Will river erosion below the Three Gorges Dam stop in the middle Yangtze?

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ABSTRACT

The environmental impact of the Three Gorges Dam has been a subject of vigorous academic, political and social debate since its inception. This includes the key issue of post-dam river channel erosion, which was predicted by the feasibility study to extend to the river mouth. In this paper we examine the geomorphic response of the channel of the middle Yangtze for 660 km downstream of the dam. Using data on channel characteristics, bed material and sediment transport, we show that in the decade following the dam closure, pre-dam seasonal erosion has been replaced by year-round erosion, a pattern most marked at the upstream end of the study area. The sediment carrying capacity of the river channel has been largely reduced below the dam. The locus of bed scour has moved progressively downstream, ceasing as the bed material became too coarse to be transported (e.g. D_{50}: 0.29 mm pre-dam coarsened to 20 mm below the dam by 2008). About 400 km below the dam there is a reduction in channel slope that changes the sediment carrying capacity from 0.25 kg m^{-3} to only about 0.05 kg m^{-3}, which is insufficient to move bed sediment. The new long-term hydro-morphological equilibrium that will be established in this section of the middle Yangtze will prevent the further incision downstream initiated by the Three Gorges Dam. The results suggest that the full extent of adverse environmental impact predicted by the pre-dam studies will not eventuate.

1. Introduction

Although river channel erosion below dams is a common phenomenon all over the world (ICOLD, 2009), there is great diversity in outcomes in response to regional geology, geomorphology, hydrology, and social/administrative factors (Petts, 1980). For example, although incision of 3–8.5 m below the Aswan Dam on the Nile River in Egypt was predicted, there was actually only a negligible about 0.45 m (Biswas, 2002). This is because ca. 60% of the water is diverted below the dam for extensive irrigation (Cao and Chen, 1998). On the Goulburn River, Australia, little incision occurred below the Eildon Reservoir because the regulated flows are not competent to transport the bed material (Erskine, 1996). Downstream of the Butgenbach Dam on the Warche River, Belgium, incision halted quickly when the bedrock base of the channel was reached (Assani and Petit, 2004). In the case of the Clatworthy Dam on the River Tone, Somerset, UK, there has been a reduction in channel capacity as channel-forming peak discharges have been reduced by ~40% (Gregory and Park, 1974). There are, of course, many examples of serious channel incision below dams in relation to regional geographic conditions: e.g. 6 m, Davis Dam, Colorado River, USA (Kondolf, 1997); 7.5 m, Hoover Dam, Colorado River, USA (ICOLD, 2009); 6 m, Saulspoort Dam, Ash River, South Africa (ICOLD, 2009). Nevertheless, bed erosion is not the only possibility and local conditions may determine a variety of outcomes.

The middle Yangtze River has a long history of erosion and sedimentation, but conditions have changed following the construction of the Three Gorges Dam (TGD, completed in 2003), the first major dam on the main channel of the river (Pan et al., 2014). For the TGD, the predictions prior to dam construction were that river channel erosion would extend downstream nearly to the river mouth (China Institute of Water Resources and Hydropower Research (CIWRHR), 2002; Changjiang River Scientific Research Institute, 2002). As there is now a record developing of the actual outcomes below the TGD, a number of papers have been produced that describe the outcomes thus far and attempt to refine the longer term predictions. For example, Wang et al. (2009) used hydro-variables and pre-dam riverbed sediments to calculate erodibility of the river channel, and from this to simulate the mor-

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phological change after damming. Yuan et al. (2012), on the basis of investigation pre- and post-dam, established the relationship between discharge and sediment flux of the middle Yangtze at a seasonal scale, and pointed out that there has been a shift to more scour in the channel post-dam and this weakens downstream. These results are consistent with those reported by Dai and Liu (2013) who observed thalweg scour post-dam that weakened with distance downstream from the dam.

These studies suggest that the model of downstream effects of the Three Gorges Dam proposed in the pre-dam feasibility studies, as described above, are not what is now being seen to occur in reality. In this paper we focus our interest on that section of the middle Yangtze River directly downstream of the TGD from Yichang to Hankou (~660 km; Fig. 1). Given the variety of possible outcomes of the interruption of sediment continuity by dams as described above, we investigate in detail what has happened in this section of river and take account of the specific characteristics of the channel to assess the likely longer term impact. Specific questions this paper deals with are: 1) how has this section of the Yangtze responded to the TGD in the decade following its completion; 2) what are the changing sediment dynamics; and, in this context, 3) can we foresee a new stage of hydro-morphological equilibrium in this section of the river-channel?

To answer these questions we use data collected during fieldwork and a large database assembled using published and unpublished sources. We use grain-size analysis, sediment rating curves, calculated unit stream power and sediment carrying capacity, to attempt a thorough examination on the post-dam river channel erosion in the middle Yangtze and an in-depth discussion on the changing sediment dynamics of the river channel before and after damming, particularly the role of local changes in channel conditions; and finally we will assess the extent of river channel transition towards a new stage of hydro-morphological equilibrium.

2. Study area

The Yangtze River originates from the Tibetan Plateau and flows >6000 km into the East China Sea (Fig. 1). The river basin area is 1.8×10^6 km^2. The middle Yangtze River basin is a typical meandering river system, extending 960 km from Yichang to Hukou (Fig. 1). The Yangtze here is flowing on deep alluvial sediments and no bedrock is exposed. The river is located in an extensive floodplain which includes Dongting Lake with a water surface area of 2500 km^2 that has experienced heavy siltation by outflows via three tributaries of the Yangtze River (Chen et al., 2001). Of note, there are 3 (originally four, though one has silted up recently) channels that connect the Yangtze mainstream to the lake (Fig. 1A). Water and sediment from the Yangtze can flow into the lake via these channels, mainly during the flood season, and return to the Yangtze at Chenglingji (Fig. 1A). The river channel gradient below Chenglingji is lower than that upstream (Wang et al., 2009). Dongting Lake has its own drainage basin from the south that supplies water and sediment to the Yangtze (Chen et al., 2001). The Han River, another tributary of the middle Yangtze flows into the Yangtze at Hankou (Fig.1A).

The Gezhouba Dam, completed in 1981, was the first dam on the main channel of the Yangtze. It is a run of the river weir, located just upstream of Yichang (Fig. 1) that trapped sediment and caused some downstream incision directly following its completion (Dai et al., 2005). The Three Gorges Dam (TGD) (Fig. 1), completed in 2003 is physically very large but is relatively small in hydrological terms as its storage capacity is only 9% of the discharge of the Yangtze at this site (Chen et al., 2016).

The major impact of the TGD on channel behavior comes from the fact that the coarser fraction of the sediment being transported by the Yangtze is retained in the dam, allowing only the finer sediment to pass through the dam, a well-known phenomenon (ICOLD, 2009). Yang et al. (2014) show that the median grain size

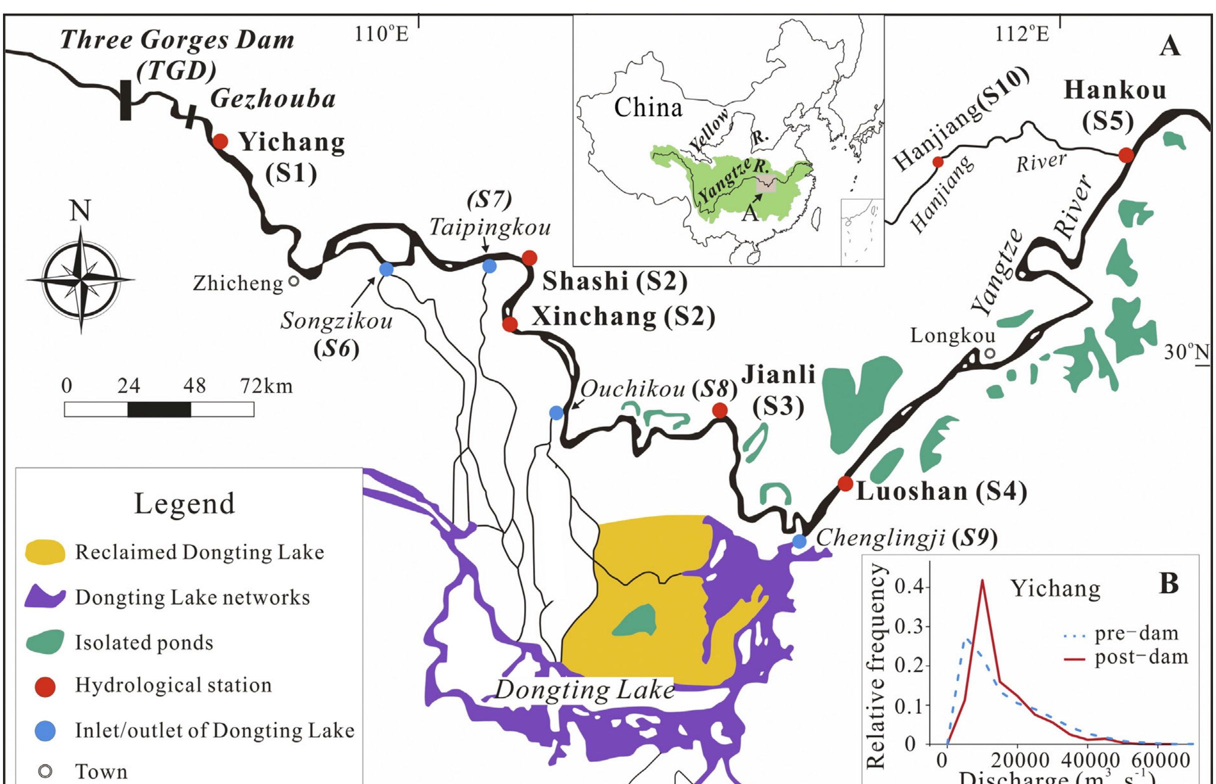

Fig. 1. The study area in the middle Yangtze River basin.

(D_{50}) of sediment trapped in the TGD is 11 μm and that sediment discharged through the dam is finer than 5 μm. Freshwater discharge is relatively little affected as it is operated for most of the year as a transparent storage. Chen et al. (2016) showed that the flow changes caused by the dam are an increase in the period January to March when extra water is released through the turbines and a decrease in October when water is retained for later release in the winter. Otherwise, flows remain little changed by the operation of the dam (Fig. 1B).

3. Materials and methods

We use data for suspended sediment concentrations pre- and post-dam to assess changes in sediment flux, and data on the grain size distributions of both suspended and bed material to assess changes related to the construction of the dam. We also assess changes in sediment carrying capacity in relation to both the changes in sediment concentration and grain size and to the changes in the nature of the channel in the downstream direction.

3.1. Data sources

Discharge and suspended sediment concentration (SSC) data (daily for 1955–1988; monthly for 2000–2014) for 9 hydrological gauging stations were sourced from the Changjiang Water Resources Commission (CWRC) (http://www.cjw.gov.cn), for the following stations (Fig. 1): Yichang (S1), Shashi (S2), Jianli (S3), Luoshan (S4), Hankou (S5), Songzikou (S6), Taipingkou (S7), Ouchikou (S8), Chenglingji (S9) and the Hanjiang River (S10). Shashi (S2) includes data from Xinchang, a nearby station that covers a different time period.

The grain size distribution of the suspended sediment was collected from stations (S1–S5) averaged for the period 1984–2002, prior to the closure of the dam, and for the period 2003–2008 after the dam came into operation (CIWRHR, 2002; Shen et al., 2011). The median grain sizes of suspended sediment were sourced from the CWRC (CWRC, 2000–2014; Yang et al., 2011) for the period 1987–2014 for S1–S5 (Supplementary Information Table A.1).

Discharge, SSC, and grain size distributions were collected by the CWRC, following standard procedures of the Chinese Ministry of Water Resources (CWRC, 1950–1988). The SSC was measured at six points down the water profile (surface, 0.2 H, 0.4 H, 0.6 H, and 0.8 H and the bottom) for water samples taken at the gauging stations. Measurement was 7–10 times per month during the non-flood season, but daily in the flood season. All measured SSC were then interpolated to daily values by the CWRC (1950–1988). Sieve and pipette methods were applied to the grain size analysis before 2010, and then by the Beckman Coulter Laser Diffraction Particle Size Analyzer after that time (CWRC, 2000–2014).

In total, 64 samples of riverbed sediment of the middle Yangtze River channel at S1–S5 were collected by the CWRC, covering the years of 1984–2008, (CIWRHR, 2002; Shen et al., 2011). The grain size distribution of the riverbed sediment was determined as follows: 1) removal of particles of gravel size and larger; 2) sieve and pipette methods were applied to determine the grain size distribution of the remaining material. The median grain size of the 64 samples was calculated, including the gravel component (Supplementary Information Table A.2). Average grain size distributions were determined for the pre- (1984–2002) and post-dam periods (2003–2008) (CIWRHR, 2002; Shen et al., 2011).

In 2003 before the closure of the TGD, we measured stream velocity, depth and bed slope using a Teledyne RD Instruments 600 kHz acoustic Doppler current profiler (ADCP) along the centre of the river from Yichang to Hankou and repeated this in 2011 (Supplementary Information Table A.3). All the location information for the two sets of measurements was recorded by a Trimble real-time differential global positioning system (DGPS).

3.2. Methods

Using mean monthly discharge and SSC data, we have calculated the mean monthly and mean annual sediment load in the main channel at each of the five gauging stations for both the pre- and post-dam periods (Fig. 2A and B). We have also calculated the sediment budget for the whole reach (S1 to S5) and the budgets for individual sections between successive gauging stations, taking account of the losses through distributary channels (S6, S7, S8) and gains from the tributaries (S9 and S10) in the relevant sections for both pre- and post-dam periods. These have been plotted as differences in monthly sediment load between the upstream and downstream stations of each reach for pre- and post-dam periods (Fig. 2C).

In this paper we use the term *'suspendable material'*, to describe that part of the suspended load coarser than the finest 10% of the bed material (i.e. the coarsest part of the suspended sediment) at each gauging site (Qian and Wan, 2003). The grain size at 10% of riverbed sediment (Fig. 3a, b) is used to distinguish between wash load (%) and *suspendable material* (%) (Fig. 3c, d) (Qian and Wan, 2003). The percentage of SSC that is *suspendable material* at each station is plotted as suspendable material concentration (SMC) in Fig. 4.

We have calculated sediment carrying capacity pre-dam and for a sequence of years post-dam, using the formula of Zhang et al. (2007), which has been used previously in the study of sediment transport of the Yangtze River:

$$S_v = \mathrm{K}\left(\frac{\mathrm{U}^3}{\mathrm{gR}\omega}\right)^{\mathrm{m}}. \tag{1}$$

where S_v – sediment carrying capacity (kg m^{-3}); U – depth-averaged flow velocity (m s^{-1}), sourced from Wang et al. (2009); g – gravitational acceleration; R – hydraulic radius (substituted by water depth, m); K and m are variables determined by the value of $\frac{U^3}{gR\omega}$, and were sourced from Zhang et al. (2007); ω – settling velocity of suspended sediment (m s^{-1}), calculated using the formula adopted by the Chinese Ministry of Water Resources in 2010 and used by Yang (1996), Kuang (2011) and Shao and Wang (2013):

$$\omega = -9\frac{\nu}{D} + \sqrt{\left(9\frac{\nu}{D}\right)^2 + \frac{\gamma_s - \gamma}{\gamma}gD}. \tag{2}$$

where ν – kinematic viscosity coefficient ($\nu = 10^{-6}$ m^2 s^{-1}); γ_s – bulk density of riverbed sediment (N m^{-3}); γ – bulk density of water (N m^{-3}); D – the median grain size of the riverbed sediment (m). At each flow level the median grain size used in Eq. (2) has been taken from Table A.2 (Supplementary Information) (note: a different descriptor applies to the y-axes in Fig. 4 for these curves even though the absolute values remain the same).

Sediment carrying capacity at each site for both pre- and post-dam conditions has been calculated using Eqs. (1) and (2) for a discharge of 40,000 m^3 s^{-1}. To estimate the sediment carrying capacity in the future, the maximum grain size of sediments buried in the channel were used, being 70 mm for Yichang (Shen et al., 2011), 60 mm on average for Shashi (Lu et al., 2012), and 2 mm for Jianli, Luoshan and Hankou (CIWRHR, 2002; Shen et al., 2011). The sediment flux post-dam at each gauging station (S1–S10) from CWRC (2000–2014), and the differences between the upstream and downstream stations were used to help estimate the load leaving or entering the channel.

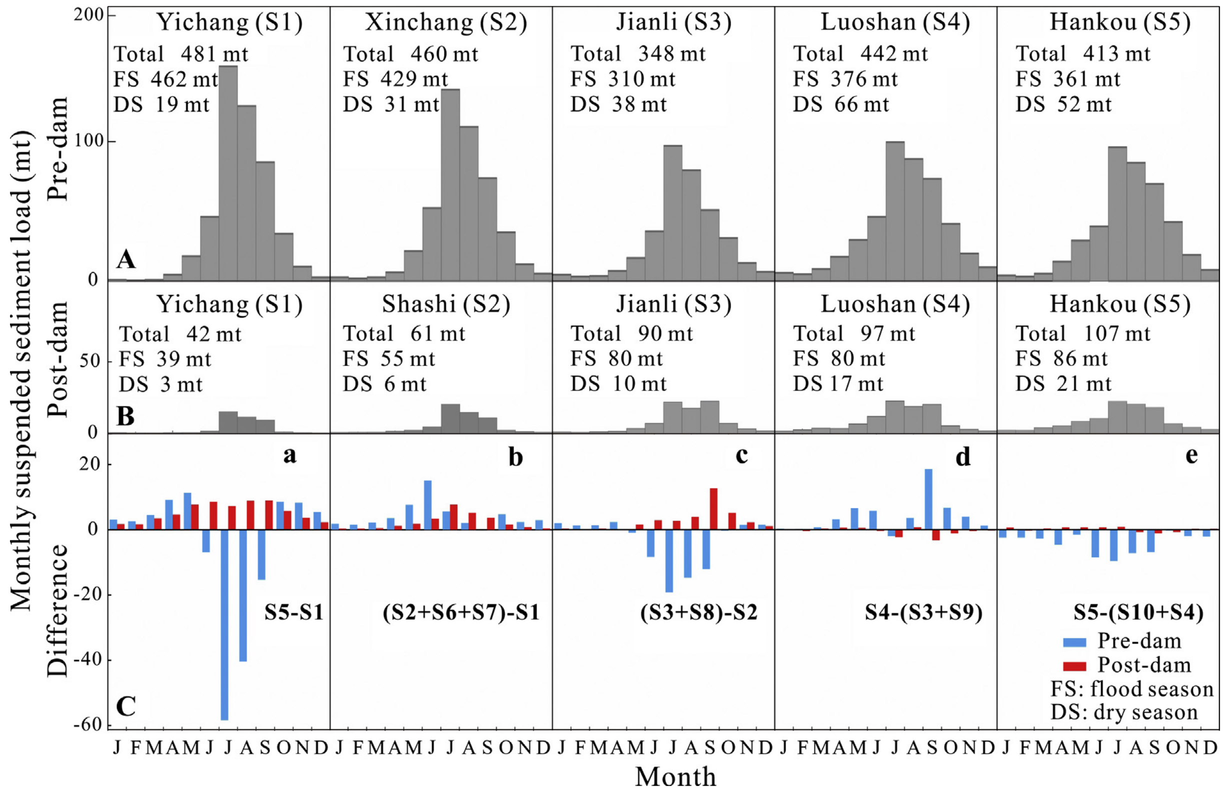

Fig. 2. Monthly suspended sediment loads at the five gauging stations on the Yangtze channel before (A) and after (B) the construction of the Three Gorges Dam. (C) Net changes in sediment load pre-and post-dam: (a) – over the whole study reach; (b) – between S1 and S2 less losses into Dongting Lake via S6 and S7; (c) – between S2 and S3 less losses into Dongting Lake via S8; (d) – between S3 and S4 plus gains from Dongting Lake at S9; (e) – between S4 and S5 plus gains from the Hanjiang River at S10.

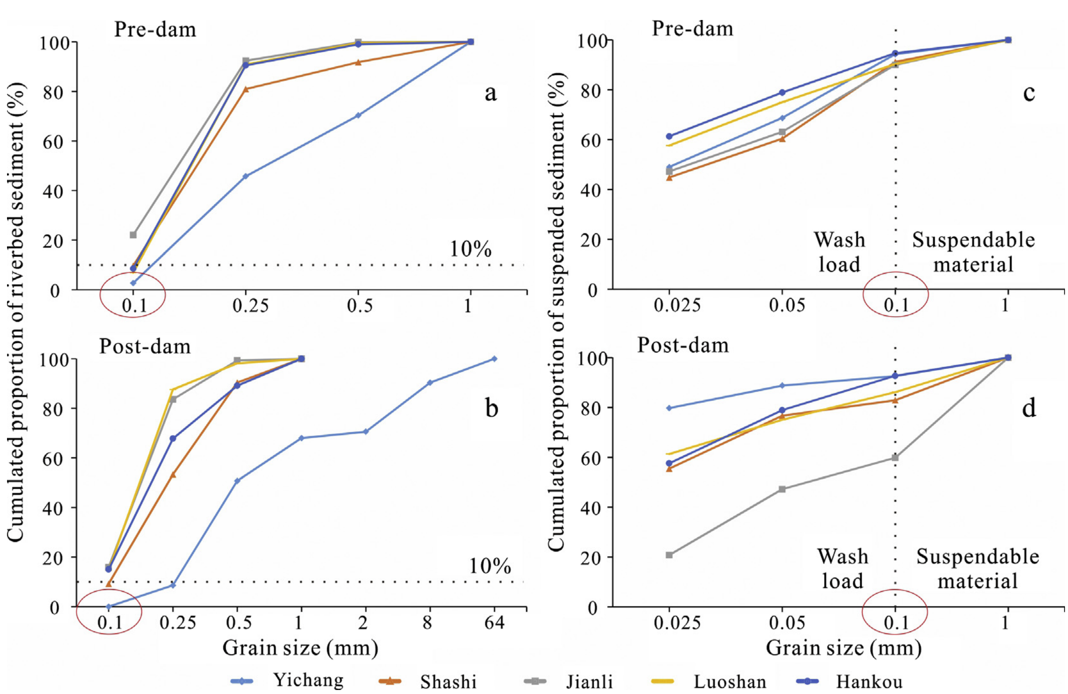

Fig. 3. Distribution of riverbed sediment of 5 gauging stations (S1-S5) pre- (a) and post-dam (b); distribution of suspended sediment of 5 gauging stations (S1–S5) pre- (c) and post-dam (d). Note: the grain size at 10% of riverbed sediment (a, b) is used to separate between wash load (%) and suspendable material (%) (c, d).

ADCP data were utilized to calculate stream power per unit channel width by the following equation (Bagnold, 1966):

$$W = \frac{\rho g Q S}{b}. \quad (3)$$

where W – the unit stream power (kg m^{-3}); ρ – the density of water (kg m^{-3}); g – gravitational acceleration (9.8 m s^{-2}); Q – the discharge (m^3 s^{-1}); S – the channel slope; b – the width of the channel (m).

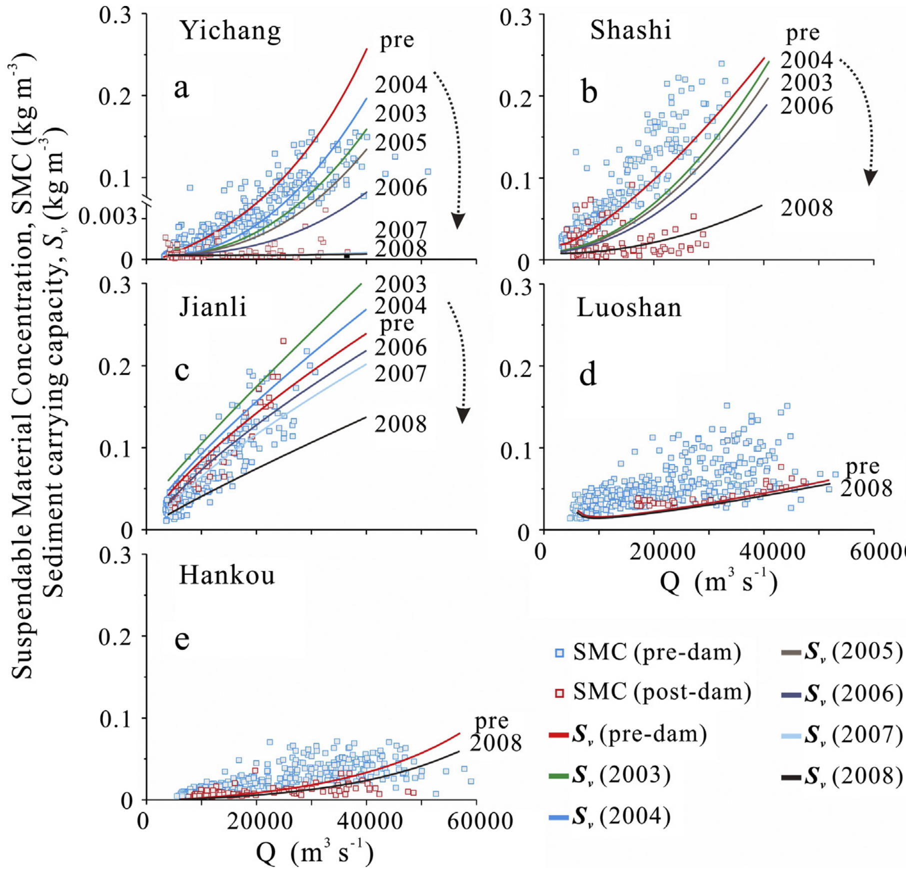

Fig. 4. Suspendable material concentration (SMC) and sediment carrying capacity (S_v) pre and post the Three Gorges Dam for five stations sequentially downstream.

4. Results

Before the TGD, the annual average sediment load delivered downstream decreased gradually from 481 mt at Yichang, to 460 mt at Shashi/Xinchang, to 348 mt at Jianli, increased to 442 mt at Luoshan, and then decreased again to 413 mt at Hankou (Fig. 2A). It is important to note that the sediment load lost from Yichang to Xinchang/Shashi consists of two parts: sediment deposited in the main channel and sediment going into Dongting Lake via 3 inlets (S6, S7 & S8; Figs. 1A; 2C). Similarly, the sediment load increase from Jianli to Loushan includes a part being eroded from main channel and a part sourced from Dongting Lake through Chenglingji (S9, Fig. 1A). The difference from Luoshan to Hankou includes the changes happening in the main channel and input from the Hanjiang River (S10, Fig. 1A). This shows that 101 mt y^{-1} was deposited in the middle Yangtze during the flood season (Fig. 2A), particularly in Dongting Lake via the 3 inlets (Fig. 2A & C) (Chen et al., 2010). In the dry season approximately 33 mt y^{-1} was eroded (Fig. 2A). Therefore this section of the middle Yangtze River was a sediment sink prior to damming by the TGD.

In contrast, after the damming in 2003, although both multi-year average and seasonal sediment load show a significant reduction at every station (Fig. 2B), sediment load increased all the way downstream for both annual average (42 mt at Yichang; 61 mt at Shashi; 90 mt at Jianli; 97 mt at Luoshan; 107 mt at Hankou) and in each season (Fig. 2B), which means erosion happening all the time (the positive values in Fig. 2C). In addition, the difference between two adjacent hydrological stations demonstrates a clear map of the erosion and siltation pattern change from seasonal periodical variation in pre-dam period to continuous erosion during the post-dam period (Fig. 2C). Apparently, this indicates that erosion is happening during the entire year and the middle Yangtze has altered from a sediment sink to source after the construction of the TGD.

Fig. 3 shows the grain size distribution of riverbed sediment (Fig. 3a, b) and suspended sediment measured sequentially downstream from S1 to S5, pre- and post-dam (Fig. 3c, d). The grain size corresponding 10% of riverbed sediment in Fig. 3a, b, (~0.1 mm) is used to divide wash load and suspendable material in Fig. 3c, d.

At Yichang SMC (determined as described above) post-dam is much lower than pre-dam as the bed material is removed without replenishment from upstream (Fig. 4a). This phenomenon is also seen at Shashi though the post-dam SMC levels are higher than at Yichang (Fig. 4b). At Jianli there is so far no separation evident in the data between the pre- and post-dam SMC (Fig. 4c). At both Luoshan and Hankou the post-dam SMC are lower than pre-dam (Fig. 4d, e).

Also shown in Fig. 4 are curves of sediment carrying capacity (S_v) for the pre-dam period and for individual years post-dam, calculated using Eqs. (1) and (2). The greatest separation between them is at Yichang (Fig. 4a) where the curves for 2007 and 2008 show very low carrying capacities (<0.01 kg m^{-3}) (Table 1). Post-dam reductions in carrying capacity are also evident at Shashi and Jianli (Fig. 4b, c), though apparently not yet as far advanced as at Yichang and there is an immediate post-dam increase in carrying capacity at Jianli. In the case of Luoshan and Hankou, only two carrying capacity curves are plotted, one for pre- and one for post-dam (2008); the whole time series has not been plotted as they all just overlie each other (Fig. 4d, e).

Fig. 4 also shows the relationships between sediment carrying capacity (S_v) and SMC for the pre- and post-dam periods, measured independently. Before damming, it is clear that much of the SMC

Table 1
Sediment carrying capacity at discharge of 40,000 $m^3 s^{-1}$.

Station	Pre-dam	2003	2004	2005	2006	2007	2008
Yichang	0.258	0.151	0.189	0.127	0.080	0.004	0.001
Shashi	0.246	0.228		0.248	0.195		0.072
Jianli	0.243	0.310	0.273	0.219	0.219	0.199	0.135
Luoshan	0.046	0.046	0.046	0.046	0.046	0.046	0.041
Hankou	0.038	0.033	0.038	0.033	0.038	0.012	0.027

lies below the available sediment carrying capacity at Yichang, especially during high discharge (e.g. 0.25 kg m^{-3} at 40,000 m^3s^{-1}) (compare the red line to the blue dots in Fig. 4a). However, this sediment carrying capacity has been reduced to 0.001 kg m^{-3} at 40,000 m^3 s^{-1} (Table 1) after damming, being closer to the SMC at this station (compare the black line (2008) in relation to the red dots in Fig. 4a). Further downstream at Shashi (S2), the SMC pre-dam lies mostly above the available sediment carrying capacity during high discharge. In comparison, most SMC post-dam lies below the sediment carrying capacity during higher discharge (Fig. 4b). Apparently, the post-dam SMC at Jianli (S3) remained almost the same as pre-dam, and much of it lies above the sediment carrying capacity (comparing the black line (2008) to the red dots in Fig. 4c)). Also, there are no obvious topographic changes at Luoshan and Hankou after damming, since most of the SMC pre- and post-dam lies above the available sediment carrying capacity (Fig. 4d, e) (more discussion given below).

5. Discussion

5.1. Erosion and deposition patterns pre- and post-dam

Changing sediment load is a useful criterion for assessing the erodibility of a river channel (Chen et al., 2010). In this study, we use this database to understand the sediment transport in relation to river channel erosion at the seasonal scale pre- and post-dam for 5 major gauging stations, covering the 660 km length of the middle Yangtze (Figs. 1 and 2).

Before damming, the multi-annual sediment load being delivered downstream decreased gradually from 481 mt at Yichang, to 460 mt at Shashi/Xinchang, to 348 mt at Jianli, to 442 mt at Luoshan, to 413 mt at Hankou (Fig. 2A). Our records further show ca. 100 mt a^{-1} sediment deposited in the middle Yangtze during the flood season, (S1–S5; Fig. 2A, C), particularly in Dongting Lake via 3 inlets (S6, S7, S8; Fig. 1A) (Chen et al., 2010), showing it to be a pre-dam sediment sink.

In comparison, post-dam sediment load at both annual and seasonal scale has greatly reduced at each station after the completion of the TGD in 2003. However, sediment load increased along the stations for both multi-annual (42 mt at Yichang; 61 mt at Shashi; 90 mt at Jianli; 97 mt at Luoshan; 107 mt at Hankou) and seasonal scale (Fig.2B,C). This shows that the middle Yangtze has changed from being a sediment sink to a sediment source after damming.

5.2. Changing sediment carrying capacity

The formula for sediment carrying capacity of Zhang et al. (2007) has been used efficiently in assessing river channel erodibility in the Yangtze River (Qian and Wan, 2003; Yuan et al., 2012; Shao and Wang, 2013). The SMC and S_V derived from Fig. 3 and the formula independently can explain the change in riverbed erosion pre- and post-dam.

At Yichang (S1), the suspendable material concentration (SMC) post-dam is much lower than pre-dam (Fig. 4a) as the finer riverbed sediment is being selectively removed and the bed material becomes coarser due to the effect of damming. This winnowing effect is also seen at Shashi (Fig. 4b) though the post-dam SMC levels are higher than at Yichang as this process is ongoing there. At Jianli (S3), there is so far no separation evident in the data between the pre- and post-dam SMC (Fig. 4c). This suggests that winnowing occurring at Yichang and Shashi has yet to start there as material eroded upstream is still being delivered to Jianli and therefore adequate material is available for transport. This can be further applied to both Luoshan and Hankou downstream (Fig. 4d, e), where the post-dam SMC are lower than pre-dam, mostly due to reduced SSC from upstream.

The differences between the curves of sediment carrying capacity for the pre-dam period and for individual years post-dam (Fig. 4) result from the increase in the value of ω in Eq. (1) as the bed material becomes coarser and the flow is less able to lift it into suspension. The greatest separation between them is at Yichang (Fig. 4a) where the curves for 2007 and 2008 show very low carrying capacities (<0.01 kg m^{-3}) as the bed sediment has become so coarse that most of it cannot be entrained. Furthermore, the lowering SMC in relation to decreasing sediment carrying capacity at Yichang after damming indicates limited sediment carrying capacity to mobilize sediment at the site, and the river channel has reached a new hydro-morphological equilibrium (Fig. 4a).

Post-dam reductions in carrying capacity affected by the winnowing are also evident at Shashi and Jianli (Fig.4b, c), though not yet as far advanced as at Yichang. At Jianli there is an immediate post-dam increase in carrying capacity, in 2003 and 2004, which appears to be the result of the short-term transport of finer material from upstream into this reach. The lowering SMC at Shashi is closely associated with the weakening sediment carrying capacity post-dam (Fig. 4b), but this has not yet happened at Jianli (Fig. 4c).

Given the very low carrying capacity at Yichang we estimate that the erosion process has been completed, or nearly so, at this site but that it is still in progress at Shashi and Jianli. In the case of Luoshan and Hankou (Fig. 4d, e), only two carrying capacity curves are plotted, one for pre- and one for post-dam (2008); the whole time series has not been plotted as they all just overlie each other. This shows no-obvious topographic change at the site, and to be further corroborated by the relationship of SMC to sediment carrying capacity in Luoshan and Hankou (Fig. 4d, e), where little influence of the Three Gorges Dam is yet evident.

5.3. Towards new channel equilibrium

The situation 5–10 years after the completion of the Three Gorges Dam is summarized in Fig. 5A. Channel bed incision post-dam is shown in Fig. 5A as reported by the CWRC (2000–2012). The river bed has eroded on average ~3.7 m from Yichang to Zhicheng (Fig. 1A), and less than 1.0 m from Jianli to Hankou. The relatively small amount of incision at Yichang in this period results from the fact that 3 m of incision had already occurred there after the construction of the Gezhouba Dam (Dai et al., 2005). It's worth noting that the erosion at Yichang has basically stopped after 2008 as indicated by the relevant data published in the Bulletin of Yangtze River Sediment (CWRC, 2000–2014).

Sediment carrying capacity at each site for both pre- and post-dam conditions has been calculated using Eqs. (1) and (2) for a dis-

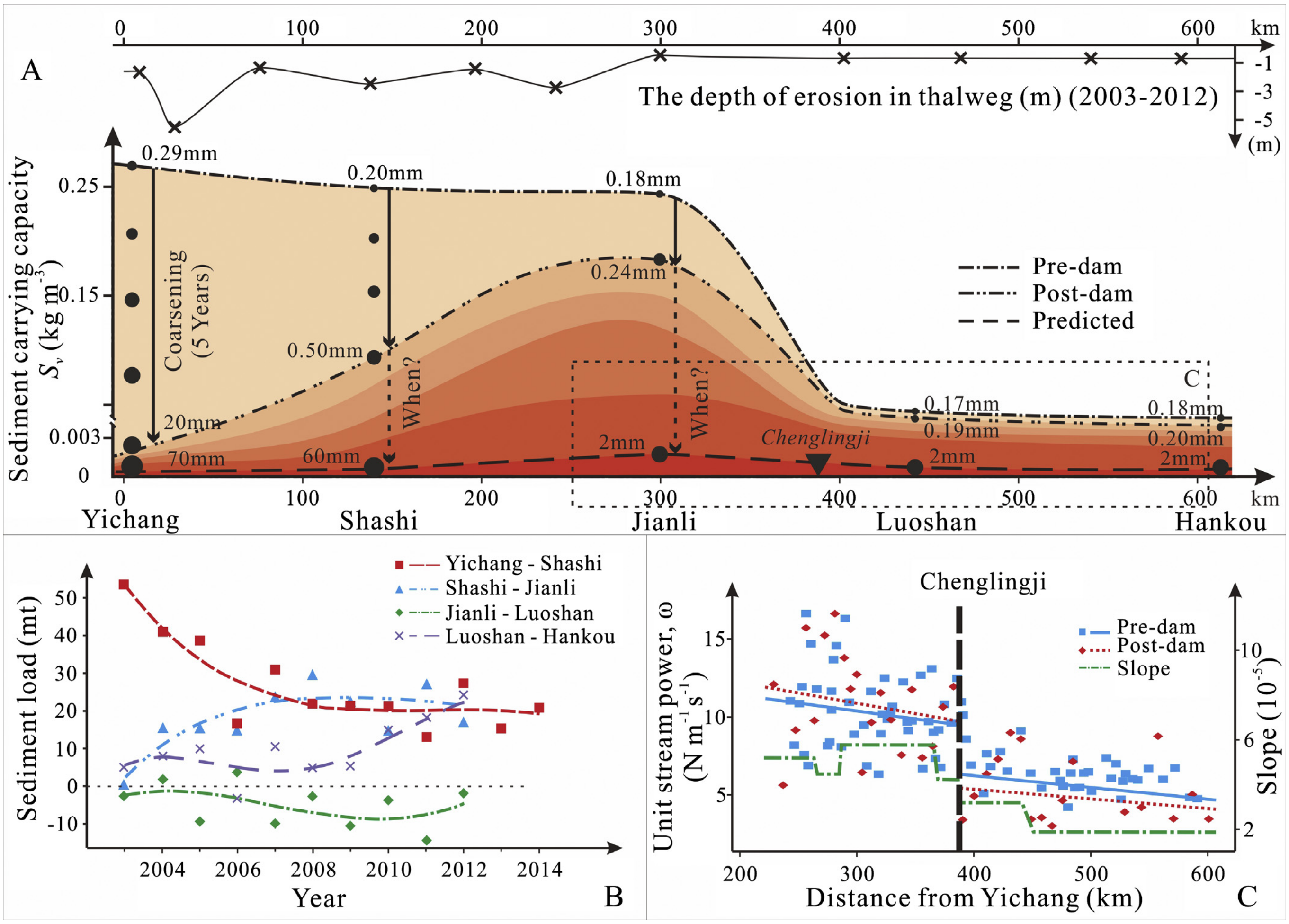

Fig. 5. A) Schematic diagram showing downstream changes in sediment-carrying capacity at a discharge of 40,000 m^3 s^{-1} in the middle Yangtze River pre- and post-dam, and the predicted value based on expected coarsening of riverbed sediment. Measured incision amount from 2003 to 2013 is plotted above (CWRC, 2000–2014); B) Annual sediment loads generated in the four reaches of this section of the river from 2003 to 2012/14 (CWRC, 2000–2014). Curve fitting by polynomial; C) Downstream trends of unit stream power from Jianli (S3) to Luoshan (S4) pre- and post-dam and river channel slope through this reach (Data sourced from Wang et al. (2009)).

charge of 40,000 m^{3}s^{-1} and is plotted in Fig. 5A. Bed material is becoming coarser at each site (Fig. 5A) where the grain sizes on the carrying capacity lines at each site are the D_{50} of the bed material. Critical variables in these calculations are sediment grain size (Supplementary Information Table A.2), and flow velocity which is a function of channel slope. Under pre-dam conditions, the carrying capacities at Yichang, Shashi and Jianli are quite similar, at around 0.25 kg m^{-3}. The pre-dam carrying capacities at Luoshan and Hankou are substantially lower at ~0.05 kg m^{-3} as a result of the lower stream gradient there. Carrying capacity post-dam increases progressively from Yichang to Jianli (Fig. 5A), as the degree of coarsening of the bed material decreases. However, no significant change in carrying capacity is evident at Luoshan and Hankou.

The end point of the erosion of the channel will be reached when the bed material becomes effectively too coarse to move or bedrock is reached. We attempt to assess this by considering the nature of the material that will be exposed by the erosion of the bed at each of these sites. Using the coarsest material in those sediments as the particle size, D, in Eqs. (1) and (2), we have calculated the sediment carrying capacity for each site as to indicate the possible outcome as the erosion currently evident in the Yichang to Jianli reach progresses, and this is plotted as the lowest line (shown as "predicted" in the figure key) in Fig. 5A.

In Fig. 5B we plot the difference in the measured sediment load between the upstream and the downstream stations but adjusted for load leaving or entering the channel via Dongting Lake. The reach just below the dam, Yichang to Shashi, shows a decline in load up to 2008 after which it appears to remain steady. The next downstream reach, Shashi to Jianli, shows an increase to 2008 after which it also appears to remain steady, in both cases at around 20 million tons per year (mt a^{-1}) (Fig. 5B). In the Jianli to Luoshan reach net deposition has been occurring throughout this period (Fig. 5B) and there is an obvious reduction in slope at Chenglingji to facilitate this deposition (Fig. 5C). The Luoshan to Hankou reach has low values until 2009, indicating no significant erosion in this reach and some evidence of net deposition (cf. Fig. 2C-d, e). After 2009 load tends to increase and the load for 2012 is the highest in the record (Fig. 5B).

Incision has now effectively ceased at Yichang (Fig. 5A). Bed erosion continues from Yichang to Shashi and Shashi to Jianli, and will carry on until the downstream progressing incision amours the bed and erosion ceases. Incision will proceed into the Jianli to Luoshan reach but will be arrested by the reduction in slope that occurs in that reach at Chenglingji (Fig. 5C). As sediment is exported from Luoshan to Hankou the bed material will become coarser leading to a reduction in sediment carrying capacity (Fig. 5A) and incision in that reach would cease. A new hydro-morphological equilibrium would be established allowing incoming sediment from the upper Yangtze (currently ~10 mt a^{-1} at Yichang) and the sediment supplied from Dongting Lake (currently ~20 mt a^{-1} at Chenglingji) and the Hanjiang River (~0.7 mt a^{-1}) to be transported through the system. There would be little sediment produced in this section of the river in future. Given the progression of the incision as shown in Fig. 5A (only ~5 years after dam completion), this new equilibrium could be established over a period of decades.

6. Concluding remarks

River channel incision in response to the construction Three Gorges Dam has attracted worldwide attention. These concerns relate to the river channel behaviour and its environmental and social consequences. The government feasibility studies before dam construction predicted that riverbed incision would extend right to the estuary, a distance ~1600 km from the dam site at Yichang. Here, on the basis of substantial field observations and sediment analysis, we show that the bed incision will probably stop at Chenglingji, ~400 km below the dam site. Bed incision is occurring immediately below the dam (Yichang), and rapidly extending downstream. The river bed sediment below the dam is becoming very coarse and incision will soon cease. However, the bed incision is rapidly extending to Chenglingji, where there is an obvious reduction in channel gradient. This minimizes the sediment carrying capacity of the flow, and the intensive river incision will cease at this point. Given the timing of river incision after damming, it is estimated that a new morpho-dynamic equilibrium will be established in the river section below Chenglingli of the middle Yangtze, perhaps over a period of decades.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.08.057.

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