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Anthropogenic sediment retention: major global impact from registered river impoundments

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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

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($n \approx 45{,}000$) 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.

Analysis of anthropogenic impoundment is important to both the earth sciences and its applications. These include emerging studies of global water resources which require an assessment of storage volumes available for flow stabilization (Alcamo et al., 2000; Vörösmarty et al., 2000a; Oki et al., 2002). The loss of storage capacity through reservoir siltation is a widespread and costly phenomenon (Ward, 1980; Vörösmarty et al., 1997a,b). A global-scale understanding of the role of reservoirs also provides a key toward articulating the role of humans in riverine nutrient transport (Humborg et al., 1997; Seitzinger and Kroeze, 1998), global carbon sequestration (Stallard, 1998; Smith et al., 2001), and trace gas emission due to decomposition of deposited organic material (St. Louis et al., 2000). The state of inland aquatic ecosystems and biodiversity is increasingly being dictated by the presence of artificial impoundments (Dynesius and Nilsson, 1994; Rosenberg et al., 2000; Revenga et al., 2000). Each of these issues requires a consideration of the fate of terrestrially derived sediments in fluvial systems. We recognize that natural lakes, wetlands, and floodplains are also of prime importance in predicting river basin sediment delivery (Stallard, 1998), but we have not considered these processes explicitly here.

In this paper, we emphasize first the contribution of large reservoirs (LRs) employing geographically specific calculations with respect to their sediment trapping potential. We assess how representative these LRs are of the global population of impoundments, offer a validation of our calculations, give continental and global-scale summary statistics, present a global mapping of fractional retention of sediment by LRs, and review the recent evolution of LR sediment trapping. We then go on to assess sediment retention by smaller reservoirs (SRs) using a set of statistical extrapolations, offering an estimate of their collective importance at the end of this paper.

2. Location and characteristics of large reservoirs

Our methodology requires information on the storage volumes, incident discharge, and geographical position of large reservoirs within river basins. We obtained information on large impoundments and their maximum water storage capacities from a series of world dam registries (ICOLD, 1984, 1988, 1998; IWPDC, 1994; IWPDC, 1989). We define large reservoirs (LRs) as having maximum storage capacities greater than or equal to 0.5 km^3. We identified a total of 749 LRs in the registries. Our final database has fewer entries ($n = 633$) and represents only those LRs that we could confidently geo-reference. Smaller registered reservoirs ($n \approx 44{,}700$) are also analyzed here, but using a statistical approach.

The LRs were geographically co-registered to a digital data set depicting the global system of rivers. The Simulated Topological Network at 30′ (longitude × latitude) spatial resolution (STN-30; Fig. 1) (Vörösmarty et al., 2000b,c) was used in this application. The ICOLD and IWPDC databases provide no geographic coordinates for the listed dams, necessitating a manual assignment of each reservoir to a corresponding location on the STN-30. We consulted several published maps (Defense Mapping Agency Aerospace Center, 1980–1986; IWPDC, 1989; Bartholomew et al., 1983, 1988) to locate each relevant entry and position it on the STN-30.

The dam registries also give no information on river flows through LRs. We obtained mean annual discharge from monitoring station data reported to UNESCO (Vörösmarty et al., 1996) and interpolated these values to specific dam sites along the STN-30 network. The interpolation was weighted by contributing area along individual river links. We estimated runoff and discharge from a water balance model (Vörösmarty et al., 1989, 1998) for reservoir sites falling outside the domain of discharge recording stations. When tested over the conterminous US on 679 watersheds with long-term discharge records, model bias was on the order of 10 mm $year^{-1}$. At the global scale, the version of the model used yielded an average bias of -29 mm $year^{-1}$ runoff when compared to several hundred UNESCO station records (i.e., our estimates are generally within 10% of observed runoff). More than 85% of the discharge predicted to pass directly through the LRs we tested was based on UNESCO records. Large reservoirs reside in 236 simulated drainage basins (all >1100 km^2), which we will refer to as “regulated basins.” Owing to their high number, a geographically referenced database for SRs was practically impossible to configure. We will, however, assess the collective behavior of SRs across an inferred geographical distribution as described below.

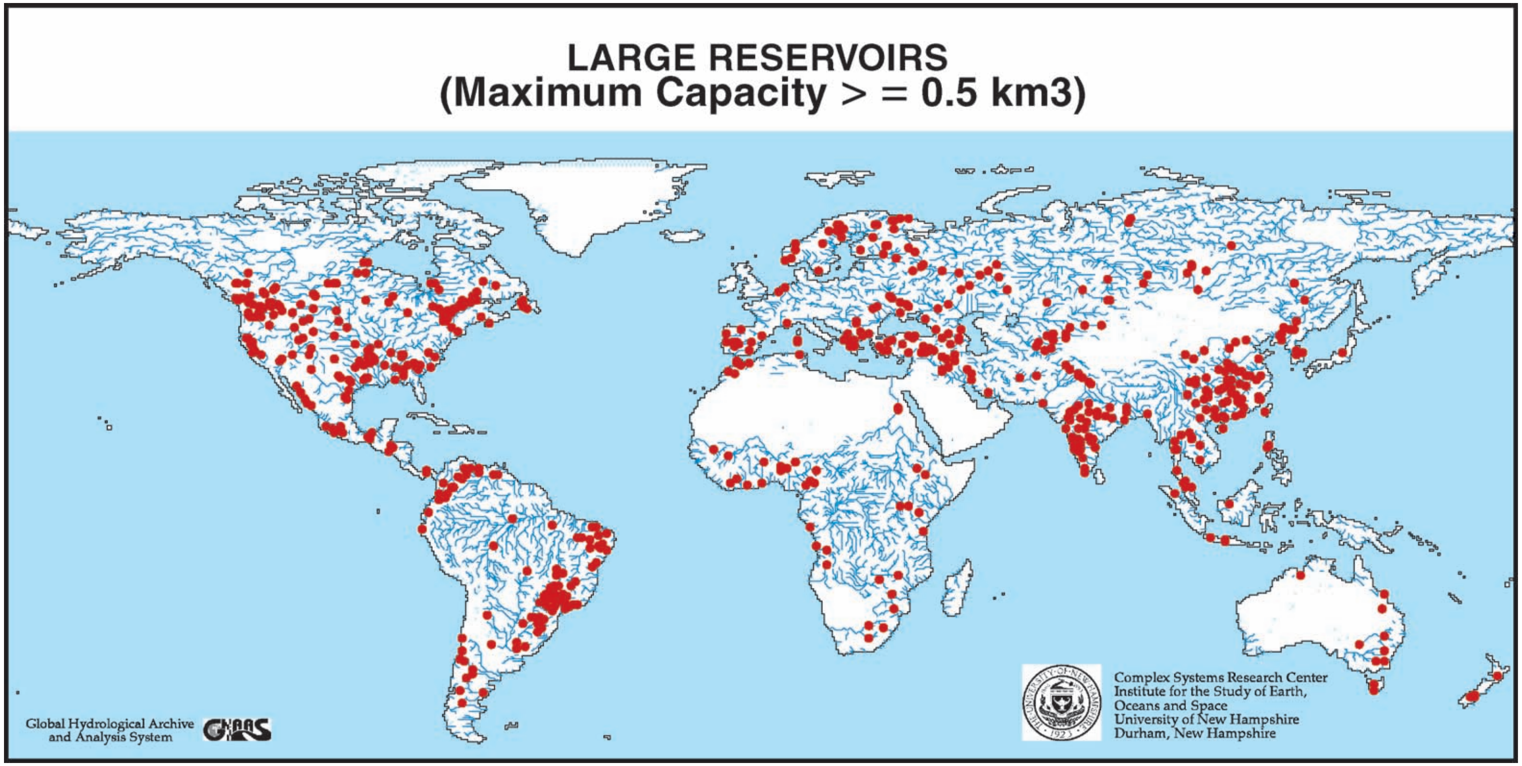


Fig. 1. Geographical distribution of the 633 large reservoirs (LRs) used in this study. Each LR has a maximum storage capacity of 0.5 km^3 or greater. The remaining smaller registered reservoirs (SRs) ($n \approx 44,700$) are also considered, but using a nonspatial statistical approach.

3. Computing change in river water residence time and sediment trapping efficiency due to LRs

As an interim step toward developing a process-based sediment delivery model, we applied a simple set of calculations based on the geo-located large reservoirs, our estimates of discharge, and the conservative assumption that suspended sediment flux is proportional to discharge, generally accepted by most authors (Milliman and Meade, 1983; Walling and Webb, 1983; Milliman and Syvitski, 1992) even if other variables such as relief and lithology may play important roles. Suspended sediment trapping efficiency is cast as a function of the change in mean residence time of river water, which we determined for individual reservoirs, entire drainage basins, and continents. We focus on anthropogenic influences. Natural lakes are therefore not considered a part of this residence time change or of human-induced sediment retention.

For a single LR, mean local residence time change for river water over unimpounded conditions ($\Delta\tau_R$) was defined as the effective reservoir volume divided by local mean annual discharge. Maximum reported reservoir capacity was multiplied by a utilization factor of 0.67, representing the proportion of maximum storage at which reservoirs are assumed to operate routinely (USGS, 1984). We applied an approximation to the relationship originally developed by Brune (1953) (see Ward, 1980) to predict individual reservoir trapping efficiencies (TE_{local}) as a function of local residence time change (in years):

$$TE_{local} = 1 - (0.05/\Delta\tau_R^{0.5}) \quad (1)$$

Brune's empirical relationship, originally developed for US reservoirs, is widely used and found to provide reasonable estimates of long-term, mean trapping efficiency (Morris and Fan, 1998). At the same time, Brune recognized significant departures as a result of changes in operating rules, in dry reservoirs, and in shallow sediment retention basins (designed for high trapping efficiency). Additional complications involve reservoir effective storage, outlet design, and inflow particle size. An envelope around Brune's mean curve for normal ponded reservoirs addresses the issue of particle size through an upper bound corresponding to highly flocculated and coarse sediments and a lower bound for colloidal, dispersed, fine-grained particles. For example, for a reservoir with a 1-day residence time, estimated retention ranges from about 30% (for fine-grained) to 55% (for coarse-grained sediment). A comparison to known siltation rates in Zimbabwe (Ward, 1980) revealed a tendency for the Brune curve to overestimate trapping, but its use was advocated nonetheless for broad-scale surveys.

Eq. (1) saturates to high levels of retention with only modest $\Delta\tau_R$. For example, less than 4 days are required to achieve 50% trapping, 2 weeks for 75%, and 3 months for 90%. Within each of the 236 regulated drainage basins, we identified all subbasins which contained LRs. For these, we determined an aggregate-impounded volume, which together with discharge yielded a subbasin residence time change and eventually an aggregate trapping efficiency associated with LRs. Whole basin sediment trapping was adjusted by a discharge weighting associated with unimpounded interfluvial areas. Fig. 2 details these computations.

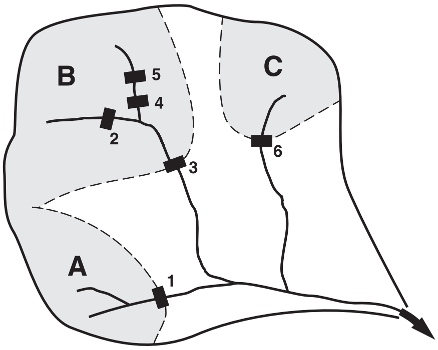
In basins where irretrievable losses of discharge (e.g., from irrigation or evaporation from the reservoirs themselves) in the downstream direction, we redefined the discharge weighting to prevent an artificial increase in apparent basinwide trapping. We did this by redefining the discharge at mouth (Q_m) (see Fig. 2) as the maximum encountered along the downstream flow path. This isolated the effect of reduced sediment conveyance due to decreasing discharge from that of reservoir sedimentation per se. The resulting distribution of residence times and trapping efficiencies were mapped onto the STN-30 and summarized at both continental and global scales.

Validation of the model in several basins where there has been a significant reduction in post-impoundment river flow presented a similar problem, since observed contemporary sediment flux is a composite of both reservoir deposition and flow diversion. Where pre- and post-reservoir flow data were available in our validation data set, we modified the original basin trapping efficiency estimate (TE_{bas0}) through the following approximation:

$$TE_{bas} = 1 + (Q_{cont}/Q_{nat})(TE_{bas0} - 1) \quad (2)$$

where Q_{nat} is the natural (pre-disturbance) and Q_{cont} the contemporary water discharge (km^3 year^{-1}), respectively, and TE_{bas} is the revised trapping efficiency estimate (unitless). This permitted meaningful comparisons to be made between simulated and observed basin fluxes. The role of flow diversion in

BASIN-WIDE TRAPPING EFFICIENCY CALCULATION



$$(1)\ \Delta\tau_{reg,j} = \frac{\sum_{1}^{n_j} V_i}{Q_j} \quad \left(\text{e.g. } \frac{(V_2+V_3+V_4+V_5)}{Q_B}\right)$$

$$(2)\ TE_{reg,j} = 1 - \frac{0.05}{\sqrt{\Delta\tau_{reg,j}}}$$

$$(3)\ TE_{bas} = \frac{\sum_{1}^{m} TE_{reg,j}\, Q_j}{Q_m}$$

$\Delta\tau_{reg,j}$ = approximated residence time of regulated portion j of basin

V_i = operational volume of reservoir i

Q_j = discharge at mouth of each regulated sub-basin j (e.g. $Q_A = Q_1$; $Q_B = Q_3$; $Q_C = Q_6$)

Q_m = discharge at basin mouth

$TE_{reg,j}$ = approximated trapping efficiency of regulated portion j of basin

TE_{bas} = discharge-weighted trapping efficiency for entire basin

n_j = number of reservoirs in each regulated sub-basin j

m = number of regulated sub-basins

Fig. 2. Protocol for predicting basin-scale sediment trapping efficiency for large reservoirs. The calculations for LRs are augmented by those for SRs which reside both in the regulated subbasins (A, B, and C) and outside of these areas. These subbasins we refer to as LR/SR-regulated and SR-regulated, respectively.

modifying continental sediment flux beyond these test basins will be considered more fully in a later study.

4. Key findings for large reservoirs

4.1. Representative nature of LR sample

The distribution of local computed residence time changes at reservoirs ($\Delta\tau_R$) can be used to assess the degree to which the database of 633 LRs can faithfully represent the global population of large impoundments. Worldwide, computed $\Delta\tau_R$ values for individual sites show an estimated range from 0.001 to 23.9 years with a median of 0.43 year and quartiles of 0.15 and 1.18 years. Our tabulation is similar to an inventory of 130 impoundments of all sizes distributed across the globe and having known residence times (from Ortiz Casas and Peña Martinez, 1984; Calvo et al., 1993; Kopylov et al., 1978). This independent assessment yields a median residence time of 0.75 year with quartiles at 0.15 and 1.5 years. For the 47 major reservoirs in the smaller data set, the observed distribution is nearly the same, with a median of 0.75 year and quartiles at 0.35 and 1.5 years. Considering the wide range of computed LR residence time changes spanning several orders of magnitude, our estimated distribution of $\Delta\tau_R$ appears reasonable.

The LR data set we assembled also represents a significant fraction of global impounded fresh water, despite the relatively small number of individual entries. The 633 LRs we use have an aggregate storage capacity of nearly 5000 km^3, which we calculate (Eq. (3), below) to constitute approximately 70% of the global total represented by all entries ($n \approx 45{,}000$) in the registries, or about 10% higher than an earlier estimate (Vörösmarty et al., 1997a). Avakyan (1987) documented a similarly skewed distribution of aggregate storage capacity, noting that the 2500 largest impoundments (about 5% of all registered reservoirs) with maximum storages in excess of 0.1 km^3 together constitute 90% of total global reservoir volume. This is true also over smaller domains. For instance, from an inventory of 198 reservoirs (each exceeding 0.001 km^3) in Turkey (D.S.I., 1991), we find that 64% of aggregate volume is represented by the two largest reservoirs (LRs) alone, while the top 10 reservoirs constitute 90% of the country-wide total. These distributions are believed to be very similar in most countries and also describe the distribution of natural lake area and volume (Meybeck, 1995), further suggesting the representativeness of our sampling. Nonetheless, our estimates of aggregate dam-induced impacts should be viewed as conservative, insofar as we have analyzed but a sample of total global impoundment, the ICOLD/IWPDC registries themselves fail to constitute a complete inventory of reservoirs (St. Louis et al., 2000, Vörösmarty and Sahagian, 2000), and small unregistered impoundments were not explicitly considered.

4.2. LR-induced impacts on individual drainage basins

We obtained encouraging results when we placed the individual, computed $\Delta\tau_R$ values into a drainage basin context to estimate aggregate sediment trapping by the 633 LRs. Results derived from the GIS-based analysis were validated against independent compilations of pre- and post-impoundment sediment fluxes (Milliman and Syvitski, 1992; Meybeck and Ragu, 1996) derived from several original sources. Table 1 offers this comparison for drainage basins from several parts of the world, representing a wide spectrum of catchment area, runoff, and sediment flux. The correspondence for many of the listed river basins is excellent, suggesting an important role for large reservoirs per se in determining basin-scale sediment flux. These results also lend hope that our mapping of LRs and relatively straightforward models of sediment flux can be used to determine the anthropogenic imprint on suspended sediment transport globally.

There are, however, conditions under which the calculation of theoretical trapping efficiency shows overestimates (e.g., Indus River) as well as underestimates (e.g., Mississippi River). Such conditions arise when the spatial distribution of water discharge and sediment loading are fundamentally decoupled, in violation of the simplifying assumption that sediment loads are proportional to water discharge. In the case of the Mississippi River, its Missouri subbasin contributes 75% of the natural sediment load (400 Mt year^{-1}) (Meade, 1995), but accounts for only 12% of mean annual discharge, while the opposite behavior characterizes its Ohio subbasin. Since the bulk (73%) of the LR volume resides on the Missouri, our theoretical estimate (here applied to the whole Mississippi basin) would be expected to greatly underestimate the true potential for trapping, in reality associated most closely with the Missouri. When a correction is made to account for this geographic asymmetry (i.e., accounting for trapping in the individual major subbasins), the basinwide trapping efficiency estimate rises from 15% to 47%, nearly identical to the observed value of 48%. This argues for a more complete and spatially explicit model of sediment flux, including variable sediment source areas, multiple trapping through sequential dams, remobilization of channel sediment downstream of dams, other hydraulic modifications such as levee construction, and the consideration of non-LR dams.

Disparities also arise from short monitoring periods and inappropriate sampling strategies applied to some of the observational records. It is generally accepted that a long-term record of at least 10 years (and up to 20 years for highly variable sediment loads) is necessary to define an average load, since year-to-year variability generally exceeds a factor of 10 and may exceed 100 for some rivers like the Eel in California (Meade and Parker, 1985; Syvitski and Morehead, 1999). In addition, routine and/or periodic sampling strategies may seriously underestimate the true sediment flux (and hence, post-impoundment trapping efficiency) where riverine transport is event-driven, for example in Costa Rican rivers that are highly susceptible to hurricanes and earthquakes (Sanchez-Azofeifa, 1996). The deterioration in monitoring capacity for constructing both hydrographic (IAHS Ad Hoc Group on Global Water Data Sets, 2001; Shiklomanov et al., 2002) and constituent flux archives (Vörösmarty et al., 1997c) has limited us in this study and will surely limit our collective capacity to validate emerging models of the contemporary global sediment cycle.

4.3. Continental-scale results for LRs

At the continental scale, the greatest number of large reservoirs and the greatest summed reservoir capacities are located in Asia and North America (Table 2). A typical large dam in these continents shows a capacity on the order of 7 km^3. Africa is ranked third in overall storage but fifth in dam numbers. It has a correspondingly high mean reservoir size, more than two to seven times larger than those from any other continental area (except for Northern Asia). In Northern Asia, several large dams in Russia and the

Table 1
Computed versus observed basin-wide sediment trapping for selected river systems regulated by large reservoirs

Continent	River	Country	Ocean or sea	Pre-dam[a] water discharge (km^3 $year^{-1}$)	Post-dam[a,b] water discharge (km^3 $year^{-1}$)	Area (10^6 km^2)	Observed basin[a,c] trapping (%)	Theoretical[d] basin trapping (%)
Africa	Nile	Egypt	Med	83.2	30.0[e]	2.87	100	99
Africa	Orange	South Africa	Atl		11.4	1.02	81	95
Africa	Volta	Ghana	Atl		36.8	0.398	92	96
Asia	Indus	Pakistan	Ind	90	57.0	0.920	76	97
Asia	Kizil Irmak	Turkey	Black		5.8	0.076	98	95
Asia	Krishna	India	Ind		30.0	0.252	75	70
Asia	Narmada	India	Ind	40.7	39.0	0.121	75	71
Asia	Sakarya	Turkey	Black		5.9	0.055	30[f]	67
Asia	Yesil	Turkey	Black		5.7	0.036	98	96
Europe	Danube	Romania	Black		207	0.810	29[g]	45
Europe	Don	Russia	Black	28.1	20.7	0.420	64	56
Europe	Ebro	Spain	Med	49.0[e]	13.5[e]	0.087	92	90
North America	Colorado	USA	Pac	18.5	0.1	0.715	100	100
North America	Columbia	USA	Pac		236	0.669	33	69
North America	Mississippi	USA	Atl	580	529	3.270	48	15 (47)[h]
North America	Rio Grande	USA/Mexico	Atl	18	0.7	0.670	96	100
North America	Savannah	USA	Atl	11.6	10.6	0.027	64	66

[a] From: Meybeck and Ragu (1996); for Ebro River discharges, UNESCO (various years).
[b] After evaporative losses in reservoirs and basin-scale consumptive use.
[c] From: Milliman and Syvitski (1992) and Milliman and Meade (1983).
[d] Estimates made based on sample calculations shown in Fig. 2. When pre/post-dam discharges were available, original estimate of trapping efficiency (TE_o), reflecting solely the spatial distribution of reservoir siltation (i.e., Fig. 2), was pro-rated using Eq. (2).
[e] From Vörösmarty et al. (1996).
[f] Based on unpublished data from B.J. Hay cited in Milliman and Syvitski (1992). This figure appears low in the context of two major and several small impoundments resident within the basin.
[g] Not known if figure reported includes influence of Iron Gates impoundments, regulating discharge from ca. 70% of the basin area.
[h] Figure in parentheses represents an explicit tabulation for the Missouri River tributary, which contributes 75% of Mississippi basin sediment flux (Meade, 1995). See text.

former Soviet Union boost mean size of LRs to 40 km^3, dwarfing the means of other continental areas. South America has nearly the same accumulated large reservoir capacity as Africa, but with approximately double the number. Mean impoundment size is similar to those for Asia as a whole and for North America. Australia/Oceania has the least large impoundment storage and smallest mean LR size. These observations corroborate those made by Avakyan (1987) based on country-level census data from around the world.

Africa, Australia/Oceania, and Endorheic (i.e., internally draining) Asia, maintain the highest discharge-weighted $\Delta\tau_R$ for a typical LR, spanning 0.7–1.2 years and indicating the relatively high degree to which reservoirs in these areas impound runoff (Table 2). More moderate residence time changes characterize impoundments in the rest of Asia, Europe, and North America. The smallest mean residence time change is tabulated for South America, less than 0.10 year. Relatively large residence time changes in Africa, Australia/Oceania, and Endorheic Asia arise from dam construction in arid and semiarid regions, where low runoff and high demand for irrigation water necessitate large storage volumes. In fact, intercepted discharge in these regions is the smallest among all continents (Table 2). Hydropower reservoirs in humid regions have generally shorter $\Delta\tau_R$ values associated with higher incident discharges, although there are exceptions (Manicouagan in Québec with a $\Delta\tau_R$ of more than 5 years).

Our inventory of intercepted discharge associated with contrasting degrees of suspended sediment trapping shows highly skewed distributions for most of the continents (Table 3). Endorheic Asia and Australia/Oceania show extremely biased distributions such that none of the discharge estimated to be flowing

Table 2
Key attributes of the geographically referenced large reservoir systems used in this study. The mean residence time change ($\Delta\tau_R$) is derived from mean annual conditions estimated locally for reservoirs in each continent of the globe

Continent[a]	n	Sum of maximum capacities (km^3)	Mean of maximum capacities (km^3)	Sum of intercepted discharge (km^3 $year^{-1}$)	Discharge-weighted mean $\Delta\tau_R$ (years)
Africa	42	912	21.7	736	0.83
Asia					
Endorheic	19	102	5.4	58.3	1.17
North[b]	14	569	40.6	903	0.42
South	176	827	4.7	2560	0.22
Australia/Oceania	16	47	3.0	44.2	0.71
Europe[c]	88	430	4.9	1770	0.16
North America	180	1195	6.6	3500	0.23
South America	98	807	8.2	6190	0.09
Total	633	4888	7.7	15,762	0.21

[a] Defined by river mouths within the STN-30 (see Vörösmarty et al., 2000b,c).
[b] Drainage into Arctic Ocean.
[c] Area west of the Ural Mountains and north of Caucasus Mountains.

through their LRs shows less than 90% sediment trapping. Africa also shows a strong bias toward high trapping. Because major portions of these continents are relatively dry (Fekete et al., 1999, 2002; Meybeck et al., 2001), large storage capacities are more typically needed to stabilize highly variable and relatively scarce river flows. This in turn increases $\Delta\tau_R$ and hence trapping. LRs in Northern Asia reflect both large impoundments (i.e., in Russia) and a relatively low discharge across the entire Arctic drainage basin (Fekete et al., 1999, 2002; Lammers et al., 2001). All continents show skewness, although for South Asia, Europe, and North and South America, we see at least modest amounts of intercepted runoff bearing relatively low sediment trapping efficiencies. The overall pattern worldwide, however, is one of bias toward high in situ trapping efficiencies, with half of all incident discharge showing a potential local sediment trapping efficiency of 80% or more (Fig. 3). Approximately 70% of the discharge flowing through large reservoirs experiences a sediment trapping of 50% or more.

The distributions of aggregate, intercepted discharge as a function of $\Delta\tau_R$ are summarized for individual continents in Fig. 4. Much of the runoff intercepted by LRs globally is associated with a residence time change of ≥ 0.01 years, which represents a 50% or greater sediment trapping efficiency. The most significant sediment trapping at LRs is in Endorheic Asia (mean = 91%), North Asia (90%), Australia/Oceania (90%), and Africa (86%). However, no region of the globe shows a discharge-weighted mean of less than 50%. The discharge-weighted, mean global $\Delta\tau_R$ of 0.21 year (Table 2) has an associated trapping efficiency of 62%.

We emphasize that these tabulations (Tables 2, 3 and Figs. 3, 4) are made locally at large reservoir sites. These $\Delta\tau_R$ values, in turn, must be placed into a drainage basin perspective (Table 4) to more fully account for interactions between the nonlinear nature of the TE function and the spatial distribution of regulated and unregulated subcatchments within the basins (unregulated contributing areas have a diluting effect on basinwide trapping efficiency). When we do this, we find, for example, that although LR-regulated basin residence times are greatest (means of 0.7 and 0.45 years) in Africa and Australia/Oceania, respectively, only a moderate mean sediment trapping efficiency ($\approx$ 40%) is tabulated at their regulated basin mouths.

Table 3
Accumulated, intercepted discharge of river water relative to different levels of suspended sediment trapping efficiencies in large reservoirs (LRs) across each continent. Fig. 3 gives the distribution globally. These numbers refer to conditions tabulated locally at the LRs

Continent[a]	% Sediment trapping efficiency[b]				
	10	25	50	75	90
Africa	0	0	0	20	40
Asia					
Endorheic	0	0	0	0	27
North[c]	0	0	0	2	46
South	11	11	32	53	82
Australia/Oceania	0	0	0	0	37
Europe[d]	10	10	10	35	91
North America	12	15	36	55	79
South America	26	29	43	58	93

[a] Defined by river mouths within the STN-30.
[b] Column entries for each continent correspond to the percentage of cumulative river water discharge having the listed sediment efficiency or less.
[c] Drainage into Arctic Ocean.
[d] Area west of the Ural Mountains and north of the Causasus Mountains.

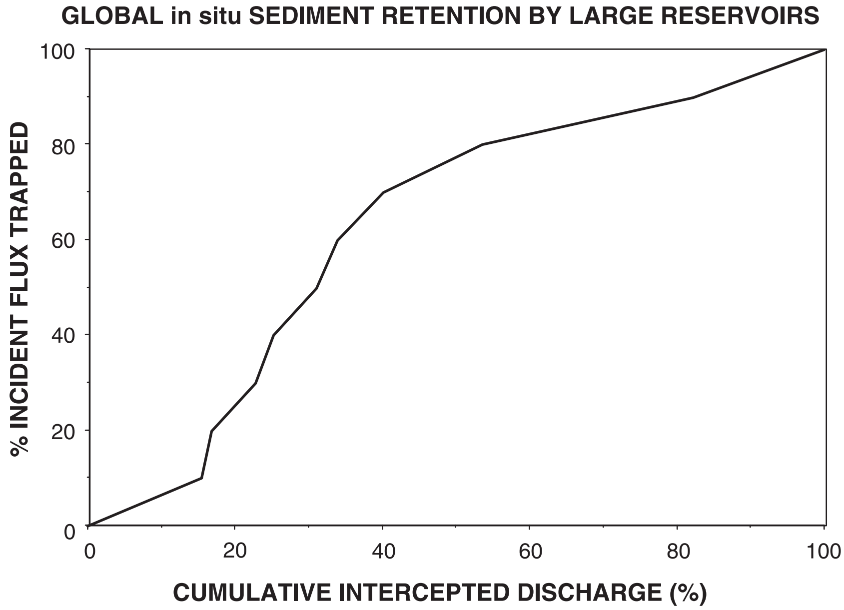


Fig. 3. Sediment trapping efficiencies with respect to accumulated discharge. The efficiency is tabulated locally at reservoirs. The intercepted discharge is expressed as a percentage of total runoff from the land mass of the Earth intercepted by LRs. Each level of accumulated discharge has the listed sediment trapping efficiency or less. Continental distributions are offered in Table 3.

In contrast, regulated basins in Europe show a relatively modest mean basin residence time (0.22 year), yet display the highest mean sediment retention (50%). The mean aggregate trapping efficiency for regulated basins within individual continents ranges from 21% to 50%. When the effects of impoundment are considered from the standpoint of all river systems on each continent (i.e., both regulated and nonregulated), we find that the range of TEs is from 4% to 23%. The least overall impact from large reservoir sedimentation is on Australia/Oceania, while the greatest is on Europe.

4.4. Global-scale sediment trapping by large reservoirs

The accumulated impoundment capacity of the LRs analyzed here is nearly 5000 km^3 (Table 2), which is noteworthy from the standpoint of representing more than four times the mean instantaneous standing stock of water held globally by river networks without impoundment (Covich, 1993). Mean, discharge-weighted residence time change for the 633 LRs is 0.21 year. The global interception of discharge by LRs represents 15,800 km^3 year^{-1} or >40% of our computed continental discharge. The distribution of aggregate discharge intercepted by the entire LR sample ($n = 633$) is shown in the bottom panel of Fig. 4 as a function of $\Delta\tau_R$ class together with the idealized trapping efficiency curve (Eq. (1)). As for individual continents, it is apparent that a significant fraction of intercepted discharge is associated with substantial potential sediment deposition.

The true significance of such statistics again becomes apparent when placed into a drainage basin context. Thus, when we remove the tabulation of sequential downstream interception, we find that approximately 9000 km^3 year^{-1} or 24% of total continental discharge from Table 4 is intercepted by the most downstream of LRs in each regulated basin, suggesting an important impact on global sediment retention and transport to the coastal zone. Furthermore, regulated basins represent more than 50% of total global runoff and their basinwide discharge-weighted residence time change is 2 months (Table 4), a delay associated with substantial sediment trapping. When the effect of dilution by unimpounded subcatchments is considered, our estimated LR retention of sediment within regulated basins per se is 30%

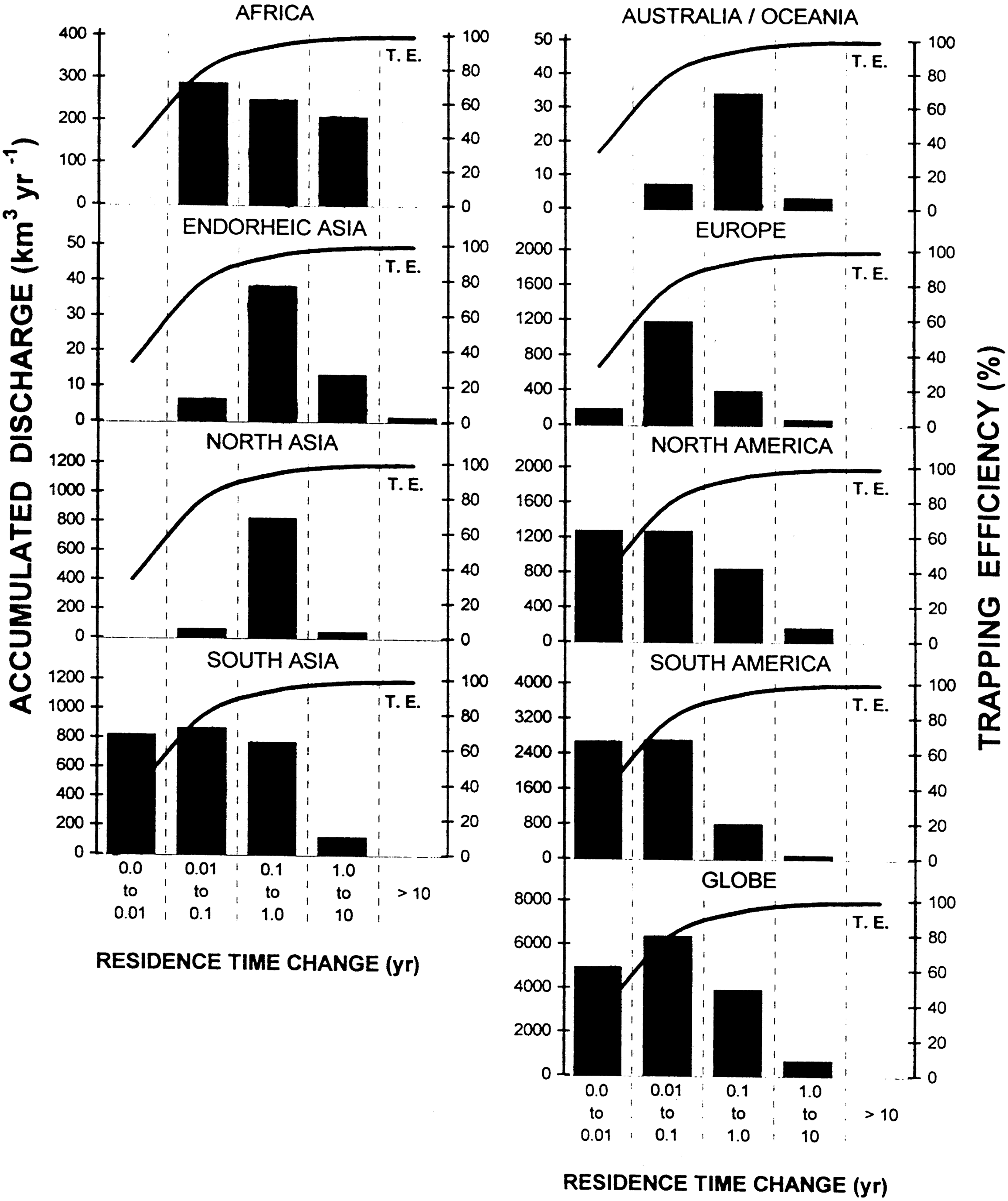


Fig. 4. Aggregate discharge intercepted by large reservoirs expressed as a function of local residence time change of river water for the globe and for individual continental areas. A theoretical trapping efficiency curve for suspended sediments is superimposed on each panel.

Table 4
Continental totals for river water discharge, drainage area, discharge-weighted residence time change, and sediment retention in the world's river basins. Regulated basins refer to control by large reservoirs (LRs) only. Composite values are determined from tabulations made at individual river mouths

Continent[a]	Discharge (km^3 $year^{-1}$) unregulated basins[b]	Area (10^6 km^2) unregulated basins	Discharge (km^3 $year^{-1}$) regulated basins[b]	Area (10^6 km^2) regulated basins	Basinwide $\Delta\tau_R$ (years) regulated basins[c]	Mean % retention regulated basins[c]	Mean % retention all basins[d]
Africa	3320 (n = 476)	18.0	870 (n = 25)	12.1	0.70	42	9
Asia							
Endorheic	210 (195)	5.7	140 (8)	2.8	0.48	26	10
North[e]	450 (313)	3.5	1560 (4)	7.8	0.24	23	18
South	6270 (1009)	11.0	4300 (64)	13.6	0.13	33	13
Australia/Oceania	690 (339)	6.9	70 (10)	1.3	0.45	41	4
Europe[f]	1490 (657)	4.5	1300 (45)	5.7	0.22	50	23
North America	3290 (1362)	12.3	2600 (52)	12.3	0.31	43	19
South America	2110 (376)	4.8	9180 (28)	13.2	0.06	21	17
Total	17,830 (4727)	66.7	20,020 (236)	68.7	Mean 0.16	30	16

[a] Defined by river mouths within the STN-30 simulated river network at 30-min spatial resolution.
[b] n refers to the number of distinct drainage basins in STN-30.
[c] Discharge-weighted and accounting for dilution by unregulated subbasins (see Fig. 2).
[d] Discharge-weighted and assuming that unregulated basins convey no additional sediment trapping potential beyond that conveyed by the large reservoirs analyzed.
[e] Drainage into Arctic Ocean.
[f] Area west of the Ural Mountains and north of the Causasus Mountains.

globally. When placed into the context of all river basins, the relative importance of the subset of LRs is, of course, diminished. The fractional retention is lowered to 16%, representing the impact of this subset of LRs on total global sediment retention.

The global geography of basinwide suspended sediment trapping by LRs shows it to be a pandemic phenomenon (Fig. 5). Many of the world's largest river basins show nearly complete sediment retention. The global land mass area representing basins showing some quantifiable change in mean residence time and thus sediment trapping by LRs is roughly equivalent to the aggregate area uninfluenced by these reservoirs. The same is generally true for the total land area on each of the continents (Table 4). The patterns in Fig. 5 are similar to those shown for the northern hemisphere by Dynesius and Nilsson (1994) assessing a variety of anthropogenically induced hydraulic modifications. It is noteworthy that the influence of artificial impoundments we show extends well into the southern hemisphere.

Our findings refer specifically to "potential" drainage area, whereas only a portion (≈ 70%) of the land mass of the Earth actively discharges river water under contemporary climate (Vörösmarty et al., 2000b). Because 92% of the area of the 236 regulated basins is active with respect to runoff while only 75% discharges water across unregulated basins, LRs control a relatively larger proportion of the global runoff and sediment-producing area than suggested by Table 4. On the other hand, our estimates do not take into account the reduction in sediment trapping caused by siltation of reservoirs. For example, while we estimate nearly 90% basinwide trapping for the Huang He in China, it is well known that due to poor design, some of its reservoirs have lost virtually all of their useful storage, in some case only a few years following construction (Vörösmarty et al., 1998). These impoundments thus return quickly to a more riverine state with little sediment trapping and, in fact, likely serving as a net source of previously deposited sediment. Nonetheless, our estimates probably understate the aggregate global impact of water engineering as they are derived from but a subset of all such hydraulic disturbances.

We can also use results from this study to hypothesize about the recent history of sediment trapping by LRs (Fig. 6). A time series of local $\Delta\tau_R$ shows that since the beginning of last century, the average global

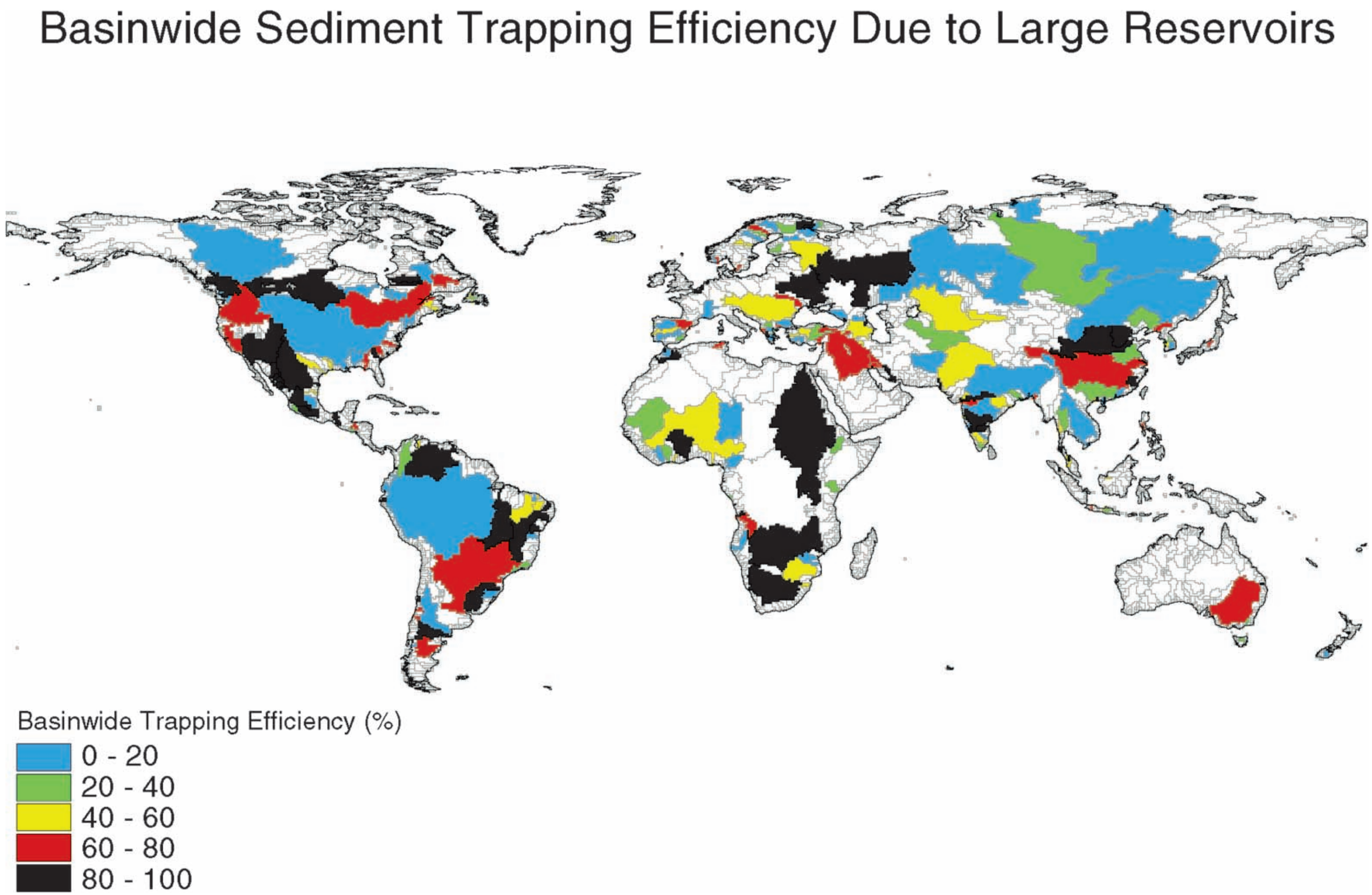


Fig. 5. The global geography of basinwide trapping of suspended sediment flux by the large reservoirs analyzed in this study. A total of 236 regulated basins with 633 LRs constitutes our subsample of reservoirs, which collectively represent about 70% of registered impoundment storage volume (i.e., ICOLD, 1984, 1988, 1998). Basin boundaries are at 30′ (longitude × latitude) spatial resolution. For the purposes of display, the basins include both discharging and nondischarging portions of the land mass (Vörösmarty et al., 2000b,c), although all numerical calculations represent discharge weighting and corrections for non-flowing areas.

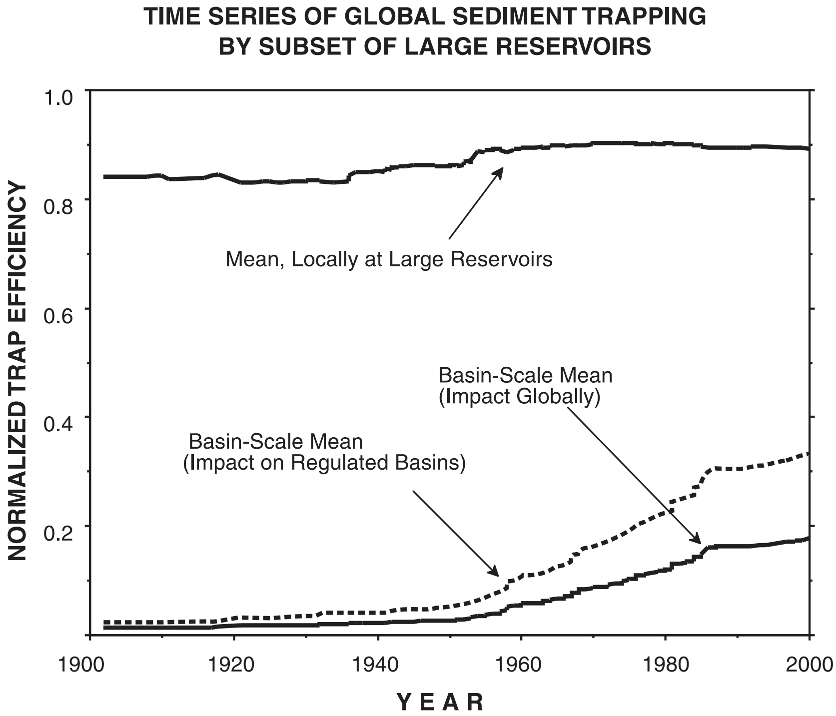


Fig. 6. Evolution of global sediment trapping efficiencies by the large reservoirs analyzed in this study. Sediment trapping both locally at the LRs and at basin mouths are shown. This calculation was based on data presented in Vörösmarty and Sahagian (2000) giving time series of maximum storage, intercepted discharge, and local residence time change, $\Delta\tau_R$. A subset of $n=549$ geographically referenced, registered LRs had reported year of construction. This subset had a combined volume of 4639 km^3 or 95% of that in the geo-referenced LR data set ($n=633$) described in the text. All trap efficiency means are discharge weighted.

reservoir maintains a mean, discharge-weighted trapping efficiency of >80%. Note the much smaller mean values at regulated basin mouths, resulting from "dilution" by unimpounded tributaries. The rise over time in the basin-scale means represents an increasing interception of discharge and hence sediment flux. For the first half of the 20th century, global sediment retention in regulated basins was modest at less than 5% of incident flux. However, after 1950, with the great expansion in dam building worldwide, we see a tripling from 5% to 15% by 1968, another doubling to 30% by 1985, and a stabilization thereafter. The still smaller values for the "Impact Globally" time series reflects the highly conservative assumption that there is no additional reservoir retention outside of LR-regulated basins. From 1900, it took 75 years to reach the level of 10% global sediment retention. Over the past 25 years, there has been a much slower increase due to a reduction in the annual rate at which new LR construction adds aggregate storage capacity, with little corresponding change in the rate at which new LRs intercept discharge (Vörösmarty and Sahagian, 2000). These findings refer specifically to an admittedly incomplete subset of geographically referenced LRs bearing a registered construction date and simple assumptions about sediment interception. The need for a much expanded analysis and one that is geographically specific is clearly warranted.

5. Additional sediment trapping by smaller registered reservoirs

Prior study suggests that relatively small reservoirs may be quantitatively significant in intercepting continental runoff and suspended sediment, even in river basins characterized by large reservoirs. For the case of the Danube, consideration of nearly 200 non-LRs collectively increased mean basin residence time change fivefold over that obtained when examining its three LRs alone (Horváth et al., 1997). We attempt here to augment our LR-based estimate of global sediment interception with inferences about the population of smaller ICOLD-registered impoundments (SRs).

Our calculations for SRs are fundamentally aspatial, necessitated by the absence of a geographically specific database on these impoundments. Our strategy is to use the statistical characteristics of the geographically referenced LR sample to anticipate the role of the remaining (n>44,000) ICOLD-registered reservoirs in global sediment retention (see St. Louis et al., 2000; Takeuchi, 1997, 1998 for similar use of such data). Assumptions on the geographical distribution of the SRs allow us to estimate sediment trapping using the approach shown in Fig. 2. We again assume that sediment flux is proportional to discharge as described for LRs in Section 3. The calculations are given immediately below, and results are summarized in Table 5. We acknowledge that these estimates are somewhat speculative and argue for a more complete geographically referenced analysis.

5.1. Step 1: establish cumulative attribute functions

Our computations require a characterization of the statistics of three key attributes of the registered dams: maximum storage capacity, intercepted discharge, and upstream area. We examined cumulative distribution functions, ranked by maximum storage capacity, for each of these variables. For the 633 LRs, these curves were stable and predictable, and we assume that they are sufficient to extrapolate the cumulative behavior of the remaining ≈ 45,000 SRs. We specifically fit three nonlinear functions:

$$V_c = (-1.2606 \times 10^7 + 5.7048 \times 10^6 \ln R_r)^{0.5}$$
$$(r^2 = 0.972\ p \gg 0.0001) \quad (3)$$

$$Q_c = -880.83 + 645.666\ R_r^{0.5}$$
$$(r^2 = 0.994\ p \gg 0.0001) \quad (4)$$

$$A_c = 1.68388 \times 10^6 + 2.7431 \times 10^6 (R_r)^{0.5}$$
$$(r^2 = 0.994\ p \gg 0.0001) \quad (5)$$

where V_c, Q_c, and A_c are, respectively, cumulative reservoir capacity (km^3), intercepted discharge (km^3 year^{-1}), and upstream area (km^2). R_r is reservoir rank. Fig. 7a,b, and c gives these relationships plus the observed distributions from the LR subset.

Table 5
Some characteristics of large and small reservoirs. Nesting of impoundments arising from the nonrandom distribution of large (LRs) and small reservoirs (SRs) are also given. These variables and derived factors were based on our database for LRs and on extrapolations using Eqs. (4) and (5) for SRs. In aggregate, small reservoirs are about 40% as effective as large impoundments at sediment trapping due to their nonuniform placement inside regulated basins. This reduction factor is required for correct discharge weighting of basin-scale trapping efficiencies (See Section 5.7)

Variable	LRs	SRs	Relative nesting		Additional SR "dilution" over LR
			LRs	SRs	
Number	633	44,367			
Mean volume (km^3)	7.72	0.047			
Mean $\Delta\tau_R$	0.21	0.011			
Mean discharge intercepted (km^3 year^{-1})					
Spatially disaggregated[a]	10.5	0.45			
			2.31	6.04	0.38
Computed locally[b]	24.3	2.72			
Mean area (10^3 km^3)					
Spatially disaggregated[a]	36	1.5			
			3.08	7.67	0.42
Computed locally[c]	111	11.5			

[a] For LRs, computed as total discharge or area specifically for LR/SR-regulated subbasins divided by the number of LRs; for SRs, computed as whole basin total discharge or area divided by number of SRs.

[b] For LRs, from our database on n = 633 geo-referenced reservoirs; for SRs, from Eq. (4) for individual reservoirs (n = 634 to 45,000).

[c] For LRs, from our database on n = 633 geo-referenced reservoirs; for SRs, from Eq. (5) for individual reservoirs (n = 634 to 45,000).

5.2. Step 2: calculate total LR and SR storage volumes

The total volume of all registered dams was computed using Eq. (3), with R_r = 45,000 (World Commision on Dams 2000), yielding an aggregate volume of 6970 km^3. From Table 2, we find a total LR volume of 4890 km^3, so that SRs collectively constitute 2080 km^3.

5.3. Step 3: determine relative interception of discharge by LRs and "dilution" of local trapping potential downstream to river mouth

From Table 2, it can be seen that the local discharge-weighted $\Delta\tau_R$ for LRs is 0.21 year, representing a trapping efficiency (TE_{local}) of 89% (Eq. (1)). However, in aggregate, this local-scale potential trapping is transformed into an effective, lower trapping efficiency of 30% at regulated basin mouths (TE_{bas}). By the discharge-weighting calculations shown in Fig. 2, the net reduction from 89% to 30% results from downstream "dilution" along the mainstem by runoff generated over unimpounded (or less impounded) tributary subbasins. Since we assume sediment flux is proportional to discharge, the mean

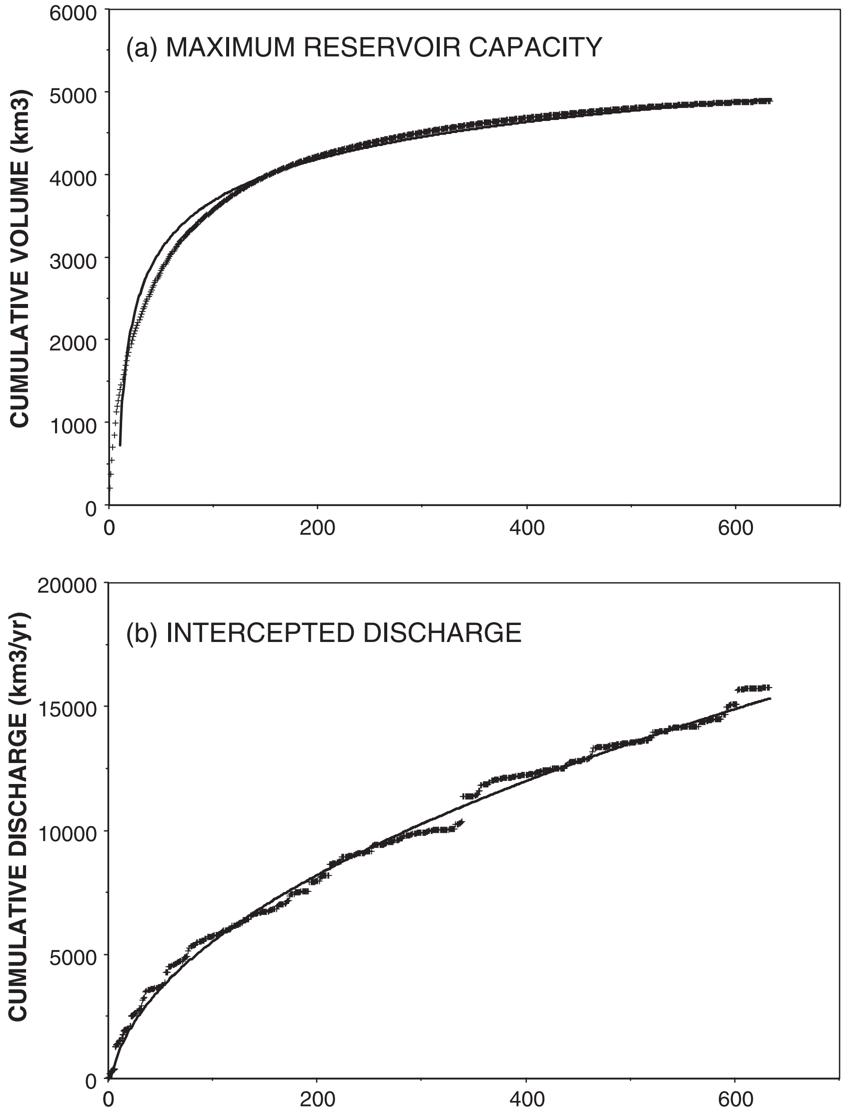


Fig. 7. Relationships between ranked reservoir size (by storage capacity) and (a) cumulative storage volume, (b) intercepted discharge, and (c) upstream area drained based on the large reservoirs ($n = 633$) analyzed in this study. The plots show the influence of individual data points as well as the trajectories defined by Eqs. (3)–(5).

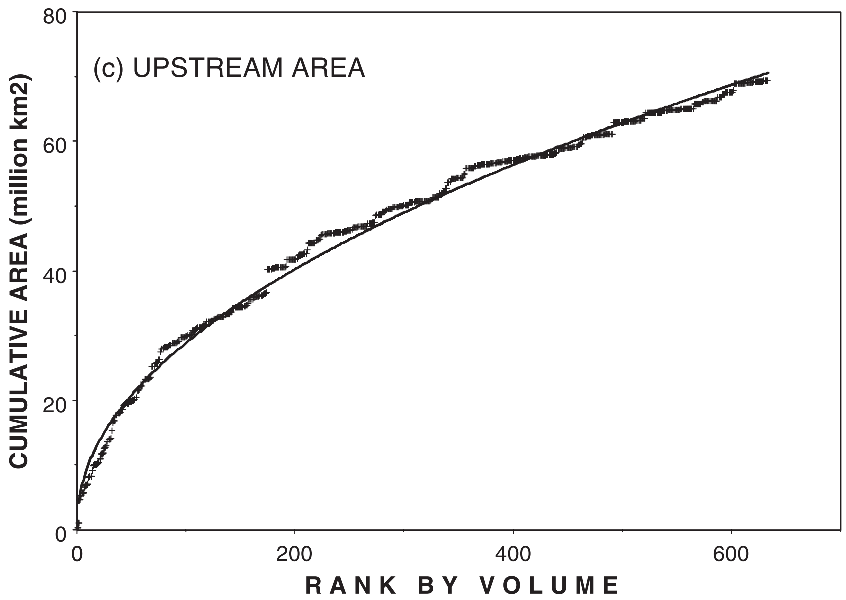


Fig. 7 (*continued*).

fraction of regulated basin runoff (discharge) upstream of LRs is then effectively 0.33 (i.e., 30%/89%), while downstream it is 0.67. Thus, of the 20,000-km^3 year^{-1} discharge emanating from regulated basins (Table 4), 6610 km^3 year^{-1} is estimated to be controlled by LRs, while 13,400 km^3 year^{-1} is not.

5.4. Step 4: assign spatial distribution of SRs

We assume that the 2080 km^3 total SR volume is confined to regulated basins as already defined by the LRs. We use this as our working assumption based on the fact that the 236 regulated basins constitute approximately 50% of the non-glacierized land area (Vörösmarty et al., 2000b,c) and more than half of world runoff, which is already higher than previous estimates of the renewable freshwater resource that is accessible to society (Postel et al., 1996).

Inside regulated basins, we distribute SR volume in relation to the aggregate proportion of total runoff associated with LRs. We thus assign one-third (i.e., 0.33 from Step 3) of the total SR volume to be in association with LRs, defining LR/SR-regulated subbasins (see Fig. 2). The remaining fraction, 0.67, is placed outside LR/SR-regulated subbasins, specifically in SR-regulated subbasins, where no LRs reside. We consider this spatial assignment to be reasonable, based on the similarity of runoff in regulated basins (mean = 291 mm year^{-1}) (Table 4) and computed to be intercepted by each LR (219 mm year^{-1}) and SR (237 mm year^{-1}) (from data in Table 5). We thus assume that the SRs are distributed widely across regulated basins and hence, one-third to be in association with LRs.

5.5. Step 5: determine total reservoir volumes in LR/SR- and SR-regulated subbasins

From the findings and assumptions in Step 4, we calculate that LR/SR-regulated subbasins globally hold a reservoir storage of 5570 km^3 ($4890 + 0.33 \times 2080$). SR-regulated subbasins maintain a total volume of 1390 km^3 (0.67×2080).

5.6. Step 6: compute residence time change and sediment trapping efficiency for LR/SR- and SR-regulated subbasins

Using the volumes from Step 5 and discharge over the two classes of subbasins (Step 3) we obtain an aggregate residence time change. LR/SR-regulated subbasins collectively show a residence time change ($\Delta\tau_{reg}$) of 0.565 year (0.67×5570 km^3/6610 km^3 year^{-1}, where 0.67 is the assumed mean reservoir filling [USGS, 1984]). SR-regulated subbasins show collectively 0.069 year (0.67×1390 km^3/13,400 km^3 year^{-1}). Using Eq. (2) of Fig. 2, the composite sediment trapping efficiency (TE_{reg}) for LR/SR-regulated subbasins is 93.3% and for SR-regulated subbasins is 81.0%.

5.7. Step 7: compute discharge-weighted mean TE_{bas} for regulated basins

To compute a discharge-weighted mean TE_{bas} at regulated basin mouths (Fig. 2), we must estimate the magnitude of the "dilution" capacity by unregulated portions of the basins in question (i.e., the reduction in apparent trapping efficiencies downstream of reservoirs arising from the nonuniform positioning and nesting of reservoirs within the larger basin). Such dilution now involves the relative contributions of both LR/SR- and SR-regulated subbasins.

For the LRs alone (in LR/SR-regulated subbasins), we noted earlier that there is a large effective loss of local trapping efficiencies moving downstream toward basin mouths (collectively, from 89% to 30%). The specific value for loss of trapping efficiency is conditioned upon the spatial distribution of LRs, which is nonrandom. A spatially homogenous distribution of LRs would result in a mean intercepted discharge of 10.5 km^3 year^{-1}, whereas the observed mean is 24.3 km^3 year^{-1} (Table 5). Similarly, mean upstream area under a random distribution is 36,000 km^2, while the spatially explicit computed value is 111,000 km^2. These statistics indicate a downstream preference in the positioning of LRs on relatively larger rivers and a likely nesting or coalescing of LRs as indicated for subbasin B in Fig. 2. Nesting withdraws LRs from unregulated portions of the basin, which remain to "dilute" the basinwide trapping. In addition, due to the nonlinear nature of the TE_{reg} function, nested multiple reservoirs (compared to an equal number more equally distributed LRs) are less effective at overall sediment retention. This arises due to the high sediment retention that can be achieved by but a single reservoir, with sequential downstream reservoirs now intercepting relatively sediment-free river water. This reduces the average trapping potential for each of the nested impoundments.

The same effect is at play with SRs, and Table 5 presents a similar set of statistics for the nesting of SRs. We unfortunately cannot make a direct geospatial calculation for the SRs of intercepted discharge and upstream area, but we can use Eqs. (4) and (5) to infer these parameters. For discharge, we see a value of 0.45 versus 2.72 km^3 year^{-1} for the randomly distributed and locally computed interception by SRs, respectively. The corresponding values for upstream area are 1500 and 11,500 km^2. In relative terms, SRs are much more effective at nesting than the LRs. Using an index of the ratio of locally computed to spatially disaggregated attributes, SRs are 2.5 times more "nested" with respect to both discharge (6.04 versus 2.31) and area (7.67 versus 3.08) (Table 5). The tabulation suggests that because of their nonrandom placement across river systems, SRs are only about 40% as effective at contributing to basinwide trapping efficiency as are LRs. We will use this factor (specifically, 0.4) in the next calculation.

We can now compute a discharge-weighted, collective mean trapping efficiency for regulated basins from local trapping efficiencies: $(93.3\% \times 6610 + 81.0\% \times 0.4 \times 13{,}400)/20{,}000 = 52.5\%$. The first term represents the LR/SR-regulated portion of the basin (based on Steps 3 and 6), while the second gives that for the SR-regulated subbasin. The weighting given to the composite LR/SR-regulated subbasin is solely in terms of its contributing discharge. By the rules of Fig. 2, the impact of SRs within the LR/SR-regulated subbasin is additive to that of LRs. For the SR-regulated subbasin, the equation accounts for both contributing discharge and the TE_{reg} dilution effect discussed in the previous paragraph and summarized in Table 5.

5.8. Step 8: compute discharge-weighted mean TE_{bas} for all basins and estimate global impact of all registered impoundments

The full impact of regulated basins on global sediment flux can be estimated by a discharge weighting against regulated and unregulated basins. The global magnitude of LR plus SR sediment trapping we thus estimate to be $27.8\% = (52.5\% \times 20{,}000 + 0\% \times 17{,}800)/(37{,}800)$.

Table 6
Contributions to global suspended sediment trapping due to large (LR) and other smaller (SR) registered reservoirs. Composite values are determined from tabulations made at individual river mouths. Entries are discharge weighted

	From LRs	From SRs	From all registered reservoirs
Mean % retention in regulated basins[a]	30	23	53
Mean % retention in all basins[b]	16	12	28
Fractional contribution to global retention	0.57	0.43	

[a] Discharge-weighted and accounting for dilution by unregulated subbasins (see Fig. 2).

[b] "All basins" refers to regulated and unregulated basins. The calculations are discharge weighted (from Table 4) and assume that unregulated basins convey no additional sediment trapping potential beyond that conveyed by the reservoirs analyzed (e.g., for the LRs we get: (17,830 (0%) + 20,020 (30%))/37,850 = 16%).

5.9. Step 9: establish relative importance of LRs and SRs

When compared locally to LRs, we find that SRs are significantly smaller (mean storage volume = 0.047 vs. 7.72 km^3), intercept less discharge (mean = 2.72 vs. 24.3 km^3 $year^{-1}$), drain smaller areas (mean = 11,500 vs. 111,000 km^2), and show more modest local residence time change $\Delta\tau_R$ (mean = 0.011 vs. 0.21 year) (Table 5). Nonetheless, our assessment suggests that SRs collectively impart an important anthropogenic signature on global sediment flux (Table 6). Mean SR-associated sediment retention within all regulated basins increases the LR-only retention by 23%, from 30% to 53%. For the globe as a whole, including SRs in the tabulation adds another 12% of retention to the LR-only estimate of 16%. Combined SR and LR retention at the global scale thus totals 28%, with SRs contributing about 40% to worldwide suspended sediment retention.

6. Discussion and conclusions

Our assessment suggests a substantial and global-scale signal of human intervention within the global sedimentary cycle. The trapping of continental runoff and suspended sediment by registered dams imparts a measurable impact on river water destined for the world's coastal and inland seas. If we assume that the global, natural sediment flux falls between 15 and 20 Gt $year^{-1}$ (see Introduction), then the aggregate impact of all registered impoundments will be on the order of 4–5 Gt $year^{-1}$. Thus, modern reservoir construction creates a modified global sediment flux from 10 to 16 Gt $year^{-1}$, a range encompassing the contemporary total of 13.4 Gt $year^{-1}$ recently proposed by Stallard (1998).

Our current estimate of modern reservoir deposition is much larger than that given earlier by Meybeck (1988), which was 1.5 Gt $year^{-1}$ or 7.5–10% of total natural river mouth flux. However, this earlier estimate was based only on the trapping in a few major basins as reported by Milliman and Meade (1983). Our consideration of many additional LRs and SRs progressively increased this original retention estimate to 16% and then to nearly 30% globally. We expect our retention estimate to increase further with inclusion of the remaining ≈ 800,000 small impoundments (McCully, 1996) as well as through continued dam construction. This preliminary estimate reasonably represents a minimum for the contemporary setting and near-term future.

The time series of impoundment effects on sediment retention gives a measure of the growing impact of humans on the global water and sediment cycles. It is interesting to note that the hypothesized global trajectory over time is in agreement with observed trends in riverine sediment flux (Walling et al., this special issue). The measurement-based time series show fluxes that are predominantly stable or in decline across many individual rivers, despite well-known increases in local erosion arising from widespread land cover change and poor land management. We hypothesize that the general absence of increasing riverborne sediment flux is fundamentally the result of modern reservoir construction, but this assertion requires further, more comprehensive study.

We have established a methodology in the hopes of providing quantitative information about one specific element within the complex amalgam of processes that route suspended sediment from source area to coastal zone. Our estimates are strictly for riverborne sediments and represent a fractional template upon which spatially varying fluvial sediment loads could be sequestered. The estimates do not include the impact of reduced or redirected flows through inter-basin transfers or irretrievable losses, nor of clear-water erosion downstream of impoundments.

For a more complete assessment, a conceptually and spatially explicit approach is required, with specific focus on variable source and sink areas. Absolute fluxes are difficult to predict, given current data availability and conceptual challenges. For example, Stallard (1998) notes the difficulties in isolating the impact of alluvial, colluvial, and aeolian deposition from purely reservoir deposition, at even regional scales. Smith et al. (2001), using registered reservoirs in the US (1.86 m or higher; $n \approx 43{,}000$), found a substantial deposition in reservoirs, citing an annual flux equal to about half that of local erosion. As specific as this estimate might seem, it is not strictly compatible with the results reported here as many interim transport mechanisms were aggregated in their study, thus obscuring estimates of fluvial inputs upstream of reservoirs, which are specifically required by our framework model. Global models of sediment routing will require improvement in nomenclature and identification of individual processes capable of explicit quantification.

Data limitations, as discussed earlier, will severely limit model specificity as well as model calibration and validation. Chief among these limits is the lack of basic biogeophysical properties of reservoirs (Vörösmarty and Sahagian, 2000). Additional registered reservoirs, many substantial in size, undoubtedly exist along internal tributaries and in other basins but are not tabulated here. Further, the impact of several hundreds of thousands of small impoundments such as farm ponds and rice paddies has similarly not been considered. Our results should therefore be considered highly conservative. The estimates are for reservoir siltation only; additional reductions in sediment flux due to flow diversion are not tabulated.

In a recent series of papers, most notably emerging for several International Geosphere–Biosphere Program (IGBP) activities, fluvial transports are being highlighted as a fundamental feature of the Earth System (Vörösmarty et al., 1997c; Meybeck, 1998; Vörösmarty and Meybeck, 1999; Kabat et al., 2001) and one that strongly reflects the influence of humans on elemental fluxes, such as for water (Vörösmarty and Sahagian, 2000), carbon (Meybeck and Vörösmarty, 1999), and nutrients (Seitzinger and Kroeze, 1998). Our results demonstrate that river impoundment should now be considered explicitly in global elemental flux studies.

Our findings are of more than simple academic interest, as a multitude of environmental impacts, often very costly to society, are associated with reduced suspended sediment flux–decline in flood regulation and hydroelectric capacity; downstream scouring of streambeds resulting in the failure or costly reinforcement of engineering structures; instability of river deltas and dieback of coastal ecosystems. We have not explicitly studied these impacts, but can conclude from our current work that because of widespread river impoundment, no populated region of the globe is immune from these potential effects. With the expected rise in global economic development and population growth, the world will experience increasing pressure to control water systems. Society will respond, as it has historically, by constructing hydraulic engineering works including impoundments. The need to develop improved models of sediment transport and its interplay with modern reservoir construction is clearly indicated.

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References

Alcamo, J., Henrichs, T., Rösch, T., 2000. World water in 2025: global modeling and scenario analysis. In: Rijsberman, F.R. (Ed.), World Water Scenarios. Earthscan, London, UK, pp. 204–271.

Avakyan, A.B., 1987. Reservoirs of the USSR and tasks of their investigation. Water Resources (Moscow) 14, 538–549.

Bartholomew, J.C., Geelan, P.J.M., Lewis, H.A.G., Middleton, P., Winkleman, B. (Eds.), 1983, 1988. The Times Atlas of the World: Comprehensive Edition. Times Books, London, UK.

Brune, G.M., 1953. Trap efficiency of reservoirs. Transactions of the American Geophysical Union 34, 407–418.

Calvo, S., Barone, R., Naselli Flores, L., Frada Orestano, C., Dongarra, G., Lugaro, A., Genchi, G., 1993. Limnological studies on lakes and reservoirs of Sicily. Il Naturalista Siciliano 13 (292 pp.).

Covich, A.P., 1993. Water and ecosystems. In: Gleick, P.H. (Ed.), Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford Univ. Press, Oxford, UK, pp. 40–55.

Defense Mapping Agency Aerospace Center (DMAAC), 1980–1986. Operational Navigation Charts. St. Louis, MO.

D.S.I., 1991. Dams and Hydroelectric Power Plants in Turkey. D.S.I. (State Water Supply) BASIN EVI Publ., Ankara, Turkey.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation in river systems in the northern third of the world. Science 266, 753–762.

Fekete, B.M., Vörösmarty, C.J., Grabs, W., 1999. Global, Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances. WMO-Global Runoff Data Center Report #22. Koblenz, Germany.

Fekete, B.M., Vörösmarty, C.J., Grabs, W., 2002. High resolution fields of global runoff combining observed river discharge and simulated water balances. Global Biogeochemical Cycles (in press).

Fournier, F., 1960. Climat et Erosion. Presses Universitares de France.

Holeman, J.N., 1968. The sediment yield of major rivers of the world. Water Resources Research 4, 737–747.

Horváth, E., Fekete, B., Bálint, G., Albert, K., Vörösmarty, C.J., Zsuffa, I., 1997. The aging of runoff in large reservoirs of the Danube River basin. In: Vermes, L. (Ed.), Proc. Of the ICER Tempus 2nd Int'l PhD Seminar on Investigation of Environmental Impacts on River Basin and/or Flood Plain Management. University of Horticulture and Food Industry, Budapest, Hungary, pp. 53–62.

Humborg, C., Ittekkot, V., Cociasu, A., Von Bodungen, B., 1997. Effect of Danube River Dam on Black Sea biogeochemistry and ecosystem structure. Nature 386, 385–388.

IAHS Ad Hoc Group on Global Water Data Sets, 2001. Global water data: a newly endangered species. Eos, AGU Transactions 82 (5), 54–58.

ICOLD, 1984, 1988, 1998. World Register of Dams. International Commission on Large Dams, Paris, France.

IWPDC, 1989. The world's major dams and hydroplants. Global map. International Water Power and Dam Construction. Reed Business Publishing, Sutton, Surrey, UK.

IWPDC, 1994. Handbook. International Water Power and Dam Construction. Reed Business Publishing, Sutton, Surrey, UK (224 pp.).

Judson, S., 1968. Erosion of the land. American Scientist 56, 356–374.

Kabat, P., Hoff, H., Hutjes, R., Claussen, M., Viterbo, P., Meybeck, M., Vörösmarty, C., 2001. Terrestrial biosphere, climate and the water cycle. IGBP Global Change Newsletter 46, 31–34.

Kopylov, A.P., Kuzin, P.S., Senkov, E.P., 1978. General information and hydrography. In: Korzoun, et al., (Eds.), World Water Balance and Water Resources of the Earth. UNESCO/IHP, Paris, France, pp. 23–41.

Lammers, R.B., Shiklomanov, A.I., Vörösmarty, C.J., Fekete, B.M., Peterson, B.J., 2001. Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research—Atmospheres 106 (D4), 3321–3334.

Ludwig, W., Probst, J.-L., Kempe, S., 1996. Predicting the oceanic input of organic carbon by continental erosion. Global Biogeochemical Cycles 10, 23–41.

McCully, P., 1996. Silenced Rivers: The Ecology and Politics of Large Dams. Zed Books, London, UK.

Meade, R.H., 1995. Setting: geology, hydrology, sediments and engineering of the Mississippi River. In: Meade, R.H. (Ed.), Contaminants in the Mississippi River 1987–1992. USGS Circular, vol. 1133. US Geological Survey, Reston, VA, pp. 13–30.

Meade, R.H., Parker, R.S., 1985. Sediment in rivers of the United States. National Water Summary, 1984. Water Supply Paper, vol. 2275. US Geological Survey, Reston, VA, pp. 40–60.

Meybeck, M., 1982. Carbon, nitrogen, and phosphorus transport by world rivers. American Journal of Science 282, 401–450.

Meybeck, M., 1988. How to establish and use world budgets of river material. In: Lerman, A., Meybeck, M. (Eds.), Physical and Chemical Weathering in Geochemical Cycles. Kluwer Academic Publishing, Dordrecht, The Netherlands, pp. 247–272.

Meybeck, M., 1995. Global distribution of lakes. In: Lerman, A., Imboden, D.M., Gat, J.R. (Eds.), Physics and Chemistry of Lakes. Springer-Verlag, Berlin, Germany, pp. 1–36.

Meybeck, M., 1998. The IGBP Water Group: a response to a growing global concern. IGBP Global Change Newsletter 36, 8–12.

Meybeck, M., Ragu, A., 1996. GEMS/water contribution to the global register of river inputs. GEMS/Water Programme (UNEP/WHO/UNESCO). World Health Organization, Geneva, Switzerland.

Meybeck, M.M., Vörösmarty, C.J., 1999. Global transfer of carbon by rivers. IGBP Global Change Newsletter 37, 18–19.

Meybeck, M., Green, P., Vörösmarty, C.J., 2001. A new typology for mountains and other relief classes: an application to global continental water resources and population distribution. Mountain Research and Development 21 (1), 34–45.

Milliman, J.M., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. Journal of Geology 91, 1–21.

Milliman, J.M., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology 100, 525–544.

Morris, G.L., Fan, J., 1998. Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use. McGraw-Hill, New York, NY (45 pp.).

Oki, T., Saruhashi, T., Yang, D., Agata, Y., Kanae, S., Musiake, K., 2002. Global assessment of current water resources using the Total Runoff Integrating Pathways. Hydrological Sciences Journal (in press).

Ortiz Casas, J.L., Peña Martinez, R., 1984. Applicability of the

OECD eutrophication models to Spanish reservoirs. Verhandlungen—Internationale Vereinigung fuer Theoretische und Angewandte Limnologie 22, 1521–1535.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.

Revenga, C., Brunner, J., Henninger, N., Kassem, K., Payne, R., 2000. Pilot Analysis of Global Ecosystems: Freshwater Systems. World Resources Institute, Washington, DC.

Rosenberg, D.M., McCully, P., Pringle, C.M., 2000. Global-scale environmental effects of hydrological alterations: introduction. BioScience 50, 746–751.

Sanchez-Azofeifa, G.A., 1996. Assessing Land Use/Land Cover Change in Costa Rica. PhD Dissertation, University of New Hampshire, Durham, NH.

Seitzinger, S.P., Kroeze, C., 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemical Cycles 12, 93–113.

Shiklomanov, A.I., Lammers, R.B., Vörösmarty, C.J., 2002. Widespread decline in hydrological monitoring threatens Pan-Arctic research. Eos, AGU Transactions 83 (13), 16–17.

Smith, S.V., Renwick, W.H., Buddemeier, R.W., Crossland, C.J., 2001. Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15, 697–707.

Stallard, R., 1998. Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12, 231–257.

St. Louis, V., Kelly, C.A., Duchemin, É., Rudd, J.W.M., Rosenberg, D.M., 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. BioScience 50, 766–775.

Syvitski, J.P., Morehead, M.D., 1999. Estimating river–sediment discharge to the ocean: application to the Eel margin, northern California. Marine Geology 154, 13–28.

Takeuchi, K., 1997. On the scale diseconomy of large reservoirs in land occupation. Sustainability of Water Resources under Increasing Uncertainty. IAHS Publication, vol. 240. IAHS Press, Wallingford, UK, pp. 519–527.

Takeuchi, K., 1998. Chapter 1: introduction. In: Takeuchi, K., Hamlin, M., Kundewicz, Z.W., Rosbjerg, D., Simonovic, S.P. (Eds.), Sustainability of Water Resources under Increasing Uncertainty. IAHS Publication, vol. 251. IAHS Press, Wallingford, UK, pp. 1–30.

UNESCO, various years. Discharge of Selected Rivers of the World, Vol. I/II. UNESCO/IHP, Paris, France.

USGS, 1984. National Water Summary—Hydrologic Events and Issues. U.S. Geological Survey Water Supply Paper #2250. US Department of the Interior, Washington, DC.

Vörösmarty, C.J., Meybeck, M.M., 1999. Riverine transport and its alteration by human activities. IGBP Global Change Newsletter 39, 24–29.

Vörösmarty, C.J., Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. BioScience 50, 753–765.

Vörösmarty, C.J., Moore, B., Gildea, M.P., Peterson, B., Melillo, J., Kicklighter, D., Raich, J., Rastetter, E., Steudler, P., 1989. A continental-scale model of water balance and fluvial transport: application to South America. Global Biogeochemical Cycles 3, 241–265.

Vörösmarty, C.J., Fekete, B., Tucker, B.A., 1996. River discharge database, version 1.0 (RivDIS v1.0), volumes 0 through 6. A contribution to IHP-V theme 1. Studies and Reports in Hydrology. UNESCO, Paris.

Vörösmarty, C.J., Sharma, K., Fekete, B., Copeland, A.H., Holden, J., Marble, J., Lough, J.A., 1997a. The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26, 210–219.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., 1997b. The potential impact of neo-Castorization on sediment transport by the global network of rivers. In: Walling, D., Probst, J.-L. (Eds.), Human Impact on Erosion and Sedimentation. IAHS Press, Wallingford, UK, pp. 261–272.

Vörösmarty, C.J., Wasson, R., Richey, J.E. (Eds.), 1997c. Modeling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems. IGBP Report, vol. 39. IGBP Secretariat, Stockholm, Sweden.

Vörösmarty, C.J., Federer, C.A., Schloss, A., 1998. Potential evaporation functions compared on U.S. watersheds: implications for global-scale water balance and terrestrial ecosystem modeling. Journal of Hydrology 207, 147–169.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R., 2000a. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R., 2000b. A simulated topological network representing the global system of rivers at 30-minute spatial resolution (STN-30). Global Biogeochemical Cycles 14, 599–621.

Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R., 2000c. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution (STN-30). Journal of Hydrology 237, 17–39.

Walling, D.E., Webb, B.W., 1983. Patterns of sediment yield. In: Gregory, K.J. (Ed.), Background to Palaeohydrology. Wiley, New York, NY, pp. 69–100.

Ward, P.R.B., January 1980. Sediment transport and a reservoir siltation formula for Zimbabwe–Rhodesia. Die Siviele Ingenier in Suid-Afrika, pp. 9–15.

World Commission on Dams, 2000. Dams and Development: A New Framework for Decision-Making. Earthscan, London, UK.