GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19603, doi:10.1029/2009GL039513, 2009

A quantitative assessment of human impacts on decrease in sediment flux from major Chinese rivers entering the western Pacific Ocean

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Received 7 June 2009; revised 1 August 2009; accepted 1 September 2009; published 9 October 2009.

[1] Major rivers with high sediment or water discharge act as natural integrators of surficial processes, including human activities within their drainage basins, and they are also the primary sources of terrestrial materials entering the ocean. The river-derived materials flux entering the coastal oceans, however, has been strongly affected by anthropogenic activities. Recent studies related to human impacts on river sediment flux have mainly focused on qualitative descriptions. Here we present a quantitative assessment of human impacts on decrease in sediment flux from nine major Chinese rivers entering the western Pacific Ocean, including Changjiang (Yangtze), Huanghe (Yellow), Zhujiang (Pearl), Songhuajiang, Liaohe, Haihe, Huaihe, Qiantangjiang, and Minjiang. During 1959–2007, dams and reservoirs, soil and water conservation programs, water consumption, as well as sand mining decreased the amount of sediment delivered to the ocean by 28, 11.5, 7.5 and 3 gigatons (Gt), respectively. If combined (50 Gt for the period 1959–2007), this reduction was close to the total decreased sediment flux (43 Gt) measured from these nine major rivers over the same period. Besides, the temporal variations in water and sediment fluxes into the ocean from these rivers generally during 1953–2007 were presented. These results are useful for further studies on Chinese and even global river-derived material flux to the ocean and associated ecological risks. **Citation:** Chu, Z. X., S. K. Zhai, X. X. Lu, J. P. Liu, J. X. Xu, and K. H. Xu (2009), A quantitative assessment of human impacts on decrease in sediment flux from major Chinese rivers entering the western Pacific Ocean, *Geophys. Res. Lett.*, *36*, L19603, doi:10.1029/2009GL039513.

1. Introduction

[2] The river-derived material entering the seas has a tremendous effect on the estuaries, coastal zones, and even continental shelves [*Chu et al.*, 2006; *Liu et al.*, 2006]. Among ~20 gigatons per year (Gt/yr) of worldwide riverine sediment supply to the ocean, 10% was delivered by major Chinese rivers [*Milliman and Meade*, 1983; *Wang et al.*, 1986]. The river water and sediment supply to the ocean, however, has been strongly affected by anthropogenic activities [*Nilsson et al.*, 2005; *Syvitski et al.*, 2005]. Thus, a goal of the International Geosphere-Biosphere Programme (IGBP) and its two core projects, Land Ocean Interaction in the Coastal Zone (LOICZ) and Joint Global Ocean Flux Study (JGOFS), has been to survey the terrestrial sediment supply to the seas and to analyze human perturbation of this flux. Recent studies related to human impacts on river sediment flux have mainly focused on qualitative descriptions [*Lu and Siew*, 2006; *Xu et al.*, 2006; *Yang et al.*, 2002, 2006], although there have been some model-based quantitative assessments of some natural factors (e.g., climate, basin area, ice cover) as well as partial assessments of anthropogenic factors (i.e. reservoir trapping, soil erosion) [*Syvitski and Milliman*, 2007]. *Wang et al.* [2007] presented a detailed assessment of the effects of natural (precipitation) and anthropogenic factors on the Huanghe decreased sediment load. *Wilkinson* [2005] and *Wilkinson and McElroy* [2007] estimated the impact of humans on continental erosion and sedimentation. *Hassan et al.* [2008] recently presented the spatial and temporal variations of sediment yield in the Huanghe basin.

[3] There are nine major rivers in China entering the coastal oceans from north to south: Songhuajiang (a major tributary of Heilongjiang or Amur to Sea of Okhotsk), Liaohe, Haihe, Huanghe and Huaihe (to Bohai Sea), Changjiang, Qiantangjiang, and Minjiang (to East China Sea), and Zhujiang (to South China Sea) (Figure 1). These major Chinese rivers play a leading role in transporting terrestrial materials to the western Pacific Ocean. In addition, they have a relatively longer and continuous measurement of water discharge and suspended sediment (over 50 years in many cases, in contrast to the scarcity of measurements from the worldwide rivers) [*Syvitski et al.*, 2005]. The total water and sediment fluxes into the ocean by the nine major Chinese rivers during 1953–1958 were 1472 cubic kilometers per year (km^3/yr) and 2027 million tons per year (Mt/yr), respectively; as a contrast, the data during 2000–2007 are 1275 km^3/yr and 409 Mt/yr, respectively. It is clear that the total sediment flux has been markedly reduced in the past five decades despite relatively stable total water discharge.

[4] In the past half century, China's population has doubled, and its GDP increased by over 200 times. The nine major Chinese rivers span from arid to humid climatic zones with a total drainage area of 4.5 million square kilometers (Mkm^2), one billion inhabitants, and most of China's GDP production. The increasing human activities within the drainage basins, such as dams and reservoirs, soil and water conservation, water consumption, and sand mining, have significantly reduced riverine sediment fluxes

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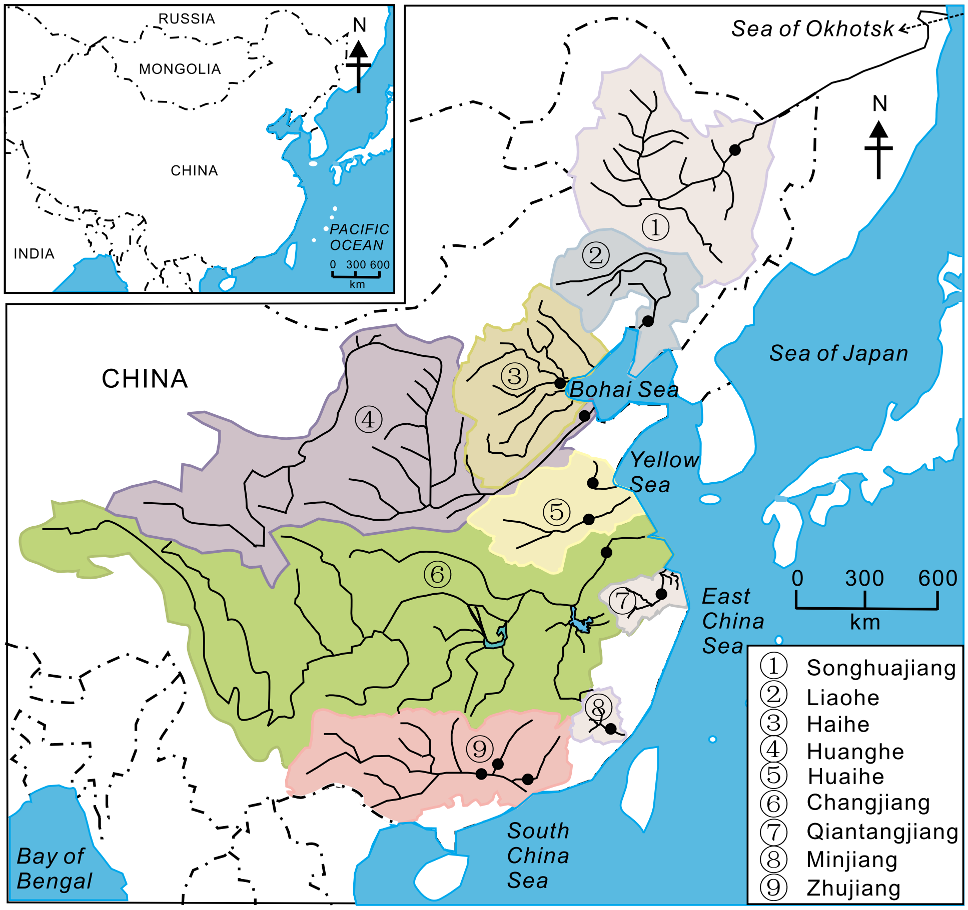

Figure 1. The nine major Chinese rivers entering the seas. Black dots indicate the hydrological stations described in the auxiliary material.

into the ocean. Yet such impacts on riverine sediment fluxes are rarely discussed in the systematic summary on the human-induced environmental problems across China [*Liu and Diamond*, 2005]. Lack of detailed information across the river basins prohibits estimating contribution from individual factors [*Lu et al.*, 2003], though there has been an attempt for individual rivers, such as the Huanghe [*Xu and Sun*, 2003; *Wang et al.*, 2007].

[5] The first objective of this study is to examine the temporal variations in water and sediment fluxes into the western Pacific Ocean by nine major Chinese rivers during 1953–2007. The second objective is to quantitatively relate human activities in these river basins to the decrease in riverine sediment flux.

2. Materials

[6] An annual record of water discharge and suspended sediment load of nine major rivers in China for the period 1953–2007 were available from Ministry of Water Resources of China (MWRC). These measurements were taken at the lowermost hydrological stations in the drainage basins (Figure 1), serving as the controlling stations for the monitoring of water and sediment discharges into the sea. Moreover, information on trapped sediment in large reservoirs, river water diversions, in-channel sand extraction, and water and soil conservancy practices, were also available.

3. Temporal Variations in Water and Sediment Flux

[7] In these rivers the suspended sediment flux into the ocean declined from ~2 Gt/yr to ~0.4 Gt/yr over the ~50 year period of record (Figure 2, top). Four phases can be determined: high sediment flux phase (1953–68) of 1.86 Gt/yr, moderate sediment flux phase (1969–85) of 1.37 Gt/yr, low sediment flux phase (1986–99) of 0.83 Gt/yr, and very low sediment flux phase (2000–07) of 0.41 Gt/yr. Sediment fluxes from the three rivers, Huanghe (749 Mt/yr), Changjiang (401 Mt/yr) and Zhujiang (73 Mt/yr), contributed 1223 Mt/yr, or 97%, to the total (1262 Mt/yr) during 1953–07. The contribution from Huanghe to the total sediment flux by the nine rivers decreased from 71.3% during 1953–59 to 37.0% during 2000–07. In contrast, the contribution from Changjiang increased from 27.8% during 1953–59 to 50.9% during 2000–07. The decline in the total sediment flux from the nine rivers was mainly due to the decline from Huanghe (primary) and Changjiang (secondary).

[8] All the rivers but Songhuajiang had a decreasing tendency of sediment supply to the ocean: Huanghe,

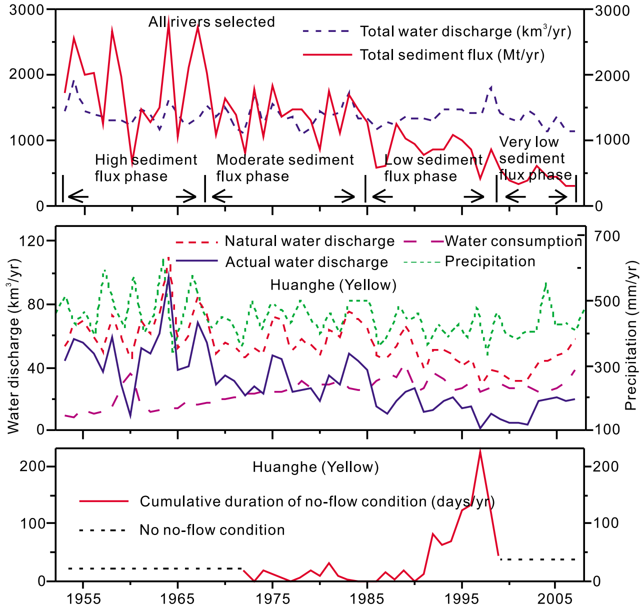

Figure 2. (top) Temporal variations in total water and sediment flux into the ocean from nine major Chinese rivers in the past five decades. (middle) Annual precipitation and water consumption in the Huanghe basin, actual and natural water discharges at Lijin. (bottom) No-flow duration at Lijin.

Changjiang, Liaohe and Huaihe since the 1960s, Haihe and Minjiang since the 1980s and 1990s, respectively, while in Zhujiang and Qiantangjiang the decline started around 1995 (Figure 3). Huanghe sediment flux, for instance, decreased from 1.44 Gt/yr during 1953–59, to 1.08 Gt/yr in the 1960s, 0.89 Gt/yr in the 1970s, 0.63 Gt/yr in the 1980s, 0.39 Gt/yr in the 1990s and 0.12 Gt/yr during 2000–07. Such decline corresponded to a decline of water discharge for the rivers in arid and semiarid climates, while in rivers located in humid climate areas the decline in sediment flux was not associated with the water discharge (Figure 3). The slight increase in Songhuajiang sediment flux since the 1990s was probably due to the increased soil erosion (see http://www.agri.gov.cn/qgxxlb/t20061124_728282.htm).

[9] The rivers within arid and semiarid zones had a decreasing tendency of water supply to the ocean: Huanghe, Huaihe and Liaohe since the 1970s, and Haihe since the 1980s, while the rivers within humid zone had a slightly increasing tendency since the 1990s. The total water supply to the ocean did not show a dramatic change in the past five decades (Figure 2, top). The markedly decreased water discharge of the rivers in arid and semiarid climates was basically offset by the slightly increased water discharge of the rivers in humid climate.

[10] Given most of reservoirs have been built since 1959, we calculated the sediment flux into the ocean for two time periods before and after 1959. The reduced sediment flux of the nine rivers during 1959–2007 was 43 Gt with a rate of 0.90 Gt/yr. This reduction is much higher compared to the worldwide reduction [*Syvitski et al.*, 2005].

4. Human Impacts

4.1. Dams and Reservoirs

[11] There were 85,160 reservoirs in China by 2004, with a total storage capacity of 866 km^3 (MWRC, Water resources statistical bulletin, 2004, available at http://www.mwr.gov.cn/xygb/sltjgb/index.aspx). The total sediment trapped in the 236-investigated large reservoirs in China by 1981 was 11.5 km^3 with a rate of 0.8 km^3/yr [*Jiang and Fu*, 1997]. About 19.39 km^3 of sediment, or 25.21 Gt assuming a density of 1.3 t/m^3, was trapped in China's 52 largest

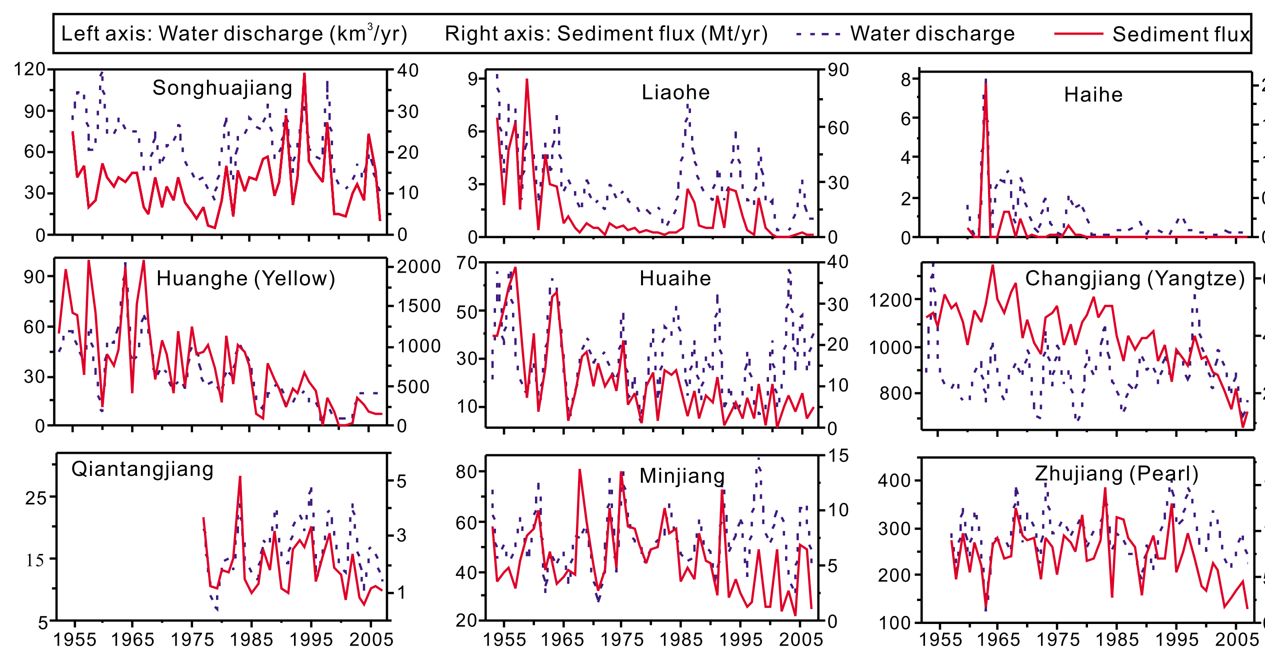

Figure 3. Temporal variations in water and sediment flux into the ocean by the nine major Chinese rivers in the past five decades.

reservoirs with dramatic trapping effect. The amounts of sediment trapped in the basins of Huanghe, Changjiang, Haihe and Liaohe were 17.52 Gt, 4.54 Gt, 1.74 Gt, and 1.26 Gt. Considering that many sedimentation records for the reservoirs selected in this study are outdated and the lack of data for other numerous small reservoirs, the amount of total sediment trapped by the dams and reservoirs during 1959–07 is estimated 28 Gt.

4.2. Soil and Water Conservation

[12] About 0.92 Mkm^2 of soil erosion areas was brought under control by 2005 from 0.02–0.03 Mkm^2/yr in the early 1990s to the present 0.04–0.05 Mkm^2/yr, mostly in the Huanghe and Changjiang basins (J. E, Lecture on the symposium celebrating fifteenth anniversary of Law of China on Water and Soil Conservation (in Chinese), 2006, available at http://www.most.gov.cn/gnwkjdt/200606/t20060630_34582.htm). The cumulative area of soil and water conservation by Changzhi Project, launched in the upper-middle Changjiang in 1988, has exceeded 0.084 Mkm^2 by 2005 (MWRC, River sediment bulletin in China (in Chinese), 2005, available at http://www.mwr.gov.cn/xygb/hlnsgb/index.aspx). This project has reduced soil erosion by 60 Mt/yr (MWRC, River sediment bulletin in China, 2000, available at http://www.mwr.gov.cn/xygb/hlnsgb/index.aspx). Another national project, which started in the 1970s mainly in the middle Huanghe, has controlled erosion in an area that in 1998 reached about 0.17 Mkm^2. This project has reduced soil erosion by 0.3 Gt/yr since the 1970s (see http://www.mwr.gov.cn/xygb/hlnsgb/index.aspx). The amount of sediment reduction by soil and water conservation is estimated: 1.20 Gt in Changjiang (with an average rate of 60 Mt/yr during 1988–07), 9.60 Gt in Huanghe (with an average rate of 0.3 Gt/yr during 1976–07), and 11.5 Gt in the nine rivers during 1959–07.

4.3. Water Consumption

[13] Water consumption practices are often seen along rivers within arid and semiarid zones, e.g. Haihe and Huanghe. For example, about 0.9 km^3 of water was diverted from Huanghe to Tianjin city during October 2004 to January 2005, and as a result, 2.29 Mt of sediment was diverted away (see http://www.mwr.gov.cn/xygb/hlnsgb/index.aspx). The water consumption from Huanghe has even exceeded the actual water discharge into the sea since 1986 and a no-flow condition has occurred in the lower Huanghe in recent years (Figure 2, middle and bottom). Due to government intervention, the no-flow condition has stopped since 2000. The natural water discharge of Huanghe (sum of actual water discharge and water consumption) and precipitation did not show a dramatic change in the past five decades, though there has been a decline in natural water discharge since 1990 due to decreased runoff renewability induced by increased soil and water conservation [*Xu*, 2005]. The water consumption from Huanghe was at a rate of 11.6 km^3/yr during 1953–58 and increased to 25.9 km^3/yr during 1959–07. The increased water consumption is estimated to reduce 7.1 Gt of sediment from Huanghe assuming an averaged sediment concentration of 10.6 kg/m^3. The estimated amount of sediment reduction in the nine rivers due to water consumption during 1959–07 was estimated 7.5 Gt.

4.4. Sand Mining

[14] In-channel sand mining across China and particularly in Changjiang and Zhujiang has intensified in recent years because of the growing demand for sands. The estimated amounts of dredged sand were 7 Mm^3/yr in Beijiang (a main tributary of lower Zhujiang) and 36 Mm^3/yr in the estuary since the mid 1990s, leading to a serious channel downcut (e.g. 5–6 m as a whole in Beijiang) (see South China News of People's Daily, 2004, http://www.people.com.cn/GB/paper49/13059/1173096.html). Dredged sand in the lower Zhujiang reached about 60 Mt/yr since the mid 1990s, and exceeded the suspended sediment flux into the sea (49 Mt/yr during the mid 1990s to 2007), indicating that the sand mining has a notable impact on the suspended sediment flux in Zhujiang (vs. 76 Mt/yr during the 1960s). The extracted sand from the mid-lower Changjiang is estimated to be from 40 Mt/yr in the early 1980s to 80 Mt/yr in the late 1990s, and meanwhile, this stretch has acted as a natural sediment sink [*Chen*, 2004]. The field investigations do not show any significant aggradations on the riverbed since the 1960s [*Hydrologic Bureau of Changjiang Water Resource Commission*, 2000], indicating that sand mining does have significantly reduced Changjiang suspended sediment flux [*Chen*, 2004]. It was reported that there were about 2000 sand-mining ships in Changjiang (Topics in focus by CCTV, 2004, http://news.anhuinews.com/system/2004/10/30/001030674.shtml), but now only 98 ships are authorized to mine sand with an upper limit under 34 Mt/yr [*Chen*, 2004]. During 2002–07, about 73.1 Mm^3 of sand was extracted from Changjiang under local official permission [*Zhao and Zhou*, 2006]. The estimated amounts of sediment reduction by sand mining are 1.5 Gt in Changjiang (during the 1980s to 2007), 0.8 Gt in Zhujiang (60 Mt/yr during the middle 1990s to 2007) and 3 Gt in the nine rivers during 1959–07.

5. Conclusions and Discussion

[15] If combined, the total sediment reduction by human activities is 50 Gt during 1959–2007, 28 Gt (56%) by dams and reservoirs, 11.5 Gt (23%) by soil and water conservation, 7.5 Gt (15%) by water consumption and 3 Gt (6%) by in-channel sand mining (Figure 4). The estimated errors of these assessments are 2.79, 0.7, 0.4 and 0.7 Gt, respectively. Due to in-stream deposition, part of these sediment loads would not be fully discharged into the ocean even without anthropogenic disturbances. Thus, the estimated total sediment reduction (50 Gt) is slightly higher than the total decreased sediment determined from the sediment flux data (43 Gt). If other factors were considered (e.g., channel erosion and deposition, deforestation, and precipitation changes), our assessments would match the measured sediment decline better. More descriptions and discussions can be found in the auxiliary material.[1]

[16] Our results of temporal variations in water and sediment fluxes into the ocean and the quantitative assessment of human impacts on the decreased sediment are helpful for further and systematic research on particulate

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2009GL039513. Other auxiliary material files are in the HTML.

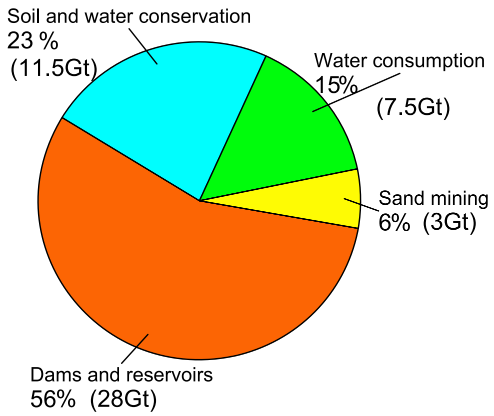

Figure 4. The sediment reduction by human impacts on decrease in nine major Chinese rivers entering the seas during 1959–2007 by pie chart.

and dissolved geochemical matter fluxes discharged into the ocean by Chinese rivers and other rivers around the world.

[17] **Acknowledgments.** The work is supported by NBRPC (2002CB412400), DFMEC (200804231011), NSFS (Y2007E14), NSFC (40906024) and Key Lab of Submarine Geosciences and Prospecting Techniques of Ministry of Education (2007). We thank the anonymous referees and GRL Editors Paolo D'Odorico and Praveen Kumar for valuable suggestions.

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