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Tropical cyclone-induced water and suspended sediment discharge delivered by mountainous rivers into the Beibu Gulf, South China

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ABSTRACT

Small mountainous rivers can deliver considerable freshwater discharge and suspended sediment discharge (SSD) to the ocean during tropical cyclones (TCs), and this has received special attention worldwide. However, little information is available on how TCs impact variations in water discharge and SSD delivered by mountainous rivers into the ocean. Here, based on the daily water discharge and SSD at the gauging stations of the tidal limit in July and August from 1965 to 2017, the Qin River (QR) and Nanliu River (NR), 2 small mountainous rivers located in the north of the Beibu Gulf, South China, were selected to quantify variations in water discharge and SSD into the Beibu Gulf during the TC period. The main results show that the net TC-induced water discharges in the QR and NR during July and August are larger than those of non-TC days, respectively. The net SSD increases in the QR and NR induced by TCs are far larger than those of normal days, respectively. Meanwhile, the water discharge and SSD in the flood season can be dominated by TC-associated rainfall, but the impacts on water discharge and SSD are influenced by the TC characteristics and basin environment. Moreover, it is found that in these 2 mountainous rivers, high water discharge delivers high SSD, but extremely high water discharge caused by TCs fails to produce extremely high SSD. It is expected that TCs will produce great impacts on SSD and water discharge of the mountainous rivers in South China behind global climatic change with increasing TCs events.

1. Introduction

Continental water discharge and fluvial suspended sediment discharge (SSD) are the fundamental materials of rivers delivered from land to the ocean and provide a large proportion of freshwater resources and wetland development necessary for inhabitants' survival (Vörösmarty et al., 2010; Grill et al., 2019). The water discharge and SSD of seagoing rivers play a key role in the land-ocean mass cycles (Walling and Fang, 2003; Dagg et al., 2004; Dai et al., 2016). Variations in fluvial water discharge and SSD may directly affect the formation and development of estuarine deltas and adjacent coastal areas, resulting in geomorphic evolution and eco-environmental changes (Milliman and Syvitski, 1992; Huang, 2010; Dai et al., 2011b). However, with the combined impact of global climate changes and anthropogenic activities, river flow and SSD have undergone drastic reductions (Dai et al., 2010; Dai et al., 2011a; Gao et al., 2015), rendering many mega-deltas economically and environmentally vulnerable (Besset et al., 2019). Furthermore, deltaic erosion induced by the decreased SSD from upstream could also be exacerbated by tropical cyclone (TC) intensity and tracks (Turner et al., 2006; Miles et al., 2015; Darby et al., 2016). However, changes in TC-induced water discharge and SSD into the sea have received little attention, as the present studies are mainly focused on the impacts of human activities, especially on dam construction.

To date, anthropogenic activities, especially for the construction of dams and reservoirs, have been proven to be one of the major factors leading to the drastic decrease in water discharge and SSD in most rivers of the world (Dai et al., 2016; Darby et al., 2016; Besset et al., 2019). For example, the SSD of the Nile River into the Nile delta decreased by nearly 98% owing to the Aswan High Dam in 1964 (Wiegel, 1996). Similarly, the annual SSD delivered by the Yangtze River has declined by 70% since the operation of the Three Gorges Dam (Dai et al., 2014). Such a reduction has also been detected in other rivers, such as the Colorado River, Mississippi River, and Yellow River (Lu, 2004; Walling, 2006; Wang et al., 2007; Yang et al., 2007; Dai et al., 2015). However, most studies on the variations in water discharge and SSD are based on annual or monthly mean data and mainly focus on large rivers (Dai et al., 2016), thus failing to address the variability in runoff and SSD associated with accidental events and neglecting small rivers, especially mountainous rivers.

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Compared to the large rivers of the alluvial plain, mountainous rivers are characterized by small river systems, rapid and large freshwater discharge, fast sediment transport, and a higher responsiveness to climate change and human interference, especially episodic events such as rainstorms, typhoons and debris flows (Farnsworth and Milliman, 2003; Wheatcroft et al., 2010). Furthermore, Milliman and Farnsworth (2011) revealed that the SSD of mountainous rivers into the ocean accounts for more than 70% of the total amount of rivers worldwide, while the catchment area of these small rivers only accounts for nearly 30%. The mountainous river systems located on the New Guinea Gulf discharge approximately 1.7×10^9 t/yr SSD, which is equivalent to the combined estimated SSDs of rivers draining North America (Milliman, 1995). Additionally, the suspended sediment concentration (SSC) of the event-derived SSD of small rivers is dramatically higher than that of large rivers, resulting in event-induced hyperpycnal flows (Liu et al., 2016). The peak SSC of the Santa Clara, Salinas and Eel Rivers, for instance, can reach 20–100 g/l, while the peak concentration in the Mississippi barely exceeds 2 g/l. Therefore, mountainous rivers can deliver a large proportion of water discharge and SSD in relatively short periods (Farnsworth and Milliman, 2003). To date, only a few mountainous rivers have received attention, and no studies have been carried out specifically on the changes in water discharge and SSD during TCs, especially in the mountainous rivers draining into the Beibu Gulf, South China. Therefore, the purposes of this study are (1) to discern the hydrological process of the Nanliu River (NR) and Qin River (QR), two typical mountainous rivers flowing into the Beibu Gulf, during July and August with and without TC forcing; (2) to examine TC-induced variations in water discharge and SSD into the ocean; and (3) to estimate the total amount of water discharge and SSD associated with TCs in recent decades. These results greatly improve the understanding of the TC-induced water discharge and SSD of mountainous rivers into the ocean and can be beneficial for understanding other similar mountainous rivers in tropical zones around the world.

2. Study area

The Beibu Gulf is a semiclosed bay in the north of the South China Sea, and there are 6 independent mountainous rivers (Nanliu River, Dafeng River, Qin River, Maoling River, Fangcheng River and Beilun River) with a drainage area of more than 1000 km^2 located in the northern part of the Beibu Gulf, Guangxi Province (Fig. 1A). These rivers are all characterized by short mainstream lengths with a range of 100–210 km, small drainage areas with a range of 750–9261 km^2, steep river slopes with a range of 0.16–7.17‰, and high water discharges and SSDs into the sea (Li et al., 2017). Here, both the NR and QR were selected as typical examples to examine how TCs impact water discharge and SSD from mountainous rivers into the Beibu Gulf, and these rivers are the easternmost and western rivers, respectively (Fig. 1A). Additionally, the NR and QR are the largest and third largest mountainous rivers among the 6 local rivers and are 9261 km^2 and 2539 km^2 in area and 210 km and 128 km in length, respectively. The monsoon climate dominates the two river basins and leads to a flood season from May to October. The intense rainfall during the flood season combined with the TCs that pass over the Beibu Gulf induce large amounts of water discharge and SSD in the mountainous rivers. It has been estimated that 305 TCs have passed over main impacts on the coastal area of the Beibu Gulf of Guangxi Province during 1950–2012 and likely produced further impacts on water discharge and SSD from these rivers into the Beibu Gulf.

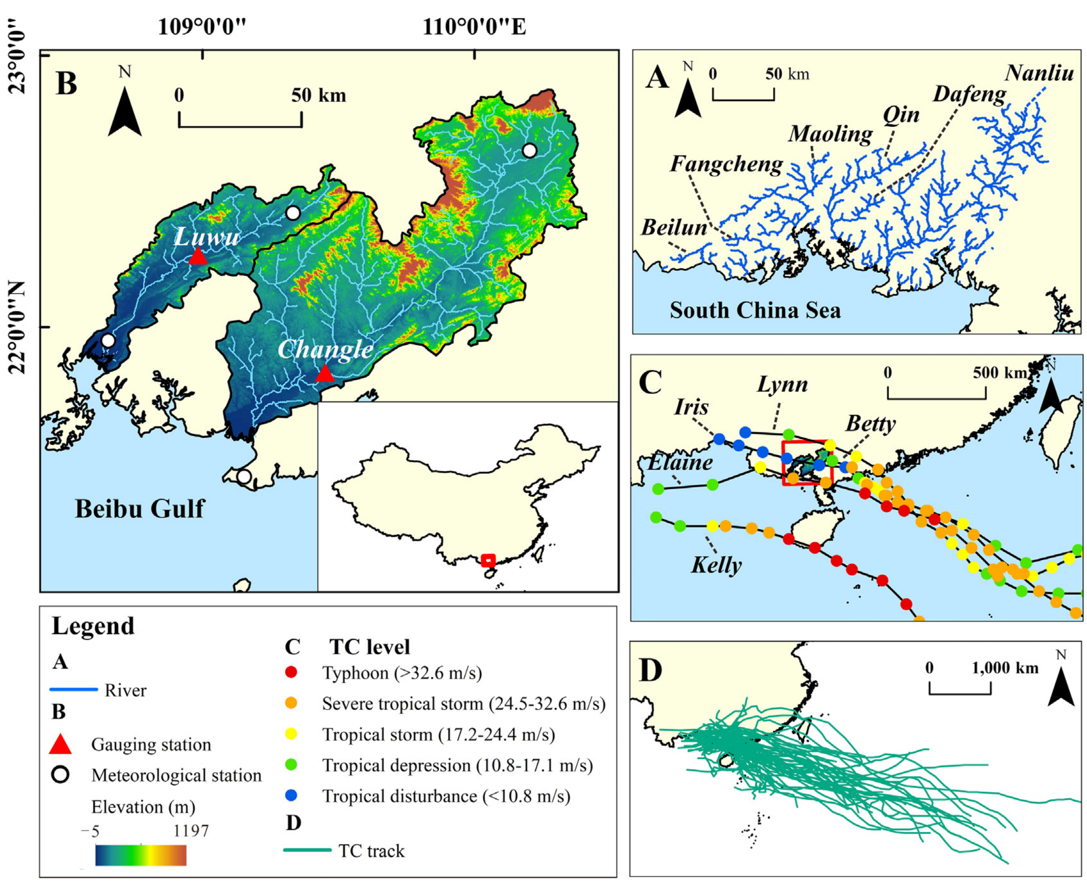

Fig. 1. Research area and TC tracks. Plot (A): 6 independent mountainous rivers in the Beibu Gulf. Plot (B): Location of gauging stations in the QR and NR catchments. Plot (C): TC levels of the 5 TCs mentioned in this study. Plot (D): Tracks of 63 TCs during 1965–2017.

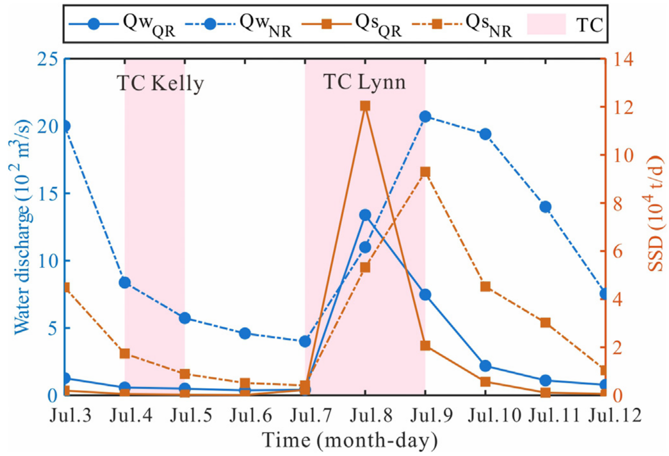

Fig. 2. Variations in daily water discharge and SSD with the effects of TCs Lynn and Kelly in 1981.

3. Materials and methods

3.1. Materials

The Luwu and Changle gauging stations are key hydrological stations that record the water discharge and SSD draining from land into the Beibu Gulf. They are located in the middle reach of the QR and the lower reach of the NR (Fig. 1B). Daily water discharge and SSD data at Luwu and Changle stations from 1965 to 2017 were collected from the Pearl River Water Resources Commission (http://www.pearlwater.gov.cn/), but some daily SSD data were unavailable, including 1967 to 1975, 1985 to 2000, and 2009 for the QR and 1967 to 1975 and 1985 to 2000 for the NR. In order to reconstruct the daily SSD for missing years, rating curves were adopted based on available daily discharge data. Daily precipitation data across the QR and NR basins from 1965 to 2017 were obtained from the China Meteorological Administration (http://data.cma.cn/). TC data from 1965 to 2017 were acquired from the Shanghai Typhoon Research Institute (http://www.sti.org.cn/) and comprised information on central pressure, wind speed, latitude and longitude positions.

3.2. Methods

3.2.1. TC selection

Considering that over 60% of the TCs occurred in July, August and September in the catchment and that the water discharge and SSD of the QR and NR in July and August account for a large proportion of the annual amount (Li et al., 2017), this study is focused on the TC-induced variations of water and sediment discharge in July and August. Additionally, previous works have indicated that the landward area impacted by TC action is approximately 500 km (Rodgers et al., 2001; Jiang and Zipser, 2010). Recent studies also show that the TCs with centers north of 19°N and west of 112°E have different effects on the coastal area of Guangxi Province (Chen et al., 2014). Therefore, TCs that affect the river basins are first selected. Then, combined with the daily runoff and precipitation data for the QR and NR, the selected TCs that significantly induced rapid increases in water discharge and SSD were further screened. For example, TC Lynn in 1981 entered the impacted zone on 7 July and exited on 8 July. The corresponding daily water discharge of the QR increased greatly from 41.8 m^3/s to 1340 m^3/s, while the flow of the NR increased from 401 m^3/s to 2070 m^3/s (Figs. 1C, 2). Therefore, TC Lynn was selected to understand the potential contribution to water discharge and SSD in the NR and QR. However, variations in water discharge induced by TC Kelly in 1981 were weak, and TC Kelly was therefore excluded (Figs. 1C, 2). Finally, 60 TCs that remarkably affected the QR and NR, 2 TCs that occurred in 1973 and 1977 and only affected the NR, and 1 TC that occurred in 1983 and only impacted the QR were selected (Fig. 1D, Table S1).

3.2.2. Sediment rating curve

There exists a nonlinear function between the water discharge and SSD, known as the sediment rating curve. In this study, the form:

$$Q_S = aQ_w^b \tag{1}$$

was obtained by regressing the water discharge against the relevant SSD. Q_S (t) in the equation is the daily SSD, while Q_w (m^3/s) is the daily water discharge, a is the y-intercept, and b is the slope of the fitted line shown in the plot (Picouet et al., 2001; Mouri et al., 2014). This formula is subsequently adopted to reconstruct the unavailable daily SSD of the QR and NR based on the corresponding water discharge in July and August of TC years.

3.2.3. Classification of hydrological years and coefficient of variation

An extreme hydrological event can be defined as the occurrence of flow values above the 75th percentile or below the 25th percentile within the observed years. In this study, a year with an annual water discharge higher than the 75th percentile is defined as a flood year, while a year lower than the 25th percentile is a dry year; others are normal years (Dai et al., 2016). The calculation method of percentile values follows Bonsal et al., 2001, and the results are shown in Table 1. The coefficient of variation (Cv) is an effective tool to compare the distributions with different units. To identify the variability of the series of daily water discharge and SSD, the hydrological variation coefficient of Cv is calculated based on the daily discharges in July and August by the Moment method (Greenwood et al., 1979).

3.2.4. Contributions of TCs to water and SSD

The net contribution of TCs to the runoff in a year is expressed by p_c, and the formula is as follows:

Table 1
Classification of hydrological years.

TC condition	River	Hydrological condition	Time
Non-TC year	QR	Flood year	1968, 1995
		Normal year	1972, 1973, 1977, 1982, 1990, 2011, 2015
		Dry year	1975, 1987, 1988, 1999, 2004, 2005, 2007
	NR	Flood year	1995
		Normal year	1968, 1972, 1975, 1982, 1983, 1987, 1990, 2015
		Dry year	1988, 1999, 2004, 2005, 2007, 2011
TC year	QR	Flood year	1967, 1970, 1971, 1976, 1979, 1981, 1997, 2001, 2002, 2003, 2013
		Normal year	1965, 1966, 1969, 1974, 1978, 1983, 1984, 1985, 1986, 1993, 1994, 1996, 1998, 2006, 2008, 2009, 2012, 2014, 2016, 2017
		Dry year	1980, 1989, 1991, 1992, 2000, 2010
	NR	Flood year	1970, 1973, 1976, 1979, 1981, 1985, 1994, 1997, 2001, 2002, 2008, 2013
		Normal year	1965, 1966, 1967, 1969, 1971, 1974, 1978, 1984, 1986, 1993, 1996, 1998, 2003, 2006, 2009, 2012, 2014, 2016, 2017
		Dry year	1977, 1980, 1989, 1991, 1992, 2000, 2010

Note: A year with an annual water discharge higher than the 75th percentile is defined as a flood year, while a year lower than the 25th percentile is a dry year.

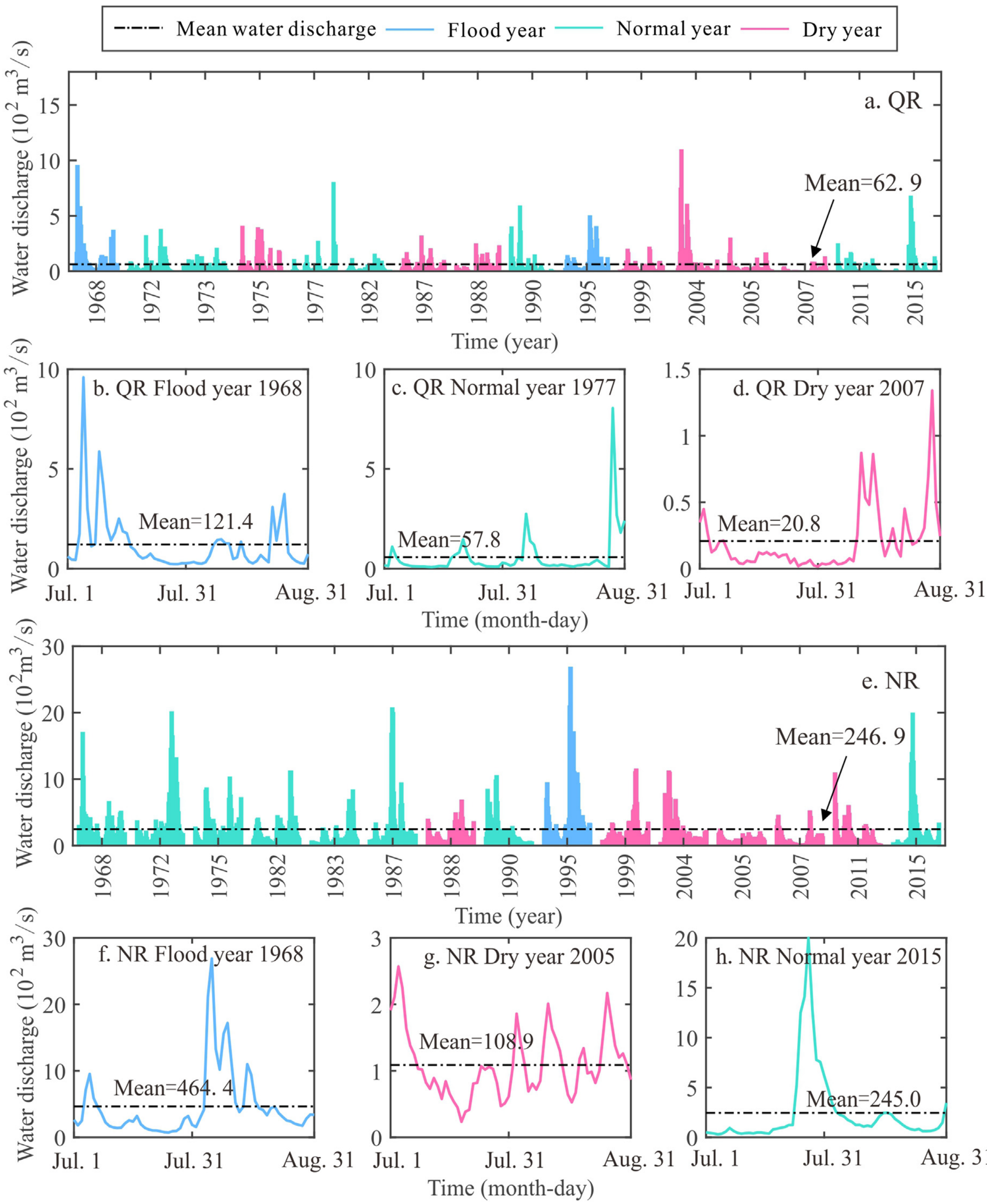

Fig. 3. Variations in daily water discharges in July and August of each non-TC year. Water discharges of different hydrological years in plots (a)–(h) are shown in different colors. Plots (b)–(d) and plots (f)–(h) represent the changes in daily water discharges in July and August of 3 specific different hydrological years.

Table 2
The max/min and Cv values of water and sediment discharges in different hydrological conditions in QR and NR.

	Time period	Non-TC year				TC year			
		Water discharge		SSD		Water discharge		SSD	
		QR	NR	QR	NR	QR	NR	QR	NR
Average max/min	All	97.5	26.6	4028.4	1052.8	71.7	26.6	1796.0	1000.8
Average Cv	All	1.3	1.0	2.9	2.1	1.5	1.0	2.7	2.2
	Flood year	1.3	1.1	–	–	1.4	1.0	2.5	1.7
	Normal year	1.3	1.1	3.1	2.3	1.4	1.0	2.8	2.2
	Dry year	1.2	0.8	2.7	1.9	1.7	1.2	3.2	2.7

Note: The average Cv of SSD in flood non-TC years were not calculated due to the lack of measured data.

$$p_c = \frac{(Q_{w\_tc} \times D_{tc} - Q_{w\_nor} \times D_{tc}) \times 24 \times 3600}{Q_{w\_a} \times D_a \times 24 \times 3600} \quad (2)$$

where Q_{w_tc} (m^3/s) is the mean water discharge during the passage of TCs that occurred in July and August of each year, Q_{w_nor} (m^3/s) is the mean water discharge of the normal days without TC impacts in July and August of each year, Q_{w_a} (m^3/s) is the mean water discharge of the whole year, D_{tc} (days) is the duration of the relevant TCs, and D_a (days) is 365 or 366. The numerator of the formula represents the absolute contribution of TCs, where the denominator represents the total amount of runoff transported each year. The p_c of SSD is calculated similarly. Moreover, combined with the reconstructed daily SSD obtained by relevant rating curves, the total amount of the net TC-induced SSD can be estimated.

3.2.5. TC-induced growth rate of water discharge and SSD

To quantitatively reflect the direct impact of TCs on water discharge and SSD and eliminate the impact of the basic discharges of normal days in the QR and NR, the growth rate (p_g) is calculated by the following formula:

$$p_g = \frac{Q_{w\_tc} - Q_{w\_nor}}{Q_{w\_nor}} \quad (3)$$

where Q_{w_tc} and Q_{w_nor} have the same meanings as those shown in the contribution formula. The growth rate of SSD in each TC year is computed similarly.

4. Results

4.1. Variations in water discharge and SSD in non-TC years

The daily water discharges of the QR under normal hydrological conditions present great differences, as a large range exists between the extreme daily water discharges of the QR (Fig. 3a). The mean maximum/minimum water discharge ratio in all non-TC years is 97.5 (Table 2). On the other hand, according to the analysis of Cv, the average Cv value of daily water discharge in July and August in non-TC years reaches 1.3, which is much higher than that of alluvial plain rivers, such as the Changjiang River (<1) (Dai et al., 2008). Throughout different hydrological conditions of the non-TC years, the average Cv values of flood and normal years are higher than that of the dry years (Table 2), which means that the water discharges of the QR are more evenly distributed in dry years than those in normal and flood years. Moreover, the daily water discharges of the QR can rapidly increase by two or three orders of magnitude and return to the normal level in a short time (0–48 h) (Fig. 3b–d). Variations in the daily water discharge of the NR resemble those of the QR and are characterized by abrupt changes and large differences (Fig. 3e–h). However, the range of daily water discharge in the NR is smaller than that in the QR. The mean ratio between the extreme values of the NR is only 26.6 (Table 2). Moreover, the Cv values of the NR are slightly lower than those of the QR, with the mean value of non-TC years being 1.0 (Table 2).

Meanwhile, variations in the daily SSD of non-TC years in QR are highly consistent with those of the relative daily water discharge (Fig. 4a–c). Specifically, the average maximum/minimum SSD ratio of QR reaches 4028.4, which obviously exceeds that of the water discharge (Table 2). On the other hand, the daily SSD in July and August of the non-TC year has an average Cv of 2.9, which is more than twice that of the water discharge (Table 2). The increasing and decreasing trends of daily SSD in the NR are in line with the related river flow, and the amplitudes of variations between the daily SSDs are much larger than those between the daily water discharges (Fig. 4d–f). The mean maximum/minimum ratio of SSD of non-TC years in the NR is 1052.8, and the average Cv value is 2.1. Additionally, the Cv values in normal and dry years in the NR also exceed the corresponding Cv values of water discharge. However, it can be found that variations in daily SSD in the NR are relatively milder than those in the QR (Table 2), which resembles the differences in the water discharges between the QR and the NR.

4.2. Variations in water discharge and SSD under the influence of TCs

Daily water discharges in TC years in the QR and NR exhibit rapid changes like those in non-TC years (Figs. 5, 6). However, the amplitude of variations in TC years is less dramatic than that in non-TC years. For instance, the average maximum/minimum ratio of water discharge in

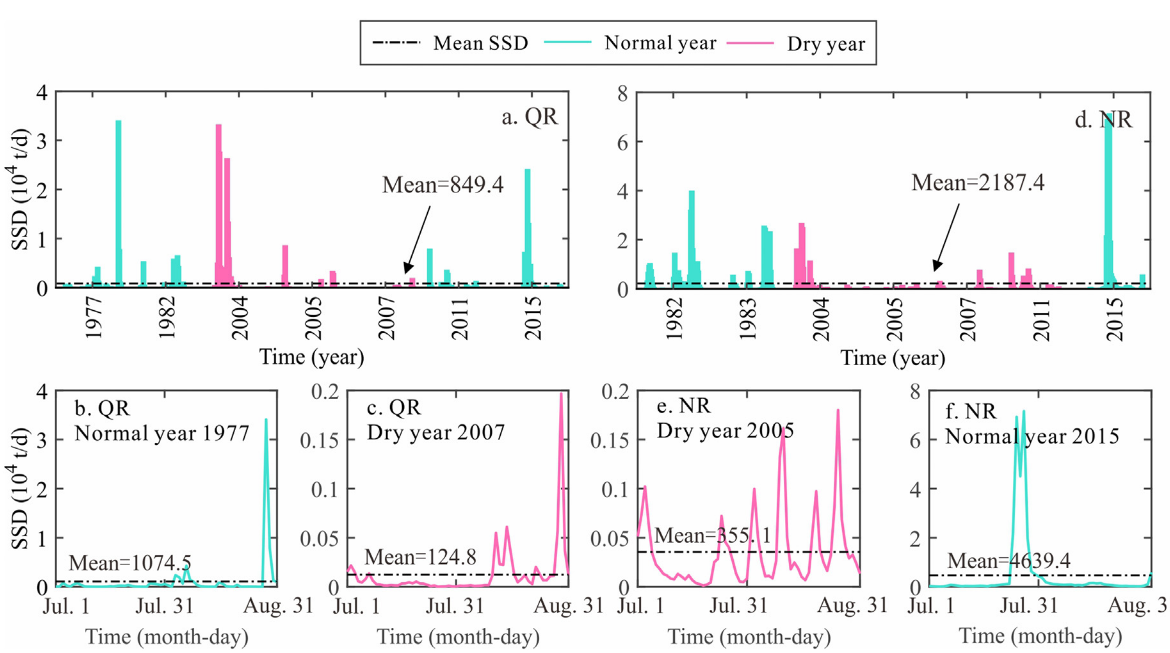

Fig. 4. Variations in daily SSDs in July and August of each non-TC year. SSDs of different hydrological years in plots (a)–(f) are shown in different colors. Plots (b), (c), (e) and (f) represent the changes in daily SSDs in July and August of specific normal and dry years. Due to the lack of daily SSD, the variations of SSD in the flood non-TC years are not shown in this figure.

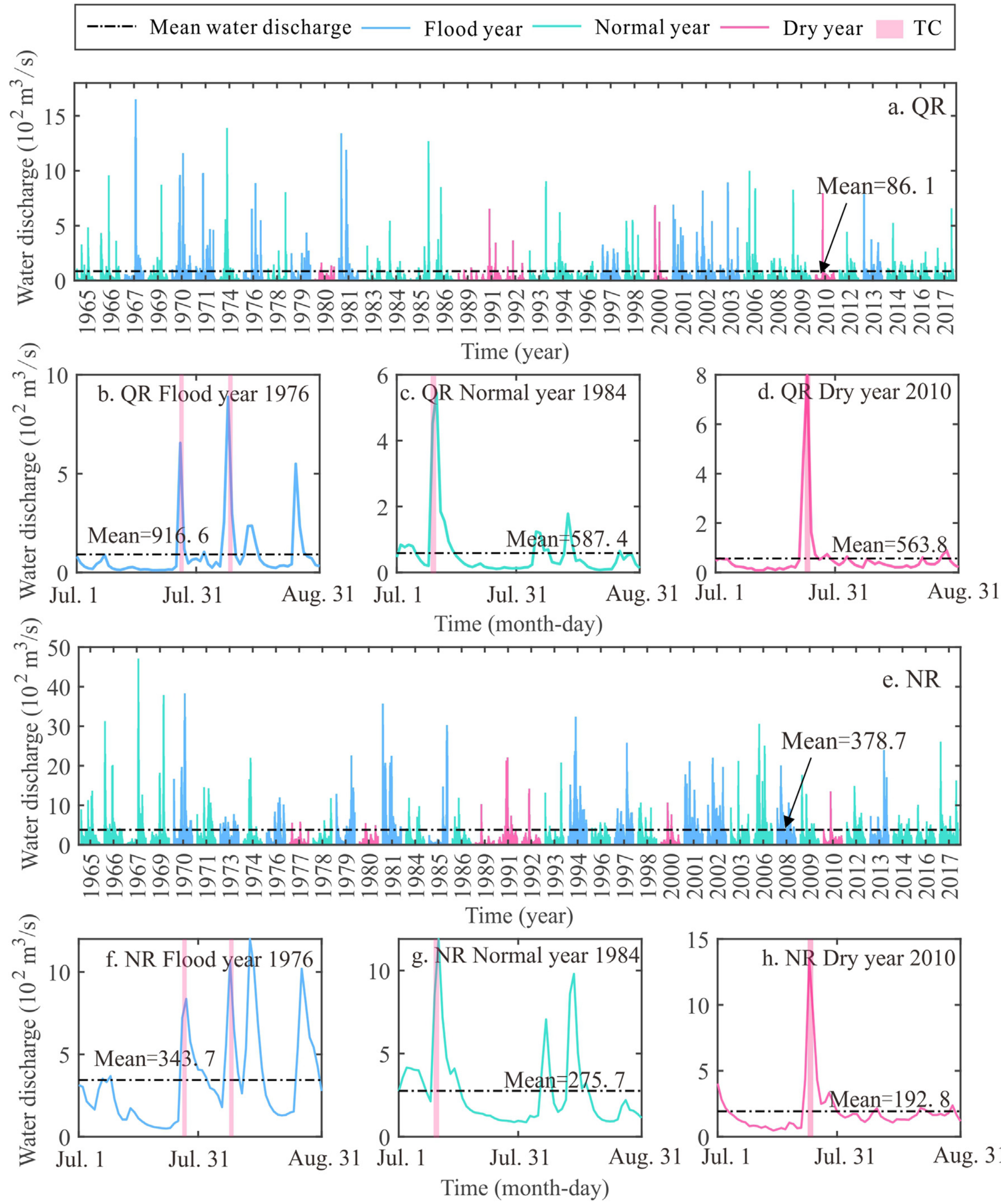

Fig. 5. Variations in daily water discharges in July and August in each TC year. Water discharges of different hydrological years in plots (a)–(h) are shown in different colors. Plots (b)–(d) and plots (f)–(h) represent the changes in daily water discharges in July and August of 3 specific different hydrological years. The pink shaded areas in plots (b)–(d) and plots (f)–(h) represent the influence of the TCs.

TC years in the QR is 71.7, which is obviously smaller than that in non-TC years (Table 2). Additionally, compared to those in non-TC years, the Cv values in TC years show great differences in different hydrological years. Specifically, the mean Cv of water discharge in dry TC years is higher than those of normal and flood TC years, and this is the opposite of the pattern in non-TC years (Table 2). On the other hand, the ranges of daily SSD of the 2 rivers in TC years are smaller than those in non-TC years as well, especially for the SSD in QR. The maximum/minimum ratio of SSD in the QR is 1796.0, less than half of that in non-TC years. Moreover, the Cv values of SSD in dry years in the QR and NR also exceed those of normal and flood years (Table 2), indicating that SSDs of QR and NR in dry TC years are rather unevenly distributed.

To further detect the effect of TCs on water discharge and SSD in each TC year, daily discharges of TC years were divided into 2 categories, namely, data during the passage of TCs and data during non-TC days. In the QR, the water discharges of TC days present remarkable increases with the impacts of TCs (e.g., Fig. 5b–d). The ratios between the peak daily discharges during the passage of TCs and the normal discharges of the day before the TCs took effect were calculated. The average ratio of water discharges in the QR is 24.0, and the average ratio in the NR is 11.0, which is less than half of that in the QR. The peak TC daily SSD/normal daily SSD ratios of each TC year are much higher than the water discharge ratios. The mean ratios of SSD in the QR and NR reach 218.6 and 129.4, respectively. This indicates that SSD is more responsive

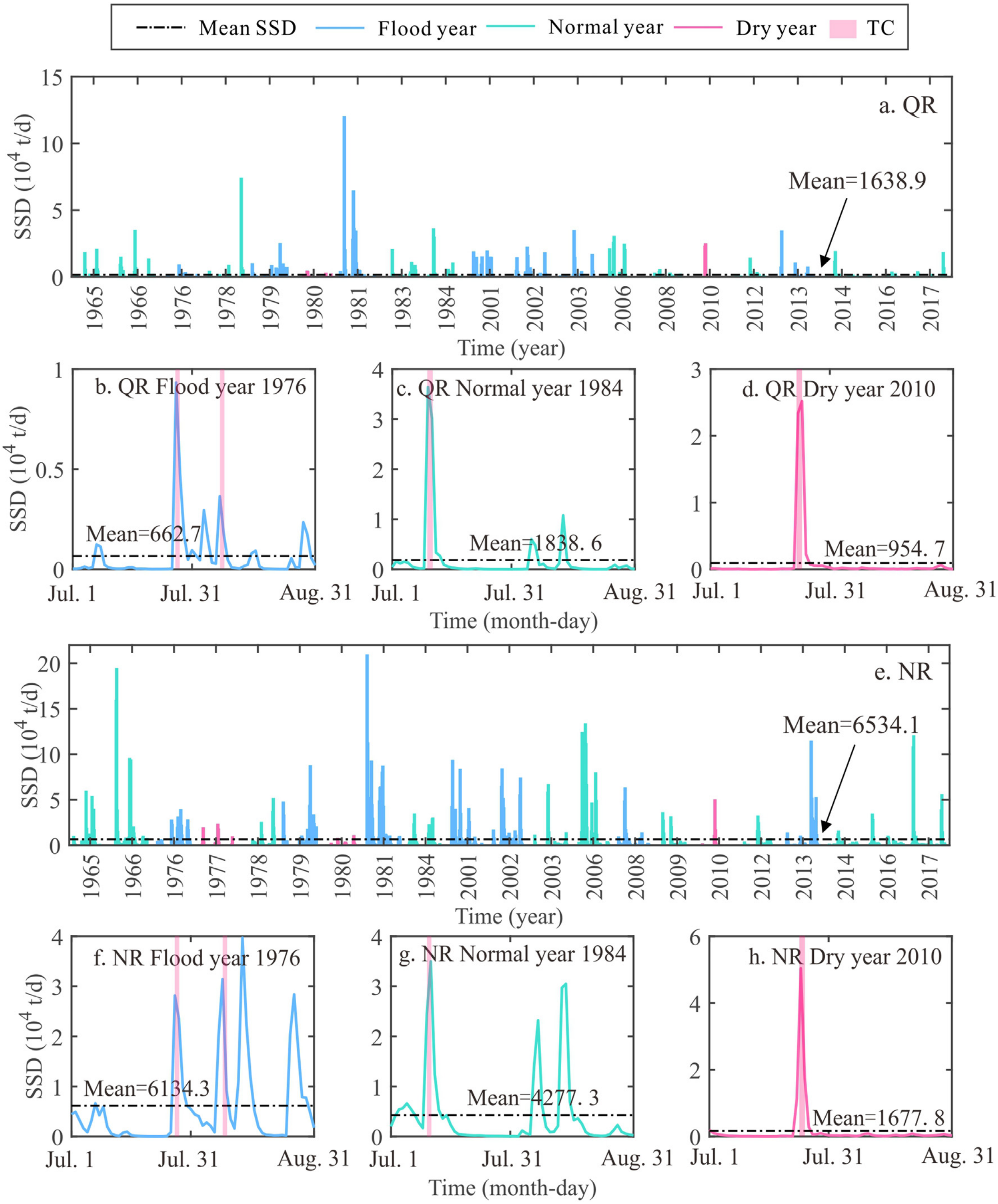

Fig. 6. Variations in daily SSDs in July and August in each TC year. SSDs of different hydrological years in plots (a)–(h) are shown in different colors. Plots (b)–(d) and plots (f)–(h) represent the changes in daily SSDs in July and August in 3 specific different hydrological years. The pink shaded areas in plots (b)–(d) and plots (f)–(h) represent the influence of the TCs.

to TCs than water discharge. Meanwhile, it can also be inferred that the QR reacts more rapidly than the NR to the impacts of TCs when TCs occur because all the ratios of the QR exceed those of the NR.

In terms of the specific TC-associated water discharge and SSD, it is evident from Fig. 7 that the daily mean water discharge and SSD of TC days are remarkably higher than those of normal days in each TC year, demonstrating the huge impacts of TCs on water discharge and SSD. In the QR, the mean water discharge of TC days reaches 403.8 m^3/s, which is approximately 6 times the relative average normal water discharge of non-TC days in TC years (Fig. 7a) or non-TC years (Fig. 3a). In the NR, the mean TC water discharges of TC days increase by 2 times (Fig. 7b). The SSDs of TC days experience sharper increases than water discharge. The mean SSD of TC days in the QR is 14,264.5 t, nearly 17 times that of the normal SSD (Fig. 7c). The response of SSD to the TC effect in the NR is relatively milder than that in the QR, and the SSD of TC days in the NR increases by nearly 4 times, with an average of 25,881.5 t (Fig. 7d).

4.3. Relationships between daily water discharge and SSD

Water discharge is an important factor controlling variations in SSD, and there exists a nonlinear function between the water discharge and SSD (Dai et al., 2016). In the QR and NR, these factors also exhibit a power law relationship at the significance level of 0.001 with or without TCs, indicating that SSD increases greatly with increasing water discharge (Fig. 8). Moreover, the slope of the rating curve, namely the

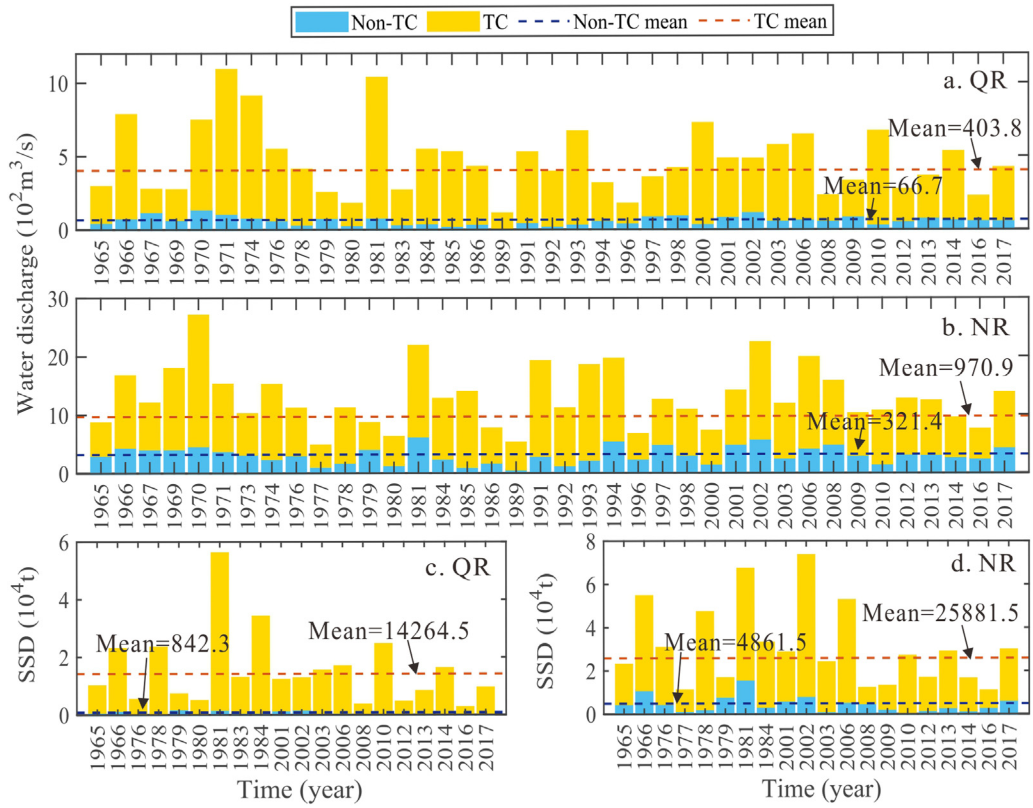

Fig. 7. Daily mean water discharge and SSD of the QR and NR on TC days and normal days in TC years.

exponent in the expressions, represents the ability of river flow to deliver sediment (Fig. 8). The larger the gradient is, the stronger the transport ability is. The gradients of TC days are smaller than those of the normal days in both the QR and the NR, which indicates that an extremely high flow does not necessarily carry an extremely high SSD. In addition, considering the influence of different hydrological years with TCs, rating curves are further fitted as shown in Fig. 8, and the functions are shown in Table 3. The sediment carrying capacity of the water discharge under the influence of TCs in flood years is weaker than that of normal days. In normal and dry years, the river flow on TC days is stronger than on normal days. Moreover, when TCs occur, river flow in flood years and normal years transports comparable sediment at the same discharges, which is different from that of non-TC days.

4.4. The contribution of TCs to the water discharge and SSD

TCs generated considerable water discharge and SSD in the QR and NR during 1965–2017 (Fig. 9). The net TC-induced water discharges in the QR and NR from 1965 to 2017 are 338.9 m^3/s and 707.9 m^3/s, respectively, which are abnormally higher than those of the normal

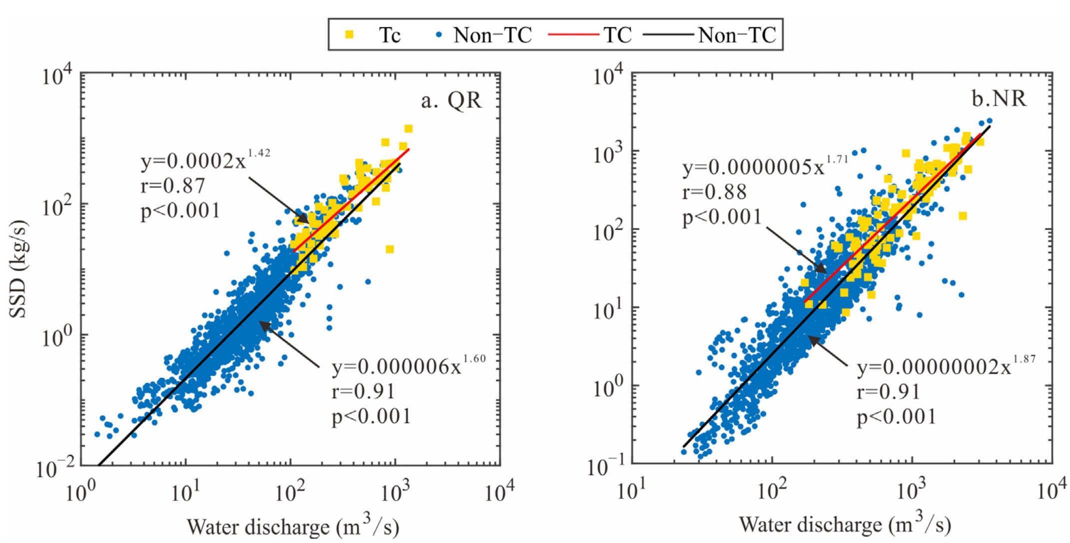

Fig. 8. Relationships between daily water discharge and SSD on TC days and normal days.

Table 3
Relationships between daily water discharges and SSDs under different hydrological conditions.

	TC days	Non-TC days
Flood year	$y = 0.0004x^{1.30}$, $r = 0.86$, $p < 0.001$	$y = 0.000009x^{1.45}$, $r = 0.89$, $p < 0.001$
Normal year	$y = 0.0003x^{1.30}$, $r = 0.81$, $p < 0.001$	$y = 0.0002x^{1.14}$, $r = 0.73$, $p < 0.001$
Dry year	$y = 0.008x^{1.16}$, $r = 0.90$, $p < 0.001$	$y = 0.0002x^{1.10}$, $r = 0.82$, $p < 0.001$

condition (Figs. 7a–b and 9a–b). Similar information in daily SSD can be seen as well (Figs. 7c–d and 9c–d). The absolute SSDs caused by TCs in the QR and NR are 154.5 kg/s and 255.7 kg/s, respectively. Furtherly, the total amounts of TC-induced water discharge in the QR and NR are 3.9×10^9 m^3 and 1.2×10^{10} m^3, and the total TC-induced SSDs reach 9.9×10^5 t and 2.3×10^6 t, respectively (Fig. 9). To estimate the TC-induced SSD during the whole period from 1965 to 2017, rating curves based on the discharges of TC days are adopted to reconstruct the unavailable daily SSD (Fig. 8). The net contributions of TCs in July and August to SSD in the QR and NR during 1965–2017 are 1.7×10^6 t and 4.9×10^6 t, respectively. Moreover, although the TCs that occurred in July and August last for only a few days, usually 2 or 3 days, the water discharge and SSD associated with TCs account for a significant proportion of the total annual amounts (Fig. 9). The mean p_c of water discharge and SSD of the QR are 9±7% and 21±16%, and in the NR, they are 5±5% and 12±12%, which also demonstrates that SSD is more sensitive to TCs. It is worth noting that the p_c of NR is nearly half of that of QR, which indicates that the QR is more responsive to TCs than the NR. However, there are great differences in the p_c among TC years. For example, TCs contributed the greatest water discharges in 2006, generating 31% of the runoff in the QR and 20% of the runoff in the NR (Fig. 9a, b). Meanwhile, 65% of the SSD in the QR and 53% of the SSD in the NR in 2006 were induced by TCs (Fig. 9c, d). However, in 1979 and 2008, TC-induced water discharge and SSD accounted for little (<5%). Unexpectedly, there is no significant trend shown in p_c among different hydrological years, and the reasons are discussed later.

5. Discussion

5.1. Impacts of precipitation

The leading factor affecting the river flow and SSD on a continental scale is precipitation, specifically the frequency and magnitude of rainfall (Meade et al., 1990). Significant positive correlations are detected in the relationships between daily precipitation and water discharge and SSD in the QR and NR (Fig. 10), which indicates that precipitation dominates the flow and SSD in the QR and NR, and high precipitation induces high water discharge and SSD. Moreover, SSD is a power function of water discharge with an exponent greater than 1, which implies that more sediment is transported by high water discharges (Meade et al., 1990). Therefore, the SSD in the QR and NR appears to vary consistently with the relative water discharge and varies even more rapidly than the water discharge (Figs. 3–6). However, extremely high flow associated with TC rainfall fails to carry extremely large amounts of sediment when compared to the amounts carried by normal water discharge, as shown in Fig. 8. The possible reason accounting for this result is the relatively low sediment supply compared to the abundance of runoff. Similar to the Langbein-Schumm rule (Langbein and Schumm, 1958), when precipitation is less than effective precipitation, the runoff induced by rainfall events is sufficient to move whatever sediment may be available. Moreover, when precipitation increases, the SSD decreases because precipitation also encourages more vegetation, which discourages runoff and soil erosion. Studies have found that the impact of TC-induced rainfall on rivers is restricted by several factors, such as the intensity of the TC and land cover, as mentioned above (Shepherd et al., 2007; Lin et al., 2008; Yu et al., 2017). Here, we discuss the possible factors that have an impact on TC rainfall and consequently affect the water discharge and SSD in the QR and NR with the growth rate (p_g), and the results are shown in Fig. 11.

5.2. Impacts of TC characteristics

TC characteristics, for instance, wind speed, track and duration, are the main factors controlling the intensity of TC rainfall (Shepherd

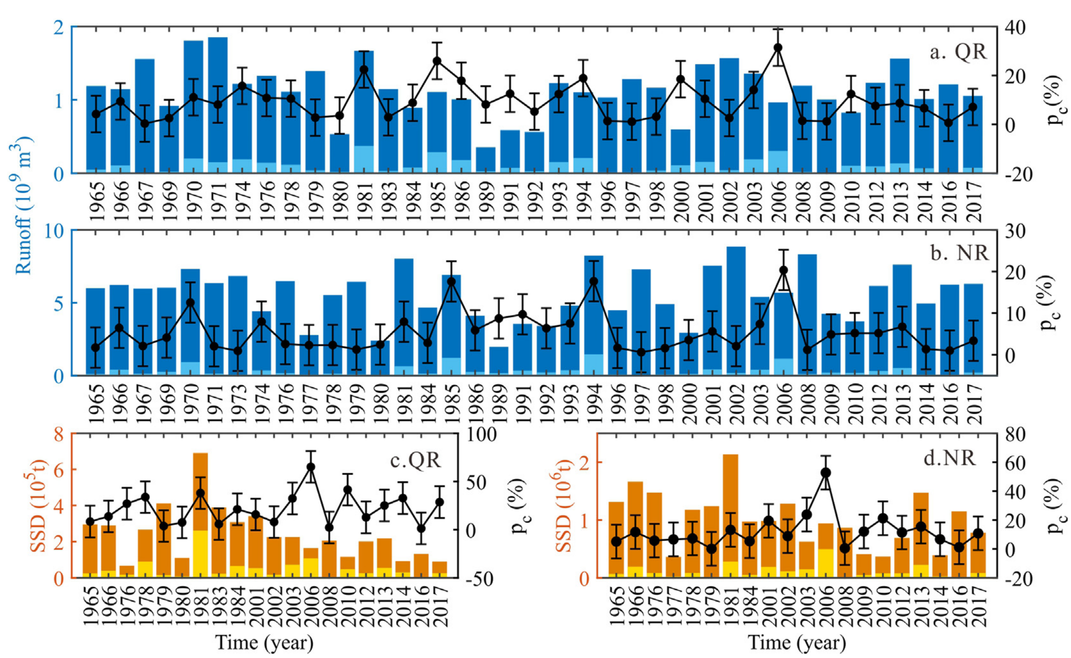

Fig. 9. The net contribution of TCs to the water discharge and SSD. Light blue and light orange bars represent the absolute amount of water discharge and SSD generated by the TCs, dark blue and dark orange bars represent the total amount of annual water discharge and SSD; the black solid lines represent the error bars of pc.

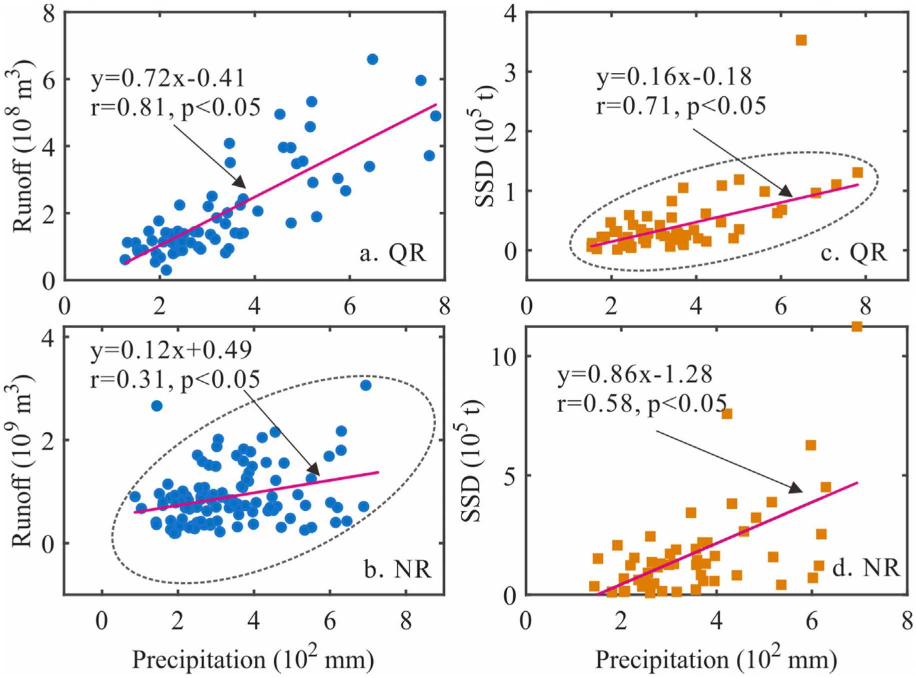

Fig. 10. Relationship between monthly precipitation and runoff and SSD in July and August during 1965–2017. Data out of the ellipse in plot (b)–(c) are not used in linear fitting.

et al., 2007; Wing et al., 2007; Kubota and Wang, 2009; Chen et al., 2011). First, the wind speed of TCs is widely used as the evaluation criterion of TC intensity. The more powerful a TC is, the more precipitation it causes (Yu et al., 2017), and the more water discharge and SSD is generated. Unexpectedly, the correlation between the wind speed of TCs and the associated increase in discharge is not significant ($p > 0.1$), indicating that the wind speed is not the dominant factor. In fact, most of the TCs did not land in Guangxi Province initially, and when TCs arrived at Guangxi, they were usually classified as a tropical storm or a tropical depression with relatively weak strength (Fig. 1C, Table S1), so the wind speed had little effect on the water discharge and SSD.

In the QR and NR, it is found that the TCs that went over the catchment have greater impacts on water discharge and SSD. For instance, TCs in 1985 passed over the river basins and generated 3.03×10^8 m^3 and 1.33×10^9 m^3 runoff in the QR and NR, which accounted for approximately 22% and 18% of the annual amount, respectively. Meanwhile, water discharges under the influence of TCs underwent the most rapid changes in 1985 as the p_g reached the highest values (18 and 11). On the other hand, the p_g of water discharge in the QR induced by the TCs outside the basin is generally below 3, while the p_g of most TCs crossing over the basin is greater than 6. The average p_g of water discharge of the 2 categories is 8.4 versus 4.2 in the QR. In the NR, they are 3.0 versus 1.7. This ratio of 2:1 demonstrates that TCs that passed outside the basins only exerted half the strength on water discharge and SSD when compared to those passing directly over the basins. Moreover, considering the relatively equal power of TCs, whether TCs pass directly over the basins appears to be important.

Studies have also found that in association with increasing overland duration, TC-induced rainfall also increases (Chen et al., 2011). Therefore, TC-induced water discharge and SSD should increase as well. The duration of TCs and water discharge and SSD in the QR and NR present significant positive correlations (Fig. 12). For example, 3 TCs, characterized by normal wind speed and normal passage tracks, occurred in 2006 and lasted for 8 days (Table S1). The accumulated runoff accounted for

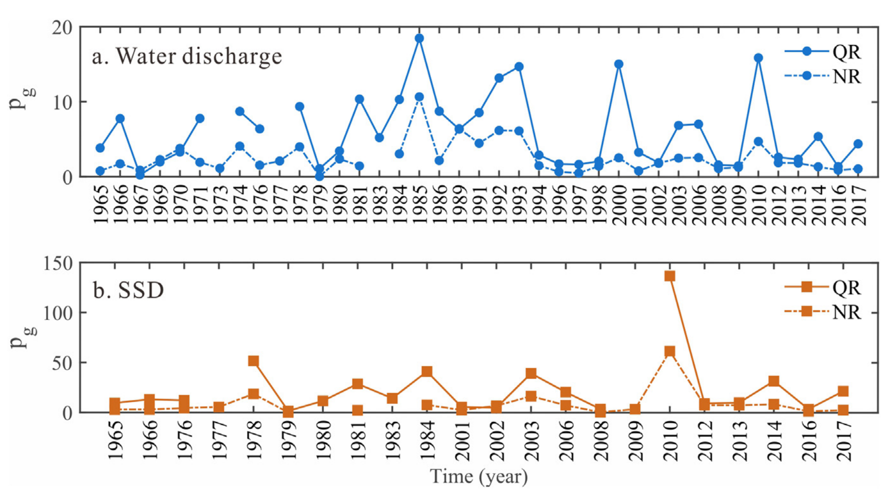

Fig. 11. Growth rate (p_g) of water discharge and SSD in the QR and NR.

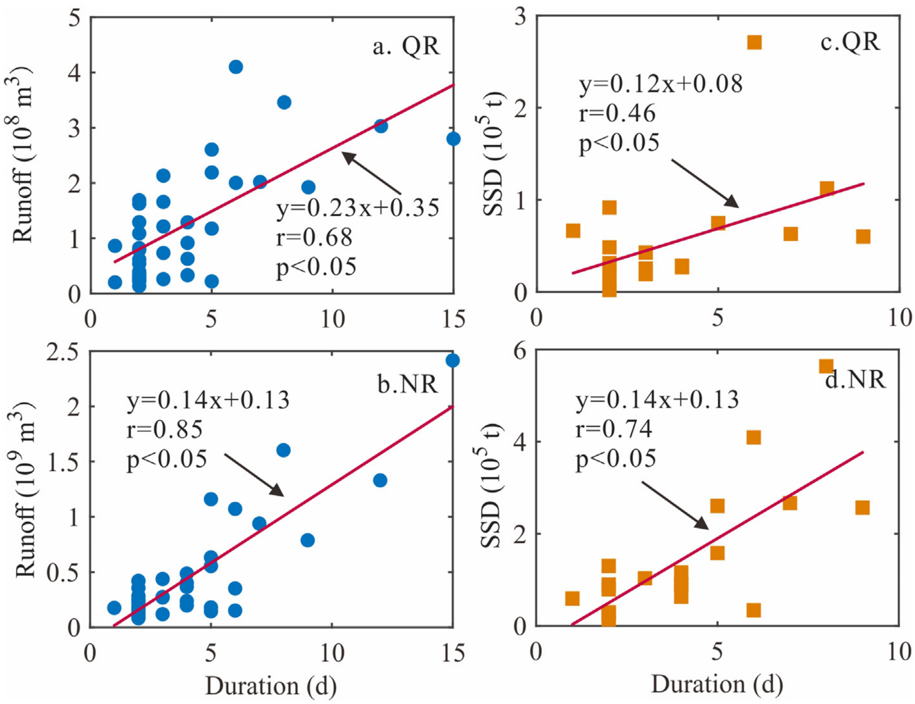

Fig. 12. Relationship between the duration of TCs and runoff and SSD in July and August during 1965–2017.

31% of the whole year. However, there are always some exceptions. No tropical cyclone passed over the QR catchment in 1978 and 1984 (TC Elaine and Betty, Fig. 1C, Table S1), whereas the p_g in these 2 years reached 10.3 and 9.4, and the p_c values were 10.5% and 8.8%, respectively. TC Iris went across the QR in 1967 (Fig. 1C), but the p_g and p_c were only 0.22 and 0.3%, respectively. Furthermore, some recent studies revealed that the intensity of TCs passing across the South China Sea would increase under the context of global warming (Redmond et al., 2015; Darby et al., 2016), water and sediment discharges in these mountainous rivers are likely to suffer from serious impacts of TCs.

5.3. Impacts of catchment environment

According to p_g, the values of the QR are obviously larger than those of the NR (Fig. 11), and the mean values of the p_g of water discharge in the QR are nearly 2.5 times higher (6.2 vs 2.5). Based on the net contribution of TCs to water discharge and SSD in the 2 rivers, it can be concluded that the QR reacts faster than the NR to TC-induced rainfall events. The differences in TC impacts on the 2 adjacent rivers can be mainly attributed to the river scales. The mainstream length of QR is shorter than that of NR (Fig. 13). Meanwhile, the mainstream slope of QR is 0.74‰, and that of the NR is about 0.43‰ (Fig. 13). Slope differences between these two rivers can induce the water discharge of the QR to be delivered faster in response to the TC rainfall when it compared to that of the NR. Meanwhile, the NR basin is larger than QR with more tributaries (Fig. 1A, B). The drainage density of NR reaches 0.42 km/km^2, while it is only 0.34 km/km^2 in the QR. It means that the river channels of QR could hold a smaller amount of freshwater than that of the QR (Fig. 1). Furthermore, combined with the gentle slope of the NR, the process of runoff confluence is slower in the NR than that in the QR, which results in the NR's response to TCs being heavily buffered. Taken altogether, the NR is larger and longer than the QR and is characterized by denser tributaries and a gentle slope. When heavy rain generated by TCs occurs, the delivered runoff produced by rainwater can be slowed down due to regulations from denser tributaries and the gentle slope of the NR, which results in the river's response to TCs being buffered. Compared to that of the NR, the smaller water discharge of the QR further highlights the influence of TCs.

On the other hand, the p_g values under different hydrological conditions show great differences. During flood years, the average p_g values of water discharge in the QR and NR are 4.1 and 2.2, while in dry years, they are 10.4 and 4.1. The p_g of the water discharge in the QR in the dry year 2010 reached 16, while in the flood year 1967, the p_g was only 0.2. In terms of SSD, the p_g of the dry year 2010 exceeded 60, whereas that of the flood year 1979 was below 0.04 due to the high water discharges on normal days. This illustrates that TC-induced rainfall exerts relatively more influence on water discharge and SSD in dry periods than in wet periods. There are 2 main possible reasons for this. First, landcover in the river basin is of great importance to fluvial water discharge and SSD, especially for mountainous rivers such as the QR and NR, which are characterized by steep slopes. When heavy rainfall occurs, this large gradient combined with relatively sparsely vegetated land causes surface runoff and sediment rapidly to flow into the rivers. Sometimes, debris flows are even triggered (Milliman, 1995; Kale and Hire, 2004; Lin et al., 2008). Moreover, in dry years,

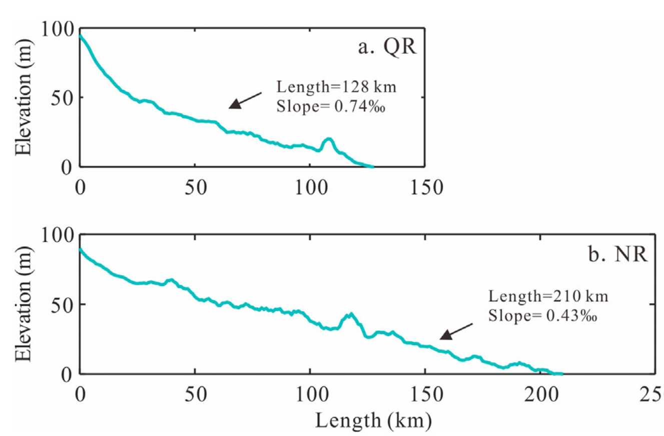

Fig. 13. Elevation of the mainstream in the QR and NR. The elevation of the mainstream was extracted based on the relative DEM data, and the slope was the ratio of the elevation to the river length.

surface soils are vulnerable to TC-associated rainfall and are prone to water and soil erosion. In the QR and NR, the p_g values of SSD in dry years are 74.2 and 33.5, while those in flood years are only 14.5 and 3.4. Second, the high (low) precipitation occurring on normal days also induces high (low) water discharge and SSD, which act as a background to weaken (enhance) the TC effect. For instance, the water discharge of TC days in flood year 1967 is slightly higher than the normal daily water discharge (150.5 m^3/s vs 130.0 m^3/s), so the effect of TCs appears to be insignificant. The situation is the opposite in 1978 and 1984. Meanwhile, according to the Cv values shown in the results, variations of daily water discharge and SSD in dry TC years are the greatest, and this is due to the low discharges of ordinary days, which magnifies the TC-associated discharges, thus magnifying the TC effect in dry periods compared to flood periods.

6. Conclusion

The water discharge and SSD of mountainous rivers have been greatly impacted by TCs, while few studies have focused on them. This paper detects the variations in the tropical cyclone-induced water discharge and SSD of the Qin and Nanliu Rivers, 2 mountainous rivers located in the north of the Beibu Gulf, and quantifies the contribution of tropical cyclones. The main findings are as follows:

(1) TC-induced daily water discharge in QR and NR during July and August are 9 and 4 times larger than those of non-TC days. TCs have generated considerable water discharges during a short period in the QR and NR.
(2) The net SSD increases in the QR and NR induced by TCs are 20 and 8 times those of normal days. High water discharge produces high SSD, but extremely high water discharge does not necessarily produce extremely high SSD in these two mountainous rivers.
(3) Daily water discharge and SSD of QR and NR are responsive to intense precipitation. The impacts of TC-induced rainfall on water discharge and SSD are restricted by the TC characteristics and basin environment. While TCs induced great variations in water and SSD of QR, large-scale river systems of NR buffer the TC power owing to the diversion of tributaries. The hydrological conditions of non-TC days play a background role that enhances or weakens the TC effect on water discharge and SSD.

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Declaration of competing interest

The authors declare that there is no conflicts of interest regarding this paper.

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