Impacts of climate change and human activities on the water discharge and sediment load of the Pearl River, southern China

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Abstract

In this study, long-term hydro-meteorological data from 1954 to 2018 from the Pearl River basin were used to investigate the impact of climate change and human activities on water discharge (WD) and sediment load (SL). The results revealed that the SL of the Pearl River exhibited a significant increasing trend at a rate of 1.38 × 104 t/yr from 1983 to 1988 and a significant decreasing trend at a rate of -2.24x104 t/yr from 1989 to 2018. WD exhibited a non-significant increasing trend of 0.3416x108 m3/yr during the entire period. The increasing trend of the SL can largely be attributed to exacerbated rocky desertification in the drainage basin, whereas the decreasing trend was mostly caused by an increase in the construction of dams and reservoirs. Mann-Kendall and double mass curve analyses revealed that a significant abrupt downward change occurred in the SL in 1998. However, the construction of dams and reservoirs in the Pearl River basin seems to have little influence on annual WD. The changes in annual WD were mainly caused by variations in precipitation. Although significant long-term changes in SL were detected, inter-annual fluctuations were found to be in good agreement with precipitation and WD data. Furthermore, El Nino/Southern Oscillation (ENSO) events are often associated with low precipitation, resulting in low WD and SL, indicating that changes in ENSO periodicity could affect the inter-annual periodic variations of WD and SL. Climate change and human activities contributed 63% and 37% to the increases in WD, respectively. The human-activities-induced decreases in SL were 1987 x 104 t/yr in the 1990s, 4143.17 x 104 t/yr in the 2000s, and 5259.83 x 104 t/yr in the 2010s. These results should serve as a reference for better resource management in the Pearl River basin.

1. Introduction

Water discharge (WD) and sediment load (SL) into the sea are dominant factors controlling beach processes, delta and estuarine evolution, and coastal zone ecological environments (Walling and Fang, 2003; Wang et al., 2011). Therefore, understanding variations of WD and SL from the rivers to estuaries and oceans has been set as one of the goals of the International Geosphere–Biosphere Programme and its core project, Land Ocean Interaction in the Coastal Zone (Syvitski et al., 2005). It has been concluded that climate change and human activities are the most important factors influencing riverine WD and SL (Syvitski et al., 2005; Walling, 2006; Milliman et al., 2008). Scientific, observations have indicated that the global surface temperature has increased by approximately 0.8 °C with a significant upward trend over the past 30 yr and a rate greater than 0.2 °C per decade (Hansen et al., 2006). Global annual precipitation has also increased significantly at a rate of approximately 0.2 mm/yr ($P < 0.001$) (Piao et al., 2007). This global climate change has influenced global and regional hydrological cycles (Easterling et al., 2000). Labat et al. (2004) estimated that global runoff could increase by 4% based on an increase in global temperature of 1°C. Additionaly, human activities, such as land use changes, freshwater extraction, and dam construction, have intensified over past several decades, often resulting in significant influences on river systems (Syvitski, 2005; Milliman et al., 2008). However, the causes for changes in WD and SL differ from river to river and vary over time. Therefore, it is necessary to expand and update knowledge regarding these influences for specific rivers, particularly large rivers, to aid in global and regional environmental management.

The Pearl River (PR) is the second largest river (after the Yangtze River) in China and the second largest river (after the Mekong River in Vietnam) that draining into the South China Sea in terms of annual WD. The Pearl River basin (PRB) covers the area ranging from 21.31° to 26.49° N and 102.14° to 115.53° E with a drainage area of 0.45 $\times$ 10^6 km^2 (Fig. 1). It covers a region of subtropical to tropical monsoon climates straddling the Tropic of Cancer. The Guangdong-Hong Kong-Macao Greater Bay Area, which is located in the Pearl River delta, is one of the most important economic centers in China. Base on the combined effects of climate change and human activities, the WD and SL of the PR have changed significantly over time. Many studies have been carried out to understand the variability of WD and SL of the PR (e.g. Dai et al., 2008; Zhang et al., 2008; Wu et al., 2012; Zhang et al., 2012; Liu et al., 2017; Wu et al., 2019). However, most of these studies have primarily focused on the influence of human activities or climate change impacts.

In the PR, similar to many other rivers, natural oscillations in the hydrological cycle and the processes influencing such oscillations must be distinguished before possible anthropogenic impacts can be analyzed accurately. For example, the El Niño/Southern Oscillation (ENSO) phenomenon in the tropical Pacific Ocean, which has been linked to climate anomalies and river flow worldwide (Dettinger et al., 2000; Ward et al., 2010), is one potential source of natural variability in the PRB. Additionally, as global climate conditions changed, the frequency of global ENSO events increased during the late 1970s (Lee and McPhaden, 2010). However, the effects of ENSO events on WD and SL in the PR have rarely been examined. Furthermore, the quantification of climatic and anthropogenic effects on WD and SL in the PRB have received little attention. This study, aimed to (1) provide updated estimates of WD and SL from the PR into the sea, (2) explore the influences of ENSO events on WD and SL, and (3) quantitatively analyze the contributions of climate change and human activities to changes in WD and SL at the basin scale. We believe this study will provide a better understanding of natural and anthropogenic contributions to major river water and sediment transport processes, which will provide scientific guidelines for global river management.

2. Data and Methods

2.1 Data

Hydrological data (monthly and annual WD and SL) covering a period from 1954 to 2018 were collected from the three main gauging stations of the Pearl River System, namly Gaoyao station on the West River, Shijiao station on the North River, and Boluo station on the East River (Fig. 1). The data were derived from the Bulletins of Chinese River Sediment. The selected stations are located at tidal limits and the relationship between water levels and WD downstream is influenced by tides. Therefore, the WD and SL of these three gauging stations represent the discharges from the PRB into the sea.

The monthly and annual precipitation over the entire PR drainage basin and various source areas are given in the form of area-weighted average values, which were calculated from data recorded at 42 rain gauges spread across the river basin. The timing and extent of human activity in the PRB, including dam construction and deforestation/afforestation, were extracted from the literature Dai et al. (2008), Zhang et al. (2008) and the database at*http://www.gxsw.gov.gn/html/index.html*.

ENSO events are closely linked to the patterns of flood and drought in different areas around the world (Glantz et al., 1991). They also strongly affect local- and regional-scale climates base on teleconnections affecting coupled ocean-atmosphere and land systems. In this study, we used the Southern Oscillation Index (SOI) as an indicator for the modes of ENSO cycles. Monthly sea surface temperature anomalies (SSTA) in the Niño 3.4 region and SOI values (1954 to2009) were collected from https://www.ncdc.noaa.gov/teleconnections/.

2.2 Methods

In this study, precipitation, WD, and SL trends from 1954 to 2018 were derived using linear regression analyses. The Mann–Kendall (M-K) test method and cumulative anomaly method were applied to detect any abrupt changes in annual precipitation, WD, and SL. The double mass curve method was used to estimate the relative effects of climate change and human activities on WD and SL in the basin.

2.3.1 Mann-Kendall test

The M-K test was originally proposed by Mann (1945) and later reformulated by Kendall (1975). It is widely used to identify the significance of trends and change points in hydro-meteorological time series (e.g. Hamed, 2008; Miao et al., 2011; Zhao et al., 2017; Wu et al., 2019). For a given time series $X = x_1 ,x_2 , \ldots, x_n$, the M-K test is defined as follows:

$Z_c = \{$

$$\begin{array}{ll} \frac{S-1}{\sqrt{\sigma}} & S > 0 \\ 0 & S = 0 \quad (1) \\ \frac{S+1}{\sqrt{\sigma}} & S < 0 \end{array}$$

where

$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)(2)$

$\mathrm{sgn}\,(\theta) = \{$

$$\begin{array}{ll} 1 & \theta > 0 \\ 0 & \theta = 0 \quad (3) \\ -1 & \theta < 0 \end{array}$$

$\sigma = \frac{n(n-1)(2n+5)-\sum_{i=1}^{n} t_i(i-1)(2i+5)}{18}(4)$

where x_i and x_j are sequential data values at times$i$and j $(i < j)$, respectively, n is the dataset length, t_i is the number of ties which an extent i , Z_c is the standardized test statistic value, and S is the test statistic. *Sgn()*is equal to 1 if x_j is greater thanx_i , -1 if x_i is less thanx_i , and 0 if x_i is equal to x_i . Positive and negative values ofZ_c indicate increasing and decreasing trends, respectively.

2.3.2 Cumulative anomaly curve

A cumulative curve (Bobrovitskaya et al., 2003) is calculated as follows:

$f\,(i) = \sum \left(x_i - x\right)(5)$

where x represents the mean value of a long time series.

2.3.3 Double mass curve

A double mass curve is a plot of the cumulated values of one variable against the cumulated values of another related variable over a concurrent period of time (Searcy and Hardison, 1960). Recently, the double mass curve has been a widely used method to identify the hydrological regime changes caused by anthropogenic disturbances (e.g. Zhang et al., 2008; Zhao et al., 2017; Wu et al., 2019). The theory behind the double mass curve method is that the plot of the two cumulative quantities exhibits a straight line for a concurrent period if the proportionality between the two variables is unchanged. A change in the slope of the double mass curve indicates that the original relationship between the two variables was broken. Thus, we used the double mass curve to estimate the relative effects of human activities and climate change on the annual WD and SL. When only influenced by climate variability the double mass curve is a straight line, whereas the inflection of the curve denotes when human activities began to significantly influence of WD or SL.

3. Result

3.1 Impact of climatic changes and human activities

3.1.1 Climatic changes

ENSO is a result of ocean-atmosphere interactions on a macro spatial scale and is treated as the strongest inter-annual signal of climatic changes. Numerous studies have shown that ENSO-driven changes in temperature and precipitation correlate well with mean annual and seasonal river discharge (e.g. Dettinger et al., 2000; Ward et al., 2010; Wanders and Wada, 2015). In the PRB, the average annual precipitation over the period of 1954 to 2018 was 1559 mm, and annual precipitation varied between 1120 mm and 1981 mm.

The warm phases of monthly SSTA were closely related to low precipitation in the PRB (Fig. 2). Large precipitation variations (>5%) were commonly associated with ENSO years, such as in 1958, 1963, 1966, 1982, 1991, 1995, 2003, 2009, and 2015. This is mainly due to the fact that changes in SST values stem from the equatorial Pacific Ocean trade winds, which feed moisture back into the atmosphere and eventually shift the pattern of regional precipitation in the PRB. Therefore, SSTA warm phases often result in low precipitation in the PRB. These results are consistent with those presented by Zhao et al. (2014). Based on continuous wavelet transform analysis, Zhao et al. (2014) confirmed that SOI is one of the main driving factors of precipitation variation in the PRB. Moreover, Niu (2013) found that the precipitation in the PRB and ENSO signals has significant statistical power and coherence within one to eight year bands.

Since the late 1970s, global ENSO events have become stronger and more frequent (Lee and McPhaden, 2010). Most of the low precipitation years in the PRB were closely associated with moderate and strong ENSO events (Fig. 2). Prior to1970s, the precipitation in the PRB had strong inter-annual variability (over 337 mm). However, inter-annual variations became milder as strong ENSO events occurred more frequently in subsequent years. The average annual precipitation in the river basin from 2000 to 2018 was only 1525 mm, which is approximately 11% less than that the 1990s. These correlations between ENSO events and lower regional precipitation indicate that regional precipitation is strongly affected by global climate systems.

Climate factors, particularly precipitation, can cause changes in WD and affect the variation in SL. Fig. 2 presents the WD trends for the PRB from 1954 to 2018 based on linear regression analysis. The mean annual WD from 1954 to 2018 varied from a minimum value of 1314×10^8 m^3 in 1963 to a maximum value of 4021×10^8 m^3 in 1994 with a mean value of 2825×10^8 m^3. There are no significant increasing trends in the WD time series. According to linear regression analysis, the annual rate of increase in WD is 0.3416×10^8 m^3/yr. When comparing WD to precipitation, it is clear that the fluctuations and tendencies of WD are consistent with variations in precipitation (Fig. 2). The correlation between cumulative annual precipitation and WD exhibits a linear trend for the entire PRB from1954 to 2018 (Fig. 3a). These results suggest that precipitation is the main explanatory variable for WD in the PR.

Figs. 4a and 4b present the results of M-K testing and accumulative anomaly curves for annual precipitation and WD, respectively. It is clear that the curves of precipitation and those of WD have similar phases and trends. According to the M-K test results and accumulative anomaly curves, an abrupt change in WD occured in 2002. Although they are less significant, 1967, 1983, 1992, and 2014 can also be identified as turning points in the WD trend. Note that these turning points largely coincide with global ENSO events. Additionally, the turning points indicate that there were three periods with decreasing trends (1954 to 1967, 1983 to 1992 and 2002 to 2014) and two periods with increasing trends (1968 to 1982 and 1993 to 2001). These findings match the perturbations in precipitation over the six decades studied. These results suggest that an increase or decrease in WD could be attributed to climate change and natural climatic oscillations (e.g., ENSO and SST). Fig. 5a also reveals that WD was consistent with precipitation during different decades and maintain synchronization, i.e., precipitation changes result in WD variability in the basin. Overall, precipitation changes have the largest influence on WD variations.

Regarding the annual SL, although large changing trends were detected from 1954 to 2018, inter-annual fluctuations were consistent with those of precipitation and WD (Fig. 2). Specifically, ENSO years often correspond to low precipitation, resulting in low WD and SL. For example, as shown in Fig. 2, strong ENSO events in 1963 and 2009 coincide with lower precipitation levels of 1138 mm/yr and 1374 mm/yr, respectively, which correspond to lower WD of 1314×10^8 m^3/yr and 2078×10^8 m^3/yr, and lower SL of 1782×10^4 t/yr and 1614×10^4 t/yr, respectively. These values are lower than the average decadal precipitation, WD, and SL values in the 1960s and 2000s, respectively. Furthermore, the inter-annual variations in precipitation, WD, and SL at time scales of two to eight years are consistent with the periodic variations of ENSO (Niu, 2013; Liu et al., 2017). This linkage indicate that changes in ENSO periodicity can affect inter-annual periodic variations in WD and SL. Similar results were also found in Columbia River, Mekong River, Yellow River and Yangtze River (Naik and Jay, 2011; Xue et al., 2011; Wang et al., 2006; Zhao et al., 2015).

The M-K abruptness test and cumulative anomaly test revealed an abrupt change in SL in 1998 (Fig. 4c). The time series for SL can be divided into three phases (a linear phase, increasing phase, and decreasing phase) with turning points in 1982 and 1988 (Fig. 3b). Prior to 1982 (linear phase), the cumulative precipitation and SL are well correlated, and precipitation and SL exhibit a significant relationship. During the periods of 1983 to 1988 and 1989 to 2018, SL exhibits a significant increasing and deceasing trends, respectively regardless of precipitation and WD. Fig. 5b also reveals that for the same level of precipitation, the SL increase from 1983 to 1988 and gradually decrease during the periods of 1989 to 1998, 1999 to 2006, and 2007 to 2018. The linear regression equations for annual SL suggest a rate of increase of 1.38×10^4 t/yr from 1983 to 1988 and a rate of decrease of 2.24×10^4 t/yr from 1989 to 2018. These opposing trends, which independent of precipitation and WD, suggest that there are external controlling mechanisms influencing SL in addition to natural climate change.

3.1.2 Human activities

The human activities affecting WD and SL include land use change and dam construction (Yang et al., 2002; Walling, 2006). Typically, soil and water loss induced by deforestation results in an increased SL. In contrast, afforestation, soil preservation, and dam construction result in reduced SL. When both positive and negative influences on SL occur in the same period of time, the magnitude of the measurable change in SL depends on the relative balance the two types of factors.

As mentioned previously, the time series of SL in the PR can be divided into three phases. In the first phase (prior to 1982), the SL exhibits no clear changes. This is mainly caused by the balance between deforestation and dam construction. According to Yang et al. (2002), after the end of two major wars (the Second World War and National Liberation War), China entered a period of peace, which resulted in rapid increases in population and deforestation. As a result, soil erosion in the PRB accelerated. Therefore, although dam construction on the PR began in the 1960s, the decreasing effect of dam construction on SL did not outweigh the increasing effect of deforestation. In the second phase from 1983 to 1988, there was a significant increase in SL. The regression relationships indicate that the SL between 1983 and 1988 was approximately 30% higher than that between 1954 and 1982. This trend is mainly caused by the acceleration of soil erosion. At the end of the 1970s, China implemented in a program of agricultural and economic reform. Land was distributed to peasants and crop planting increased significantly, which accelerated deforestation. According to Zhang et al. (2008) and Dai et al. (2008), the total land area suffering from rock desertification in the PRB was 48,650 km^2 (11.0% of the total drainage area). However, dam construction in the PRB slowed in the 1980s (Wu et al., 2012). Therefore, we can conclude that deforestation exceeded dam construction in the 1980s, resulting in an increase in SL. In the third phase from 1989 to 2018, the SL decreased dramatically. This variation was caused by efforts to rehabilitate rocky desertified areas. The Soil Preservation Law of the Republic of China was enacted in 1991. Since then, many water and soil conservation projects have been carried out to prevent soil erosion. It has been suggested that during 1990s, the area of land erosion in the PRB decreased by 23% (Zhang et al., 2012). However, variations can also be attributed to an increase in large dam construction. The total storage capacity of reservoirs in the PRB sharply increased after the 1980s and reached a maximum of approximately 75×10^9 m^3 in the 2010s (Wu et al., 2019). Similarly, it has been reported that soil preservation is the second most important factor for decreasing SL in the Yangtze River (Yang et al., 2006; Zhao et al, 2015) and Yellow River (Wang et al., 2006; Miao et al., 2011) following dam construction.

China has been particularly active in dam and reservoir construction since its liberation movement and now contains more than half of the world's large dams and reservoirs (Xu and Milliman, 2009). In the PRB, over 9000 dams and reservoirs have been constructed since the 1950s. Fig. 6 presents the main large reservoirs with storage capacities exceeding 10^8 m^3, all of which are scattered across the PRB. The total storage capacity of reservoirs in the PRB was estimated to be approximately $75 \times 10^9 m^3$ in the 2010s, which is 27% of the multi-annual mean discharge of the PR (Wu et al., 2019). This value can be compared to the findings of Vörösmarty et al. (2003), who determined that more than 40% of global river discharge is intercepted by large reservoirs. From the 1960s to the 1990s, the total storage capacity of the PRB increased slowly, followed by a boom in dam reservoir constructions after the 1990s (Fig. 7a). Based on this change, the sediment has load decreased significantly since late the 1990s (Figs. 5b and 7d) as large amounts of sediment have been trapped in reservoirs.

From Fig. 3b, one can see that the double mass curve of SL has two notable turning points at approximately 1998 and 2006, which are closely related to the construction of reservoirs in the basin. In 1999, the SL decreased by one third following construction of the TD, YD, and FD. In 2007, the SL decreased to 15.08×10^4 t/yr, which is approximately 19% of the 1954 to 1979 reference level, based on the construction of the LD (the largest dam in the PR, constructed in 2006 with a storage capacity of $29.9 \times 10^9 \mathrm{m}^3$). As mentioned previously, various water and soil conservation projects have been implemented to stop the expansion of soil erosion in the PRB since the 1990s. Since then, dam and reservoir constructions have begun to play a dominant role in SL reduction.

In the PRB, reservoirs typically impound water during the latter half of the wet season (decreasing trend in discharge from August to November) and release water during the driest months (increasing trend in discharge in January and February) to satisfy the demands of agricultural irrigation. Based on the seasonal regulation of reservoir water storage in the PRB, the ratios of flood discharge to annual discharge have exhibited a significant decreasing trend over the past 65 y (Fig. 7a). For example, measured WD during flood seasons accounted for more than 70% of the annual WD in the 1950s, but this value decreased to 60% in the 2010s.

Fig. 8 presents multiyear averages of monthly precipitation, WD, and SL in different periods based on abrupt changes in SL. Seasonally, the monthly precipitation and WD of the PR are the highest in June and lowest in December and January (Figs. 8a and 8b). These extreme monthly values occur approximately month earlier than the corresponding values for the Yangtze River (Zhao et al., 2015). This is likely because the PRB is closer to the ocean (South China Sea) compared to the Yangtze River basin. Therefore, in summer, the southwesterly monsoon winds should transport vapor to the PRB earlier than to the Yangtze River basin. Monthly precipitation and WD exhibit no significant changes between the pre-abrupt and post-abrupt periods in the PRB (Figs. 8a and 8b). However, the SL exhibits a significant difference. The SL in the post-abrupt period is lower than in the pre-abrupt period, with the largest difference occurring in summer (Fig. 8c). This change is a result of dam construction. Furthermore, the SL in winter in the post-abrupt period is greater than that in the pre-abrupt period. This result is largely caused by the seasonal regulation of reservoir water storage.

3.2 Quantitative hydrological responses to climate change and human activities

From Fig. 3, one can see that the WD and SL exhibit no obvious changes prior to 1960. Furthermore, the first large dam in the PRB was constructed in 1960 (Fig. 6). Accordingly, it can be assumed that the effects of human activities were negligible prior to the 1960s. Therefore, the period from 1954 to 1960 can be used as a benchmark period to quantify the influences of climate change on WD and SL variation. Here, we applied the linear regression method to establish annual WD and SL responses to climate change based on precipitation data for the PRB. The linear regression equations between the precipitation data and both WD (6) and SL (7), as well as their significance levels, are presented below.

$y = 1.96x - 281 \ \left(R^2 = 0.96\ P < 0.01\right)$ (6)

$y = 8.32x - 5110\ (R^2 = 0.86\ P < 0.01)$ (7)

These equations were used to predict WD and SL in response to climate change, where differences between predicted and observed data were assumed to reflect human impacts.

Fig. 9 presents the baseline data, reconstructed data, and observed data for WD and SL in the PRB. Regarding WD, the predicted annual values are in agreement with the observed data in terms of extreme values throughout the period of observation (Fig. 9a), which indicates that the inter-annual fluctuation of WD in the PR is ultimately controlled by climate change. Regarding SL, the predicted annual values are in good agreement with the measured data prior to 1998 (Fig. 9b), which also suggests that inter-annual fluctuations in SL are dominated by climate change. Since 1999, although the measured values of SL are lower than the observed values, the inter-annual fluctuations are still in phase with those of the predicted SL, which indicates that the impact of climate change has been significant during the post-dam period.

Table 1 lists the decadal variations in mean annual precipitation, mean annual WD, and mean annual SL, as well the percentage differences with respect to the baseline values. One can see that both the reconstructed WD and reconstructed SL values are close to the observed data for the baseline periods, which supports the simulated values obtained for the 1960s to 2010s. During the 1960s to 1970s and 1990s to 2000s, precipitation increased in the PRB, which directly increased the predicted WD and SL. This is especially true for the 1990s, when WD exhibited the largest increase. The observed and predicted values of WD and SL increased by 14% and 12%, respectively, during this period. During the 1980s and 2010s, decadal precipitation decreased in drainage areas, which had a positive effect on the generation of runoff, which directly increased the reconstructed WD and SL data. However, for the 1980s, based on the acceleration of soil erosion, the observed values are significantly higher than the predicted values for SL. For the 1990s to 2010s, the observed values are significantly lower than the predicted values of SL based on soil preservation efforts and large dam constructions in the PRB, such as the TD, YD, FD, LD, and BD.

Table 2 summarizes the contributions of climate change and human activities to changes in WD and SL during different periods. Regarding WD, the greatest change occurred during the 1990s, where the value increased by 366.21×10^8 m^3/yr relative to the baseline. Climate change and human activities contributed 91% and 9% of this increase, respectively. The most significant impacts of human activity on WD occurred in the 2000s, where the contribution of human activities to water reduction was 164%. Generally, in the PRB, climate change contributes much more to hydrological factors, regardless of whether its effects are negative or positive. As shown in Table 2, from the 1960s to 2000s, climate change and human activities contributed 63% and 37% to the reduction in WD, respectively. Regarding SL, the greatest increase occurred in the 1980s, where the value increased by 1192.94×10^4 t/yr relative to the baseline. The contribution of human activities to this increase was 124%. SL decreased from the 1990s to 2010s. The SL decrease caused by human activities was 1987×10^4 t/yr in the 1990s, 4143.17×10^4 t/yr in the 2000s, and 5259.83×10^4 t/yr in the 2010s. The contribution of human activities also increased from 98% to 479%, with the most obvious increase occurring in the 1990s. Over the entire study period, the decreases in total SL in the PR caused by climate change and human activities were -347.07 x 10^4 (-34%) and 1379.12 x 10^4 t/yr (+134%), respectively. These results suggest that the impact of human activities on SL exceeds that of climate change, meaning human activities play a dominant role in terms of sediment change.

4. Discussion

Variations in precipitation regimes in both space and time can significantly influence the spatiotemporal distributions of water resources and result in either severe flooding or drought. In addition to strong ENSO events that have significant impacts on regional precipitation in the PRB, other global climate changes and large-scale ocean-atmosphere processes, such as Pacific Decadal oscillation (PDO), Indian Ocean dipole (IOD), and North Atlantic oscillation (NAO), also influence the hydrological cycle of the PR. The inter-annual relationships between ENSO and global climate changes are non-stationary and PDO, which is a largely interdecadal oscillation, can modulate inter-annual ENSO-related teleconnections (Krishnan and Sugi, 2003; Wang et al., 2008). The in-phase/out-of-phase relationships between ENSO and PDO typically have distinct effects on precipitation and streamflow in different regions. Regarding summer monsoons in south China, when the ENSO and PDO are in-phase, the early (May and June) summer monsoon rainfall over South China (SCMR) tends to be below or above average. In contrast, when the ENSO and PDO are out-of-phase, the SCMR shows no wet or dry preference (Chan and Zhou, 2005). Such relationships appear to be related to the intensity of subtropical factors based on the superposition of the effects of ENSO and PDO. Using continuous wavelet transform analysis, Zhao et al. (2014) determined that the return period of the extreme precipitation is very consistent with PDO in the PRB. Overall, PDO is one of the most important factors influencing precipitation. Based on such oceanic-atmospheric oscillations, the inter-annual variation of WD in the PRB is highly complex.

Riverine sediment discharge into the sea has been a topic of global concern in recent years. Knowledge regarding sediment flux is of great significance not only for determining the accuracy of multi-year river sediment data, but also for understanding the evolution of deltas and estuaries, as well as coastal environments (Yang et al., 2002). As shown in Fig. 2, over the past two decades, the SL in the PR has decreased dramatically. This variation can be attributed to the construction of large dams. Since the beginning of the 1990s, dam construction in the PRB has accelerated significantly. The total storage capacity of reservoirs increased sharply and nearly tripled in the 2000s when compared to the capacity in the 1980s (Fig. 7a). Dramatic decreases in sediment discharge accelerate delta and shoreline recession, which has been observed in many deltas, such as the Nile River delta (Fanos, 1995), Ebro River delta (Mikhailova, 2003), Red River delta (Dang et al., 2010), Mekong River delta (Xue et al., 2011), Yellow River delta (Yu et al., 2011), and Yangtze River delta (Yang et al., 2006). Therefore, it is reasonable to conclude that anthropogenic impacts on WD and SL have changed the evolutional pattern of the Pearl River delta and its coast. Recently, a deceleration of the delta growth rate has been reported in the Pearl River delta, although the general trend is still prograding (Wu et al., 2018). Most river outlets began eroding in the 1990s to 2000s, rather than silting up as they had previously (Zhang et al., 2015). Although there are other factors contributing to these changes, such as in-channel sediment mining and unreasonable coastal construction, the decline of SL is a dominant factor. Furthermore, given the large number of reservoirs in the PRB and their enormous storage capacity, the SL in the main river is expected to remain low on a century timescale (Dai et al., 2008; Wu et al, 2012). Therefore, in future scientific research and management projects, increased attention must be paid to the long-term effects of a reduction in sediment flux on environmental changes. Furthermore, the remarkable variation in SL in the PR combined with nearly unchanged levels of WD (Fig. 2) is also a good example of the effects that human activities can have on a river system.

5. Conclusions

In this study, WD and SL in the PR were investigated based on long-term hydro-meteorological data from 1954 to 2018. The M-K test and double mass curve analysis were used to detect trends and abrupt change points in WD and SL, and to quantify the effects of climate change and human activities on WD and SL. The main conclusions of this study are as follows:

(1) The annual WD in the PRB exhibited a non-significant increasing trend of 0.3416 x 10^8 m^3/yr during the period from 1954 to 2018. This change was mainly controlled by variations in precipitation. One abrupt change occurred in 2002. In contract, the SL exhibited a natural phase (1954 to 1982), increasing phase (1983 to 1988) at a rate of 1.38 x10^4 t/yr, and significant decreasing phase (1989 to 2018) a rate of -2.24 x10^4 t/yr. The increasing phase can be attributed to exacerbated rocky desertification in the drainage basin, whereas the decreasing phase was mainly caused by a boom in dam and reservoir construction. A significant abrupt downward change in SL occurred in 1998.

(2) Although long-term changing trends in SL were detected, its inter-annual fluctuations were consistent with those of precipitation and WD. Furthermore, ENSO events often corresponded to low precipitation, resulting in low WD and SL, indicating that changes in ENSO periodicity could affect inter-annual periodic variations in WD and SL.

(3) WD is largely influenced by climate change, whereas human activities exert a dominant influence on changes in SL. Specifically, climate change and human activities are responsible for 63% and 37% of the increases in WD, respectively. The decreases in SL caused by human activities were 1987 x 10^4 t/yr in the 1990s, 4143.17 x 10^4 t/yr in the 2000s, and 5259.83 x 10^4 t/yr in the 2010s. The contributions of human activities also varied from 98% to 479%, with the most obvious contribution occurring in the 1990s. Decreases in sediment supply from the PR should receive special attention because they may have serious impacts on the delta and coastal ocean.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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