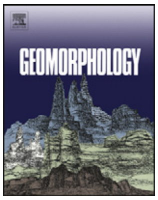
Geomorphology 227 (2014) 49–59

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Estimate of cumulative sediment trapping by multiple reservoirs in large river basins: An example of the Yangtze River basin

Xiankun Yang [a], X.X. Lu [a,b,]*

[a] Geography Department, National University of Singapore, 117570, Singapore
[b] Global Change and Watershed Management Center, Yunnan University of Finance and Economics, Kunming, Yunnan, China

ARTICLE INFO

Article history:
Received 20 March 2013
Received in revised form 18 December 2013
Accepted 28 January 2014
Available online 2 February 2014

Keywords:
Yangtze River
Reservoir sedimentation
Trap efficiency
Sediment yield

ABSTRACT

Most existing models are unable to model large spatial pattern of reservoir sedimentation due to the difficulty in accounting for trapping by upstream reservoirs in a multiple reservoir system. In this study we developed and applied a framework on 1358 of large and medium-sized reservoirs ($\geq 10^7$ maximum storage capacity) for calculating reservoir sedimentation rates in the multi-reservoir Yangtze River system while accounting for the effect of reduced sediment input due to upstream traps. We further used statistical inferences to assess the sedimentation rates of remaining 42,000 smaller reservoirs. Our results indicate that annual sediment accumulated in the Yangtze reservoirs is approximately 691 (±93.7) million tons (Mt), 669 (±89.1) Mt of which is trapped by 1358 large and medium-sized reservoirs and 22 (±4.6) Mt is trapped by smaller reservoirs. Despite the large amount of sediment trapped by reservoirs, the reduction in sediment load at outlet (Datong station) was merely 305 Mt over the last 60 years. The difference may reflect uncertainties in estimates; but it also indicates the important discrepancy between the estimate of the current rate of sediment sequestration in reservoirs and the estimate of the reduction in the land–ocean sediment flux. We further estimated a mean annual rate of storage loss of 5.3×10^8 m^3 yr^{-1}; but against the world trend, the Yangtze River is now losing reservoir capacity much lower than new capacity is being constructed.

1. Introduction

There are around 45,000 large reservoirs worldwide used for water supply, power generation, flood control, etc. (Vörösmarty et al., 2003). For example, about 20% or 3 million km^2 of cultivated land worldwide is irrigated by reservoirs; about 20% of the worldwide generation of electricity is attributable to hydroelectric projects, equating to about 7% of worldwide energy usage (White, 2001). Reservoir construction currently represents the most important influence on land–ocean sediment fluxes (Syvitski et al., 2005; Kummu and Varis, 2007). However, due to dramatic reservoir sedimentation, it has dramatically decreased sediment loads of many rivers thereby triggering erosion of many deltas (Milliman, 1997; Syvitski et al., 2009), including those of the Nile (Stanley and Warne, 1993), Colorado (Topping et al., 2000), Mississippi (Blum and Roberts, 2009), and Yellow (H. Wang et al., 2007) rivers. Inadequate investigations of these and other rivers, unfortunately, have limited the extent to which changes in sediment discharge and their impacts could be identified, let alone adequately quantified.

A large number of approaches and models are available for estimation of reservoir sedimentation (Table 1). However, each model differs greatly in terms of their complexity, inputs and other requirements. In the simplest way at a small scale, the fraction of sediment deposited in an individual reservoir can be determined through the knowledge of its trap efficiency, but this method is usually confined to individuals or to a small spatial scale (Brown, 1944; Camp, 1945; Churchill, 1948; Brune, 1953; Dendy et al., 1973; Ward et al., 1977). In a more sophisticated way, reservoir sedimentation in a multi-reservoir system can be estimated through basin-scale trap efficiency (Vörösmarty et al., 2003; Kummu et al., 2010; Ran et al., 2013), or geographic information system (GIS) models (de Vente et al., 2005; Minear and Kondolf, 2009) on the basis of land use and hydrological data at a large scale.

However, the applications of existing reservoir sedimentation models at a large scale are limited by two important factors: the effect of upstream traps and the excessive dependence on hydrological data. As upstream reservoirs are built, they can significantly reduce sediment yield to downstream reservoirs. Besides, reliable hydrological records accompanying reservoir construction history are important to predict sediment trapped in reservoirs, but they are usually absent for reservoirs of interest. In addition, in a huge basin, the models based on basin-scale trapping efficiency can predict decreased sediment load at the catchment outlet, but sometimes the amount of reservoir sedimentation is not directly equivalent to the reduction in sediment load at its outlet due to the considerable distance of dams from the outlet and the interaction of different drivers (Walling, 2006).

Focusing on the reservoirs in the Yangtze River basin, this study aimed (a) to develop a model to estimate reservoir sedimentation in a

---

* Corresponding author. Tel.: +65 6516 6135; fax: +65 6777 3091.
E-mail address: geoluxx@nus.edu.sg (X.X. Lu).

0169-555X/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2014.01.014

Table 1
A summary of the existing models for reservoir sedimentation prediction.

Model	Study area	References	Notes
Trap efficiency for individual reservoirs			
Capacity–watershed area ratio	Small scale or individual reservoirs	Brown (1944)	Empirical model
capacity–annual inflow ratio	Small scale or individual reservoirs	Brune (1953)	Empirical model; hydrological data required
Sedimentation index	Small scale or individual reservoirs	Churchill (1948)	Empirical model; hydrological data required
Theoretical models	Small scale or individual reservoirs	Camp (1945) Ward et al. (1977)	Based on sedimentation principles and variable discharge conditions
Trap efficiency for multiple reservoirs			
Basin-wide trap efficiency	Global/basin-wide scale	Vörösmarty et al. (2003); Kummu et al. (2010); Ran et al. (2013)	Measurement of the interception of global or basin-wide sediment flux by large reservoirs; hydrological data required
Sedimentation rate for multiple reservoirs			
Semi-quantitative model	National scale	de Vente et al. (2005)	Less data required
Spreadsheet-based model	State-wide scale	Minear and Kondolf (2009)	accounting for the effect of upstream traps but massive sedimentation survey data required
Other black box models			
Computer models	Multi-reservoir systems	Labadie (2004); Garg et al. (2010)	The drawback of the “black box” nature

multi-reservoir system by integrating the effect of upstream traps; (b) to estimate the current impact of sediment trapping by reservoirs in the Yangtze basin; and (c) to analyze the variation in the rates of storage loss in different tributary basins.

2. The Yangtze River and its basin

The Yangtze (Changjiang) River in southern China lies between 91°E and 122°E and 25°N and 35°N, has a basin area of 1.8×10^6 km^2 and is the third largest river in the world (Fig. 1). The river is generally divided into three parts: the upper, middle and lower reaches. The upper reach, including the Jinshajiang, Minjiang, Jialingjiang and Wujiang tributaries, extends approximately 4300 km to Yichang from the headwaters in the Himalayan Mountains, with a drainage area of approximately 1.0×10^6 km^2. At Yichang, the Yangtze River exits the Three Gorges Dam and enters the 950-km middle reach (Yichang to Hukou). It receives more water from three large water bodies in this section: the Dongting Lake, the Hanjiang River and the Poyang Lake. The 930-km lower reach extends from Hukou to the river mouth approximately 20 km north of Shanghai and has a drainage area of 1.2×10^5 km^2.

About half of the river water and nearly all its sediment originate from the uplands upstream from Yichang (Lu et al., 2003), which has a catchment area of about 55.6% of the whole drainage basin and is 1837 km away from the sea (Fig. 1). The annual water discharge and sediment load from the upper Yangtze River, recorded at the Yichang station, averaged 451 km^3 yr^{-1} and 516 Mt yr^{-1} between 1955 and 1965, amounting to approximately 50 and 116% of those at Datong, the most downstream hydrological station (Chen et al., 2002; Yang et al., 2002). The main sources of sediment load at Yichang are the Jinshajiang and Jialingjiang rivers, accounting for 73–90% of the total sediment load (Z.Y. Wang et al., 2007). Most of the sediment is from the area between the confluence of the Yalong River and the Jinshajiang River down to Pingshan (Zhou et al., 2002).

In the Yangtze River basin, rapid economic growth has increased the pressure for greater hydropower production and other water-related developments, such as large-scale irrigation. The mainstream and its tributaries are being dammed at a dazzling pace. Since the 1950s, numerous reservoirs have been constructed in the river basin. There are 44,000 reservoirs of different sizes in the Yangtze River basin with a total storage capacity of approximately 290 km^3, among which 1358 reservoirs are large and medium-sized with storage capacity greater than 0.01 km^3 (Yang and Lu, 2013). As a result of reservoir construction, sediment discharge data from the upper, middle, and lower reaches of the river indicate that the reduction of the Yangtze sediment load has

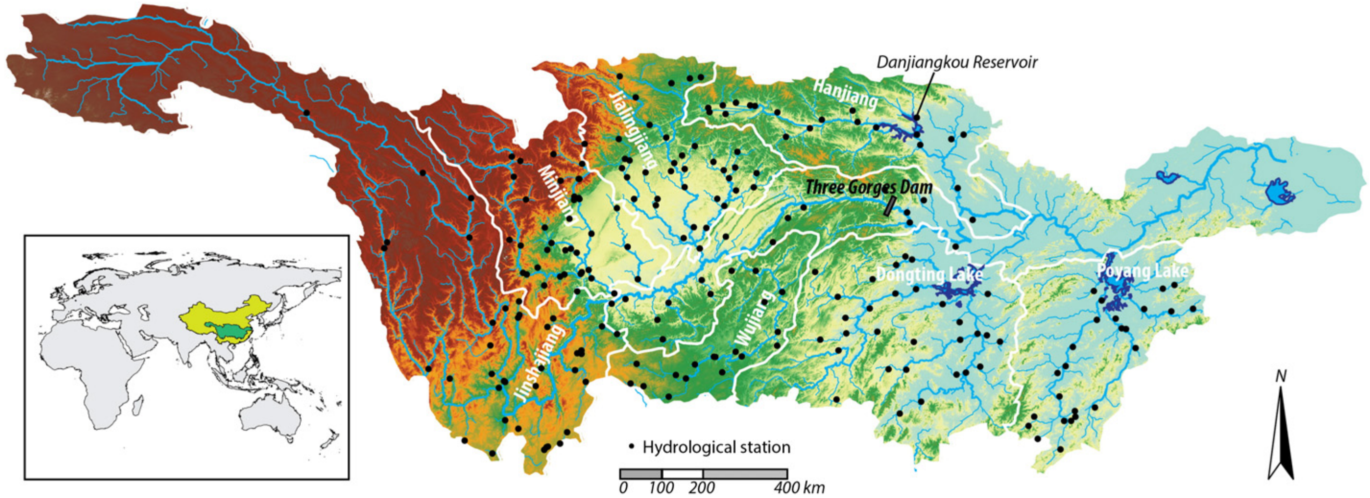


Fig. 1. Geographical setting of the Yangtze River and its sub-basins. Data at hydrological stations shown in this figure were used to establish empirical relationship for sediment yield prediction.