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The role of impoundments in the sediment budget of the conterminous United States

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Abstract

Previous work on sediment budgets for U.S. agricultural regions has concluded that most sediment derived from accelerated erosion is still on the landscape, primarily in colluvial and alluvial deposits. Here we examine the role of small impoundments in the subcontinental sediment budget. A recent inventory based on a 30-m satellite imagery reveals approximately 2.6 million ponds, while extrapolation from a sample of 1:24,000 topographic quadrangles suggests the total may be as large as 8–9 million. These ponds capture an estimated 21% of the total drainage area of the conterminous U.S., representing 25% of total sheet and rill erosion. We estimate the total sedimentation in these small impoundments using three different methods; these estimates range from 0.43 to 1.78×10^9 m^3 yr^{-1}. Total sedimentation in ~43,000 reservoirs from the National Inventory of Dams is estimated at 1.67×10^9 m^3 yr^{-1}. Total USLE erosion in 1992 was 2.4×10^9 m^3 yr^{-1}, and export to coastal areas is estimated at 0.6×10^9 m^3 yr^{-1}. Total sedimentation in impoundments is large in relation to upland erosion, in apparent contradiction to previous studies that have identified colluvial and alluvial deposition as the primary sinks. Several alternative hypotheses that could help explain this result are proposed. Regardless of which of these alternatives may prove to be the most significant in any given setting, it is clear that most sedimentation is now taking place in subaqueous rather than subaerial environments, and that small impoundments are a major sediment sink.

Keywords: Reservoirs; Sedimentation; Sediment budget; Erosion; Dams

1. Introduction

Among human modifications of the geomorphic/hydrologic landscape of the United States, two major impacts stand out: accelerated erosion, largely associated with agriculture, and construction of impoundments, creating new sediment sinks. Together, these two modifications have transformed the fluvial sediment transport system of the continent, at once multiplying the rate of sediment input to the system manyfold and creating millions of sediment sinks

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throughout the drainage network. In addition to local impacts on streams and their dynamics, these landscape modifications alter the fluvial sediment budget. The conterminous U.S. is an attractive region in which to study these impacts because of the wealth of internally consistent information across this relatively large region. In particular, we now have available data sets that quantitatively characterize, in the aggregate, a few key elements of erosion and sedimentation. These data sets allow the construction of a subcontinent-scale sediment budget, against which we can compare specific case studies. In this paper, we construct a sediment budget for the conterminous U.S., focusing on the role of artificial impoundments as sediment sinks.

In recent years, much attention has been focused on the individual and cumulative effects of dams on rivers (Collier et al., 1996; Graf, 1999). The most significant impact of dams on the fluvial sediment system is in trapping sediment, with both upstream and downstream consequences (Meade et al., 1990). Relatively large dams are particularly conspicuous in this regard, and have received considerable attention among both scientists and the general public. In contrast, small impoundments, which are many times more numerous and therefore have the potential for large cumulative impacts, have received relatively little attention.

Previous work on sediment budgets for U.S. agricultural regions has shown that, in general, most sediment derived from accelerated erosion is still on the landscape (Meade, 1982). The principal sinks identified include colluvial and other upland deposits, alluvial deposits, and reservoirs. For example, in the Maryland piedmont, Costa (1975) estimated that 52% of soil eroded between ~1800 and 1950 was deposited as colluvium, 14% was deposited as alluvium, and 34% was exported. In Coon Creek, Wisconsin, Trimble (1983) found that, for the period 1853–1977, 49% of sediment was deposited as colluvium, 45% in alluvial storages, and 6% was exported. Phillips (1991) and Beach (1994) working in North Carolina and Minnesota, respectively, also found that most sediment was deposited in alluvial and colluvial storages while a relatively small amount was exported.

Sediment that is deposited in alluvial and colluvial settings is available for remobilization. Several studies have examined the post-depositional fate of stored sediment. For example, in southwestern Wisconsin, sediment deposited in low-order valleys is being remobilized today so that smaller streams have become net sources while larger streams are still net sinks (Knox, 1987; Faulkner and McIntyre, 1996; Trimble, 1999). Similar patterns have been described in the Georgia Piedmont (Ruhlman and Nutter, 1999). James (1989), studying hydraulic mining debris in the Sierra Nevada range, found that the vast majority of sediment stored there is still in upland areas, but gradual remobilization of this sediment provides a large and continuing input of sediment to the system.

While much of the sediment derived from 19th century accelerated erosion was apparently stored in alluvial and colluvial settings, in the 20th century reservoirs have proven a major sediment sink. The National Inventory of Dams (NID) includes over 75,000 dams; of these over 60% were built between 1920 and 1970. Stallard (1998) estimated that about 1.2×10^9 kg yr^{-1}, or 30–40% of sediment eroded in the conterminous U.S., is deposited in reservoirs included in the NID.

As comprehensive as the NID is, it only includes 1–2% of the impoundments in the U.S. The NID includes features that exceed 2 m in height and 61,700 m^3 of storage or 8 m in height and 18,500 m^3 of storage, or that present a significant hazard. It therefore excludes millions of smaller impoundments that have been constructed in the past several decades (Graf, 1993; Smith et al., 2002). These are features of a few hectares in area or less; 85% are less than 0.5 hectare. They serve a variety of purposes including water supply for livestock, sediment trapping and erosion control, and recreation. They have been built by private landowners as well as by government agencies (principally the Soil Conservation Service), and most were built since the early 20th century. Many thousands more are built each year. They are widely distributed, but heavily concentrated in agricultural regions. Collectively, these small impoundments represent a major modification of the hydrologic landscape, with the potential to act as a substantial and relatively new sediment sink.

Here we examine the role of these small impoundments in the sediment budget, at the sub-continental scale. Specifically, we estimate the total volume of sedimentation occurring in small impoundments, and

Table 1
Number and sizes of water bodies in the National Land Cover Data (NLCD), National Inventory of Dams (NID), and USGS 1:24,000 topographic quadrangles (DLGs)

Data set	Number of water bodies (thousands)	Total surface area (1000 km^2)	Average area (m^2)	Maximum area (m^2)	Minimum area (m^2)
NLCD	2600	21	7×10^3	2.53×10^7	6.00×10^2
NID[a]	43	62	1.45×10^7	1.84×10^9	8.00×10^1
USGS DLGs	9000	–	–	–	2.5×10^1

[a] The National Inventory of Dams includes ~75,000 dams; a subset of these was used in our analysis. See text for details.

compare that quantity to other components of the fluvial sediment budget for the conterminous U.S. We use the term "impoundments" to refer to artificial water bodies regardless of size, "reservoirs" for those listed in the NID (surface areas generally greater than ~1 km^2), and "ponds" for smaller impoundments.

2. Methods

2.1. Pond inventory

Our inventory of ponds is derived from the USGS National Land Cover Data (NLCD; http://landcover.usgs.gov/nationallandcover/html). Details of the inventory are reported elsewhere (Smith et al., 2002). This Landsat-derived data set maps water areas at 30-m pixel resolution. Our inventory excludes features within 1 km of streams in National Atlas hydrography layer (http://www.nationalatlas.gov/hydrom.html) or within 5 km of major streams in ESRI coverage as well as any other water features that were clearly identifiable as streams. Contiguous water pixels were converted to polygons, and counted. The resulting data were compared with polygons extracted from the hydrography (blue-line) layer of a sample of 336 1:24,000 USGS topographic quadrangles (DLGs). These maps include features as small as 5 m across, so many features are shown on the DLGs that are not included in the NLCD data. The DLGs were processed using the same masks applied to the NLCD data. We were unable to extend this procedure to the full conterminous U.S. because of the excessive amount of data processing necessary (~54,000 quadrangles) and because not all these quadrangles were available in digital form. We therefore estimated the total number of DLG ponds by extrapolation from the sampled quadrangles to the conterminous U.S. The numbers of ponds estimated by these methods are given in Table 1, and their distribution (expressed as density, or number/km^2) is mapped in Fig. 1. The inventory does not distinguish between natural and

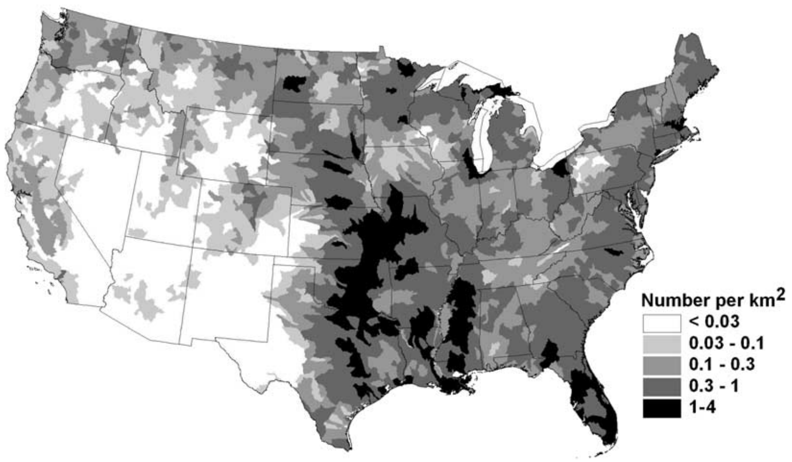

Fig. 1. Density of small water bodies visible in the NLCD data set, by 8-digit Hydrologic Unit.

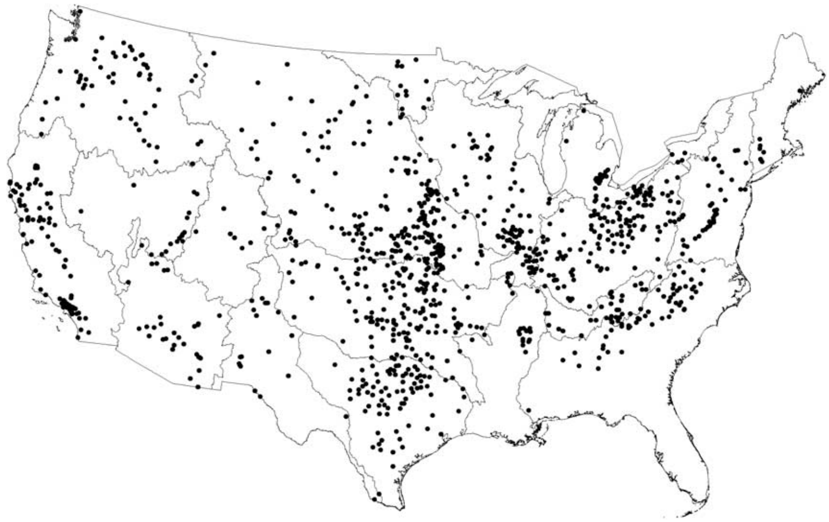

Fig. 2. Distribution of reservoirs in the RESIS database, and 2-digit Hydrologic Unit code regions.

artificial features, however, it is evident that the highest concentrations of ponds are found in areas such as the eastern Great Plains and the southeast where natural lakes are relatively rare. We therefore conclude that they are overwhelmingly of human origin.

2.2. Pond sedimentation rates

We used three different methods to estimate sedimentation rates in ponds. Two of these are based on estimates of specific sedimentation rates (sedimentation per unit drainage area) in impoundments, while one is based on erosion rates in tributary areas.

The RESIS database (Reservoir Sedimentation Survey Information System; Steffen, 1996) was our principal source of information on specific sedimentation rates. This database, which primarily consists of data originally published by Dendy and Champion (1978), currently includes 3902 sediment surveys from 1771 reservoirs—roughly a 10% increase over the original Dendy and Champion data set. The reservoirs represented in the data set are widely distributed across the conterminous U.S. (43 states are represented), but concentrated in Southern Plains, Corn Belt, Piedmont, and California (Fig. 2). Time periods between 1755 and 1992 are represented, but the bulk of the measurements cover periods in the mid-20th century. We grouped these data by 2-digit Hydrologic Unit Code (HUC2; Fig. 2), and for each of the 18 subsets regressed log of specific sedimentation rate against log of drainage area. The results of these regressions are listed in Table 2. All the regression slopes are negative, indicating deposition as sediment moves downstream. There is considerable scatter in the relationships. The r^2 values average 0.14, and 11

Table 2
Regression coefficients for log specific sedimentation rate ($m^3\ km^{-2}\ yr^{-1}$) (dependent) versus log drainage area (km^2) (independent) in the RESIS data set

Region (2-digit HUC)	N	r^2	Slope	Intercept	p
New England (1)	9	0.06	−0.21	1.72	0.52
Mid-Atlantic (2)	59	0.02	−0.11	2.00	0.24
South Atlantic-Gulf (3)	61	0.15	−0.21	2.59	0.00
Great Lakes (4)	51	0.20	−0.31	2.22	0.00
Ohio (5)	175	0.05	−0.11	2.37	0.00
Tennessee (6)	43	0.25	−0.20	2.59	0.00
Upper Mississippi (7)	128	0.02	−0.06	2.57	0.09
Lower Mississippi (8)	37	0.61	−0.31	3.16	0.00
Souris-Red-Rainy (9)	23	0.16	−0.22	1.84	0.06
Missouri (10)	311	0.20	−0.27	2.62	0.00
Arkansas-White-Red (11)	236	0.08	−0.12	2.51	0.00
Texas-Gulf (12)	126	0.09	−0.13	2.63	0.00
Rio Grande (13)	52	0.18	−0.25	2.58	0.00
Upper Colorado (14)	38	0.14	−0.32	2.24	0.02
Lower Colorado (15)	79	0.03	−0.08	1.95	0.12
Great Basin (16)	22	0.06	−0.15	2.14	0.28
Pacific Northwest (17)	109	0.11	−0.21	1.77	0.00
California (18)	210	0.10	−0.20	2.80	0.00

of the 18 regressions are significant at $p<0.01$. Regional variations in the relation between specific sediment yield and drainage area are discussed by Renwick (1996).

Using these regression equations to estimate sedimentation rates depends on knowing the drainage areas tributary to ponds, but our NLCD inventory contains only water surface areas, not drainage areas. We used two different methods to estimate the drainage areas of ponds. In one, we first eliminated from consideration all 1:24,000 quadrangles that contained no ponds. For the remaining area in each HUC2 region, we estimated drainage area by dividing total area by the number of ponds-in effect assuming that all remaining area in quadrangles with ponds is tributary to one and only one pond. The resulting drainage areas, averaged by HUC2, were applied to the specific sedimentation rate regression equations to estimate average sedimentation rate per pond; this was multiplied by total number of ponds to estimate total sedimentation. This assumes that all land in these quadrangles drain to ponds, and thus produces higher average drainage areas but lower specific sediment yields than is actually the case. The net result is a high estimate of sedimentation.

A second approach to estimating drainage areas tributary to ponds is based on the relation between pond surface area and drainage area. In general, small ponds have small drainage areas and large ones have large drainage areas. We selected a sample of 16 watersheds ranging in area from 275 to 5704 km^2, and in each of these watersheds delineated the drainage areas of all ponds (Fig. 3; Table 3). Drainage divides were drawn using ArcInfo and 1:24,000 (30-m) USGS digital elevation models (http://edc.usgs.gov/geodata/). A total of ~17,000 drainage basin boundaries were so drawn. We regressed log of drainage area (DA, m^2) against log of pond area (PA, m^2), and used the resulting equation ($\log DA = 2.40 + 0.77 * \log PA$; $r^2 = 0.18$) to estimate drainage areas for all ~2.6 million ponds in the NLCD data set.

An alternative approach to estimating sedimentation is one based on erosion rates in areas tributary to ponds. The total area tributary to at least one pond was determined for each of the 16 sample watersheds discussed above (Table 3). This total tributary area varied from 4 to 100% of watershed area, and generally increased with increasing pond density (Fig. 4). We used the relation between pond density and percent area tributary to at least one pond to estimate that tributary area for each 8-digit HUC (HUC8). This percentage was multiplied by the total estimated sheet and rill erosion (discussed below) in each HUC8, summed by HUC2, and converted from a mass of eroded sediment to a volume assuming a bulk density of 1.1 tons m^{-3} (the average of reported bulk densities in the RESIS database). We assumed a sediment delivery ratio upstream of ponds of 1.0. We then adjusted the resulting volume by an estimated trap efficiency of 80%, based on average capacity/inflow ratios from 33 Ohio ponds applied to the Brune method (Brune, 1953; Hayes-Bohanan, 1989), to

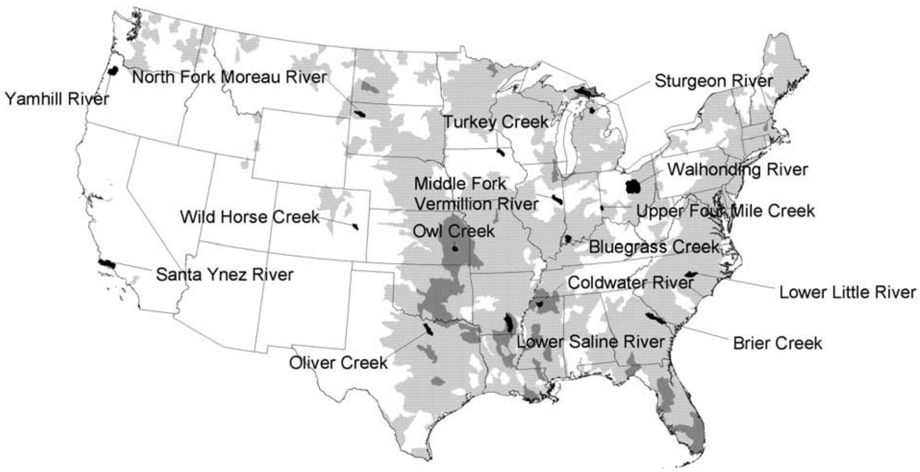

Fig. 3. Sample watersheds selected for mapping of drainage basins of all impoundments identified in the NLCD data.

Table 3
Characteristics of sample drainage basins and their impoundments

Drainage Basin	Total drainage area (km^2)	Number of ponds	Ponds per km^2	Percent area upstream of at least one pond
Bluegrass Creek, IN	985	1076	1.09	67.7
Brier Creek, GA	1746	1167	0.67	52.0
Coldwater River, MS	597	1457	2.44	33.0
Lower Little River, NC	1216	836	0.69	29.6
Lower Saline River, AR	3195	6384	2.00	99.9
Middle Fork Vermillion River, IL	1179	163	0.14	10.2
North Fork Moreau River, SD	1022	689	0.67	58.4
Oliver Creek, TX	1310	1359	1.04	48.0
Owl Creek, KS	506	957	1.89	70.2
Santa Ynez Creek, CA	2310	72	0.03	4.4
Sturgeon River, MI	530	360	0.68	37.7
Turkey Creek, IA	729	37	0.05	7.5
Upper Four Mile Creek, OH	275	47	0.17	5.9
Wallhonding River, OH	5704	2055	0.36	38.4
Wild Horse Creek, CO	444	7	0.02	13.5
Yamhill River, OR	1906	318	0.17	31.4

arrive at an estimate of total sedimentation in NLCD ponds. In reality, many ponds lie within the drainage areas of other downstream ponds, which would tend to raise the overall system trap efficiency.

2.3. Sedimentation in larger reservoirs

We used data from the National Inventory of Dams (http://crunch.tec.army.mil/nid/webpages/nid.cfm) to estimate sedimentation in larger impoundments, here called reservoirs. Many of the dams listed in the NID do not impound reservoirs, and in some cases, there are multiple dams per reservoir. For some dams, drainage area information is included, while for many it is not. We selected a sample of dams in the NID for which drainage areas were available. Dams that did not impound flowing water were excluded, as were those on the Great Lakes and navigation dams on the Mississippi and Ohio Rivers which have very low capacity/inflow ratios and thus trap relatively little

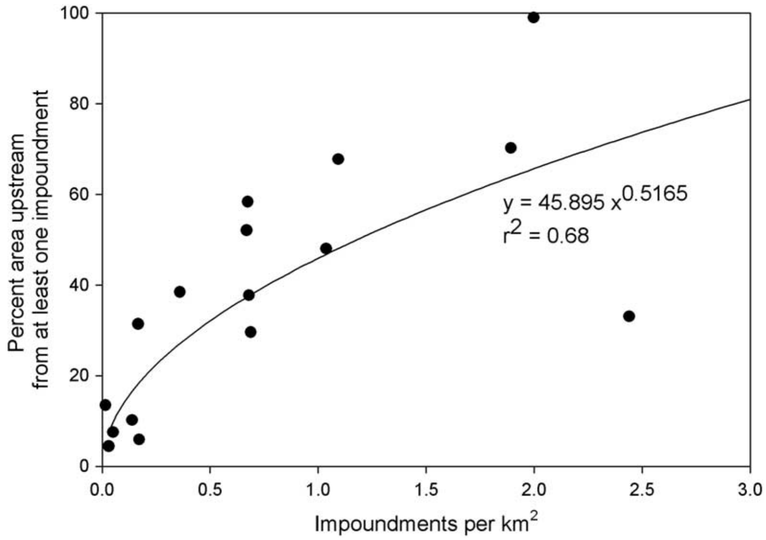

Fig. 4. Relation between impoundment density and percent area upstream of at least one impoundment for 16 watersheds listed in Table 3.

sediment. In segments of the Connecticut, Kennebec, and Tennessee Rivers where numerous dams are closely spaced, dams were excluded from the analysis unless the drainage area impounded was at least 10% greater than that impounded by the next dam upstream. This reduced a tendency to overestimate sedimentation rates in systems where close spacing of dams would prevent sediment from reaching downstream reservoirs. Sedimentation rates in the remaining ~43,000 NID reservoirs thus selected were estimated based on the RESIS regression equations described above (Table 2).

The two impoundment data sets–reservoirs (from the NID) and ponds (from the NLCD)–do overlap slightly, but the amount of overlap is negligible. The largest reservoirs in the NID are also included in the National Atlas hydrography layer that was used as a mask in analyzing the NLCD data. Many smaller reservoirs in the NID are also represented in the NLCD data, but the number of such features (<40,000) amounts to only about 1.5% of the total number of ponds in the NLCD data. The overlap thus does not significantly affect our sedimentation estimates.

2.4. Erosion rates

Estimates of upland erosion rates were based on the 1992 National Resource Inventory (NRI) (NRCS, 1994). The NRI provides estimates of sheet and rill erosion based on the Universal Soil Loss Equation (USLE). Although wind erosion is a larger share of the total estimated soil loss (Smith et al., 2001), we assume that most wind-eroded soil is deposited in upland areas and thus do not include it in the fluvial sediment budget describe here. In the NRI, erosion rates are calculated for a sample of approximately 1 million points on non-Federal land. These erosion rates were extrapolated to include Federal land for each HUC2 region, assuming equal proportions of cropland, forest, pasture/range, and other land on Federal land as on non-Federal land. Because most Federal land is non-agricultural, and because erosion rates are generally higher on cropland than under other uses, this extrapolation may overestimate sheet and rill erosion on Federal land in regions in which there is substantial cropland. This is probably most significant in the Pacific Northwest where most Federal land is forest and there is a substantial amount of (non-Federal) cropland. For the conterminous U.S., we do not believe the bias is large enough to alter our conclusions.

3. Results and discussion

Results of sedimentation rate estimates are given in Table 4. For the ~2.6 million ponds, the method that assumes all land drains to ponds produces a total sedimentation rate of 1.78×10^9 m^3 yr^{-1}. When drainage areas are estimated individually based on pond surface areas, the total sedimentation is 0.22×10^9 m^3 yr^{-1}. Finally, using the relation between pond density and percent of land upstream from at least one pond (Fig. 4) and extrapolating to the conterminous U.S. indicates that 21% of land, representing 25% of erosion, is upstream from at least one small impoundment visible in the NLCD data. This resulting total sedimentation rate is 0.43×10^9 m^3 yr^{-1}.

The fact that the erosion-based estimate is roughly comparable to the lower estimate based on measured sedimentation rates indicates that these values constitute a relatively robust estimate of sedimentation in the ~2.6 million NLCD ponds. Both of these lower estimates are sensitive to pond density, however, and if we were able to include all 8–9 million ponds estimated based on the 1:24,000 DLGs, these estimates would be significantly higher. It is not surprising that the two estimates from sedimentation rates differ by a factor of ~8, as they rely on very different

Table 4
Estimates of total sedimentation in ~2.6 million NLCD ponds (10^9 m^3 yr^{-1}). See text for details of methods

Method		Sedimentation (10^6 m^3 yr^{-1})
Extrapolating from specific sedimentation rates	Regressions applied to all land using average drainage area=total area/ number of impoundments	1.78
	Regressions applied to estimated drainage areas on impoundment-by-impoundment basis	0.22
Using erosion occurring on land tributary to impoundments and 80% trap efficiency		0.43

assumptions about the drainage areas of ponds. The high estimate of 1.78×10^9 m^3 yr^{-1} is a maximum, as it assumes that all land in quadrangles with ponds drain to ponds (even though the larger drainage areas thus calculated imply lower specific sedimentation rates). We therefore believe that the range of sedimentation estimates: 0.22 to 1.78×10^9 m^3 yr^{-1}, is indicative of the true value.

The total estimated sedimentation in ~43,000 reservoirs from the NID is 1.67×10^9 m^3 yr^{-1}, near the high end of the range of estimates for ponds. The reservoirs thus appear to trap an amount similar to that being deposited in ponds, despite the fact that the total surface area of the NID reservoirs is ~4 times that of the ponds (Graf, 1993; Smith et al., 2002). The small features, by virtue of their smaller drainage areas, have higher specific sedimentation rates as well as higher vertical sedimentation rates (thickness per time).

These and other components of the aggregate sediment budget are listed in Table 5. Total USLE erosion in 1992 was 2.4×10^9 m^3 yr^{-1}. To this, an unknown quantity of upland erosion from other sources should be added. Such sources include gully erosion, mass movements, and erosion in urban areas not included in the USLE estimates. We have no way of estimating these quantities at the sub-continental scale, but it is our belief that they are generally of local significance only. Net stream bank erosion (bank erosion less alluvial deposition) is another potential sediment source, the quantity of which is unknown at this scale. If, as has been shown in some areas, alluvial environments are a net sink then this term would be negative. Colluvial deposition is another quantity that is unknown at this scale. In general, this term has been considered to be quite large, but a large value for this term seems unlikely given the apparent magnitudes of erosion and impoundment sedimentation. Our estimate of export to coastal areas (areas below the downstream-most sediment-sampling stations on rivers) is based on suspended-sediment data in the GLORI database (Milliman et al., 1995) adjusted upward by 0.2×10^9 m^3 yr^{-1} to account for bedload transport (Smith et al., 2001).

Table 5
Components of a sediment budget for the conterminous U.S. (10^9 m^3 yr^{-1})

Sources	
Total ULSE erosion, 1992	2.4
Other upland erosion (gullies, mass movements)	?
Net stream bank erosion	?
Sinks	
Colluvial deposition	?
Sedimentation in small impoundments	0.2–1.8
Sedimentation in NID reservoirs	1.67
Export to coastal areas	0.6

It is evident that total estimated sinks (sedimentation in impoundments plus export to coastal zones) are large in relation to upland erosion, in apparent contradiction to previous studies that have identified colluvial and alluvial deposition as the primary sinks. We propose several alternative hypotheses that could help explain this result:

1. *Actual upland erosion is much larger than that estimated from the USLE.* It seems possible that large (in relation to USLE erosion) quantities of sediment may be derived from mass movements in high-relief areas such as the Sierra/Cascade ranges and the Appalachians (Blaschke et al., 2000; Montgomery et al., 2000; Madej, 2001). However, sediment accumulation in impoundments is concentrated in the central and southeastern part of the country and erosion in the Sierras/Cascades could not account for the high rates of sedimentation in these regions. Gully erosion is another possible significant source of sediment, as is erosion in urban areas. Erosion rates on land during construction can be extremely high (Wolman, 1967) and in some cases channel erosion stimulated by runoff from impervious surfaces may also be large (Trimble, 1997).
2. *Channel systems are functioning as net sources, or at most very small net sinks.* Numerous case studies have documented net deposition in stream systems resulting from accelerated erosion (Costa, 1975; Trimble, 1981; Phillips, 1991), and these trends can also be inferred from sediment yield data at the subcontinental scale (Renwick, 1996). However, following the period of greatest upland erosion, there is a tendency for streams that have experienced deposition to then become net sediment sources (Knox, 1987; James, 1989; Ruhlman and Nutter, 1999; Trimble, 1999). Increased sedi-

ment yield and possibly other hydrologic impacts of land use change continue to contribute to stream instability that is manifest in widespread bank erosion (Simon and Rinaldi, 2000) and may result in net removal of sediment from alluvial storages. In some regions, such as those with widespread glacial deposits in stream valleys, net stream bank erosion has been documented (Church and Slaymaker, 1989). If streams have, on average, become net sources rather than sinks, this would imply a major reversal of the previously identified general trend in the central and eastern U.S.

3. *Estimated erosion and sedimentation rates are not comparable because of changes in erosion over time*. The apparent imbalance of the sediment budget may be a result of the temporal mis-match between 1990s erosion and mid-20th-century sedimentation estimates, in the context of a general decline in upland erosion rates (Trimble and Crosson, 2000). Sheet and rill erosion on cropland as estimated using the USLE declined 30% between 1982 and 1997 (NRCS, 2000), and in some areas a more substantial decline took place in the mid-20th century (Trimble and Lund, 1982; Argabright et al., 1995). We may therefore be comparing sedimentation in a period of higher rates with erosion in a period of lower rates. The fact that upland erosion has declined does not necessarily mean that sediment delivery to streams has declined proportionately, however, because historically eroded sediment is still moving through the transport system (Faulkner and McIntyre, 1996; Evans et al., 2000). Given the amount of sediment estimated to have been deposited in alluvial storages, it is possible that relatively high sediment yields may be sustained for a considerable period of time following significant reductions in upland erosion.
4. *The proliferation of dams has altered the relation between drainage area and sedimentation*. There are many more dams today than existed in the mid-20th century when much of the sedimentation reported in the RESIS data set was taking place. Because these dams trap sediment, the throughput of sediment in many river systems is significantly reduced (Meade and Trimble, 1974; Meade and Parker, 1985; Meade et al., 1990). In few places, there is evidence that sedimentation rates are declining (McIntyre, 1993; Brown, 2002) but other studies show continued high rates of sedimentation (McHenry et al., 1980; Bernard et al., 1996). The critical test of this hypothesis is whether sedimentation rates in the 1990s are similar to those predicted from the RESIS data. Independent data sets available for small impoundments in Hamilton County, Ohio (Fig. 5; Hayes-Bohanan, 1989), and Kansas (Holland, 1971; Mau and Christensen, 2000) reveal rates that are at least as high as those predicted by the regression equations from the RESIS data. Unfortunately, government agencies' interest in sedimentation appears to have waned so that sedimentation data from the 1990s are few, not collected into a central database, or both. It may be that the apparent lack of interest in the topic is indicative of a reduction in problems associated with sedimentation, but we have no systematic way of determining whether that is the case.
5. *Sedimentation previously assigned to alluvial or colluvial sinks is actually occurring in impoundments.* Quantifying sedimentation that is widespread and patchy rather than concentrated and uniform is always difficult, usually relying on extrapolation from relatively few observations to a large area (the current study is an example). Estimates of alluvial or colluvial deposition have been made using a variety of methods including soil stratigraphic data (Trimble, 1974; Costa, 1975; Phillips, 1993; Beach, 1994), extrapolation based on sediment delivery ratios (Kreznor et al., 1990), and by difference from other terms (Trimble, 1981; Kondolf and Matthews, 1991; Phillips, 1991). In some cases, reservoir sedimentation is used as a tool to estimate sediment yield or sediment delivery to streams; in such cases, it is implicitly assigned to those components of the budget. If only the larger reservoirs are used as indicators of sediment delivery to streams then sedimentation in small water bodies may be implicitly assigned to the alluvial/colluvial sink. Finally, several published sediment budgets cover the entire period since European occupation, a substantial portion of which precedes widespread construction of impoundments. Thus, it is possible that, in many cases, sedimentation that has been inventoried or assigned to alluvial or colluvial sinks could be re-

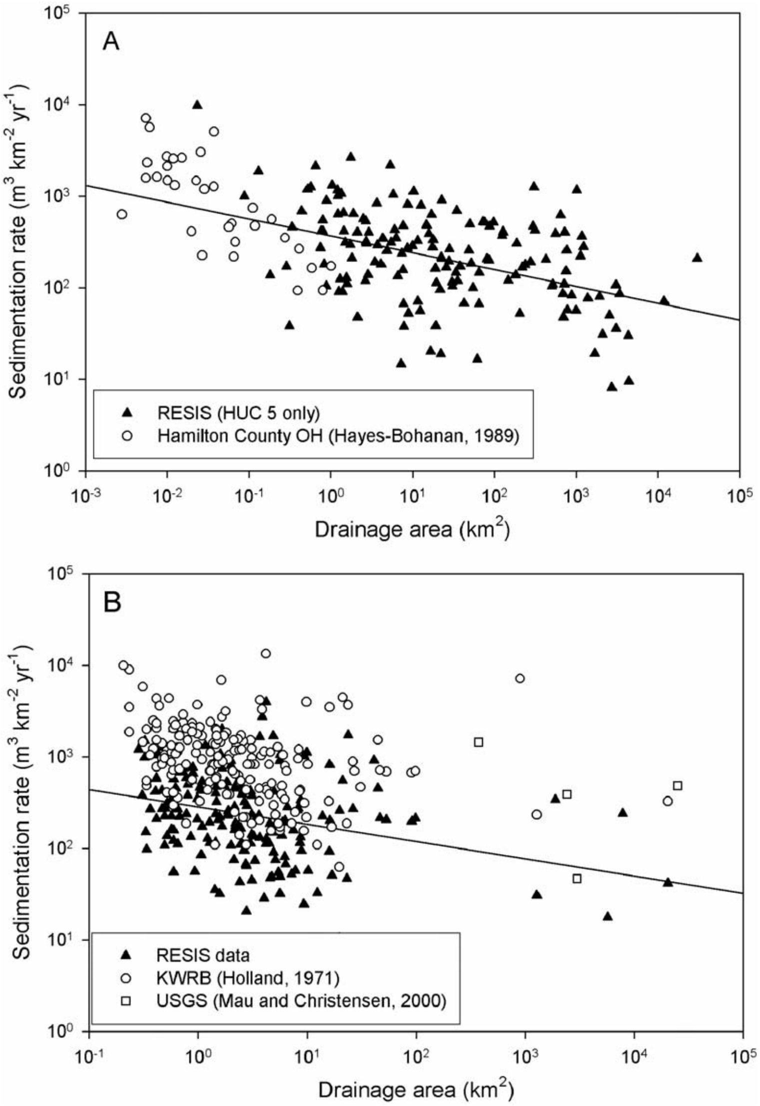

Fig. 5. Relation between specific sediment yield and drainage area for the Ohio River basin (A) and for the state of Kansas (B). Regression lines are those listed in Table 2, based only on points in the RESIS database. Additional points are from independent data sets.

assigned to impoundments, at least for periods in the latter part of the 20th century.

There is evidence to support each of these hypotheses, and there may be other explanations for the apparent budget imbalance as well. In all likelihood, different explanations will be applicable to varying degrees depending on local physical and historical conditions—these are issues that cannot be resolved in a study of this scope. It is possible that, prior to the construction of large numbers of small impoundments, the bulk of sediment derived from accelerated erosion was deposited in alluvial and colluvial settings. However, we feel that there is strong evidence that since the mid-20th century, small impoundments have become a major sink for eroded soil, and that as a consequence very little sediment is moving from uplands to downstream areas. The proliferation of small dams is a major contributor to the decoupling of upland erosion from downstream sediment yield (Phillips, 1995).

4. Conclusions

The construction of millions of small artificial impoundments along with tens of thousands of larger structures on large and small streams has transformed the hydrologic landscape of the U.S. This alteration of the drainage system is continuing and dynamic. Between 1950 and 2000, the total storage volume of reservoirs in the conterminous U.S. increased by an average of about 14×10^9 m^3 yr^{-1} (Graf, 1999), ensuring that reservoirs will continue to function as effective sinks despite the fact that some may lose trap efficiency due to sedimentation (Batten and Hindall, 1980). This is almost certainly true for ponds as well. For example, comparison of sequential aerial photography for one 260 km^2 watershed in Ohio showed that over time the number of ponds on the landscape has grown despite the fact that some older ponds were filled with sediment and replaced by perennial vegetation. Ponds are not static features of the landscape—they are constructed, sometimes maintained through dredging, and replaced when they fill with sediment.

This transformation has profound implications for the sediment transport system. Despite considerable uncertainties in the data and methods used to estimate total sedimentation in these impoundments, it is clear that, in aggregate, they play a quantitatively central role in the sediment budget for the conterminous U.S. The amount of sediment accumulating in large and small impoundments is at least as large as the amount of sheet and rill erosion taking place. We have proposed several alternative hypotheses that, if confirmed, may explain this apparent imbalance in the sediment budget. It is likely that some of these hypotheses may be valid in some regions but not others, and in a particular setting, the sediment budget is likely to be substantially different. Regardless of which of these alternatives may prove to be the most significant in any given setting, it is clear that a much larger portion of total sedimentation is now taking place in subaqueous rather than subaerial environments, with the result that sediment is likely to be stored for much longer time periods than would be imagined if it were deposited in active transport zones on slopes or along streams.

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