Reservoir sedimentation trends in Ohio, USA: sediment delivery and response to land-use change

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Abstract In Ohio, USA, a sufficiently large number of reservoir sediment surveys is available to characterize spatial and temporal patterns in sediment fluxes in a disturbed landscape. In this study we analyse 156 sediment surveys from 68 reservoirs, representing sedimentation rates in the latter 20th century. The study area includes two major physiographic regions: a glaciated low-relief till plain dominated by agricultural land use, and a mostly unglaciated dissected plateau with greater relief dominated by forest land use. Despite about 80% agricultural land use in the till plain, specific sedimentation rates are lower than in the plateau region. The agricultural region shows a significant negative relation between specific sediment yield and drainage area, while the upland does not. This is interpreted as indicating significant alluvial deposition associated with accelerated erosion in the agricultural region. The absence of such a relationship in the plateau area implies more efficient sediment delivery there. Comparison of sedimentation rates from the early part of the record (pre-1960) with those of the latter part shows that sedimentation rates are declining in the agricultural region, but not in the upland area, consistent with a reduction of agricultural erosion in the latter half of the 20th century. There is also a weak trend toward flattening in the specific sediment yield–drainage area relation. If confirmed this would imply that the channels in some areas are beginning to shift from net sediment sinks to a neutral condition, roughly a century after the time of maximum upland erosion.

Key words reservoir sedimentation; sediment delivery

INTRODUCTION

Reservoir sediment surveys provide one of the most reliable and readily available long-term records of sediment export from the landscape. They integrate export across the full range of flow conditions and over long periods of time. In addition, because reservoir sediment surveys are relatively inexpensive, the number of watersheds for which data are available is much larger than for other data sources. Reservoir sedimentation data have been used to address a variety of questions relating to spatial patterns in erosion and sediment yield, particularly their relation to climate, topography, and the impacts of human land use on erosion and sediment yield (Langbein & Schumm, 1958; Dendy & Bolton, 1976; Jansson, 1988; Renwick, 1996).

Studies of the relations between sedimentation and source-area erosion always face the problem that sediment delivery dominates the sediment yield signal, rather than erosion (Trimble, 1975; Evans *et al*., 2000). The effect of sediment delivery is, however, readily visible in the relation between sediment yield per unit drainage area (specific sediment yield) and drainage area (Church & Slaymaker, 1989). The widespread negative relationship between these variables in the USA is evidence of the impact of accelerated erosion on the sediment transport system (Walling, 1983).

Sediment budget studies have shown that most of the sediment eroded in the historic agricultural era in the USA has not left medium- to large-sized watersheds (Meade, 1982; Trimble, 1983; Phillips, 1991). In addition, there is evidence that the transition to net channel erosion following reduction in erosion has begun in small watersheds in some regions (Knox, 1987; Trimble, 1999; Ruhlman & Nutter, 1999). One important question concerns the timing of the return to net excavation, and the duration necessary to remove the sediment deposited in the accumulative phase (James, 1989). Identification of long-term trends in reservoir sedimentation remains elusive, however, largely because most reservoirs for which data are available lie in downstream settings and thus integrate signals from diverse watershed environments.

Despite clear evidence of changing upland erosion (Trimble & Crosson, 2000), overall trends in reservoir sedimentation remain uncertain. Bernard *et al*. (1996) found evidence that sedimentation rates in the USA are increasing. Renwick *et al*. (2005b) used sediment budgets to show that total reservoir sedimentation at present probably exceeds total upland erosion. If this is the case, then either channel systems must be functioning as net sediment sources rather than sinks, or reservoir sedimentation rates must decline, or both.

In some areas of the USA, sufficiently large numbers of resurveys are now available to begin to address questions of long-term trends in sediment yield, in the context of land use change and related erosion patterns at the decade to century time scale. In this study we examine temporal and spatial variations in the sedimentation–drainage area relation as indicators of changing erosion and sediment delivery in Ohio.

STUDY AREA AND DATA

Ohio is located at the boundary between the Appalachian plateaus to the east and the central North American lowlands to the west. We used a generalization of the US Department of Agriculture’s Land Resource Regions (USDA, 1981), to separate Ohio into two regions (Fig. 1; Table 1). To the northwest the landscape is a glaciated till/lake plain that is generally low in relief, with highly productive agricultural soils. To the southeast is the dissected Appalachian plateau, which is mostly unglaciated, higher in local relief and mainly forested today, although in the 19th and early 20th centuries agriculture and forest harvesting were more widespread.

Land use/land cover was characterized using the USGS National Land Cover Dataset (NLCD; http://landcover.usgs.gov/). The coverage is based on Landsat satellite imagery from the early 1990s. The National Elevation Database Digital Elevation Model used for watershed delineation was also used to describe topographic characteristics of the study watersheds. Minimum and maximum elevation and mean percent slope were extracted for each watershed.

We assembled existing sedimentation data from four sources: the RESIS database (Steffen, 1996); a 1990 Soil Conservation Service/Forest Service report (SCS, 1990); the US Army Corps of Engineers, and previous studies by Renwick *et al*. (2005a) (Table 2). All data were converted to common units and expressed as water volume in

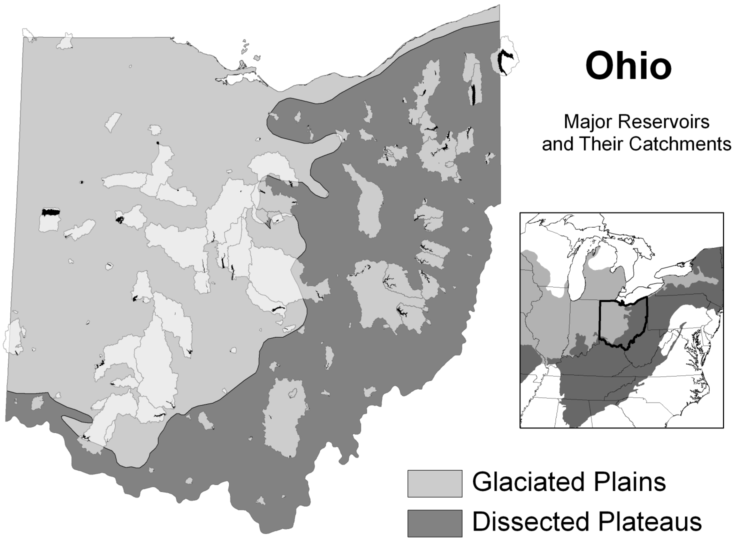


Fig. 1 Major reservoirs their catchments, and landscape regions of Ohio, USA.

Table 1 Summary characteristics of two study regions of Ohio.

	Urban (%)	Forest (%)	Agriculture (%)	Water (%)	Mean slope (%)	Total relief (m)
Northwest	5.8	13.0	79.1	2.0	2.1	323
Southeast	5.8	52.4	37.7	3.7	11.2	330

Table 2 Sources of sedimentation data.

Data source	Number of reservoirs used in this study	Number of sediment surveys[1]	Number of sediment surveys used in this study
RESIS	33	88	86
Army CoE	16	28	27
SCS/FS	26	26	20
Ohio DNR	52	52	8
MiamiU	12	27	27
Total[2]	68	168	156

[1] For RESIS, CoE, SCS/FS and MiamiU the number of surveys listed is the number of paired surveys that span a time period within which sedimentation is measured. For ODNR the number of surveys listed is the number of recent bathymetric surveys, none of which have comparable previous surveys but some of which can be compared with other data to produce estimates of recent sedimentation.

[2.] Totals differ from the sum of the rows above because of duplication and/or combination of data from different sources.

the reservoirs at specific time periods, with differences in water volume from one time period to the next reflecting sedimentation (accounting for dredging where appropriate). Sedimentation rates were expressed in volumetric rather than mass terms because bulk density data were not available for all reservoirs. In many cases the time periods represented by surveys from different sources overlapped. In most cases we were able to exploit these overlaps in order to increase the temporal resolution of the database. In a few cases there were clear inconsistencies in the data. For example, a survey from one source taken after a survey from another source might show a significant increase in volume, implying negative sedimentation, in a reservoir for which we have no evidence of dredging. In such cases we eliminated those surveys that seemed least consistent with other surveys for that reservoir. The average total length of record is 45.8 years, giving a total of 3112 reservoir-years of sedimentation data. For purposes of regional comparisons and comparisons of sedimentation rates with land use we averaged sedimentation rates across the entire period of record for each reservoir (n = 68). In analyses of changes in sedimentation rates over time we used sedimentation rates for all individual periods for which data were available (n = 156).

RESULTS

The watersheds in our study cover a total of 24 926 km^2, or roughly 24% of the total area of the state (excluding Lake Erie). The land use within these watersheds contains a lower portion of urban area than the state as a whole (2.84 as opposed to 5.84%) and slightly more agricultural area than the state as a whole (64.06 as opposed to 59.85%) but otherwise are representative. The logarithmic mean specific sedimentation rate for all 68 reservoirs is 196.5 m^3 km^{-2} $year^{-1}$; the arithmetic mean is 386.9 m^3 km^{-2} $year^{-1}$ (Table 3). Rates of this magnitude are fairly typical for this part of the USA. Specific sedimentation rates in the southeastern part of Ohio are higher than those in the northwest—logarithmic mean of 249.5 as compared to 147.7 m^3 km^{-2} $year^{-1}$. This difference is not significant (p = 15, 2-tailed t test). The higher sedimentation rates in the southeast are despite the fact that the northwest is predominantly agricultural, while the southeast is mostly forest. We analysed correlations among watershed variables and sedimentation rates in the two regions and found no meaningful correlations between sedimentation rates and either land use or topographic variables other than the expected negative relation between drainage area and specific sedimentation rate.

Table 3 Mean specific sedimentation rates (m^3 km^{-2} $year^{-1}$).

Region	*N*	Mean	SD	Logarithmic mean
Northwest	31	361.9	425.5	147.7
Southeast	37	407.7	506.0	249.5
Total	68	386.9	468.1	196.5

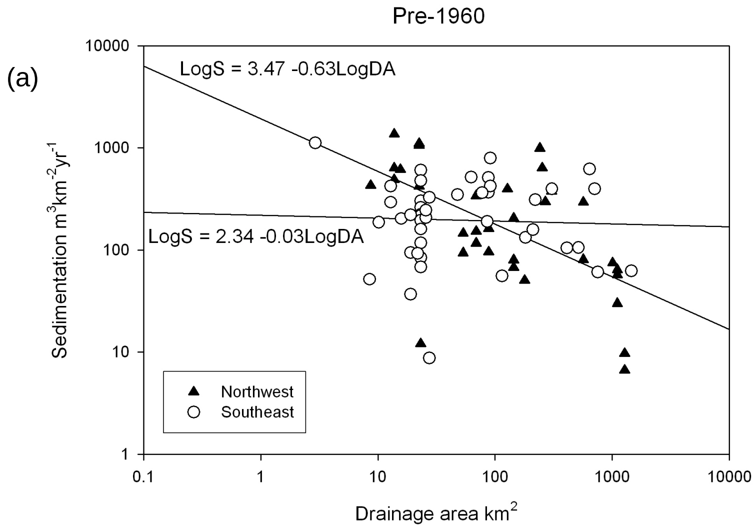
Mean sedimentation rates for surveys with midpoints before 1960 are higher than those for surveys with midpoints after 1960, but the difference is not statistically significant (Table 4). As a second test for a temporal trend in sedimentation we regressed log of specific sedimentation rate against the midpoint year of sediment survey (Table 5). The result is a significant negative trend for the northwest region (p = 0.037) but no significant trend for the southeast. Recognizing that the northwest region is mostly agricultural with low relief, this is where one would expect to find a negative trend. The land-use history in the southeast certainly is one of declining agricultural cultivation over the last century or so and replacement of cropland with forest, but the extent of cropping in the southeast was never as great as in the northwest.

Table 4 Mean sedimentation rates pre- and post-1960. The differences in mean rates are not significant (p = 0.094 for raw data, p =0.61 for log-transformed data).

Period	*n*	Mean	Std dev.	Logarithmic mean
Pre-1960	78	295.7	287.1	170.5
Post-1960	78	501.6	1038.4	191.0

Table 5 Regression of sedimentation rate against midpoint year for sedimentation period, for northwest and southeast regions.

Region	R^2	B	Constant	p
Northwest	0.063	–0.008	17.984	0.037
Southeast	0.010	–0.004	8.932	0.357



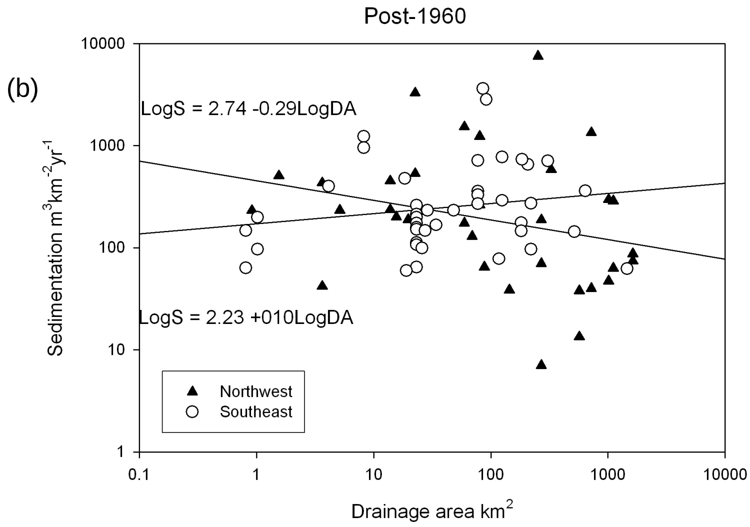


Fig. 2 Relation between log of specific sedimentation rates and log of drainage area. (a) periods with midpoints prior to 1960. There is a strong decrease in sedimentation with increasing drainage area for the northwest region, but no significant relation in the southeast. (b) periods with midpoints after 1960. The relation between sedimentation and drainage area has disappeared, and there is a weak indication that downstream rates may be higher than those in smaller upstream reservoirs.

In the context of the Ohio landscape, the negative relation between sedimentation and drainage area can be seen as a consequence of inefficient sediment delivery through the stream system, in a period of accelerated erosion. Sediment delivery itself, however, is a function of processes in the channel system. In general, landscapes with steeper valley slopes, laterally constricted valleys and narrow flood plains should be expected to have higher sediment delivery rates than landscapes with gentle slopes and broad flood plains. In the Ohio landscape we thus would expect a stronger negative effect of drainage area on sedimentation and in the northwest part of the state than in the southeast.

Regional and temporal variations in the sedimentation–drainage area relation are shown in scatterplots of sedimentation rates and drainage area in Fig. 2. The effect of drainage area is stronger in the northwest than in the southeast, and greater prior to 1960 than since then. In the southeast there is a weak (p = 0.26) indication of increasing sedimentation downstream. If such a trend were confirmed it would indicate that streams are remobilizing sediment through bed and bank erosion, moving formerly deposited sediment downstream through the drainage system.

SUMMARY AND CONCLUSIONS

Sedimentation rates in Ohio reservoirs show no clear correlation with watershed land-use or topographic variables. When comparing the more agricultural and low-relief northwest region with the less agricultural and more hilly southeast, however, clear trends emerged. These trends indicate that sedimentation rates are beginning to respond to declining agricultural erosion resulting from 20th-century adoption of soil conservation practices. This response is most evident in the northwest region. The data also show that sediment delivery exerts a strong influence on sedimentation patterns. This is evident in the differences in the sedimentation–drainage area relations between the northwest and southeast. Taken together, these trends indicate that land use alone is less significant than land management, and erosion rates are less significant than sediment delivery in determining the downstream impacts of human activity on reservoir sedimentation.

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