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ORIGINAL ARTICLE

Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China

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Abstract Planning for the extraction of aggregates is typically dealt with at a case to case basis, without assessing environmental impacts strategically. In this study we assess the impact of sand mining in Poyang Lake, where dredging began in 2001 after sand mining in the Yangtze River had been banned. In April 2008 concern over the impact on the biodiversity led to a ban on sand mining in Poyang Lake until further plans could be developed. Planning will require consideration of both sand extraction in relation to available sediment resources and also environmental impacts within the context of future demand for sand in the lower Yangtze Valley. We used pairs of near-infrared (NIR) Aster satellite imagery to estimate the number of vessels leaving the lake. Based on this we calculated a rate of sand extraction of 236 million m^3 $year^{-1}$ in 2005–2006. This corresponds to 9% of the total Chinese demand for sand. It qualifies Poyang Lake as probably the largest sand mining operation in the world. It also indicates that sand extraction currently dominates the sediment balance of the lower Yangtze River. A positive relation between demand for sand and GDP, revealed by historic data from the USA, suggests that the current per capita demand for sand in China might increase in the near future from 2 to 4 m^3 $year^{-1}$. We review various environmental impacts and question whether it will be possible to preserve the rich biodiversity of the lake, while continuing at the same time satisfying the increasing Chinese demand for sand. Finally we review alternative options for sand mining, in order to relieve the pressure from the Poyang Lake ecosystem.

Keywords Sand mining · Environmental impact · Hydrology · Sediment balance · Biodiversity

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Introduction

The demand for sand and gravel is growing around the world, particularly in newly developing countries, such as India and China, where the rapid economic development causes strong growth of the construction industry. Extraction of sand and gravel resources has a number of adverse environmental impacts (Sonak et al. 2006; Kondolf 1994, 1997), which were first reported in the developed world. As a result of the above-mentioned globalization of sand mining, concern about environmental impacts is increasingly reported from other countries: for example China (Wu et al. 2007; Lu et al. 2007), Ghana (Mensah 2002) and India (Padmalal et al. 2008). Consequently, it has been argued that, because of this globalizing extent and the magnitude of its impacts, sand mining should be considered as an aspect of global environmental change (Sonak et al. 2006).

However, few studies have considered the impact of sand and gravel mining in a wider context over time scales beyond the duration of mining activities at individual sites. Instead, most studies report the magnitude of extraction and its impacts locally for specific sites and projects. This local orientation reflects a policy setting, which regulates the extraction industry while relying on environmental impact assessment (EIA) to approve individual proposals for extraction at sites of specified and limited extent. In cases of rapidly growing demand, an initial EIA for resource extraction will usually be followed by subsequent ones, as the growing demand renders the existing extraction capacity insufficient. In such cases environmental impact assessment is not an effective tool to protect the environment, because the subsequent EIA's gradually change the environment a scale beyond that envisaged in any individual EIA (Wang et al. 2003). This leads to the situation, where multiple officially approved projects may have combined impacts, which are undesirable and beyond control of the applied planning and impact assessments instruments.

Strategic environmental assessment has been advocated to overcome this shortcoming by reviewing the likely impacts of human activities in the long term and at spatial scales beyond the scope of individual project-based assessments. In the case of sand mining, strategic environmental assessment would require considering the environmental impacts of exploiting available resources in the light of current and future demand. So far, no such strategic environmental assessment of sand mining has been reported.

Recently, intensive sand mining has been reported in Poyang Lake (Wu et al. 2007). The demand for sand is driven by economic growth in the lower Yangtze River valley, where mega-cities like Shanghai and Wuhan are rapidly expanding (Zhao et al. 2006). Dredging of alluvial sediments developed in the lower Yangtze River in the 1990s to supply the construction industry's increasing demand for sand. However, the hundreds of small dredging vessels flocking the stream channel caused frequent accidents on the Yangtze River.

A ban of sand mining was therefore imposed in the middle and lower Yangtze River in 2000 (People's Daily 2000). This led to displacement of dredging to Poyang Lake (Wu et al. 2007), an internationally renowned wetland (Fig. 1). The sand mining in Poyang Lake quickly developed into an industry involving hundreds of large vessels and causing highly turbid waters (Wu et al. 2007). Environmental concerns over this rapidly growing and uncontrolled sand extraction (Guo 2006; Zhang 2007) resulted in a recent decision by the Jiangxi Provincial Government to temporarily postpone sand mining, as of 1 April 2008, so as to carry out an impact assessment and to develop a plan to regulate resumption of sand extraction at reduced scale (Shanghai Daily 2008). Given the future rise in demand of sand it would be wise to plan this continuation strategically.

The time for a strategic assessment might be ripe, as several Chinese scholars (Tang et al. 2007; Bao et al. 2004; Che et al. 2002) appealed for more frequent utilization of strategic environmental assessment. Strategic assessment would require insight in the current magnitude and impacts of sand mining, the expected rise in the regional demand for aggregates, assessment of the impact when satisfying this demand from Poyang Lake and review alternative possibilities. Such assessment would require quantification of current levels of sand extraction, which, although it has been suggested that sand mining in the middle and lower Yangtze River is significant (Yang et al. 2002), has not been quantified to date.

In this paper we present an innovative application of remote sensing imagery to estimate the rate of sand extraction from Poyang Lake, to place this extraction rate in the context of the current and future demand for sand in China and to review limitations to continuation of the current sand extraction in Poyang Lake and examine opportunities for alternative sand resource extraction.

Study area and methods

Study area

Poyang Lake is the largest freshwater lake in China (Fig. 1). Five large rivers carry sediments into the lake, which drains through a channel into the Yangtze River near Hukou. Six protected areas, including one Ramsar site (Poyang Lake National Nature Reserve), have been established to protect the biological diversity of Poyang

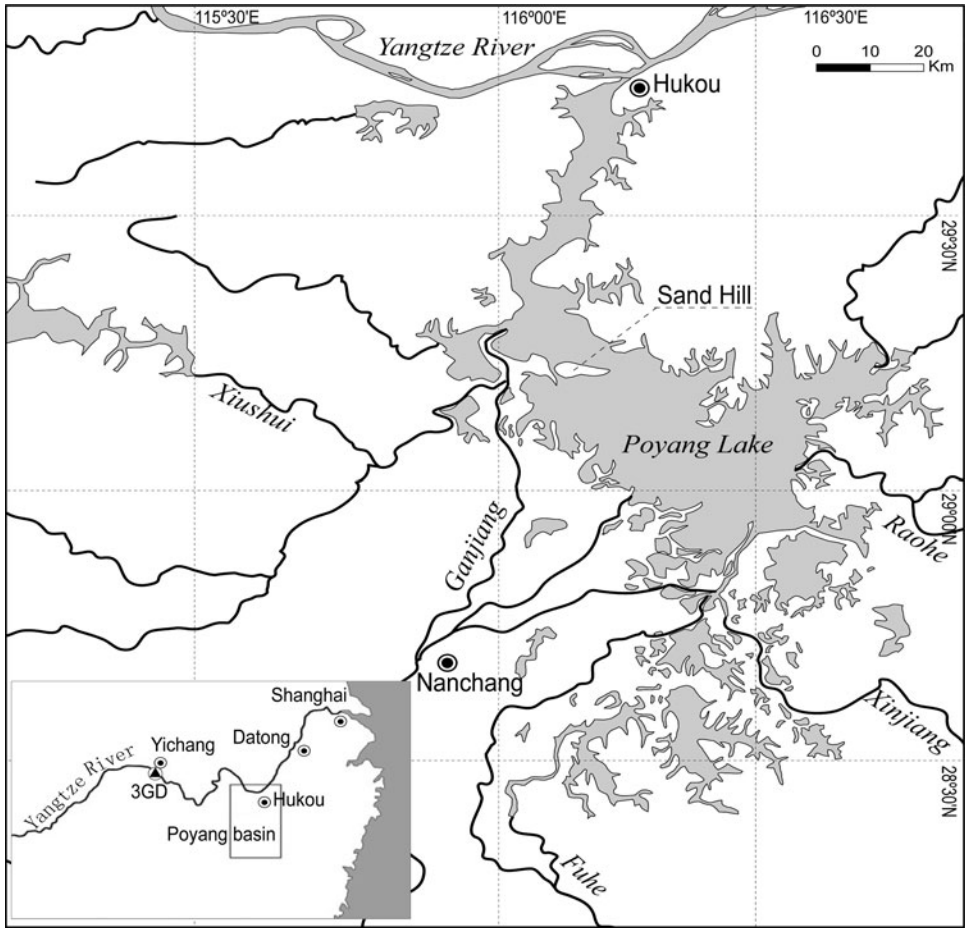

Fig. 1 Map of Poyang Lake showing the channel between Hukou and Sand Hill and the lower Ganjiang River, where the sand extraction is concentrated, and an inset showing the location of Poyang Lake in relation to the Yangtze River and the Three Gorges Dam (3GD)

Lake, which is particularly important for millions of wintering birds. It hosts, for example, 95% of the world population of the endangered Siberian crane (*Grus leucogeranus*) and significant proportions of other red-listed bird species, such as the swan goose (*Anser cygnoides*) and the lesser white fronted goose (*Anser erythropus*) (Barter et al. 2004).

Image processing and calculation of sand exports

Records on the number and load of vessels leaving Poyang Lake collected at Hukou, were unfortunately not at our disposal for the purpose of the current research. We therefore developed an alternative remote sensing approach to assess the volume of sand exported from Poyang Lake, using four Aster images of 3rd July and 24th November 2005 and 17th April and 6th June 2006, to estimate the number of vessels leaving the lake. The Aster sensor creates pairs of near-infrared (NIR) images of the same area, the first image taken at nadir (N) and the second broom (B) image 55 s later. We geo-referenced both images of each pair and visually identified and classified all moving and stationary objects while comparing their location in the N and B image (Fig. 2). Next, we estimated two variables from every image pair: (1) the speed of the moving objects by measuring their displacement in the 55 s between the N and B image; and (2) the distance between neighboring vessels. The average number of vessels leaving per hour was calculated dividing the average velocity by the average inter-vessel distance.

The carrying capacity of the barges, recorded at Hukou on November 23rd 2007, varied between 2,000 and 5,000 tonnes. We used the lower capacity of 2,000 tonnes, in combination with the estimated number of vessels leaving the lake per unit time, to calculate the weight of sand leaving the lake annually. This approach assumes that the flow of barges continued day and night, which was confirmed by observation, and is unaffected by season. To confirm the second assumption we analyzed Aster imagery from both high waters during the monsoon season and low waters in spring and autumn. The sand and gravel export by weight (g) was converted to volume (m^3) using the specific weight of saturated sand of 1.9×10^6 g m^{-3}. Using the specific weight of sand might lead to under-estimation of the volumetric export in the case of a significant fraction of gravel, which has a lower specific weight.

Sediment balance of Poyang Lake

A sediment balance of Poyang Lake prior to the start of dredging was determined using records of average (1960–1990) monthly imports of sediment from upstream and exports into the Yangtze River (JPLDRRI 1995). A sediment balance for the period after the commencement of dredging was determined assuming the same influx from upstream as before, whereas the outflow was based on suspended sediment load measured at Hukou in 2004 and 2005. We compared the sediment balance and the amount of sediment exported from Poyang Lake through sand mining with the average suspended sediment load of the Yangtze River at Yichang and Datong (See Fig. 1) for the period before (1980–2000) operation of the Three Gorges Dam (Chen et al. 2008) and the average suspended sediment load over the first five years (Chinese Sediment Bulletins 2003–2007) after the start of filling of the reservoir.

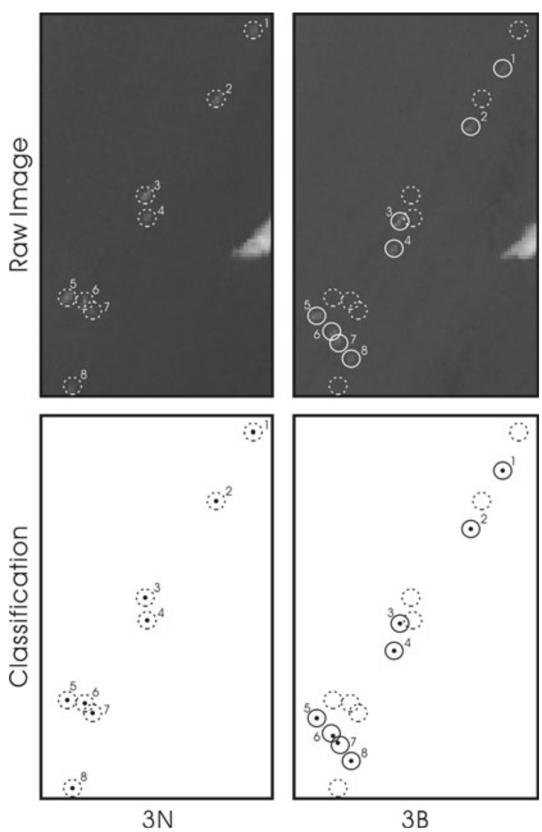

Fig. 2 Example of the processing of a pair of NIR Aster imagery (20th June 2006) showing the displacement of eight vessels during the 55 s between the capture of the nadir (*3N*) and the after broom (*3B*) band, displayed, above according to the original infrared reflectance with low reflective water in *black* and vessels carrying sands in *white*, and below after classification with vessels in *black* and water in *white*

Production of sand and gravel

We combined annual statistics on the production of sand and gravel in the United States for the period 1910–2006 (USGS 2007), Europe for 2006 (statistics for 19 European countries; UEPG 2008) and China for 2006 (Cheng 2006) with information on population size and gross domestic product per capita (expressed in 1990 US $ converted for purchasing power, data from Maddison 2007 and CB & GGDC 2008) to relate the sand production to the gross domestic product on a per capita basis. We assume that sand production represents demand because transportation costs prohibit imports of these commodities.

Results

Measurement of vessel displacement on pairs of NIR Aster images of four different dates revealed that ships moved along the channel out of the lake at average speed of 9.35–12.34 km h^{-1}, while the vessels maintained an average inter-vessel distance of 322–552 m (Table 1). The table further shows that the number of vessels leaving the lake, which averaged 25.6 h^{-1}, varied between dates without evidence of reduced shipping intensity at lower water levels, an observation which suggests that sand mining continued year-round, irrespective of water level.

Taking an average of 25.6 vessels leaving per hour, with an average ship capacity of 2,000 tonnes (2×10^9 g), results in an annual weight of sand exported, 448×10^{12} g $year^{-1}$, which is equivalent to a volume of sand exported (Fig. 3) from Poyang Lake, 236×10^6 m^3 $year^{-1}$. Figure 3 further shows that Poyang Lake had a positive sediment balance (10.3×10^6 m^3 $year^{-1}$) before the introduction of sand mining, which resulted in ca. 2.5 mm $year^{-1}$ sedimentation within the 4,000-km^2 lake. This pre-sand mining sedimentation rate corresponds well with sediment deposition estimates of 2.1 to 2.8 mm $year^{-1}$

Table 1 Water level at Hukou (m above Wusong datum) and average (and standard error) of the velocity (km h^{-1}), distance (km) between neighboring vessels and flux (N h^{-1}) of barges moving out of Lake Poyang estimated from pairs of NIR Aster imagery for four dates in 2005 and 2006

Date	Water level	Velocity	Distance	Flux
3rd July 2005	16.46	10.86 (0.16)	0.552 (0.075)	20.8
24th November 2005	11.95	10.34 (0.42)	0.551 (0.117)	18.8
17th April 2006	13.35	12.34 (0.16)	0.322 (0.024)	38.4
6th June 2006	14.43	9.35 (0.18)	0.439 (0.063)	24.3
Average				25.6

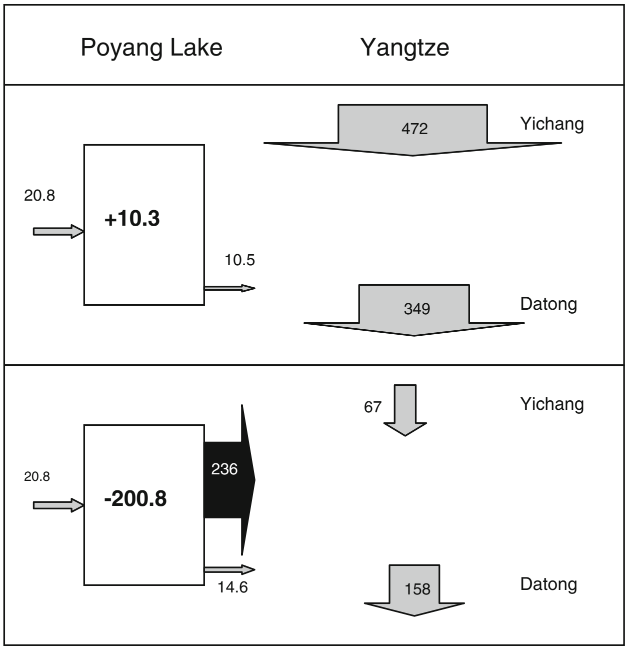

Fig. 3 Sediment budget (10^6 m^3 $year^{-1}$) of Poyang Lake (*gray* = riverine fluxes, *black* = commercial sand export) before (*top*) and after (*bottom*) the introduction of sand mining (2001) and utilization of the Three Gorges Dam reservoir (2003) in relation to the suspended sediment flux of the Yangtze River at Yichang (905-km upstream, see Fig. 1) and Datong (196-km downstream). *Bold figures* represent the net sediment balance of the lake

(Table 2), derived from sediment flux measurements and stable isotope studies.

Remotely sensed analysis of the location of the vessels led Wu et al. (2007) to conclude that the sand mining was concentrated mainly in the channel between Sand Hill and Hukou. Figure 4 shows two high-resolution satellite images taken during low water in winter, revealing dredging-induced scars and local widening of the stream channel created by sand mining.

Figure 3 further reveals that sand mining changed the lake from a net sediment accumulating system ($+10.3 \times 10^6$ m^3 $year^{-1}$) into a sediment exporting system (-200.8×10^6 m^3 $year^{-1}$). The figure also indicates that Poyang Lake contributed an increasing amount of material to the Yangtze River, which we attribute to dredging-induced increase in sediment concentration of the waters leaving the lake. The contribution of Poyang Lake to the sediment balance of the Yangtze River increased from 3 to 9.2%, as a result of combination with a significant reduction of the suspended sediment flux through the Yangtze, following the filling of the reservoir of the Three Gorges Dam.

China's demand for sand is likely to increase as the construction industry expands (Fernandez 2007). The current Chinese per capita sand consumption (based on an estimated sand production of 2.6 billion m^3 $year^{-1}$, Cheng 2006) of ca. 2 m^3 $year^{-1}$ per capita is below that of the USA and the European Union (Fig. 5). Historical data from the USA revealing a strong relation between sand consumption and per capita income suggest that Chinese sand consumption increases to 3–4 m^3 $year^{-1}$ when its per capita GDP surpasses $ 15,000 in 2030 (Maddison 2007). When also considering an 11% population increase by 2030 (Maddison 2007), this suggests that, over the next 20 years, Chinese demand for sand will increase by 55 to 110%.

Discussion

In this study we present a new method to quantify the magnitude of sand mining, based on an innovative application of pairs of NIR Aster imagery. The reliability of the annual volumetric traffic estimation depends on errors in the flux of vessels leaving the lake as well as their volume. We argue that the reported export of 236×10^6 m^3 $year^{-1}$ should be considered as a conservative estimate for two reasons, first because we used the specific weight of sand rather than a mixture of unknown composition of sand and gravel and second because our calculations were based on the lower range of the observed carrying capacities of 2,000–5,000 tonnes. Reduction of the latter error component should be achievable as the Aster imagery has the potential to estimate the size distribution of vessels, an interesting topic for further study.

Although port and river management authorities commonly record shipping intensity, the described method can

Table 2 Sediment deposition rates in Poyang Lake

Source	Period	Sediment deposition		
		Range (mm $year^{-1}$)	Average (mm $year^{-1}$)	Volume (10^6 m^3 $year^{-1}$)
Zhang et al. 1988[a]	1956–1980		2.6	10.4
Ye 1991[b]	1960–1985	1.0–3.2	2.1	
Han and Zhu 1992[b]	1960–1980	1.6–5.2		
Xiang et al. 2002[b]	1960–1990	1.0–6.2	2.8	12.5[c]
Wang 1996[a]	1952–1984		2.4	9.7[c]

[a] Based on measured suspended and estimated bedload sediment moving into Poyang Lake

[b] Sedimentation since 1960s using ^{137}Cs and ^{210}Pb

[c] Calculated based on lake surface area of 4,000 km^2

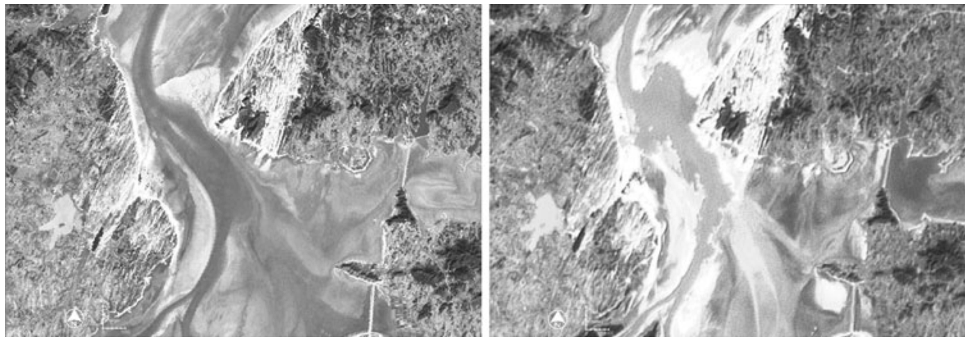

Fig. 4 Landsat TM image of 10th December 1999 (*left*) and Beijing image of 2nd February 2007 (*right*) of the area just above Sand Hill, taken during low waters in winter, which reveal that dredging locally widened and created scars along stream channels

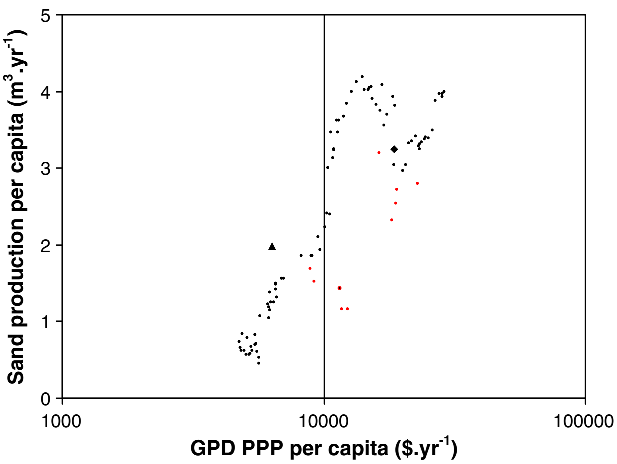

Fig. 5 Sand production per capita (m^3 year^{-1}) in relation to gross domestic product per capita in 1990 international dollars corrected for purchasing power parity (GDP PPP) in the United States (*filled circle*, 1910 to 2006, *filled red circle* = fall back during and after WW II and recessions), European Union (*filled diamond* 2006) and China (*filled triangle* 2006). The surge and peak in the US data above \$10,000 corresponded to the 1950–1966 period when construction of the Interstate Highway System increased demand (Tepordei, undated)

provide independent data on the intensity of aquatic transport, where it is difficult to access data collected by port authorities. Second, it offers an independent method to assess the extent of resource extraction, which might be useful in view of audits requiring independent cross-checks of official data.

The export of sand from Poyang Lake of 236 × 10^6 m^3 year^{-1} represents 9.1% of the total Chinese production of sand in 2006 (2.6 × 10^9 m^3 year^{-1}, Cheng 2006), 17.9% of that of the USA in 2006 (1.32 × 10^9 m^3 year^{-1}, USGS 2007) and exceeds the 2006 sand and gravel production of Germany (UEPG 2008). Furthermore, the total sand and gravel production in Germany and the USA are derived from hundreds of sites dispersed throughout these countries. For example, in 2000 the three largest operations in the USA together accounted for a total of 16 million m^3 (Bolen 2000). The rate of extraction of sand and gravel from Poyang Lake is probably the highest in the world as it is more than an order of magnitude higher than the three largest sand mining operations in the USA combined.

How does this intensive dredging affect the lake environment? Comparison of 1999 and 2007 satellite imagery (Fig. 4) revealed that dredging resulted in a local widening of the channel linking Poyang Lake to the Yangtze River. Extrapolating the extracted 236 × 10^6 m^3 year^{-1} over the 400-km^2 channel would imply that the bottom of the channel was lowered by 59 cm year^{-1}. Such deepening and widening of the channel would ease the discharge from Poyang Lake, which might lead to a closer relation between water levels of the lake and the Yangtze River. The extremely low lake water levels in January 2008 were attributed to low water level in the Yangtze River (Li 2008). It would be interesting to investigate to what extent this low lake level has been the result of the widening and deepening of the channel. Besides, reduced winter water levels in the lake will result in increased hydrological gradient and stream velocities upstream, which might enhance erosion upstream (People's Daily 2000), a possible impact which requires attention as this would weaken the man-made levees which protect the reclaimed lands around the lake.

How much longer will Poyang Lake be able to contribute to the country's increasing demand for sand and gravel without losing its ecological integrity? The lake serves the regional market for sand of the lower Yangtze Valley, because transportation costs prohibit exports from further away. As the lower Yangtze Valley below the Three Gorges Dam has a population of approximately 300 million people, this market would, when considering a per capita consumption of 2 m^3 year^{-1}, currently represent a demand of 600 million m^3 year^{-1}. According to these calculations the current level of sand extraction from Poyang Lake represents approximately 40% of the present regional demand for sand in the lower Yangtze Valley. Our forecasts of a 55–110% increase of demand for the country as a whole also suggest that the demand in the lower Yangtze valley might grow until 2030 to 1 billion m^3 year^{-1} or more.

An important environmental concern to consider would be the possible negative impact of sand mining on the biodiversity hot spots of Poyang Lake (Wu et al. 2007). Dredging-induced turbidity might for example reduce light intensity and the productivity of *Vallisneria spiralis* (Wu et al. 2007, 2009), the tubers of which form the food source of the endangered Siberian crane (Kanai et al. 2002), which winters almost exclusively in Poyang Lake. Dredging-induced noise may also affect echolocation of the red-listed finless porpoise (*Neophocaena phocaenoides*) (Wen and Zhang 2002). So far, however, no evidence of negative impacts of sand mining on Lake Poyang's unique biodiversity has been reported, possibly because of the segregation between the dredging activities, which thus far concentrated in the channel in the north, and the biodiversity hotpots concentrated in the marshes of the lacustrine deltas of the rivers entering Poyang Lake south of Sand Hill. This will change if dredging moved further south, extracting sands from the rivers or the central part of the lake—a development which appears to be ongoing, given recent observation that increasingly larger number of barges are moving up and down the Ganjiang River. This development brings dredging closer to the lacustrine environments in Poyang Lake Nature Reserve, with risk of erosion of creek banks of these protected lakes due to incision of the rivers or overflow of sediment-rich waters during floods. While biodiversity impacts remain speculative, they are definitely not inconceivable and we suggest that negative impacts of dredging on the biodiversity hotpots of Poyang Lake deserve further attention.

Strategic implications for sand supplies in the lower Yangtze Valley

The current research revealed that demand for sand is likely to continue to grow and, in view of the concerns about environmental degradation in Poyang Lake, it is appropriate to explore alternative possibilities to satisfy this increasing demand. Resource depletion and environmental concern restrict the possibilities of sand mining not only in China, but also in the densely populated northwestern Europe. Sand mining in the North Sea has developed in response to this and in 2006 more than half of the sand and gravel production in the Netherlands originated from marine resources (UEPG 2008). Cheng (2006) recently suggested considering marine resources to satisfy the demand for sand in China.

There is another alternative, however. Extensive levee systems constructed since the 1950s (Lu and Zheng 2004) separated the Yangtze River from its broad floodplain, and significantly reduced its floodwater storage capacity, as well as the biodiversity associated to these lakes (Ma et al. 2005). Current policy aims to enlarge flood storage capacity and restore the ecological values (People's Daily 2005) through widening the flood plain and reconnecting lakes to the Yangtze River. Interventions larger than the 500 km^2 reconnected thus far (Ma et al. 2005) would, however, be required to significantly reduce flood risk. Diversion of sand mining toward lakes currently disconnected from the Yangtze River would offer an opportunity to achieve three goals at once: to increase flood storage capacity and to achieve ecological restoration along the Yangtze River, while releasing the pressure on and maintaining the ecological integrity of Poyang Lake.

Conclusions

The results of this research reveal that sand mining occurs in Poyang Lake at unprecedented scale. We further demonstrated that the demand for sand and gravel is likely to increase. Yet, the environmental impacts of sand and gravel mining at this scale remain largely unknown. We suggest that it would be opportune to assess these impacts strategically, as Poyang Lake delivers a number of important ecosystem services which might come under pressure were sand mining to continue uncontrolled. This paper has provided a first step to achieve such strategic assessment, while quantifying the magnitude of the sand mining operations and providing insight into impacts of current sand mining practice, to predict the rise in demand for sand and identify alternative ways to meet the demand for sand. Much of our review of the impact on hydrology, morphology and ecology remains speculative. More research on impacts of sand mining on these aspects of the Poyang Lake ecosystem would be required to provide the science base to support the sustainable management of this unique lake ecosystem.

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