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The potential impact of neo-Castorization on sediment transport by the global network of rivers

CHARLES J. VÖRÖSMARTY
Institute for the Study of Earth, Oceans, and Space and Earth Sciences Department, University of New Hampshire, Durham, New Hampshire 03824, USA

MICHEL MEYBECK
Laboratoire de Géologie Appliquée, Université de Paris VI, Place Jussieu, F-75257 Paris, France

BALÁZS FEKETE & KESHAV SHARMA
Institute for the Study of Earth, Oceans, and Space and Earth Sciences Department, University of New Hampshire, Durham, New Hampshire 03824, USA

Abstract In this paper, we assess the potential impact of global reservoir construction on sediment transport from the continental land mass. Our study links information on 633 of the world's largest reservoirs (LRs) ($\geq$0.5 km^3 maximum storage capacity) to a digitized river network at 30-minute spatial resolution. A residence time change ($\Delta\tau_R$) is used in conjunction with a retention function to predict the proportion of incident sediment flux trapped within each impoundment. The discharge-weighted mean $\Delta\tau_R$ for individual LRs distributed across the globe is 0.21 years. We estimate that more than 40% of global river discharge is intercepted by the large impoundments we studied and that a significant proportion ($\approx$70%) of this discharge maintains a theoretical sediment trapping efficiency in excess of 50%. For regulated drainage basins the global, discharge-weighted residence time change is 0.16 years, representing a 30% potential sediment trapping. For all river systems, we estimate a 16% sediment trapping. From the standpoint of sediment retention, the most heavily regulated drainage basins are in Europe. North America, Africa, Australia/Oceania are also strongly affected.

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 range from 9.3 gigatons per year (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 & Webb 1983; Milliman & Meade 1983; Milliman & Syvitski, 1992) converging at 15-20 Gt year^{-1}.

This wide breadth of results has emerged from the admixture of assumptions, approaches, and uncertainties embedded within these global inventories. For example, the available data 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 of global patterns of runoff, relief, and climate. 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 transport from anthropogenic erosion and of decreased delivery through sediment trapping within reservoirs.

This paper seeks to clarify the role of one component of the global sediment budget, namely, the trapping of suspended sediment within large reservoirs. Humans are prodigious dam builders with more than 36 000 dams over 15 m high in operation worldwide, representing a 688% increase from 1950 to 1986 (ICOLD, 1984, 1988). We therefore could reasonably expect to monitor an important anthropogenic "signal" within the global sediment cycle at continental and global scales. We test this hypothesis by establishing a preliminary estimate of the potential for large reservoirs to sequester sediments on the continental land mass and prevent their ultimate delivery to inland and coastal receiving waters. We refer to the anthropogenic impoundment of rivers as neo-Castorization, after another prolific dam-builder, *Castor spp.*, the beaver.

DATA

We obtained information on large impoundments and their maximum water storage capacities from a series of world dam registries (ICOLD, 1984, 1988; IWPDC, 1994; IWPDC, 1989). We define large reservoirs (LRs) as having maximum storage capacities greater than or equal to 0.5 km^3. Our final database of geographically-positioned impoundments, drawn from the registries, contains a total of 633 LRs.

The impoundment data were geographically co-registered to a global system of rivers at 30-minute (longitude × latitude) spatial resolution (Fig. 1). The Simulated Topological Network (STN-30) was derived from a spatial aggregation of the ETOPO5 five to ten-minute digital elevation model (NOAA/NGDC, 1989) and in-house software that ensured simulated river courses adhered to those depicted on independent map sources. 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 used several published maps (DMAAC, 1980-1986; IWPDC, 1989; Bartholemew *et al.*, 1988, 1983) to locate each relevant entry and position it on the STN-30.

The dam registries give no information on river flows. We obtained mean annual discharge from UNESCO monitoring stations (UNESCO various years, Vörösmarty *et al.*, 1996a) and when necessary interpolated these values to specific dam sites along the STN-30 rivers. The interpolation was weighted by contributing area along individual river links. We estimated runoff from a water balance model (Vörösmarty *et al.*, 1996b; Vörösmarty *et al.*, 1989) for reservoir sites lacking interpolated discharge. At the global scale this computation has 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 analysed was based on UNESCO records. Large reservoirs are located in 236 simulated drainage basins (>1100 km^2) which we will refer to as "regulated basins".

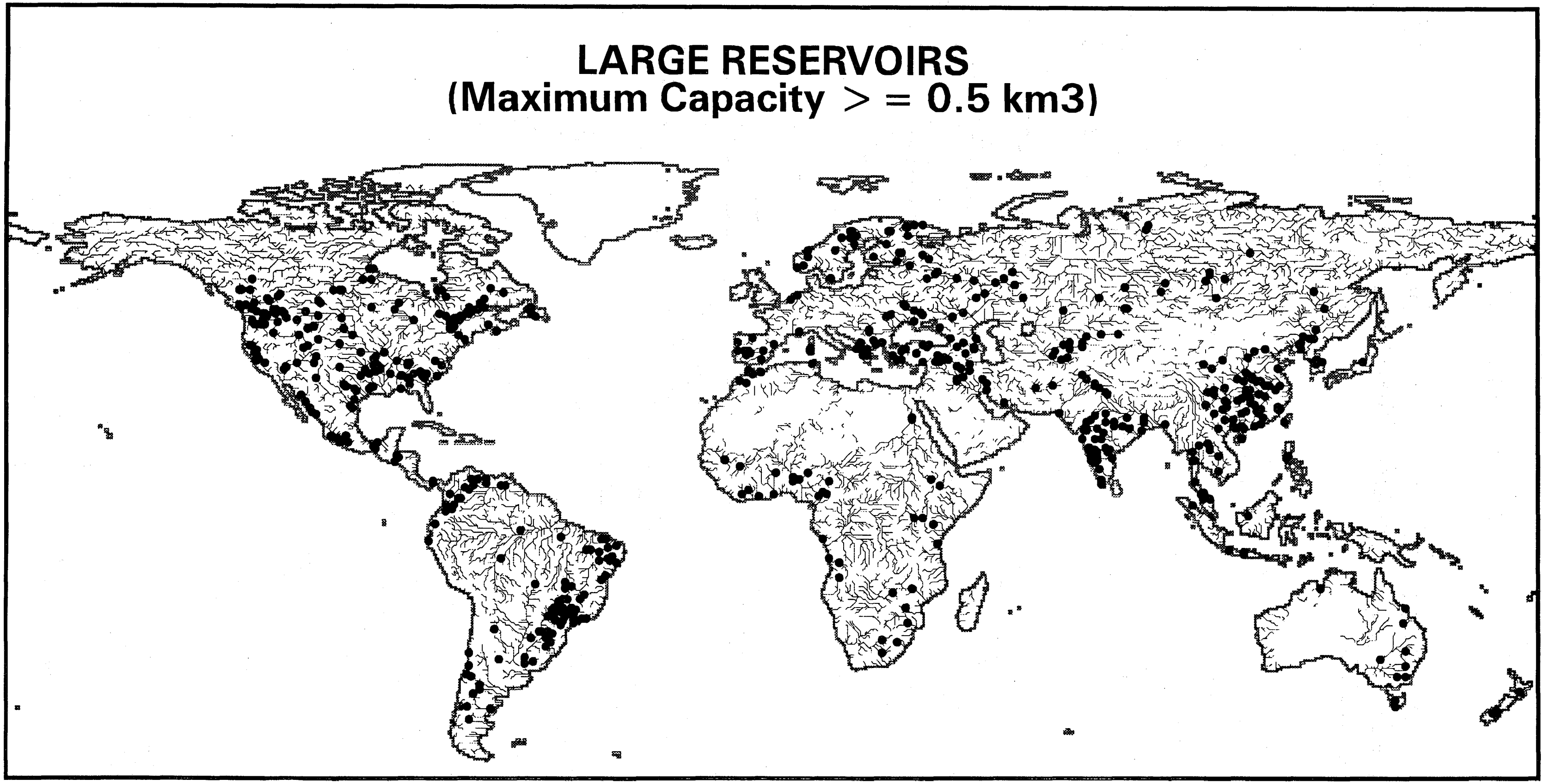


Fig. 1 Geographical distribution of the 633 large impoundments used in this study.

COMPUTATION OF RESIDENCE TIME AND TRAPPING EFFICIENCY

As an interim step toward developing a process-based sediment delivery model, we applied a simple set of calculations based on the geo-located reservoirs. Our estimates of discharge, and the conservative assumption that suspended sediment flux is proportional to discharge, generally accepted by most authors (Milliman & Meade, 1983; Walling & Webb, 1983; Milliman & 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 mean residence time change, which we determined for individual reservoirs, entire drainage basins, and continents. For single reservoirs, we approximated a mean residence time change ($\Delta\tau_R$) relative to free-flowing rivers as the reservoir volume divided by local mean annual discharge. Maximum reported reservoir capacity was multiplied by a utilization factor of 0.67, representing the average proportion of maximum storage at which reservoirs are assumed to routinely operate (USGS, 1984). We applied an approximation to the relationship originally developed by Brune to predict individual reservoir trapping efficiencies (TE) as a function of residence time (Ward, 1980):

$$\mathrm{TE} = 1 - (0.05/\Delta\tau_R^{\,1/2})$$

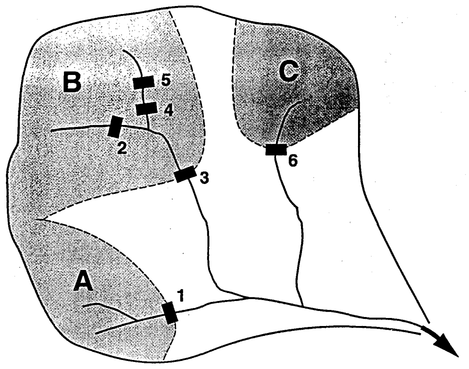
Within each of the 236 regulated drainage basins, we identified all sub-basins which contained large reservoirs. For these we determined an aggregate impounded volume, which together with discharge yielded a sub-basin residence time change and eventually an aggregate siltation capacity. Whole basin sediment trapping was adjusted by a discharge-weighting associated with unimpounded interfluvial areas. Figure 2 details these computations. The resulting distribution of residence times and trapping efficiencies were mapped onto the STN-30 and summarized at both continental and global scales. We emphasize that this paper addresses sediment trapping by *large reservoirs* only. Sediment retention by smaller reservoirs and natural lakes are of prime importance in predicting river basin sediment delivery, but we have not considered these processes here.

KEY FINDINGS

Representative nature of LR sample

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

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.

residence time changes spanning several orders of magnitude, our estimated distribution of $\Delta\tau_R$ appears reasonable.

The LR data set we have assembled also represents a significant fraction of global impounded freshwater, 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 estimate to constitute approximately 60% of the global total represented in the registries (Vörösmarty *et al.*, 1996c). Avakyan (1987) documented a skewed distribution of aggregate storage capacity, noting that the 2500 largest impoundments 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 200 reservoirs (each exceeding 0.001 km^3) in Turkey (DIS, 1991), we find that 64% of aggregate volume is represented by the two largest reservoirs alone, while the top 10 reservoirs account for 90% of the country-wide total. These distributions are believed to be very similar in most countries and also mirror the distribution of natural lake volumes (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 analysed only a sample of total global impoundment, and the ICOLD/IWPDC registries themselves fail to constitute a complete inventory of reservoirs.

Distribution of $\Delta\tau_R$ and 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 compared to independent compilations of pre- and post-impoundment sediment fluxes (Milliman & Syvitski, 1992, Meybeck & 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 afford a prospect that our mapping of LRs and relatively simple flux models can be used to determine the anthropogenic imprint on suspended sediment transport globally.

There are, however, conditions under which the theoretical trapping efficiency computation creates overestimates (e.g. Indus River) as well as underestimates (e.g. Mississippi River). Such conditions arise when the spatial distribution of discharge and sediment loading are fundamentally decoupled, in violation of the simplifying assumption that sediment loads are proportional to discharge. In the case of the Mississippi River, its Missouri sub-basin contributes 75% of the natural sediment load (400 Mt year^{-1}) (Meade, 1995) which is transported by only 12% of the mean annual discharge. Since the bulk (73%) of the LR volume resides on the Missouri our theoretical estimate would be expected to greatly underestimate the true potential for trapping. This argues for a more complete 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 & Parker, 1985). 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).

Continental-scale results

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

Table 1 Computed versus observed basinwide sediment retention for selected river systems regulated by large reservoirs.

Continent	River	Country	Ocean or Sea	Pre-dam[1] discharge (km^3 year^{-1})	Post-dam[1] discharge (km^3 year^{-1})	Area (10^6 km^2)	Observed[1,2] basin trapping (%)	Theoretical[3] basin trapping (%)
Africa	Nile	Egypt	Med	83.2	30.0[6]	2.87	100	99
Africa	Orange	S. 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[4]	67
Asia	Yesil	Turkey	Black		5.7	0.036	98	96
Europe	Danube	Romania	Black		207	0.810	29[5]	45
Europe	Don	Russia	Black	28.1	20.7	0.420	64	56
Europe	Ebro	Spain	Med	49.0[6]	13.5[6]	0.087	92	90
N.America	Colorado	USA	Pac	18.5	0.1	0.715	100	100
N.America	Columbia	USA	Pac		236	0.669	33	69
N.America	Mississippi	USA	Atl	580	529	3.270	48	15(47)[7]
N.America	Rio Grande	USA	Atl	18	0.7	0.670	96	100
N.America	Savannah	USA	Atl	11.6	10.6	0.027	64	66

[1] From: Meybeck & Ragu (1996); for Ebro River discharges, UNESCO (various years).

[2] From: Milliman & Syvitski (1992); Milliman & Meade (1983).

[3] Estimates made based on sample calculations shown in Fig. 2. When pre/post dam discharges were available, original estimate of trapping efficiency (TE_0), reflecting solely the spatial distribution of reservoir siltation (i.e. Fig. 2), was pro-rated using the following expression: $(1 - [\text{post-dam } Q \, / \, \text{pre-dam } Q]) + (TE_0 * [\text{post-dam } Q \, / \, \text{pre-dam } Q])$.

[4] Based on unpublished data from B. J. Hay cited in Milliman & Syvitski (1992). This figure appears low in the context of two major and several small impoundments resident within the basin.

[5] Not known if figure reported includes influence of Iron Gates impoundments, regulating discharge from *ca.* 70% of the basin area.

[6] From Vörösmarty *et al.* (1996a).

[7] Figure in parentheses represents an explicit tabulation for the Missouri River tributary, which contributes 75% of Mississippi basin sediment flux (Meade, 1995). See text.

Table 2 Key attributes of the geographically-referenced large reservoir systems used in this study.

Continent[1]	*n*	Sum of maximum capacities (km^3)	Mean maximum capacity (km^3)	Discharge-weighted mean residence time change(year)
Africa	42	912	21.7	0.83
Asia:				
Endorheic	19	102	5.4	1.17
North[2]	14	569	40.6	0.42
South	176	827	4.7	0.22
Australia/Oceania	16	47	3.0	0.71
Europe[3]	88	430	4.9	0.16
North America	180	1195	6.6	0.23
South America	98	807	8.2	0.09
Total	633	4888	7.7	0.21

[1] Defined by river mouths within the STN-30.
[2] Drainage into Arctic Ocean.
[3] Area west of the Ural Mountains.

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

Endorheic Asia, Africa, and Australia/Oceania maintain the highest discharge-weighted $\Delta\tau_R$ for a typical LR, spanning 0.7-1.1 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 shortest mean residence time change is tabulated for South America, less than 0.10 year. Relatively long $\Delta\tau_R$ in endorheic Asia, Africa, and Australia/Oceania arise from dam construction in arid and semi-arid regions where low runoff and high demand for irrigation water necessitate large storage volumes. Hydropower reservoirs in humid regions have generally shorter $\Delta\tau_R$ values although there are exceptions (e.g. Manicouagan in Québec with a $\Delta\tau_R$ of more than 5 years).

Such a summary of "local" residence time changes provides but a partial view of the aggregate capacity of LRs to trap suspended sediment. A statistical distribution of $\Delta\tau_R$ does not in itself provide much insight into the global or continental-scale impact of reservoir retention. Examining the relationship between $\Delta\tau_R$ and discharge does, however, offer a more complete picture, since it is river flow that ultimately transports sediment through drainage basins. The distributions of aggregate, intercepted discharge as a function of $\Delta\tau_R$ are summarized for individual continents in Fig. 3. Much of the runoff intercepted by LRs globally has a residence time of ≥0.01 years, representing 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,

Table 3 Aggregate discharge; continent-wide, discharge-weighted residence time change; and, suspended sediment trapping due to large reservoirs. Composite values are determined from tabulations made at individual river mouths.

Continent[1]	Discharge (km^3 year^{-1}) Unregulated basins[2]		Regulated basins[2]		Basinwide $\Delta\tau_R$ (year) Regulated basins[3]	Mean % susp. sed. retention Regulated basins[3]	Mean % potential sed. retention All basins[4]
Africa	3320	(*n*=476)	870	(*n*=25)	0.70	42	9
Asia:							
Endorheic	200	(195)	140	(8)	0.48	26	10
North[5]	450	(313)	1560	(4)	0.24	23	18
South	6270	(1009)	4300	(64)	0.13	33	13
Australia/Oceania	690	(339)	70	(10)	0.45	41	4
Europe[6]	1490	(657)	1300	(45)	0.22	50	23
North America	3290	(1362)	2600	(52)	0.31	43	19
South America	2110	(376)	9180	(28)	0.06	21	17
Total	17820	(4727)	20020	(236)	Avg. 0.16	30	16

[1] Defined by river mouths within the STN-30 simulated river network at 30-minute spatial resolution.

[2] *n* refers to the number of distinct drainage basins in STN-30.

[3] Discharge-weighted and accounting for dilution by unregulated sub-basins (see Fig. 2).

[4] Discharge-weighted and assuming that unregulated basins convey no sediment trapping potential.

[5] Drainage into Arctic Ocean.

[6] Area west of the Ural Mountains.

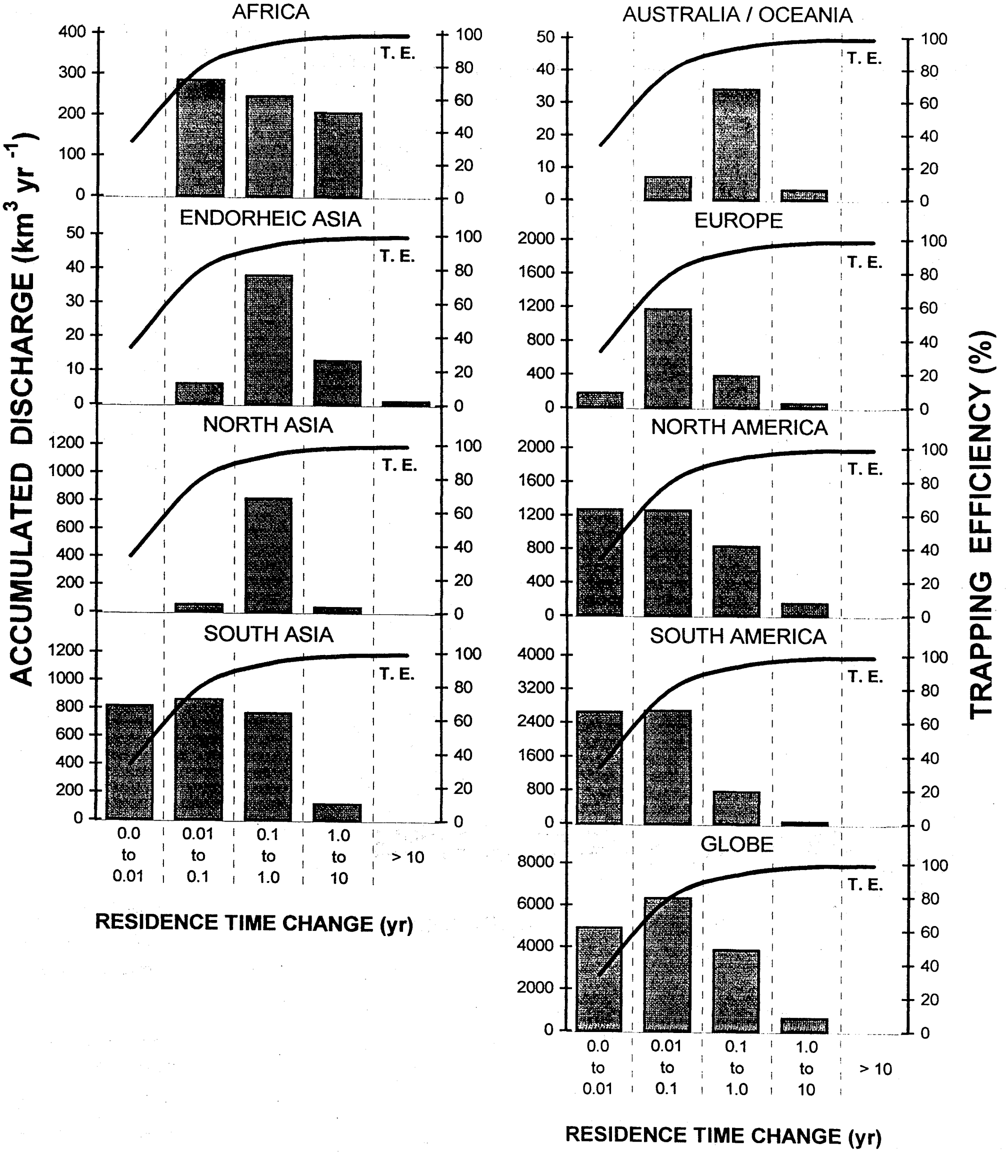


Fig. 3 Aggregate discharge intercepted by large reservoirs expressed as a function of local residence time change for the globe and for individual continental areas. A theoretical trapping efficiency curve for suspended sediments is superimposed on each panel.

mean global trapping efficiency is 62%.

We emphasize that these tabulations are made locally at the reservoirs. These, in turn, must be placed into a drainage basin perspective to account more fully 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 regulated basin residence time changes are greatest (mean ≈ 0.7 year) in Africa and Australia/Oceania, only a moderate mean sediment trapping efficiency (≈ 40%) is tabulated for their regulated basin mouths (Table 3). In contrast, regulated basins in Europe show a relatively modest mean basin residence time change (0.22 year), yet display the highest mean sediment retention (50%). The mean aggregate trap efficiency for regulated basins within individual continental areas ranges from 21 to 50%. When the effects of impoundment are considered from the standpoint of all river systems on each continent, we find that the range of TEs is from 4 to 23%. The least overall impact from neo-Castorization is on Australia/Oceania, while the greatest is on Europe.

Global summary

The aggregate impoundment capacity of the subset of global LRs we tested is nearly 5000 km^3 (Table 2), which is noteworthy from the standpoint that it represents a nearly four-fold increase in the mean, instantaneous standing stock of water in river systems globally (Covich, 1993). Mean, discharge-weighted residence time change for the 633 LRs is 0.21 years. 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 Fig. 3 as a function of $\Delta\tau_R$ class together with the idealized trap efficiency curve. As for individual continents, it is apparent that a significant fraction of intercepted discharge is associated with substantial potential sediment deposition. For the globe, approximately 70% of discharge flowing through large dams is associated with a sediment trap efficiency of 50% or more.

The true significance of such statistics 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 runoff from Table 3 is intercepted by the most downstream of LRs in each regulated basin, suggesting an important impact on global sediment retention. Furthermore, regulated basins represent more than 50% of total global runoff and their mean discharge-weighted residence time change is two months (Table 3), a $\Delta\tau_R$ associated with substantial sediment trapping. When the effect of dilution by unimpounded subcatchments is considered, our estimated retention of sediment within regulated basins globally is 30%. When placed into the context of all river basins, this fractional retention is 16% for the entire globe.

Our estimate of the impact of neo-Castorization on global suspended sediment transport is twice that given earlier by Meybeck (1988), 1.5 Gt $year^{-1}$ or 8% of total flux, but this earlier estimate was based only on the trapping of a few major basins as reported by Milliman & Meade (1983). Likewise, we expect our retention estimate to increase with consideration of the remaining >35 000 reservoirs as well as through continued dam construction. We thus view our preliminary estimate a minimum. We postulate that the actual global sediment retention by reservoirs may exceed 25% of the global flux.

CONCLUSIONS

Our analysis has demonstrated that the trapping of continental runoff by large dams has had a measurable impact on river water destined for the world's coastal zone and inland seas. Although the apparent sequestration of suspended sediment by major reservoirs at the global scale appears to be less than 20%, such trapping is probably substantially higher when considering the impact of all reservoirs of all sizes. Sediment trap efficiency can also significantly exceed the global average when viewed regionally and within regulated basins, for example in impounded European rivers where we estimate a mean 50% trapping. Individual basins experience even greater effects, like the Nile and Colorado Rivers with virtually complete sediment loss downstream of their large reservoirs.

These 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 generation 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 region is immune from these potential effects. The need for development of improved models of sediment transport and its interplay with neo-Castorization is clearly indicated.

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