SMALL ARTIFICIAL PONDS IN THE UNITED STATES: IMPACTS ON SEDIMENTATION AND CARBON BUDGET.

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Abstract: The proliferation of small artificial ponds constitutes a major human alteration of the hydrologic landscape. We have estimated the total number of such features across the conterminous United States to be between 2.6 and 9 million, with densities in some areas exceeding 5 per km^2. The majority of ponds have been built in agricultural settings, and densities are highest in the eastern Great Plains and the Southeast. Ponds intercept and temporarily store about 25% of runoff from the conterminous U.S., and in regions of high pond density that proportion may approach 100%. Ponds are a major sediment and carbon sink. Based on erosion and sedimentation rates typical of the mid-to late- 20th century they capture 0.2 to 1.8 x 10^9 tons of sediment and 4 to 36 x 10^6 tons of carbon annually. Case studies in eastern Kansas and southwestern Ohio indicate that while total numbers of ponds have increased steadily since the early 20th century, ponds are transient features on the landscape, with 30 to 90% of those present in the 1950s disappearing by 2000. Ponds disappear mainly by two processes: infilling with sediment, and replacement with other land uses. These processes are spatially variable with infilling by sediment being the dominant cause of disappearance in most areas. Trends in pond sedimentation rates are likely highly variable depending on local conditions. Erosion rates from lands used for row crop agriculture are declining, and ponds with these types of agricultural land uses in their headwater areas are the first to be affected by a reduction in sediment flux. The locus of pond construction appears to be shifting from agricultural to suburban settings, and the dominant rationales for pond construction are changing from provision of livestock water to aesthetic considerations and urban runoff management.

INTRODUCTION

In many parts of the world, especially in agricultural regions, small artificial impoundments (here called ponds) are common features of the landscape. They are built for a variety of purposes, both utilitarian and aesthetic. Despite their ubiquity and, in the U.S. at least, relatively recent appearance on the landscape, they have received little attention in the scientific literature. Individually they are small in comparison to the many named lakes and reservoirs that are generally better-studied, but they are much more numerous. Perhaps most importantly, they reach their highest densities in some areas that have virtually no natural standing surface water, and thus constitute a fundamental transformation of the hydrologic landscape. In this paper we: 1) discuss a recent continent-scale inventory of small ponds in the conterminous U.S.; 2) quantitatively estimate the cumulative impacts of these ponds on total fluxes of sediment and carbon; and 3) describe recent trends in pond construction and replacement and the relation of land-use and land-management trends to pond distribution and impacts.

INVENTORY

The publication of the National Inventory of Dams (NID) called attention to the proliferation of dams on the hydrologic landscape of the U.S. (Graf, 1999). The NID includes ~75,000 features exceeding specific height thresholds (2 m for capacity > 61,700 m^3; 8 m for capacity > 18,500 m^3). While the relatively large dams included in the NID represent the vast majority of total water storage volume in large and small impoundments, the actual number of artificial impoundments in the U.S. is 2 orders of magnitude higher. Smith and others (2002), using data in the satellite-derived National Land Cover Database (NLCD), inventoried small water bodies in the conterminous U.S. While their inventory does not distinguish between natural and artificial impoundments, it is clear from their distribution (Fig. 1) and a knowledge of the geomorphology of the continent that the vast majority of these features are artificial. The NLCD-based inventory concluded that there were ~2.6 million ponds in the early 1990s, the approximate date of the imagery used in the NLCD (Table 1). This number is a minimum estimate, however. Extrapolation from a ~1% sample of USGS 1:24,000 quadrangles suggested a total exceeding 8 million, and detailed analyses of parts of Kansas and Ohio using high-resolution aerial photography rather than the 30-meter Landsat imagery used in the NLCD confirm that the NLCD inventory underestimates the total by a factor of 1-3. For example, in southwest Ohio, a count of ponds from recent (2000) aerial photographs in three counties found 1.0-3.3 times as many ponds as were identified from the NLCD inventory. In Kansas, identification of ponds on air photos found 0.9 to 1.9 times as many ponds as the NLCD inventory. Based on these data, the inclusion of small ponds in our inventory adds about 20% to the total water surface area of the conterminous U.S., although that number would be higher if we used a higher estimate of pond numbers.

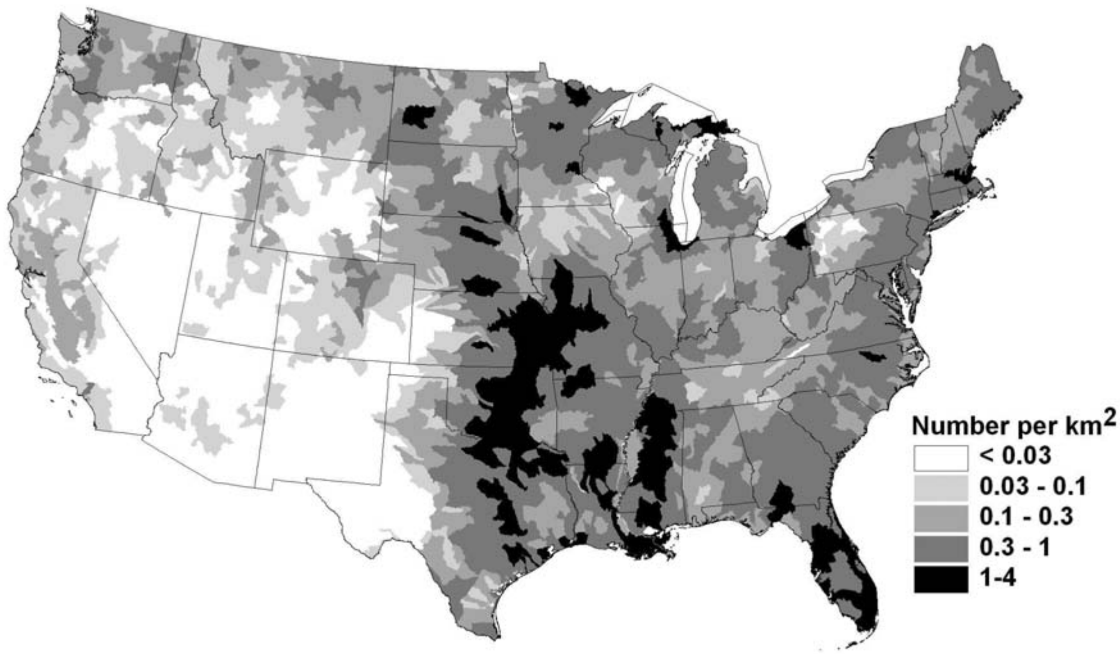

Figure 1 Density of small water bodies in the conterminous U.S., based on NLCD data (from Smith and others, 2002).

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 quadragles (DLGs) (Smith and others, 2002).

Dataset	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*	43	62	1.45×10^7	1.84×10^9	8.00×10^1
USGS DLGs	9000	--	--	--	2.5×10^1

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

IMPACTS ON CONTINENT-SCALE MATERIAL FLUXES.

It is well documented that dams have profound effects on sediment fluxes through watersheds. For example, Meade and Trimble (1974) showed that dams constructed on the major streams draining eastward from the Appalachians have virtually shut off the flow of sediment to the Atlantic. In the Colorado system, the dramatic decrease in sediment flux is similarly well documented, (Carriquiry and Sanchez, 1999; Williams and Wolman, 1984; Collier and others, 1997). Until recently, however, the cumulative impact of millions of large and small dams on continental sediment flux has been unknown. Smith and others (2002), extrapolating from sedimentation rates in ~1600 reservoirs listed in the RESIS database (Steffen, 1996) have estimated the total volume of sediment deposited in ~43,000 large dams listed in the NID at $1.67 \times 10^9 m^3 yr^{-1}$. Estimates of the total amount of sedimentation in the millions of smaller impoundments not included in the NID are more difficult to make, but appears to be in the range of 0.1 to 1.8 x $10^9 m^3 yr^{-1}$ (Renwick and others, 2005). The total sedimentation in small ponds is thus apparently of similar magnitude to that occurring in the larger reservoirs in the NID. While the small ponds probably only account for a small percentage of the total water storage capacity, they are far more numerous and they exist higher in the drainage network, where sediment yields per unit drainage area are high. Based on relations between pond density and proportion of the landscape upstream of ponds we estimate that approximately 21% of land area of the conterminous U.S., representing 25% of runoff and 25% of total sheet and rill erosion, lies upstream of at least one pond. The total amount of sediment accumulating in impoundments in the 48 conterminous U.S. is thus in the range of 1.9 to 3.5 x $10^9 m^3 yr^{-1}$. For comparison, total sheet and rill erosion in the U.S. approximately 2.4 x $10^9 m^3 yr^{-1}$, based on the 1990 National Resource Inventory extrapolated to include Federal lands (Renwick and others, 2005). It appears that ponds and reservoirs are the dominant sink for soil eroded by water.

Table 2 Estimates of total sedimentation in ~2.6 million NLCD ponds ($10^9 m^3 yr^{-1}$) (Renwick and others, 2005).

Method		Sedimentation
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

Several studies have shown that substantial amounts of carbon are accumulating in lakes and reservoirs (Stallard, 1998; Dean and Gorham, 1998; Mulholland and Elwood, 1982; Smith and others, 2001). The carbon content of sediment in ponds is variable, but similar to that of the soils that are being eroded (Ritchie, 1989). Smith and others (2005) estimated that the average carbon content of soils in the Mississippi basin is 1.5%. Applying this figure to our estimate of pond sedimentation suggests that 3 to 30 x 10^6 tons of carbon are accumulating in small ponds each year. A similar amount accumulates in larger reservoirs.

CHANGES IN POND NUMBERS OVER TIME

Although documentary evidence is scant, it appears that widespread pond construction in agricultural areas began in the early 20th century. Many ponds were first built for agricultural purposes—primarily livestock water—especially in areas of significant seasonal water shortage such as the Great Plains and southeast. Beginning in the 1940s and accelerating in the 1950s large numbers of ponds were built with technical and/or financial assistance from the Soil Conservation Service (Helms, 1992; ASCS, 1981). Ponds were encouraged as part of Farm Management Plans, and construction costs were subsidized. Ponds were seen as serving multiple uses including livestock water, sediment control, recreation, and emergency water supplies. Very large numbers of ponds were built in this period.
By the 1970s the rate of pond construction in agricultural settings declined in both Kansas and Ohio, but a new phase of pond construction began, especially in urbanizing areas. Two main purposes have dominated pond construction in the last 2-3 decades: aesthetics/recreation, and stormwater management. As suburban development expanded rapidly into surrounding rural areas, residential construction became more common on larger lots and at lower densities than was typical of the 1960s. With homes being built on lots of 1 hectare or more, there is room to include a pond on the lot. Ponds are attractive amenities for homes in semi-rural settings. At the same time, increased concern about the water quality and flood impacts of urban development has led local regulatory agencies to require construction of stormwater detention basins as part of higher-density suburban developments. Although a quantitative estimate of pond construction for this purpose is not available, it is likely that thousands of ponds are being built annually as part of stormwater management programs. In some areas aquaculture is also an important factor driving construction of ponds.

In order to gain a better understanding of pond distribution over time and space we mapped ponds from aerial photography for several time intervals in two regions of the U.S.: southwest Ohio and eastern Kansas (Figure 2). In both cases we assembled available historic aerial photography from the earliest imagery available (typically 1930s or 1940s) up to the most recent. In Ohio we mapped all the ponds in three counties that represent a transect of agricultural, suburban and urban landscapes. In Kansas we focused on four USGS 1:24,000 quadrangles that represent a range of environments. The Allen SE, Gridley, and Burlington quads are all in areas where livestock raising, particularly cattle grazing, was a dominant activity. The Gridley and Burlington quadrangles represent

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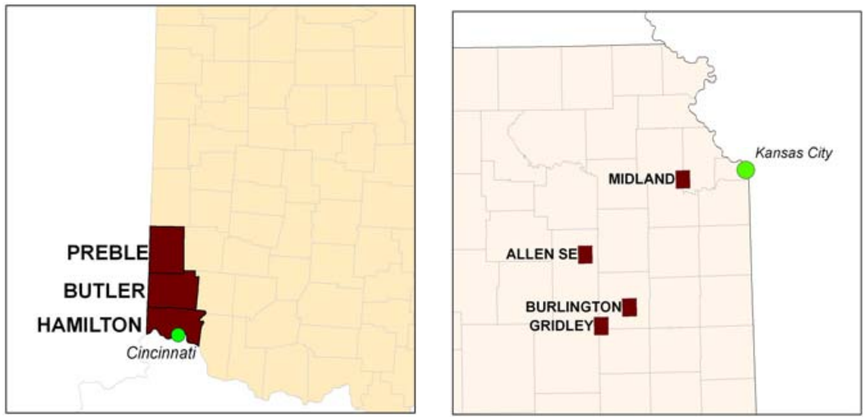

Figure 2 Case study regions where ponds were mapped from aerial photography at multiple time intervals from the earliest available imagery to the most recent. A) Three counties in southwest Ohio. B) Four USGS 1:24,000 quadrangles in eastern Kansas.

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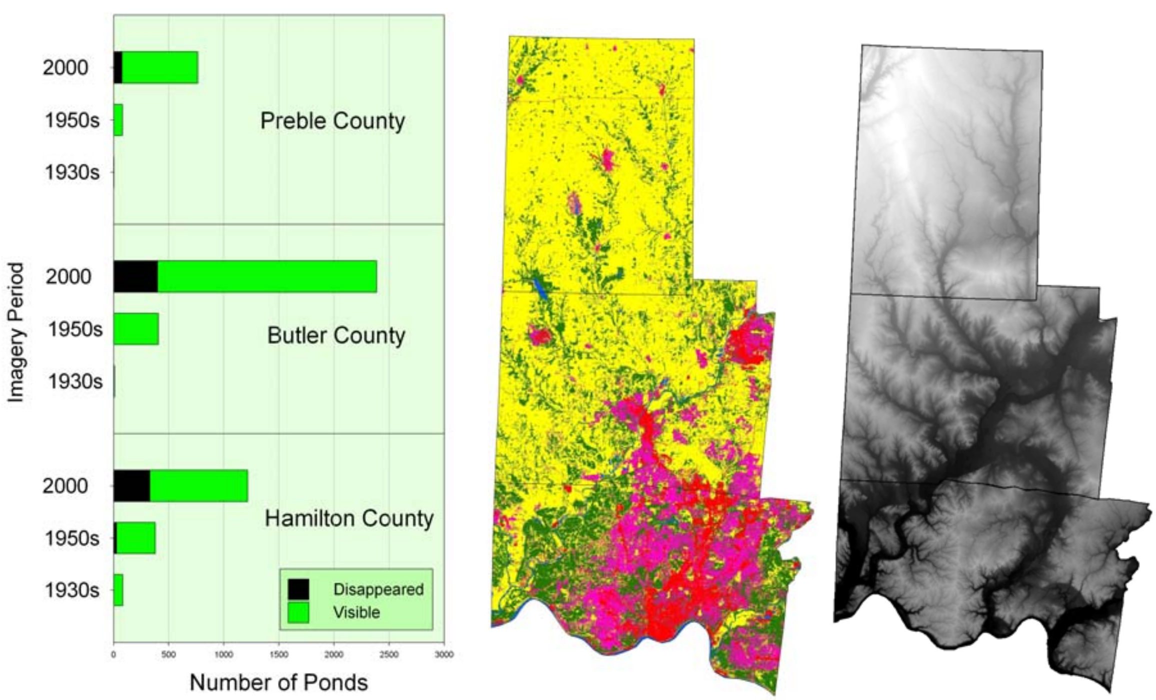

Figure 3 Numbers of ponds at three time periods in three counties in southwest Ohio. The three counties represent a transect from relatively low-relief topography and mostly agricultural land use in Preble County to relatively high relief and mostly urban and forest land use in Hamilton County (metropolitan Cincinnati). A) Pond densities are highest in Butler County, which is intermediate in topography and land use. B) Land use, from the National Land Cover Dataset (NLCD; http://landcover.usgs.gov/nationallandcover/html). Yellow is agricultural, green is forest, magenta is suburban and red is urban. C) Elevation, from USGS 30-meter DEMs. In general local relief increases from north to south, reaching a maximum near the Ohio River and its tributary valleys.

upland and floodplain-dominant landscapes. The Midland Quadrangle is an area which probably had fewer cattle and more row crop agriculture, and today it is in an area of urban growth. We also inventoried all ponds in four Kansas counties using aerial photography, as a comparison to the counts derived from the NLCD database.

In both cases the total number of ponds on the landscape has increased dramatically, from near zero in the earliest aerial imagery to thousands per county today (Figures 3 and 4). The data also show that ponds are dynamic features of the landscape, being both created and destroyed. For example, of a total of 867 ponds that existed in Preble, Butler and Hamilton Counties in the mid-1950s or earlier 810, or 93%, disappeared before 2000 (Figure 3). In the four quadrangles we sampled in Eastern Kansas, 292 of 520 or 57% of ponds disappeared between the first photographic record and 2002-03 (Figure 4). Thus average pond lifespan in these environments is in the range of a few to several decades.Based on the aerial photographic record two processes account for the long-term disappearance of ponds: sedimentation, and replacement with other land uses—principally urban uses. Infilling with sediment is especially common in agricultural areas undergoing accelerated erosion, and is dependent on erosion rates and the ratio of watershed area to pond volume. For example, consider a pond 0.5 hectare in size and averaging 1 m deep, and a drainage area of 80 hectares delivering 2 tons of sediment per hectare per year. Such a pond would fill completely in about 35 years. In areas undergoing significant urban and suburban development, land-use change is responsible for significant pond disappearance as well as construction of new ponds (Figure 5). In southwest Ohio urbanization is the dominant cause in urban and suburban areas, while sedimentation dominates in agricultural areas.

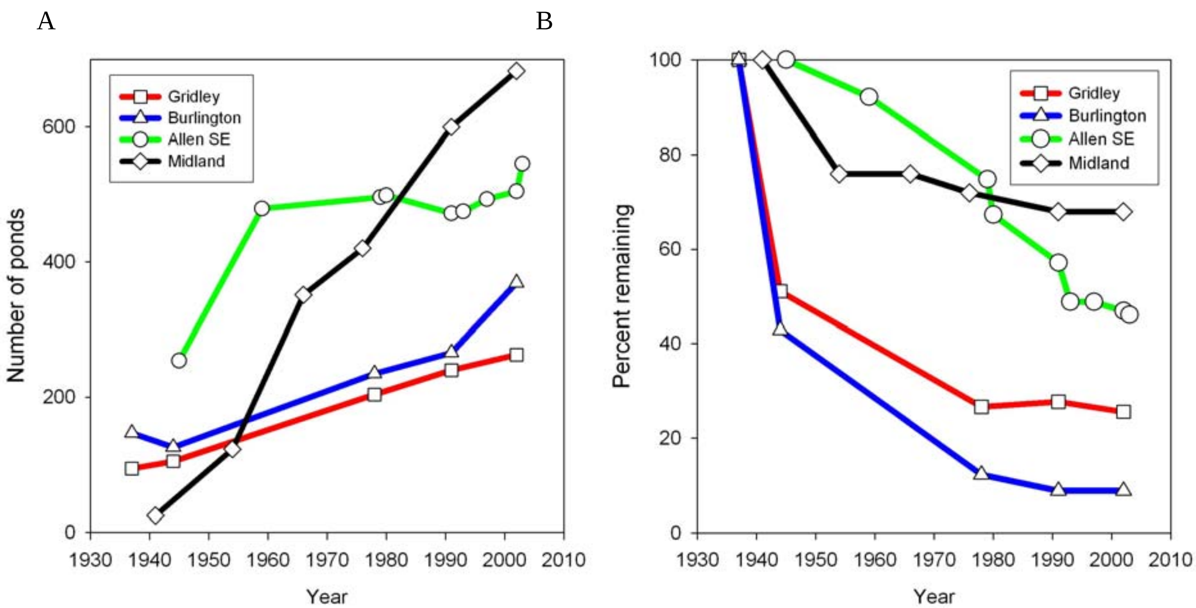

Figure 4 Construction and disappearance of ponds based on aerial photography for four sample quadrangles in eastern Kansas. A) Pond numbers increased through the last 60 years. The drop in pond numbers in the Allen SE quadrangle in the 1980s is attributable to a combination of drought and reduced profits in the cattle industry, which is particularly dominant in that area. In the Midland Quadrangle rates of pond were initially low because row-crop agriculture is more important in this area than in the other quadrangles. Pond construction there has been especially rapid in the last 2-3 decades as a result of urban/suburban development. B) Number of ponds mapped in the earliest aerial photography that remained in successive images for four 1:24,000 USGS quadrangles. The rates of pond disappearance vary considerably among the four quadrangles, but show that many ponds disappear in time scales of 10-50 years. In the Burlington and Gridley quadrangles the rate of pond disappearance was initially high, probably because the initial photography dates from a time when pond-building technology was poorly developed and sedimentation rates were high.

Pond construction is a form of land management and as such is intimately connected to the land use systems existing at any point in time. These systems are themselves linked to technologic, economic, political and cultural factors. A full understanding of the factors controlling pond construction and destruction is thus well beyond the scope of this paper. However, it is instructive to place the history of pond construction in the context of historic changes in land use and land management, so that we can better understand recent and future trends in pond numbers and condition.

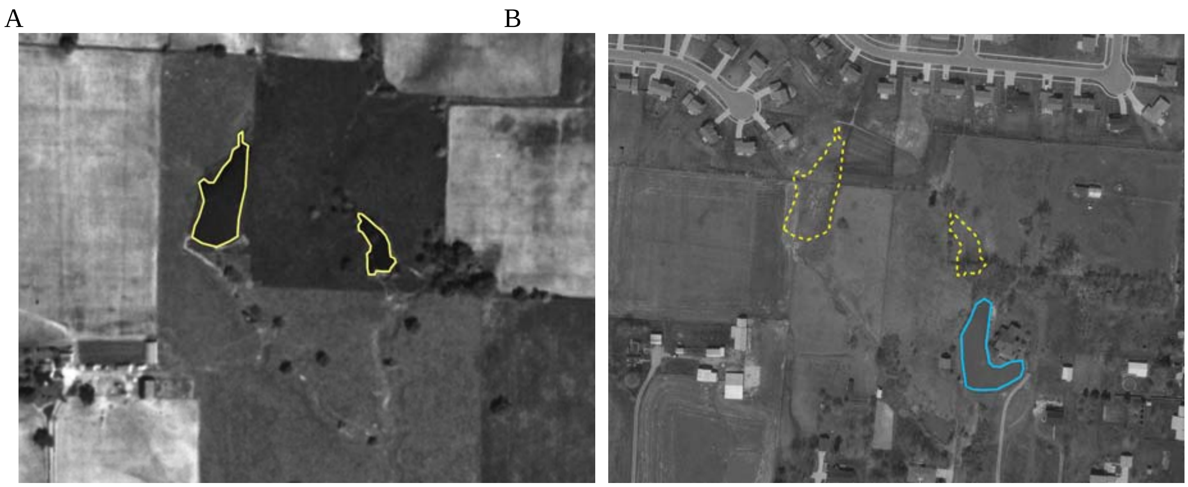

Figure 5 An area of Butler County, Ohio, in 1950 and 2000. A) In 1950 two ponds were present in what was then an agricultural landscape. B) By 2000 those two ponds had disappeared, presumably by sedimentation, and a third had appeared.

SUMMARY AND CONCLUSIONS

Artificial ponds, while individually small, have become so numerous that they represent a profound human alteration of the hydrologic landscape. Their impact is comparable in magnitude to that of larger reservoirs, both in terms of surface area and sedimentation. Because ponds occupy sites with small drainage areas they are close to source-areas for sediment and other substances moving in stormwater runoff, and hence have proportionately higher sedimentation rates than larger reservoirs. They appear to be a major carbon sink.

Ponds are dynamic features of the hydrologic landscape. They have appeared relatively recently—within the last 100 years—and their numbers have increased dramatically in that time period. Pond densities and dynamics are closely tied to both natural and human features of the landscape. The dominant purposes for which ponds are constructed appear to be shifting, but total pond numbers continue to increase.

Ponds that disappear from the landscape cease to be active sinks for sediment and carbon, but they retain the materials that accumulated when they were active. Ponds that remain on the landscape but are dredged also continue to accumulate sediment and associated materials. Although conditions will vary considerably among ponds, our observations indicate that dredged materials are typically buried and stabilized near the site of dredging so that they do not re-enter mass transport systems.

Changing land management upstream of ponds will affect their role as material sinks, with the magnitude and direction of change dependent on local circumstances. In areas where soil conservation technologies are reducing source-area erosion pond sedimentation rates can be expected to decline. In suburban areas ponds may temporarily serve as sinks for construction-period erosion, but thereafter sediment inputs are probably slow and pond lifespan is likely long. On the other hand, increased runoff from urban land will tend to mobilize sediment in and adjacent to streams, increasing sediment loads to ponds. Soil conservation and the shift in locus of pond construction from agricultural to suburban settings are likely to reduce rates of sediment accumulation in ponds.

The downstream effects of ponds are unclear. To the extent they reduce the magnitude of flood peaks they may help stabilize stream channels. On the other hand, reductions of sediment load caused by sedimentation in ponds may encourage net erosion downstream. In any case, because of their high density and upstream position in the hydrologic system ponds will continue to exert a significant influence on biogeochemical cycles.

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