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1 **Recent changes of water discharge and sediment load in the Yellow River basin, China**

2
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9
10 **Abstract:** The Yellow River basin contributes about 6% of the total river sediment load in the
11 world. Recent variations in water discharge and sediment load of the Yellow River basin are
12 important, as its annual runoff directly supports 12% of the Chinese population. The present study
13 considers the annual hydrologic series of water discharge and sediment load of the Yellow River
14 basin obtained from 15 gauging stations (10 mainstream, 5 tributaries). The Mann-Kendall test is
15 used to detect both gradual trends and abrupt changes in the hydrological series since the 1950s.
16 The results show, except for the area draining to the Upper Tangnaihai station, that both water
17 discharge and sediment load have decreased significantly ($p < 0.05$). These trends intensify in the
18 downstream direction. The drainage area is strongly correlated with the rates of decline. Abrupt
19 changes in river discharge occurred in a period lasting from the late 1980s to the early 1990s
20 because of the increased abstraction of water for human consumption. The sediment load also
21 experienced disruption due to the construction and operation of several large reservoirs.

22
23 **Keywords:** Yellow River; water discharge; sediment load; climate change; human activity;
24 reservoir

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26 **1. Introduction**

27 The hydrologic cycle describes processes that contribute to the upland source, and the yield
28 of water and sediment resources as they flow through the fluvial system (Julien, 2002). As a
29 complicated, sensitive and fragile system, the hydrological cycle reflects the interaction of the
30 hydrosphere, atmosphere, lithosphere and biosphere. In the hydrologic cycle, water discharge and
31 sediment flux are the two most important components, whose changes directly affect the fluvial
32 estuarine, and coastal shelf environment (Zhang et al., 2008). River morphology depends on
33 temporal and spatial variations in water discharge, the relationship between sediment load and the
34 sediment-transport capacity of the flow. Examples of rivers whose morphology is changing
35 include the Burdekin River in Australia (Amos et al., 2004), Ben River in Bolivia (Gautier et al.,
36 2007), Rhone River in France (Petit et al., 1996; Arnaud-Fassetta, 2003), Wisloka River in
37 southern Poland (Wyzga, 1997), Cache Creek and Stony Creek in California, USA (Collins and
38 Dunne, 1990; Kondolf, 1997) and the Yangtze and Yellow River in China (Chen et al., 2001a;
39 Saito et al., 2001; Zhang et al., 2006a; Xu, 2006).

40 The water discharge and sediment flux from river systems provide humans with water
41 resources, renewable energy, fertile soil, etc. However, excessive changes to the water discharge
42 and sediment flux threaten the eco-environment and can have disastrous socio-economic
43 consequences through more frequent and intense droughts and floods, water eutrophication, the
44 raising of the riverbed, and spreading of the river delta. Researchers have come to view
45 understanding both river flows and sediment transport as crucial, especially in relation to climate
46 variability and human activities (e.g. Lettenmaier et al., 1994; Burn and Elnur, 2002; Kahya and
47 Kalayci, 2004; Wang et al., 2006a; Zhang et al., 2006a). In the latter half of the 20th century, global

48 change resulting from human activities has intensified at an increasing rate, gradually altering
49 global river systems, such that hydrologic changes are receiving greater attention.

50 In ancient times, China's emperors attempted to control rivers, and dynasties were
51 remembered as being "good" or "bad" depending on whether or not they succeeded in the struggle
52 to harness water and sediment transport in large rivers (Julien, 2002). It is likely that large-scale
53 water-sediment management commenced with the Chinese hero Yu (2205~2198 B.C.), who was
54 selected to be the emperor of China because of his talent at constructing flood countermeasures
55 such as dams, dikes, and river training (Dudgeon, 2000). The Yellow River is fundamentally
56 important to Chinese civilization, due to the very long history of human activities along its middle
57 and lower reaches (Xu and Ma, 2009). The Yellow River is notable for its relatively small water
58 discharge and huge sediment load. Although its mean annual discharge is only about 0.7% that of
59 the Amazon (the largest river in the world) and 4.5% of the Yangtze (the largest river in China),
60 the annual sediment load of the Yellow River almost equals that of the Amazon and is more than
61 twice that of the Yangtze. Wang et al. (2007) calculate that sediment from the Yellow River basin
62 contributes about 6% of the total global river load to the oceans. Frequent changes in sediment
63 flux have caused switches between recession and growth of deltaic coastlines (Ren and Shi, 1986),
64 and in turn influence the form of river deltas. Figure 1 compares the Yellow River delta with the
65 bird's foot delta of the Mississippi River. On the other hand, although the annual runoff of the
66 Yellow River basin is only about 2% that of China's total runoff, the Yellow River directly
67 supports 12% of the national population (mostly farmers and rural people) and supplies water to
68 15% of the irrigation area of China, and contributes to 9% of China's GDP (YRCC, 2009). In
69 addition, catastrophic floods and droughts have occurred many times in the Yellow River basin

70 throughout history, leading to enormous cumulative losses of life and damage to property (Hu et
71 al., 1998). In the Yellow River, the sediment load and water discharge are characterized by large
72 spatial and temporal variations, which are interpreted in the present paper in the context of global
73 climate change and intensive regional human activity.

74 Previous studies have shown that the hydrologic cycle has changed over interannual and
75 decadal scales (Hu and Feng, 2001), and that the discharges in the headwater of Yellow River
76 (Zheng et al., 2009), middle Yellow River (Xu, 2005), lower Yellow River (Wu et al., 2008) and
77 water fluxes to the sea (Wang et al., 2006a) have all declined significantly since the 1970s. This
78 has resulted in a progressive increase in water stress along the downstream reaches of the Yellow
79 River (Vörösmarty et al., 2000; Xu et al., 2008). Meanwhile, there has also been a decline in
80 sediment load that can be correlated with a similar decline in water discharge (Wang et al., 2006b).
81 Although many publications have discussed the changes of river delivery in the Yellow River
82 (especially in the Chinese literature), these were based on limited hydrological data acquired over
83 the latter half of the 20th Century from a few hydrologic gauging stations, mainly located along the
84 lower Yellow River rather than the whole Yellow River. As a consequence, the factors that
85 influence changes in water discharge and sediment load in the whole Yellow River were not fully
86 discussed.

87 The goal of the present work is to examine recent changes, both gradual and abrupt, in water
88 discharge and sediment load for the whole Yellow River basin from the 1950s to the 2000s
89 (primarily 1956 to 2007). Natural and anthropogenic factors are identified and their potential
90 impacts discussed.

91 **2. The Yellow River basin**

92 The Yellow River is the second-longest river in China, and is located between 96°~119° E
93 longitude and 32°~42° N latitude. Its catchment area occupies about 753,000 km², and the length
94 of the main river channel is about 5,464 km (Figure 2). The river originates in the Tibetan plateau.
95 It then flows through the semi-arid region of north China, the Loess Plateau, and the eastern plain,
96 before discharging into the Pacific Ocean (Xu and Ma, 2009). In 2000, the population within the
97 drainage area was about 110 million. The catchment consists of 12.6 million ha of farmland, of
98 which 40% is under irrigation, with the Yellow River supplying the water (Xia et al., 2002).

99 As indicated in Table 1, the Yellow River basin is usually divided by its physical
100 characteristics into three water source areas: upper (above Hekou), middle (between Hekou and
101 Huayuankou); and lower (below Huayuankou) reaches (see e.g. Yang et al., 2004; Wang et al.,
102 2007) (Table 1).

103

104 **Table 1**

105

106 **3. Data and methods**

107 **3.1 Data**

108 In the present study, hydrologic data from the 15 gauging stations listed in Table 2 are
109 analyzed to investigate changes in water discharge and sediment load. Ten stations (at Tangnaihai,
110 Lanzhou, Shizuishan, Hekou, Longmen, Sanmenxia, Huayuankou, Gaocun, Aishan, and Lijin) are
111 located along the main stem of the Yellow River. The remaining five stations (at Jingyuan,
112 Huangfu, Baijiachuan, Zhuangtou, and Huaxian) are situated at major tributaries of the Yellow
113 River basin. Being spatially well distributed, the data from these stations reflect hydrologic

114 changes occurring in the upper, middle, and lower reaches of the Yellow River. The observed
115 series cover the period from 1956 to 2007. [Figure 2](#) and [Table 2](#) provide information on the station
116 locations, associated drainage area, annual mean water discharge, and annual mean sediment load
117 over the entire period of observations. The Yellow River Water Conservancy Commission (YRCC)
118 supplied the data acquired before 2000. The data since 2000 were extracted from the China Water
119 Resources Bulletin (Ministry of Water Resources, MWR).

120 The precipitation data come from two sources. The annual regional precipitation series from
121 1956 to 2000 were interpolated from data from 175 meteorological stations, provided by the
122 National Meteorological Information Center, China Meteorological Administration. [Figure 2](#)
123 shows the locations of these stations in and around the Yellow River basin. Data on annual
124 regional precipitation after 2000 were taken from the China Water Resources Bulletin (Ministry of
125 Water Resources, MWR). However, the Bulletin (2001~2007) only provides information on the
126 annual precipitation in the drainage areas above Tangnaihai, Lanzhou, Hekou, Longmen,
127 Sanmenxia, Huayuankou and Lijin stations, and so it is only possible to discuss the influence of
128 precipitation (from 1956 to 2007) on the water discharge and sediment load in these areas.

129

130

Table 2

131

Figure 2

132

133 **3.2 Methodology**

134 The non-parametric Mann-Kendall test (MK), originally proposed by Mann ([1945](#)) and later
135 reformulated by Kendall ([1948](#)), is used to detect changes in the data. This test has the advantage

136 of not assuming any distribution form for the data and has similar order of accuracy as its
 137 parametric competitors (Serrano et al., 1999). Consequently, the MK test has been strongly
 138 recommended by the World Meteorological Organization for general use (Mitchell et al., 1966).
 139 Besides application to climatic time series, the MK test has been widely used to evaluate
 140 statistically monotonic trends (see e.g. Xu et al., 2004c; Zhang et al., 2008; Chen et al., 2009) and
 141 abrupt changes (see e.g. Zhang et al., 2006a, 2006b; Zhao et al., 2008) in hydrological series.

142 (1) Mann-Kendall test for monotonic trend

143 The Mann-Kendall test for monotonic trend is given as follows:

$$144 \quad Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & , S > 0 \\ 0 & , S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & , S < 0 \end{cases} \quad (1)$$

145 where

$$146 \quad S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (2)$$

$$147 \quad \text{sgn}(\theta) = \begin{cases} 1 & , \theta > 0 \\ 0 & , \theta = 0 \\ -1 & , \theta < 0 \end{cases} \quad (3)$$

$$148 \quad \text{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right]}{18} \quad (4)$$

149 in which x_i and x_j are the sequential data values at times i and j respectively, provided $j > i$, n is the
 150 length of the time series, q is the number of tied groups, t_p is the p th group and \sum denotes
 151 summation over all ties (Gilbert, 1987; Xu et al., 2007). A positive (or negative) value of Z
 152 indicates an upward (or downward) trend. The magnitude of trend slope can be also calculated as:

153
$$Slope = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad (5)$$

154 where a positive (negative) value of *Slope* indicates an upward (downward) trend, i.e. increasing
 155 (decreasing) values with time.

156 The null hypothesis (H_0) is no trend ($Slope=0$). The H_0 is accepted if $-Z_{1-\alpha/2} \leq Z \leq Z_{1-\alpha/2}$,
 157 where α is the significance level of the test. Here, a typical confidence level of 95% (i.e. $p = 0.05$)
 158 was used.

159 (2) Mann-Kendall test for abrupt change

160 A sequential version of the original Mann-Kendall test (also called the
 161 Mann-Kendall-Sneyers test) proposed by Sneyers (1975), is used to determine abrupt changes in a
 162 data series. For a time series (x_1, x_2, \dots, x_n), the null hypothesis is as follows: the sample under
 163 investigation shows no evidence of a developing trend. The following test is performed to prove or
 164 disprove the hypothesis, based on the rank series r of the progressive and retrograde rows of the
 165 sample. First, the MK test statistic, d_k is calculated from:

166
$$d_k = \sum_{i=1}^k r_i \quad (2 \leq k \leq n) \quad (6)$$

167 where

168
$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases} \quad (j=1, 2, \dots, i) \quad (7)$$

169 Presuming that the series is random and independent, the statistic d_k is normally distributed
 170 with expected value $E[d_k]$ and variance $Var[d_k]$ given as follows:

171
$$E[d_k] = \frac{n(n-1)}{4} \quad (8)$$

172 and

173
$$Var[d_k] = \frac{n(n-1)(2n+5)}{72} \quad (9)$$

174 Hence, the statistical index Z_k is determined from:

175
$$Z_k = \frac{d_k - E[d_k]}{\sqrt{Var[d_k]}} \quad (k = 1, 2, 3, \dots, n) \quad (10)$$

176 Here, Z_k follows the standard normal distribution. Unlike the original MK test which calculates the
 177 above statistical variables only once for the whole sample, in the modified MK test the
 178 corresponding rank series for the retrograde rows are also obtained for the inverse series ($x_n,$
 179 x_{n-1}, \dots, x_1). Using the same procedure as listed in Eqs. (6) ~ (10), the statistical variables, $d_k, E[d_k],$
 180 $Var[d_k]$ and Z_k are calculated for the inverse series. The Z values calculated via progressive and
 181 retrograde series are named Z_1 and Z_2 . If the intersection point of the two lines, Z_1 and Z_2 lies
 182 between the two confidence lines (with the confidence level set at 95% in the present research), it
 183 is judged that an abrupt change has taken place at that point (Demaree and Nicolis, 1990; Moraes
 184 et al., 1998).

185

186 3.3 Preliminary data analysis

187 The Mann-Kendall test assumes that the series is independent (Yue and Wang, 2004).
 188 However, hydrologic series are often autocorrelated due to coherence and inertial effects from
 189 their influence factors (such as precipitation and human activities). The effective sample size is
 190 reduced because of the existing autocorrelation, and this affects the outcomes of the MK test. The
 191 autocorrelation coefficient r_k between the hydrologic time series and the same series lagged by k
 192 time steps is given by:

193
$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (11)$$

194 where k is the number of lagged time steps, n is the length of hydrologic series, x_i is the i th value in the
 195 series, and \bar{x} is the overall average value . The critical value of r_k for a given significance level
 196 (e.g., 95%) is calculated as follows (Salas et al., 1980) :

197
$$r_k(95\%) = \frac{-1 \pm \sqrt{n-k-1}}{n-k} \quad (12)$$

198 Table 3 lists the results of the autocorrelation test. Free pre-whitening (Yue and Wang, 2002)
 199 was applied to the hydrologic series with significant autocorrelation in order to eliminate the effect
 200 of serial correlation.

201

202 **Table 3**

203

204

205 **4. Results**

206 **4.1 Trend analysis**

207 Table 4 summarizes the results obtained using the Mann-Kendall trend analysis test applied
 208 to the water discharge and sediment load series for the Yellow River basin. All the water discharge
 209 series present a downward trend. Except for the series at Tangnaihαι, the downward trends of all
 210 the other water discharge series are significant at the 95% confidence level (with two series at the
 211 95% level, and twelve series at the 99% level). For the sediment load series, although no trend was
 212 detected at Tangnaihαι, all the other stations show significant downward trends with 95%

213 confidence level (again with two series at the 95% level, and twelve series at the 99% level).

214 The absolute value of slope during the MK test reflects the local rate of change of the
215 variables being analyzed. Looking at the results in Table 4, it can be seen that the declining trend
216 of water discharge series steepens in the downstream direction. The rate of decline (or slope)
217 grows from about $-0.07 \times 10^9 \text{ m}^3/\text{yr}$ at Tangnaihai to about $-0.81 \times 10^9 \text{ m}^3/\text{yr}$ at Lijin. Although the
218 changes in the sediment load series present relatively similar characteristic behaviour to that of the
219 water discharge along the main course, the greatest reduction occurs at Huayuankou at a rate of
220 $-28 \times 10^6 \text{ ton/yr}$. Figure 3 plots the slopes of water discharge change and sediment load change
221 against drainage area. From Figure 3, it can be seen that for both water discharge and sediment
222 transport in the Yellow River, there is a strong correlation with drainage area.

223

224 **Table 4**

225 **Figure 3**

226 Table 5 presents the decadal changes in the water discharge and sediment load. These are
227 obtained by comparing the decadal mean values with reference mean values over the period from
228 the start of the series in the mid 1950s (the exact date depending on the data availability) to 1969.
229 Unlike the other stations, the annual mean water discharge series at Tangnaihai during the 1970s
230 and 1980s increased in magnitude, with respect to the reference mean value. The annual sediment
231 load series at Tangnaihai increased in the 1970s, 1980s, and 1990s, but fell in the 2000s. The
232 maximum change at Tangnaihai occurred in the 1980s. Lijin (which is located close to the mouth
233 of the Yellow River) experienced the greatest decline in water discharge, with the annual mean
234 water discharges reducing by 70.74% during the period from 2000 to 2007 compared with the

235 overall mean value for the period from 1956 to 1969. The largest decline in sediment load occurred
236 at Huayuankou, with its annual mean sediment load dropping by over 90% in the period from
237 2000 to 2007 compared with the reference value. This is mainly due to the Xiaolangdi reservoir
238 becoming operational during the early 2000s. In terms of percentages, the proportional reduction
239 in sediment load is generally larger than that of the water discharge from the 1980s onwards.

240

241 **Table 5**

242

243 **4.2 Abrupt change analysis**

244 Table 6 shows the results of the Mann-Kendall test for abrupt changes to the hydrologic
245 series. Here, the single most abrupt change is identified, and the year in which it occurs denoted
246 by T. No significant abrupt changes are detected in the water discharge series at Huangfu and in
247 the sediment load series at Longmen. For the annual water discharge series at stations located
248 along the main stem of the river, the MK test indicates that abrupt changes occurred in the late
249 1980s and early 1990s. These abrupt changes in annual water discharge follow an antedated trend
250 in the downstream direction. However, the years during which abrupt changes occur in the annual
251 sediment load series do not display any obvious correlation with the corresponding values for the
252 water discharge series. At Lijin, abrupt changes in water discharge and sediment load occur at
253 1985 and 1990 respectively (Figure 4). In this case, the mean values of the annual water discharge
254 and sediment load series averaged over the period before the abrupt changes occurred are
255 $40.10 \times 10^9 \text{ m}^3/\text{yr}$ and $935 \times 10^6 \text{ t/yr}$, respectively. The corresponding mean values of the annual
256 water discharge and sediment load series averaged over the period after the abrupt changes

257 occurred reduce to about $14.73 \times 10^9 \text{ m}^3/\text{yr}$ and $284 \times 10^6 \text{ t/yr}$, respectively. Table 6 lists the
258 differences between the pre-T and post-T series at all stations. Although most of the abrupt
259 changes for the water discharge appear to have occurred during the late 1980s and early 1990s,
260 this is not the case for the sediment load series. Of the 15 hydrologic series, the most significant
261 difference in water discharge before and after the abrupt change occurs at Lijin where the mean
262 annual value has reduced by 63.27%. The greatest difference in sediment load appears at
263 Zhuangtou where the mean annual load has decreased by 82.41%. In general, the percentage
264 change in the average sediment load over the pre-T and post-T is larger than that of corresponding
265 annual water discharge series.

266

267

Figure 4

268

Table 6

269

270 **5. Discussion**

271 **5.1 Influence of climate change**

272 In general, climate change is mainly characterized by changing temperature and precipitation
273 variability. Precipitation drives runoff, and hence directly influences both the discharge of a river
274 and its sediment transport capacity. The recent decreasing trend of precipitation in the Yellow
275 River basin ([e.g. Liu et al., 2008](#)) is consistent with the reduction of water discharge and sediment
276 load of the Yellow River.

277 We define the net water discharge and sediment load emanating from a given drainage area,
278 as being the difference in water discharge and sediment load between two stations at the upstream

279 and downstream boundaries of the sub-catchment. For example, the net water discharge in the
280 Tangnaihai~Lanzhou area is given by the water discharge at Lanzhou minus that at Tangnaihai
281 station. Figure 5 presents the correlation of regional annual precipitation with the net discharge
282 data for seven sub-catchments. It can be seen that the annual precipitation and net water discharge
283 are quite well correlated for most drainage areas, except Tangnaihai~Lanzhou. The positive
284 correlation indicates that the reduction in precipitation causes an associated decrease in net water
285 discharges along the Yellow River. By analyzing water discharge data from 1956 to 2000, Liu and
286 Zhang (2004) found that the reduced precipitation was directly responsible for 75% and 43% of
287 the reduction in river discharge in the upper and middle drainage basin respectively. Moreover, the
288 present study shows that the annual net water discharge due to runoff from the Lanzhou~Hekou
289 sub-catchment was negative, which means that runoff generated from the precipitation in this area
290 did not compensate for the overall net water discharge loss due to infiltration, evapo-transpiration,
291 and abstraction for domestic, agricultural, and industrial use. As the water discharge decreased so
292 did the river's capacity for sediment transport.

293 Figure 6 presents the net sediment load as a function of precipitation for each of the
294 sub-catchment. In all cases, the correlation between the net sediment load and precipitation is
295 weaker than for the net water discharge (due to the greater sensitivity of net sediment load to
296 human activities), but nevertheless invariably remains positive. Significant correlation is only
297 apparent for data from the upper Tangnaihai, Tangnaihai~Lanzhou, Hekou~Longmen, and
298 Huayuankou~Lijin sub-catchments. Wang et al. (2007) found that the decrease in precipitation
299 was responsible for 30% of the decrease in sediment load at Huayuankou. In Figure 6, the net
300 sediment loads in the Lanzhou~Hekou and Sanmenxia~Huayuankou sub-catchments are negative

301 in certain years when sediment deposition exceeds entrainment. The sub-catchment most likely to
302 have been influenced by climate change appears to be the drainage area upstream of Tangnaihai,
303 where the correlations of both net water discharge and net sediment load with precipitation are
304 maximum, with $R = 0.79$ and 0.74 , respectively. The drainage area above Tangnaihai is located on
305 the Southern Qinghai Plateau, and has an average altitude $> 3,000$ m above sea level and a low
306 mean annual temperature of -0.87°C . Due to the relatively inhospitable natural conditions, the
307 population is low, and so there is hardly any human impact, such as large reservoirs, in this area.

308

309 **Figure 5**

310 **Figure 6**

311

312 **5.2 Influence of soil and water conservation practices**

313 Recent population growth, economic development, reclamation, deforestation, and other
314 human related activities have led to serious and widespread soil erosion in the Yellow River basin
315 (Fu, 1989; Fu and Gulinck, 1994; Chen et al., 2001b). This severe soil loss, which can exceed
316 20000 t/km/yr in certain areas (Fu and Chen, 2000), has reduced land productivity, degraded the
317 river ecosystem, and due to increased sediment concentrations and deposition caused a remarkable
318 rise in the riverbed elevation along the lower reaches of Yellow River (Shi and Shao, 2000). Soil
319 conservation practices (such as afforestation, grass-planting, creation of level terraces, contour
320 plowing, non-tillage, ridge reconstruction, and building check dams) have been implemented since
321 1949, once the severity of soil loss was recognized (Liu, 2005). As the conservation area expanded,
322 the measures against soil erosion became increasingly effective, particularly since the late 1970s.

323 The Normalized Difference Vegetation Index (NDVI) is effective at representing the
324 vegetation cover and so is widely employed for monitoring purposes (Trishchenko et al., 2002).
325 Figure 7 plots NDVI against time, from 1982 to 2006, showing the significant improvement in
326 vegetation cover that occurred in the Yellow River basin due to the increased forest and grassland
327 in that period. Figure 8 shows the expansion in different types of soil conservation area in the
328 Yellow River basin from 1959 to 1989. According to Zhang et al. (2007), the increase in soil
329 conservation area due to afforestation and grass-planting reached 11.57×10^6 ha at 2000, and is
330 predicted by Chen et al. (2004) to reach 17.25×10^6 ha by 2010. Besides the absorption of water
331 during the growth-phase, trees and grass intercept precipitation, enhance evaporation, improve soil
332 structure, increase infiltration, and thus reduce runoff. Moreover, wooded areas and grasslands
333 significantly increase terrain roughness, and thus slow the runoff speed (Xu, 2004b) reducing
334 sediment entrainment and transport, thus lowering the sediment load.

335 **Figure 7**

336 **Figure 8**

337 Creation of level terraces can change the local micro-topography and greatly reduce the
338 gradient of the hillsides. Chen et al. (2004) have estimated that the creation of level terraces
339 decreased the runoff and sediment load by 86.70% and 95.00% in the middle Yellow River, where
340 the most serious erosion occurs. Contour plowing and ridge reconstruction alter the direction of
341 the flow of runoff and entrained sediment, while elongating its path.. Chen et al. (2004) observe
342 that contour plowing and ridge reconstruction reduced runoff by 19~39% and 75% respectively,
343 and reduced soil loss by 31~67% and 90% respectively in the Tianshui area of the upper Yellow
344 River. Figure 8 also indicates the growth in soil conservation area due to the creation of terrace

345 levels and the construction of check dams from 1959 to 1989. No-till is a way of growing crops
346 that involves leaving crop stubble on the ground surface instead of plowing it under (Montgomery,
347 2007). No-till increases the water content of the soil and, because it does not disturb the soil,
348 decreases erosion. Montgomery (2007) observed that no-till can reduce soil loss by a factor of
349 more than 20 in comparison with that of conventional cultivation. In the Yellow River basin,
350 no-till is an emerging agricultural practice that has only recently been introduced. Of the
351 afore-mentioned measures for controlling soil loss, check dams have the greatest effect .

352 The soil and water conservation measures have not only decreased precipitation-induced
353 runoff and sediment flow rates, but have also caused more runoff-sediment to deposited on the
354 surface of hillsides instead of flowing into the river channel. Mou (1996) analyzed the changes to
355 the sediment load contributed by the middle Yellow River basin due to the soil and water
356 conservation measures in the 1980s; the results are summarized in Table 7. Wang et al. (2007)
357 estimated the average decrease of sediment yield due to soil conservation practices from 1969 to
358 1999 to be 0.24×10^9 t/yr in the Yellow River basin. In short, the conservation measures have
359 played a major part in reducing water flow and sediment flux in the Yellow River basin.

360

361 **Table 7**

362

363 **5.3 Abstraction and reservoir construction**

364 Since 1952, the population of the Yellow River basin has grown at a rate of about 1.23
365 million/year, reaching 0.11 billion in 2000, and is estimated to reach 0.12 billion by 2030
366 (YRCC, 2002). Meanwhile, domestic, agricultural, and industrial water consumption has increased

367 greatly. In order to meet the food requirements of the local population, the cultivated land area has
368 expanded remarkably (Figure 9), with the irrigation area increasing by almost a factor of 10 during
369 the last 50 years (Xi, 1996). In the Yellow River basin, irrigation-based agriculture with high grain
370 yield is used to alleviate the potential food shortage, but at the cost of worsening the water
371 shortage due to the low efficiency of water utilization. Li (2003) estimates that water diverted
372 from the Yellow River for irrigation-based agriculture accounts for only 30 to 45% of the total
373 irrigation water; the remainder is due to extensive floodwater irrigation. The irrigation water-use
374 ratio (defined as annual gross water transfer to irrigation divided by annual runoff) has increased
375 from 21% to 68% during the last 50 years (Yang et al., 2004). The Yellow River Conservancy
376 Commission (YRCC) predicts that by 2010, the average annual water shortfall will be about 4
377 billion m³ in the Yellow River basin (YRCC, 2009). Figures 5 and 6 show that the annual net
378 water discharge and sediment load in the Lanzhou~Hekou area are negative, mainly because the
379 Lanzhou~Hekou area is a major irrigation zone covering 116 ha. Most irrigation takes place in the
380 lower Yellow River basin, causing the observed water discharge to exhibit the strong downward
381 trend indicated in Table 5.

382

383

Figure 9

384

385 In order to generate electricity, store water, trap sediments, mitigate floods, and sluice
386 sediment, more than 3147 reservoirs have been constructed in the Yellow River basin, with a
387 combined storage capacity of 57.4 km³ (Zhang et al., 2001). These include 24 large reservoirs
388 whose individual storage capacity exceeds 0.1 km³ (Wang et al., 2007). Along the main stem, the

389 five major reservoirs listed in [Table 8](#) make the greatest contribution to water regulation and
390 sediment retention ([Wang et al., 2006a](#)). Most of the reservoirs adjust the water resource through
391 storage in the wet season and discharge in the dry season each year, without having a significant
392 influence on the annual water discharge. In fact, reservoir construction impacts on the water
393 discharge eventually due to increasing evaporation and water losses from the system. Liu and
394 Zhang ([2004](#)) estimated that reservoir construction has led to surface water evaporation of 1.05
395 billion m³ along the upper and middle Yellow River, which is 0.42 billion m³ higher than that
396 under natural conditions (without the reservoir construction). All the reservoirs impact the annual
397 sediment load greatly through sedimentation and flushing processes, though the former inevitably
398 reduces the storage capacity of the reservoir ([Table 8](#)).

399

400

Table 8

401

402 Usually, the double mass curve between water discharge and sediment load is approximately
403 linear if the sediment load is solely dependent on the transport capacity of water discharge.
404 However, the double mass curves in Figure 10 for the Yellow River contain inflection points when
405 the reservoir commences operation. There is no large-scale hydro-electric scheme in the drainage
406 area upstream of Tangnaihai, and so the double mass curve does not present any obvious
407 deflections in this case. In the drainage area related to Hekou, the Qingtongxia, Liujiaxia and
408 Longyangxia upstream reservoirs respectively commenced operation in 1968, 1969 and 1986. The
409 double mass curve at Hekou therefore contains two discrete changes in gradient corresponding to
410 changes in the ratio of sediment load to water discharge. It is also evident that the hydrologic

411 series observed at Sanmenxia and Huayuankou stations are affected by the operation of the
412 reservoirs at Sanmenxia and Xiaolangdi.

413

414 **Figure 10**

415 Net water diversion is the amount of water used for reservoir storage, agricultural irrigation
416 and domestic and industrial consumption. It is equal to the quantity of water diverted from the
417 river minus that returned to the river after water use (Xu, 2005). Figure 11 shows that the net water
418 diversion appears to have increased approximately linearly from 1955 to the mid 1980s and then
419 saturated (allowing for fluctuations which are much more evident after the 1980s, except for a
420 single large-scale event in 1960 associated with the initial operation of the reservoir at Sanmenxia).
421 The trend in net water diversion may be linked to the decrease in annual water discharge, indicated
422 in Table 5. In the Yellow River basin, the river flow at its farthest downstream station Lijin is
423 usually regarded as the flux from the Yellow River to the sea. Table 9 shows that the increasing net
424 water diversion at Lijin has a strong influence on the declining water discharge, given that the
425 contribution ratio always exceeds 50% .

426

427 **Figure 11**

428 **Table 9**

429

430 **6. Conclusions**

431 In the Yellow River basin, except for the drainage area of the upper Tangnaihai station, the
432 water discharge and sediment load have undergone distinct stepwise decreases from the 1950s to

433 the 2000s, the downward trends being significant at the 95% confidence level. By interpreting the
434 annual mean water discharge series, it has been found that the declining trend in water discharge is
435 exacerbated in the downstream direction, and that the sub-catchment drainage area positively
436 correlates with the rate of decrease in water discharge and sediment load. Precipitation, water
437 consumption and anthropogenic activities (such as water conservation practices, and the
438 construction and operation of reservoirs) have had a large impact on the variation of water
439 discharge and sediment load. In particular, the reduction in precipitation due to climate change has
440 had a **direct** influence on the decreasing water discharge in the Yellow River basin. Moreover, the
441 steady rise in water consumption has severely worsened the water crisis. Given all that, the human
442 consumption and the construction-operation of reservoirs should be chiefly responsible for the
443 decreasing water discharge and sediment load respectively.

444

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453

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624

625 **Table captions**

626 **Table 1.** Physical characteristics of the upper, middle and lower reaches in the Yellow River basin.

627 **Table 2.** Detailed information of hydrological stations in the Yellow River basin.

628 **Table 3.** The results of autocorrelation analysis ^a; (^a Lag=0 means the series is independent, Lag \neq

629 0 means the series has significant autocorrelation with the corresponding lagged time

630 steps.).

631 **Table 4.** Results of the trend analysis by use of the Mann-Kendall test.

632 **Table 5.** Percentage changes in water discharge and sediment load ^a. (^a The reference value is the

633 mean of the annual series during 1950s~1960s).

634 **Table 6.** Results of abrupt change analysis by use of the Mann-Kendall test. (^a Time when the

635 abrupt change occurs; ^b Mean value before the abrupt change; ^c Mean value after the

636 abrupt change; ^d Change of the mean value between Pre-T and Post-T).

637 **Table 7.** Effects of soil and water conservation practices in the middle Yellow River basin during

638 the 1980s^a. (^aData from Mou (1996)).

639 **Table 8.** Summary information of 5 major reservoirs along Yellow River ^a. (^aData from Wang et

640 al., (2007); Jiao (2004); Chen et al., (1999) and YRCC (2002); ^bData in parentheses

641 indicate the observation period).

642 **Table 9.** The change in water discharge and net water diversion at Lijin station ^a. (^a The reference

643 value is the mean of the annual series over the period from 1956 to 1969; Symbol “-”

644 means decrease and “+” means increase.)

645

646 **Figure Captions**

647 **Figure 1.** Comparison between (a) Yellow River delta and (b) Mississippi river delta. The images
648 are derived from NASA's Landsat 7 satellite.

649 **Figure 2.** Yellow River Basin: location of hydrological and meteorological stations, and major
650 reservoirs.

651 **Figure 3.** Correlation between the drainage area and the slope calculated by the MK test

652 **Figure 4.** Changes in water discharge and sediment load at Lijin before and after the change point

653 **Figure 5.** Correlation between precipitation and net water discharge

654 **Figure 6.** Correlation between precipitation and net sediment load

655 **Figure 7.** Variation of annual average NDVI in the Yellow River basin from 1982 to 2006. The
656 NDVI data are derived from Global Inventory Monitoring and Modeling Studies
657 (GIMMS) dataset.

658 **Figure 8.** Growth of soil conservation area in the Yellow River basin (after Xu, 2004a)

659 **Figure 9.** Growth of irrigation area in the Yellow River basin.

660 **Figure 10.** Double mass plots relating cumulative annual sediment load to cumulative annual
661 water discharge at Tangnaihai, Hekou, Sanmenxia, and Xiaolangdi.

662 **Figure 11.** Temporal variation of net water diversion in the Yellow River basin. The public data
663 from 1955 to 1989 is supplied by the Yellow River Water Conservancy Commission
664 (YRCC). The interpolated data is generated by net water diversion at Lijin (the
665 correlation $r = 0.98$, $p = 0.000$).

666

667 **Table 1**

668

	Length (km)	Drainage area (km ²)	Altitude range (m)	Annual mean precipitation (mm)	Annual mean temperature range (°C)
Upper reaches (above Toudaoguai)	3471	385,996	4480~1000	368	1~4
Middle reaches (Toudaoguai~Huayuankou)	1206	343,751	1000~106	530	8~14
Lower reaches (below Huayuankou)	787	22,726	106~0	670	12~14

669

670

671 **Table 2**

672

No.	Location	Station	Data period	Drainage area (10 ³ km ²)	Mean water discharge (10 ⁹ m ³ /a)	Mean load (10 ⁶ t/a)	sediment
1	mainstream	Tangnaihai	1956~2007	122.0	19.9	12.3	
2	mainstream	Lanzhou	1956~2007	222.6	30.6	63.8	
3	tributary	Jingyuan	1955~2002	10.7	0.11	48.9	
4	mainstream	Shizuishan	1956~2003	309.1	27.5	114.5	
5	mainstream	Hekou	1956~2007	367.9	21.1	101.2	
6	tributary	Huangfu	1954~2007	3.2	0.14	43.9	
7	tributary	Baijiachuan	1956~2007	29.7	1.15	114.5	
8	mainstream	Longmen	1956~2007	497.6	25.9	711.2	
9	tributary	Zhuangtou	1956~2007	25.6	0.84	73.4	
10	tributary	Huaxian	1956~2007	106.5	6.75	329.4	
11	mainstream	Sanmenxia	1956~2007	688.4	33.6	1035.8	
12	mainstream	Huayuankou	1956~2007	730.0	37.1	890.4	
13	mainstream	Gaocun	1956~2007	734.1	34.5	803.2	
14	mainstream	Aishan	1956~2007	749.1	33.2	767.5	
15	mainstream	Lijin	1956~2007	751.9	29.4	709.7	

673

674 **Table 3**

675

Station No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Water discharge series															
Lag=	1	1	0	1	3	0	9	9	0	1	9	6	1	1	6
Sediment load series															
Lag=	0	3	0	3	8	0	3	3	2	0	1	1	3	3	9

676

677

678 **Table 4**

679

No.	Location	Station name	Length (yr)	Water discharge			Sediment load		
				Slope	Sig.	Trend	Slope	Sig.	Trend
1	mainstream	Tangnaihai	52	-0.07	0.140	↓	0.0	0.893	—
2	mainstream	Lanzhou	52	-0.15	0.006	↓	-1.70	0.000	↓
4	mainstream	Shizuishan	48	-0.24	0.000	↓	-1.60	0.003	↓
5	mainstream	Hekou	52	-0.23	0.000	↓	-3.00	0.000	↓
8	mainstream	Longmen	52	-0.34	0.000	↓	-21.10	0.000	↓
11	mainstream	Sanmenxia	52	-0.55	0.000	↓	-24.80	0.000	↓
12	mainstream	Huayuankou	52	-0.56	0.000	↓	-28.00	0.000	↓
13	mainstream	Gaocun	52	-0.60	0.000	↓	-27.90	0.000	↓
14	mainstream	Aishan	52	-0.65	0.000	↓	-24.40	0.000	↓
15	mainstream	Lijin	52	-0.81	0.000	↓	-27.40	0.000	↓
3	tributary	Jingyuan	48	-0.002	0.020	↓	-0.80	0.026	↓
6	tributary	Huangfu	54	-0.003	0.000	↓	-0.90	0.000	↓
7	tributary	Baijiachuan	52	-0.018	0.000	↓	-2.90	0.000	↓
9	tributary	Zhuangtou	53	-0.005	0.018	↓	-1.10	0.005	↓
10	tributary	Huaxian	54	-0.107	0.000	↓	-5.10	0.000	↓

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682 **Table 5**

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No.	Station	Change in Water discharge (%)				Change in Sediment load (%)			
		1970s	1980s	1990s	2000s	1970s	1980s	1990s	2000s
1	Tangnaihai	1.55%	20.03%	-12.34%	-18.70%	16.70%	89.76%	4.12%	-26.49%
2	Lanzhou	-5.61%	-1.00%	-22.90%	-22.59%	-45.84%	-65.22%	-57.78%	-79.26%
4	Shizuishan	-6.61%	-3.11%	-28.33%	-40.19%	-30.16%	-37.85%	-44.54%	-63.80%
5	Hekou	-8.36%	-6.04%	-38.39%	-44.29%	-33.61%	-43.49%	-76.24%	-78.12%
8	Longmen	-12.07%	-14.67%	-38.77%	-47.91%	-27.47%	-60.73%	-56.61%	-82.72%
11	Sanmenxia	-19.50%	-16.64%	-45.55%	-57.05%	-2.07%	-39.85%	-43.18%	-72.03%
12	Huayuankou	-22.71%	-16.41%	-47.96%	-53.22%	-6.31%	-40.86%	-48.13%	-91.14%
13	Gaocun	-25.14%	-22.27%	-53.89%	-56.78%	-13.91%	-44.42%	-61.03%	-87.61%
14	Aishan	-29.57%	-29.65%	-60.09%	-59.45%	-18.31%	-40.59%	-57.92%	-85.36%
15	Lijin	-35.62%	-40.84%	-70.87%	-70.74%	-23.44%	-45.52%	-66.73%	-87.10%
3	Jingyuan	-25.86%	-37.21%	-33.33%	-61.03%	-31.17%	-49.13%	-42.80%	-77.42%
6	Huangfu	-16.16%	-38.73%	-55.84%	-79.84%	0.81%	-31.17%	-59.36%	-80.83%
7	Baijiachuan	-21.02%	-32.25%	-38.97%	-51.48%	-46.30%	-75.59%	-61.26%	-80.12%
9	Zhuangtou	-12.55%	-3.51%	-21.45%	-29.78%	-23.96%	-53.97%	-15.42%	-73.44%
10	Huaxian	-36.78%	-15.75%	-53.39%	-50.63%	-18.79%	-41.56%	-43.35%	-66.61%

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686 **Table 6**

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No.	Station name	Water discharge				Sediment load			
		Time ^a	Pre-T ^b	Post-T ^c	Change ^d	Time ^a	Pre-T ^b	Post-T ^c	Change ^d
			(10 ⁹ m ³ /a)	(10 ⁹ m ³ /a)	(%)		(10 ⁶ t/a)	(10 ⁶ t/a)	(%)
1	Tangnaihai	1994	20.84	16.66	-20.06	2005	12.60	3.80	-69.84
2	Lanzhou	1990	32.99	25.70	-22.10	1973	105.40	63.70	-39.56
4	Shizuishan	1995	29.26	18.87	-35.51	1982	137.80	87.00	-36.87
5	Hekou	1990	24.25	14.69	-39.42	1986	141.20	42.10	-70.18
8	Longmen	1991	29.66	18.16	-38.77	No significant abrupt change			
11	Sanmenxia	1991	39.57	21.29	-46.20	1996	1190.00	458.00	-61.51
12	Huayuankou	1990	43.48	23.83	-45.19	1996	1073.00	211.00	-80.34
13	Gaocun	1988	41.40	21.56	-47.92	1993	1003.00	310.00	-69.09
14	Aishan	1985	42.53	20.55	-51.68	1991	972.30	346.00	-64.41
15	Lijin	1985	40.10	14.73	-63.27	1990	921.80	273.00	-70.38
3	Jingyuan	1968	0.16	0.10	-38.10	1965	84.30	40.00	-52.55
6	Huangfu	No significant abrupt change				1992	54.10	18.00	-66.73
7	Baijiachuan	1983	1.37	0.91	-33.53	1971	215.50	70.00	-67.52
9	Zhuangtou	2003	0.87	0.55	-36.69	2002	79.60	14.00	-82.41
10	Huaxian	1988	7.98	4.61	-42.30	1996	372.80	168.00	-54.94

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690 **Table 7**

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Soil and water conservation practices	Intercepting sediment yield	Percentage of overall change
	(10 ⁶ t)	(%)
Level Terrace	42	16.60
Afforestation	43	17.10
Grass-planting	12	4.80
Check dam	79	31.30

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694 **Table 8**

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Reservoir	Longyangxia	Liujiaxia	Qingtongxia	Sanmenxia	Xiaolangdi
Commencement of operation	1986	1969	1968	1960	2000
Storage capacity ($10^9 \times m^3$)	24.70	5.70	0.61	35.40	12.65
Siltation capacity ^b ($10^9 \times m^3$)	0.30 (1999)	1.50 (2006)	0.58 (2005)	9.51 (2005)	2.40 (2008)

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698 **Table 9**

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	1970s	1980s	1990s	2000s
Change in water discharge ($10^9\text{m}^3/\text{a}$)	-17.21	-19.73	-34.24	-34.13
Change in net water diversion ($10^9\text{m}^3/\text{a}$)	+9.44	+18.47	+20.84	+18.14
Contribution Ratio of net water diversion (%)	54.89%	-93.64%	60.87%	53.14%

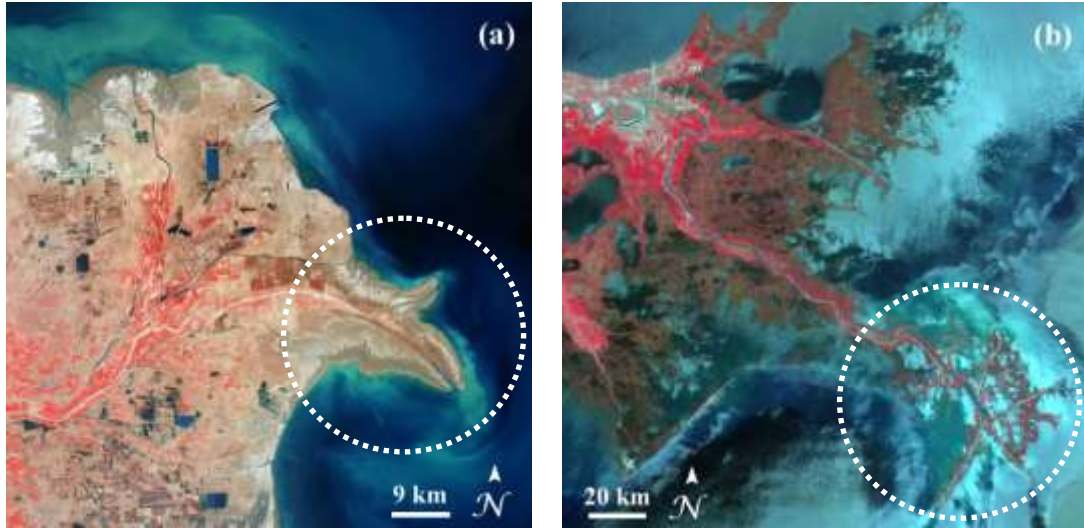
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702 **Figure 1**

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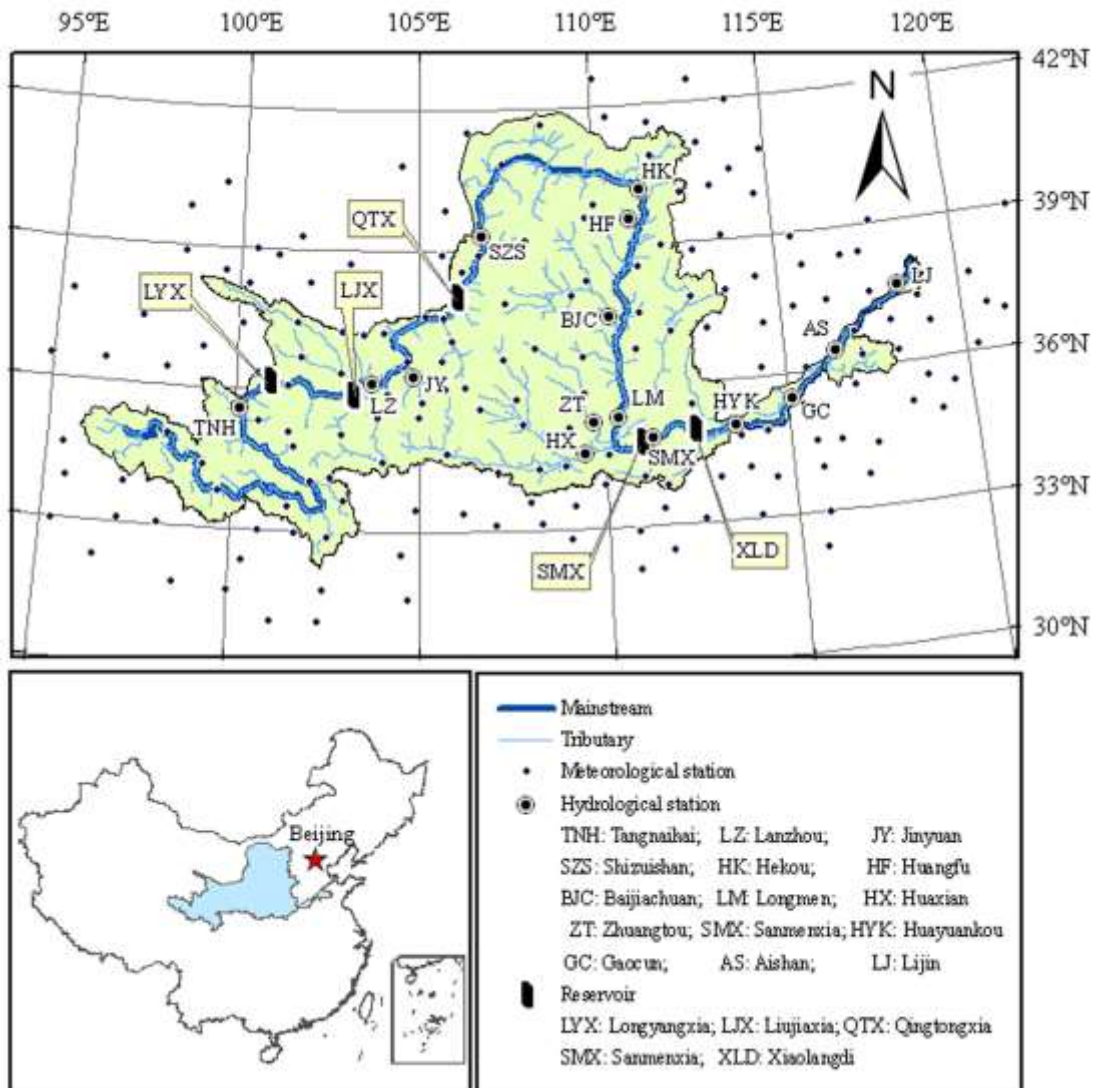


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707 **Figure 2**

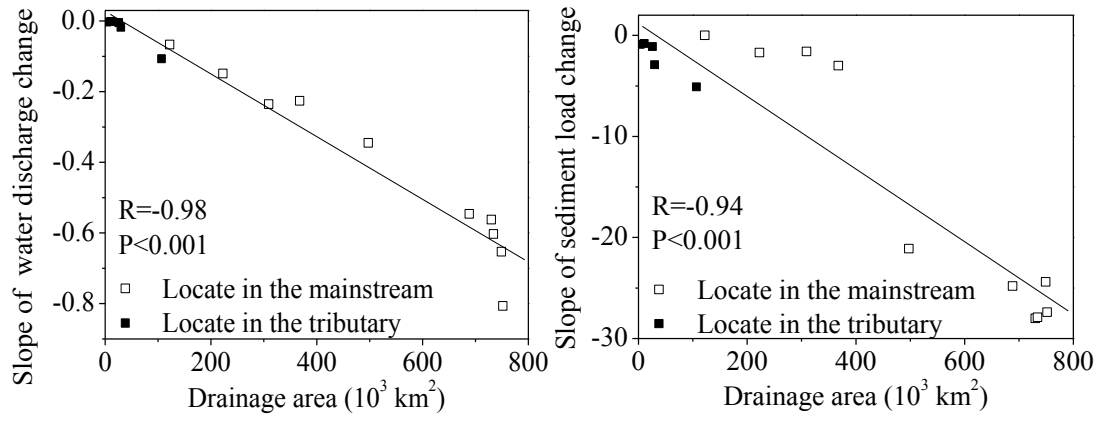
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711 **Figure 3**



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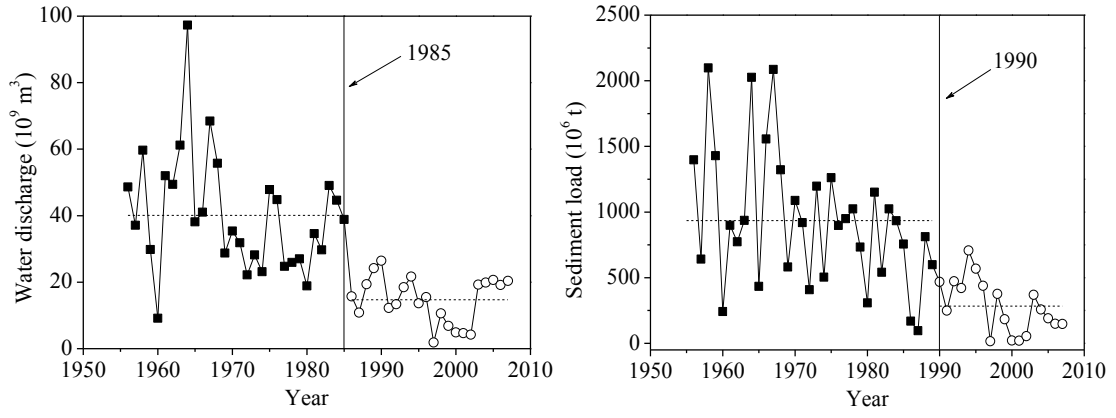
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716 **Figure 4**

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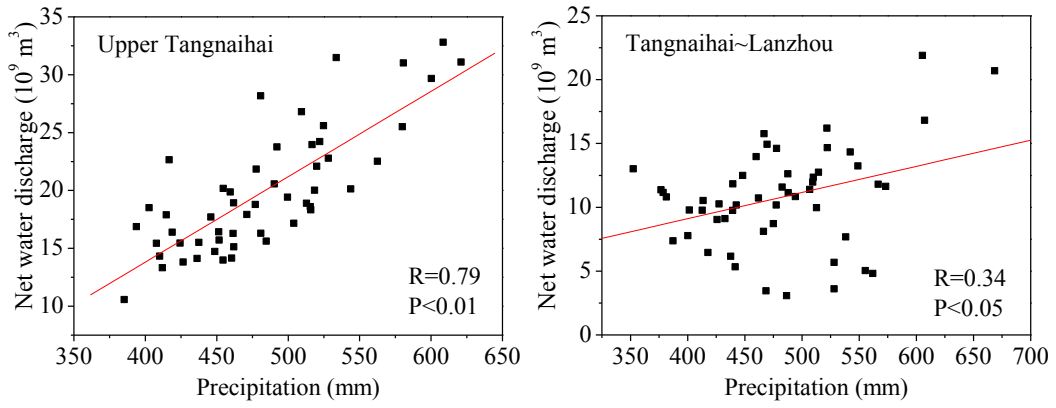
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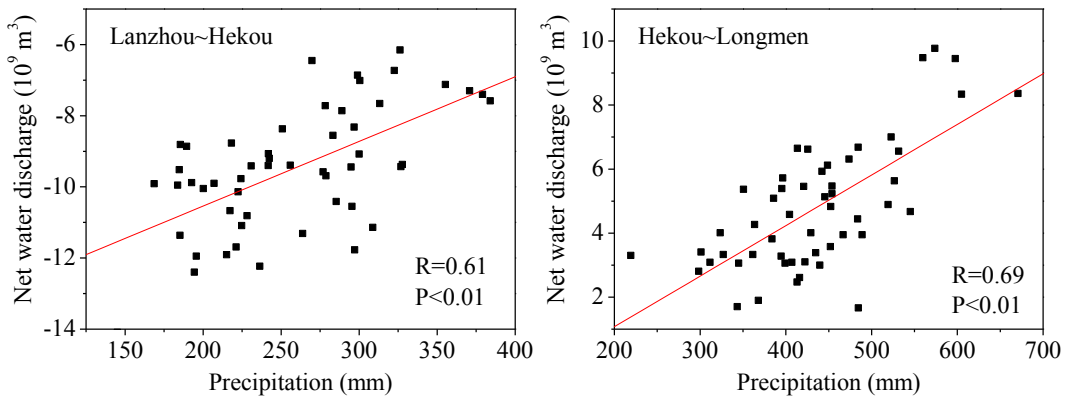
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722 **Figure 5**

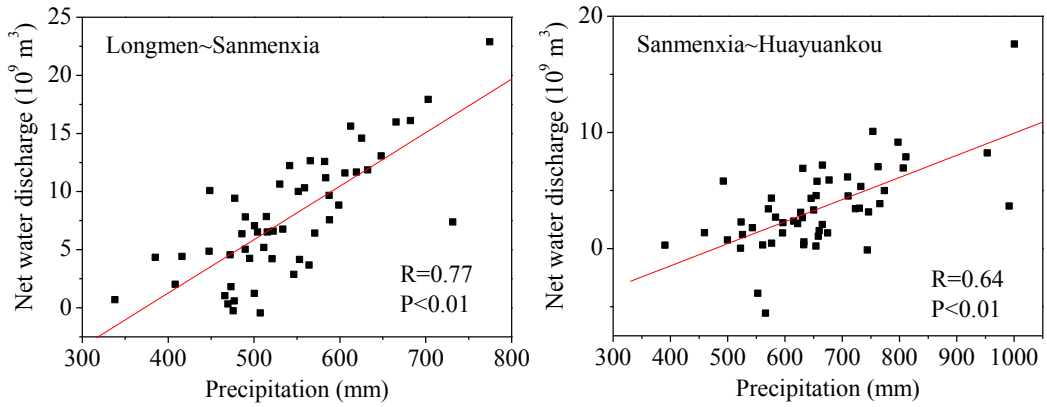
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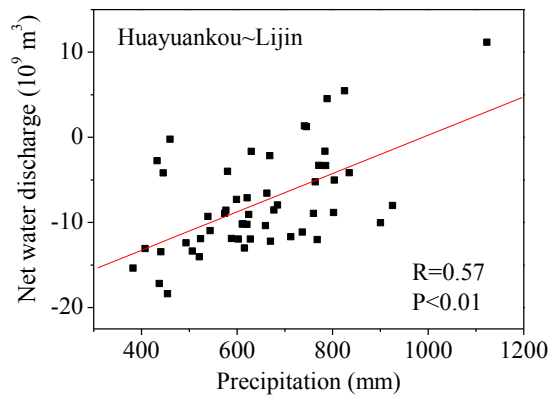
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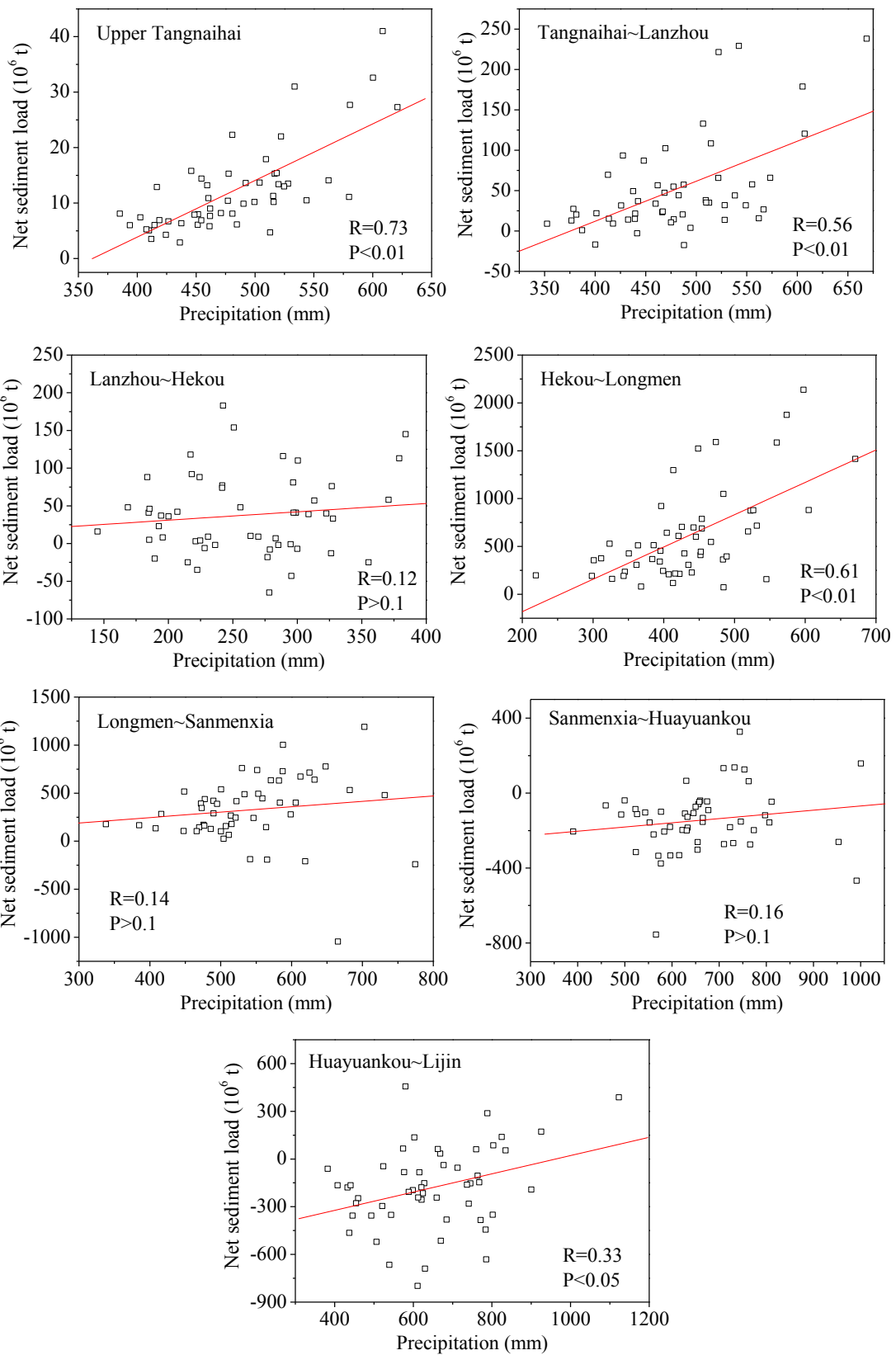


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729 **Figure 6**

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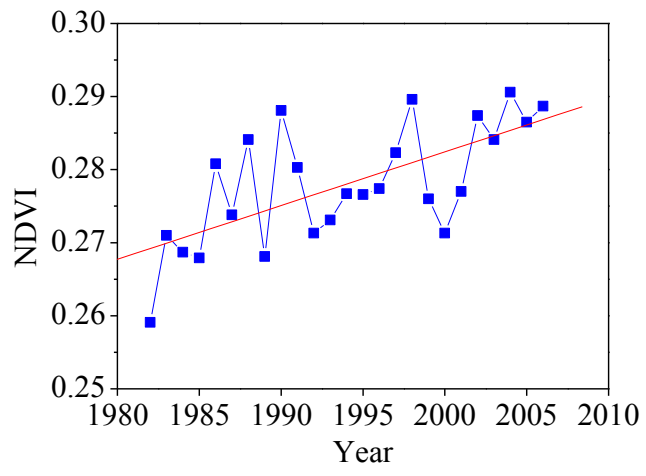
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736 **Figure 7**

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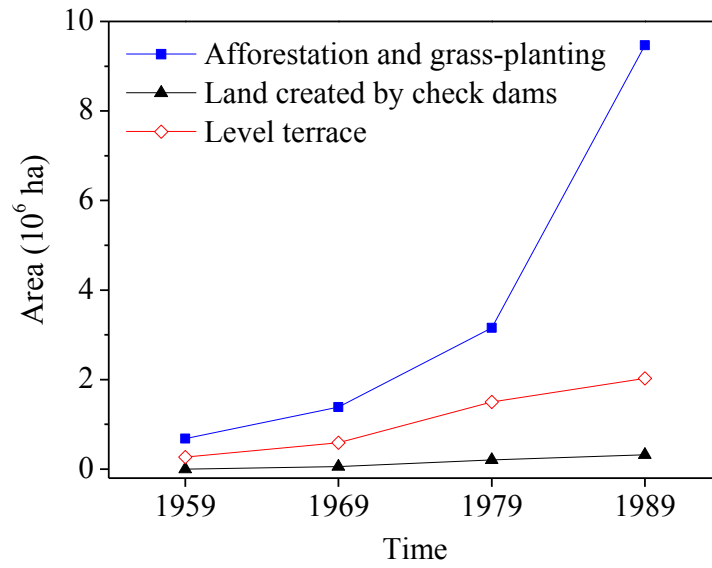
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740 **Figure 8**

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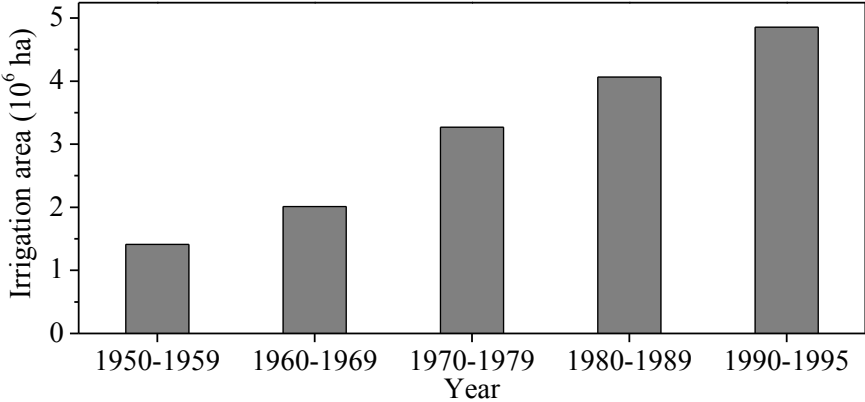
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746 **Figure 9**

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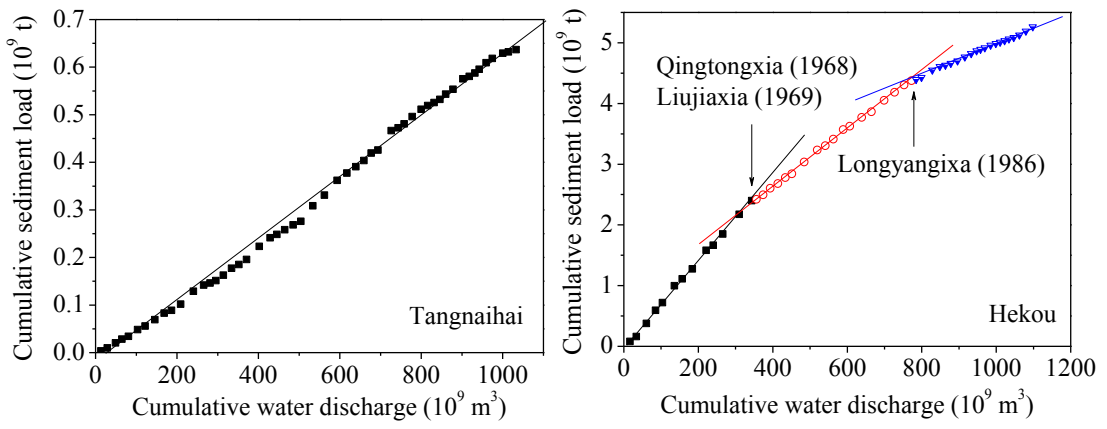


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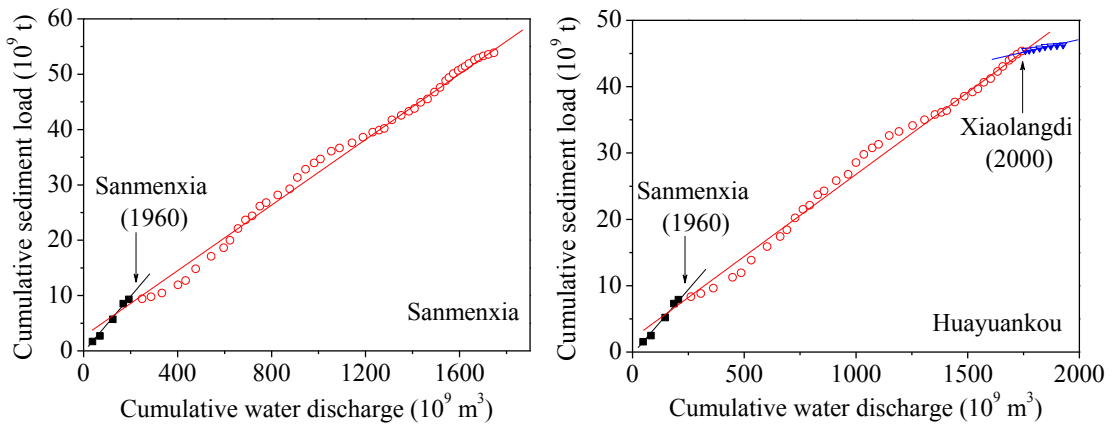
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750 **Figure 10**

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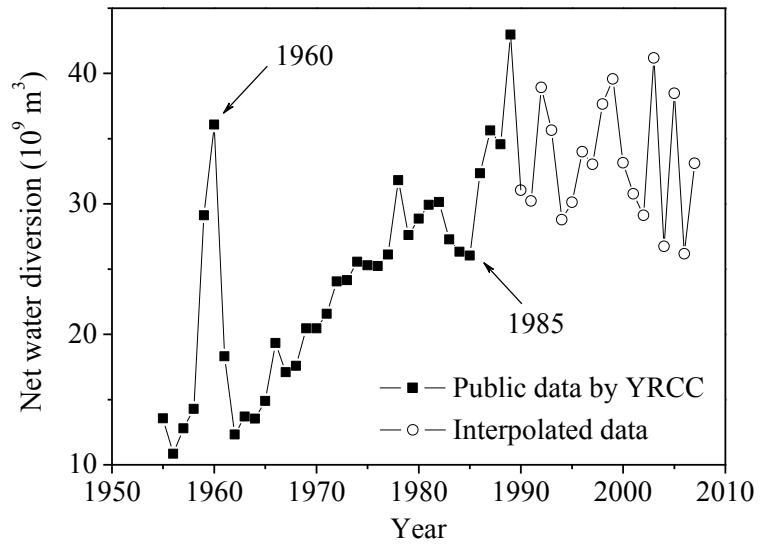
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756 **Figure 11**

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