring reconstructions of river flow for the Daly River in the Northern Territory (Higgins et al., 2022) show that river discharge in northern Australia has increased considerably in the past few decades relative to the past 500 years. Increased river discharge to the GBR is invariably linked to increased pollutant loads and resultant exposure of greater areas within the GBR (e.g. D'Olivo and McCulloch, 2022) which result in negative impacts to keystone coral reefs and seagrass meadows in the inner GBR lagoon (Coates, 1992; Jones and Berkelmans, 2014; Lough et al., 2015; Fabricius et al., 2016; Lambert et al., 2021). In that regard, a comprehensive spatial and temporal analysis of flow and rainfall data (e.g. Wasko et al., 2024) is critical to determine key trends and better understand the extent of influence within the GBR lagoon.

5. Conclusions

This study compiled data from gauging station records to examine spatial trends for the river basins of the Great Barrier Reef (GBR) catchment area. The data reveal distinct spatial variability in terms of annual discharge and baseflow discharge which largely separates the northern Cape York and Wet Tropics NRM regions from the southern NRM regions of the Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary. The drivers of this spatial gradient relate to the climate regime and in particular the higher and less variable rainfall received in the northern latitude catchments. This difference in climate regime results in the streams of the Cape York and Wet Tropics NRM regions generally having higher stream discharge per unit area of runoff, lower coefficients of variation for both inter- and intra-annual discharge, higher runoff to rainfall ratios, higher baseflow contributions and less zero flow days relative to the other NRM regions. The zero flow days metric is also strongly influenced by irrigation releases in the streams of the Burdekin-Haughton Irrigation Area. The other driver that influences the total and peak discharge is the upstream catchment area with the larger basins such as the Fitzroy, Burdekin, Burnett, Mary and Herbert having much higher peak and maximum discharge compared to the other basins. Finally, we developed scaling factors to better estimate total discharge for the river basins, NRM regions and the GBR catchment area for the most recent 30 year period (1990/91–2019/20). The data show two major events in the record where total discharge exceeded the long-term median by more than 2-fold. The scaling factors also provide a method to extend the length of the annual discharge records beyond the period covered by the hydrological models. This method allows accurate basin discharge and associated modelled loads to be reconstructed and compared to proxy-based records such as from coral cores.

Further analysis of streamflow data in the GBR catchment area should include consideration of baseflow determination to provide greater confidence in potential groundwater contribution to surface water discharge. In addition, the outputs of the two key hydrological models need to be investigated to examine the differences particularly for the basins that have no gauges or contain a very low proportion of area gauged. Finally, temporal analyses of the longer flow gauge records (some now contain records > 100 years) should be conducted to quantify hydrological changes in the GBR catchment area related to climate variability, land use change and dam construction.

CRediT authorship contribution statement

Oscar Puignou Lopez: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Stephen E Lewis:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Cassandra S James:** Conceptualization, Formal analysis, Methodology, Writing – review & editing, Supervision. **Aaron M Davis:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Stephen J Mackay:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stephen E Lewis and Cassandra S James reports financial support was provided by the Great Barrier Reef Marine Park Authority

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102603.

Data availability

Data will be made available on request.

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