Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Global and Planetary Change 39 (2003) 169–190
GLOBAL AND PLANETARY CHANGE
www.elsevier.com/locate/gloplacha

Anthropogenic sediment retention: major global impact from registered river impoundments

Charles J. Vörösmarty[a,b,*], Michel Meybeck[c,1], Balázs Fekete[a], Keshav Sharma[d,2], Pamela Green[a], James P.M. Syvitski[e,3]

[a] *Water Systems Analysis Group, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Morse Hall, Durham, NH 03824, USA*
[b] *Earth Sciences Department, University of New Hampshire, Durham, NH 03824, USA*
[c] *UMR Sisyphe, Université de Paris VI, France Case 123, Tour 26, 5éme étage, 4 Place Jussieu, 75257, Paris Cedex 05, France*
[d] *Department of Hydrology and Meteorology, Babar Mahal, PO Box 406, Kathmandu, Nepal*
[e] *Institute of Arctic & Alpine Research, University of Colorado at Boulder, 1560 30th Street, Campus Box 450, Boulder, CO 80309-0450, USA*

Received 21 September 2002; accepted 18 December 2002

Abstract

In this paper, we develop and apply a framework for estimating the potential global-scale impact of reservoir construction on riverine sediment transport to the ocean. Using this framework, we discern a large, global-scale, and growing impact from anthropogenic impoundment. Our study links information on 633 of the world's largest reservoirs (LRs) (≥ 0.5 km^3 maximum storage capacity) to the geography of continental discharge and uses statistical inferences to assess the potential impact of the remaining >44,000 smaller reservoirs (SRs). Information on the LRs was linked to a digitized river network at 30′ (latitude × longitude) spatial resolution. A residence time change ($\Delta\tau_R$) for otherwise free-flowing river water is determined locally for each reservoir and used with a sediment retention function to predict the proportion of incident sediment flux trapped within each impoundment. The discharge-weighted mean $\Delta\tau_R$ for individual impoundments distributed across the globe is 0.21 years for LRs and 0.011 years for SRs. More than 40% of global river discharge is intercepted locally by the LRs analyzed here, and a significant proportion ($\approx$ 70%) of this discharge maintains a theoretical sediment trapping efficiency in excess of 50%. Half of all discharge entering LRs shows a local sediment trapping efficiency of 80% or more. Analysis of the recent history of river impoundment reveals that between 1950 and 1968, there was tripling from 5% to 15% in global LR sediment trapping, another doubling to 30% by 1985, and stabilization thereafter. Several large basins such as the Colorado and Nile show nearly complete trapping due to large reservoir construction and flow diversion. From the standpoint of sediment retention rates, the most heavily regulated drainage basins reside in Europe. North America, Africa, and Australia/Oceania are also strongly affected by LRs. Globally, greater than 50% of basin-scale sediment flux in regulated basins is potentially trapped in artificial impoundments, with a discharge-weighted sediment trapping due to LRs of 30%, and an additional contribution of 23% from SRs. If we consider both regulated and unregulated basins, the interception of global sediment flux by all registered reservoirs

* Corresponding author. Water Systems Analysis Group, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Morse Hall, Durham, NH 03824, USA. Tel.: +1-603-862-0850; fax: +1-603-862-0587.

E-mail addresses: charles.vorosmarty@unh.edu (C.J. Vörösmarty), meybeck@biogeodis.jussieu.fr (M. Meybeck), balazs.fekete@unh.edu (B. Fekete), k.p.sharma@dhm.gov.np (K. Sharma), pam.green@unh.edu (P. Green), james.syvitski@colorado.edu (J.P.M. Syvitski).

[1] Fax: +33-1-4427-5125.
[2] Fax: +977-1-262348.
[3] Fax: +1-303-492-3287.

doi:10.1016/S0921-8181(03)00023-7

($n \approx 45{,}000$) is conservatively placed at 4–5 Gt year^{-1} or 25–30% of the total. There is an additional but unknown impact due to still smaller unregistered impoundments ($n \approx 800{,}000$). Our results demonstrate that river impoundment should now be considered explicitly in global elemental flux studies, such as for water, sediment, carbon, and nutrients. From a global change perspective, the long-term impact of such hydraulic engineering works on the world's coastal zone appears to be significant but has yet to be fully elucidated.

Keywords: Sediment transport; Reservoirs; Hydrology; Sediment deposition; Dams

1. Introduction

The transport of riverborne sediment from the continental land mass to the world's oceans is a fundamental feature of the geology and biogeochemistry of our planet. However, despite numerous attempts at its estimation, the magnitude of global suspended sediment flux to the ocean is still a matter of debate. Estimates have ranged from 9.3 Gt year^{-1} (Judson, 1968) to more than 58 Gt year^{-1} (Fournier, 1960 as calculated by Holeman, 1968) with more recent studies (e.g. Meybeck, 1982, 1988; Walling and Webb, 1983; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Ludwig et al., 1996) converging around 15–20 Gt year^{-1}.

This wide breadth of results emerges from an admixture of assumptions, approaches, and uncertainties embedded within these global inventories. Estimates have been based on soil erosion (Fournier, 1960), on sediment transport by major rivers, some already impounded (Milliman and Meade, 1983), or on multiregression analysis of present-day fluxes (Ludwig et al., 1996). The range in results is also not surprising considering that the available data represent river basins that barely cover more than 50% of the continental land mass, necessitating significant extrapolation. The sampled rivers are also poorly checked for how representative they are in terms of runoff, relief, and climate. Time series are often incomplete, of short duration, or sampled at an insufficient frequency to capture both long-term and episodic fluxes. In addition, the manner in which exorheic and endorheic basins are distinguished is poorly documented. Estimation of the true global flux is also made difficult by insufficient treatment of the countervailing influences of increased sediment mobilization from anthropogenically induced soil erosion and of decreased delivery caused by flow diversion and sediment trapping in reservoirs.

This paper seeks to clarify the role of one component of the global sediment budget, namely, the trapping of suspended sediment within registered reservoirs. Humans are prodigious dam builders, with more than 45,000 registered dams over 15 m high in operation today worldwide, representing nearly an order of magnitude greater number than in 1950 (World Commission on Dams, 2000). This dam building has resulted in a substantial distortion of freshwater runoff from the continents, raising the "age" of discharge through channels from a mean between 16–26 and nearly 60 days (Vörösmarty et al., 1997a). The present study extends the earlier work of Vörösmarty et al. (1997b) by exploring further the relationships between reservoir sediment trapping and intercepted continental discharge, offering a geography of artificial retention of riverborne sediment, and estimating the collective, global-scale impact of smaller registered reservoirs.

Because of the close links between water and sediment source areas (Meybeck et al., 2001) and growing human control over continental runoff (Postel et al., 1996; Vörösmarty et al., 2000a), we can reasonably expect to observe a substantial anthropogenic signature within the global sediment cycle. We test this hypothesis here by establishing a preliminary estimate of the potential for large reservoirs to sequester sediments on the continental land mass and to prevent their ultimate delivery to inland and coastal receiving waters. The framework we present is a precursor to a more fully spatially explicit analysis of actual suspended sediment fluxes, which will simulate the geography of sediment routing from source areas, river corridors and depositional environments, and of eventual delivery to the coastal zones of the world. Our focus here is not on predicting suspended sediment flux per se, but instead on estimating the proportion of such flux that could be intercepted and stored within registered reservoirs.