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Distribution and significance of small, artificial water bodies across the United States landscape

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Abstract

At least 2.6 million small, artificial water bodies dot the landscape of the conterminous United States; most are in the eastern half of the country. These features account for approximately 20% of the standing water area across the United States, and their impact on hydrology, sedimentology, geochemistry, and ecology is apparently large in proportion to their area. These features locally elevate evaporation, divert and delay downstream water flow, and modify groundwater interactions. They apparently intercept about as much eroded soil as larger, better-documented reservoirs. Estimated vertical accretion rates are much higher, hence, inferred sedimentary chemical reactions must be different in the small features than in larger ones. Finally, these features substantially alter the characteristics of aquatic habitats across the landscape.

Keywords: Artificial water bodies; Sediment accumulation; Hydrology; Conterminous United States

1. Introduction

The extent and importance of large, artificial water catchment reservoirs across the landscape are increasingly appreciated. Graf (1999) used the National Inventory of Dams (NID; Table 1) to conclude that ~75 000 artificial dams across the United States impound an amount of water approximately equivalent to 1 year's run-off from the continent. He identified dams as '…significant features of every river and watershed of the nation.' These features significantly slow the rates of transport of water and contained dissolved and particulate materials from land to the sea; elevate water loss to evaporation; alter rates, pathways and locations of chemical reactions in freshwater; and disrupt freshwater aquatic habitats by fragmenting water flow to the ocean (e.g. Dynesius and Nilsson, 1994; Graf, 1999; Vörösmarty and Sahagian, 2000; St. Louis et al., 2000).

A particular effect of reservoirs is the enhanced trapping of sediments carried by rivers towards the ocean (Trimble and Bube, 1990). This trapping is dramatically illustrated by Meade et al. (1990) in their analysis of sediment transport by United

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Table 1
Databases, www addresses, and data characteristics for water body datasets used in this analysis

Database (abbreviation)	Source URL	Data characteristics, comments
USGS National Land Cover image files (modified NLCD)	http://landcover.usgs.gov/nationallandcover/html	Gridded 30-m pixels for individual states of conterminous United States; data nominally for 'leaf-off' period, 1992. Processing discussed in detail in text. $\sim 2.6\times10^6$ discrete water bodies.
US Census Bureau inland water bodies, 'Topologically Integrated Geographic Encoding and Referencing' (as ArcView shape files available from Environmental Systems Research Institute (ESRI) (TIGER)	http://www.esri.com/data/online/tiger/index.html	Water bodies and double-line stream polygons on USGS 1:100,000 quadrangle maps (see http://www.census.gov/ftp/pub/geo/www/GARM/Ch15GARM.pdf). Data collated from county data. ~75,000 discrete water bodies, including reservoirs, lakes, and streams.
1998 National Inventory of Dams, maintained by US Army Corps of Engineers text file (NID)	http://crunch.tec.army.mil/nid/webpages/nid.cfm	Tabulated geographic coordinates (points) for ~75,000 artificial dams across United States. Database designed for flood hazard assessment. Sizes of water bodies and catchments given. From this we used ~43,000 water bodies.
Water features data layer from National Atlas data clearinghouse shape file (NA)	http://nationalatlas.gov/index.html	Polygons collated by USGS from hydrography layer of 1:2 000 000 digital line graphs (DLGs). ~5000 discrete water bodies (excluding rivers) for conterminous United States. Most are listed as 'lakes' but most are apparently artificial reservoirs.
US Geological Survey digital line graphs (DLG)	http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html	Hydrography layer (polygons) of 336 US Geological Survey 1:24 000 DLGs (7.5 minute quadrangles) were analyzed. Processing details similar to modified NLCD, as discussed in text. Extrapolation to conterminous United States yields ~9 000 000 discrete water bodies.

States rivers. In the case of the Colorado River, for example, impoundments have reduced sediment delivery to the Gulf of California by ~100-fold. Downstream effects can also be dramatic (Williams and Wolman, 1984). At the mouth of the Colorado, tidal scour and erosion have overtaken delta construction in the virtual absence of sediment supply (Carriquiry and Sanchez, 1999).

The focus of these analyses has been on relatively large water bodies. These features apparently dominate the area and volume of fresh water storage. In contrast, the role of 'small water bodies' (loosely defined to have surface areas smaller than approx. 10^4 m^2) has been largely overlooked, in spite of their probable significance to sediment and sedimentary carbon deposition (Mulholland and Elwood, 1982; Ritchie, 1989; Dean and Gorham, 1998; Stallard, 1998; Smith et al., 2001). Specific sediment yield (sediment export from a catchment per unit of catchment area) and the related variable, sediment delivery ratio (ratio of sediment delivered to a catchment outlet to sediment eroded within the basin) tend to decrease with increasing basin area (e.g. Walling, 1983). Milliman and Syvitski (1992) observed that river basin sediment yield to the ocean decreases as basin size increases. An explicit application of this to catchments and reservoirs within the conterminous United States is given by Renwick (1996).

Here we estimate the distribution of number and area of small water bodies across the conterminous United States. The majority of water bodies in the study appear to be artificial rather than natural, so the results reflect the significance of anthropogenic alteration of the landscape as well as of the water bodies in themselves. We also provide quantitative examples of the importance of these features.

2. Data sets and data analysis

Several data sets were used in this analysis (Table 1). Modifications of the original data are described briefly in the table and further elaborated below. The data were processed using ArcView 3.2 (http://www.esri.com/software/arcview/index.html). We used three available inventories of large water bodies: the National Atlas (NA), the Census Bureau's TIGER data, and the National Inventory of Dams (NID). The NA hydrography layer is mapped at a scale of 1:2 000 000, and includes ~5000 discrete water bodies (excluding rivers) for the conterminous United States. Most are listed as 'lakes,' but most are apparently artificial reservoirs. The TIGER dataset (1:100 000) includes lakes, reservoirs and rivers, but they are not distinguished as such. Approximately 75 000 discrete water bodies are mapped. The NID, a database designed for flood hazard assessment, includes tabulated geographic coordinates (points) for ~75 000 artificial dams across the United States. Shapes are not mapped, but areas and volumes of water bodies and catchment areas are given for most features. We eliminated features that are obviously multiple dams on the same water body; features for which catchment size or impoundment size was not available or could not be estimated; features for which the geographic coordinates were in error; and features in the States of Alaska and Hawaii. This reduced the number of features to ~43 000.

None of these data sets provides comprehensive information on small water bodies. In general they provide a fairly complete inventory of features of at least several hundred thousand square meters; they miss virtually all features smaller than ~10^5 m^2. While we do not establish an absolute size boundary defining 'small' vs. 'large' water bodies, ~10^4 m^2 is a useful working boundary between the small and large water bodies.

The primary information used for the comprehensive evaluation of small water bodies is a modified version of the US Geological Survey National Land Cover Data (modified NLCD). The nationwide land-use, land-cover dataset consists of gridded 30-m pixels for individual states of conterminous United States; the data are nominally for the 'leaf-off' period of 1992. All water bodies in the dataset were identified and converted to polygons of contiguous pixels. Touching polygons were joined and treated as individual water bodies.

In order to enumerate discrete water bodies not being counted in other inventories, a 1-km buffer was constructed around the large water bodies and rivers identified in the National Atlas (NA) database, and water features inside this buffer were subtracted from the data. This buffer allowed for slight mismatches in the mapped locations of features. Further inspection identified linear features that were clearly streams; these features were deleted. Finally, water bodies were deleted from a 5-km buffer around the coastline and large rivers in the ESRI ArcView data layers for the United States. This step eliminated large riverine features such as floodplain swales that appear as impounded water bodies but are functionally parts of the river systems, as well as some coastal wetlands. These data processing steps should lead to a conservative (low) estimate of the total number, distribution, and area of small water bodies.

One limitation of this procedure is that some extensive wetland areas such as the Everglades in Florida are resolved as many small individual water bodies, rather than as single features. This leads to an over-estimate of the number of water bodies, hence an underestimate of average water body area, in these regions. For example, ~41 000 individual water bodies are resolved in the Florida Everglades by our technique. Overall, this effect seems fairly small. In total, approximately 3% of water bodies in the modified NLCD data are located in areas mapped as 'swamp or marsh' in the NA data.

We also examined portions of the 1:24 000 (7.5 minute) US Geological Survey Digital Line Graph (DLG) coverage. While it would be desirable to undertake this analysis for the entire conterminous United States, most of the ~55 000 quadrangles are not available in this form. We downloaded and analyzed the hydrography layer from a sample of 336 quadrangles distributed through the study area. The distribution of available 7.5 minute DLGs is not random, but apparently reflects local priorities. Our sample does include quadrangles from each of the 48 conterminous United States, and we believe is reasonably representative of the overall study area. The DLG data were masked using the same procedures as used for the modified NLCD data, in order to eliminate riverine and coastal features and to make these two datasets comparable.

The remaining features in the modified NLCD and DLG layers were mapped as numbers and areas of discrete water body features in each of the ~2100 US Geological Survey eight-digit hydrologic cataloging units (HUC-8) across the conterminous United States (http://water.usgs.gov/GIS/huc.html) (Seaber et al., 1987). These modified datasets represent the small water bodies only, and are referred to hereafter as the modified NLCD and DLG data used in this analysis.

3. Results: distribution and abundance of water bodies

3.1. Overall data characteristics

Results are summarized in Fig. 1 and Tables 2 and 3. The modified NLCD dataset contains $\sim 2.6 \times 10^6$ water bodies. While the nominal resolution of this coverage is 30×30 m pixels (i.e. 900 m^2), the smallest features are resolved by ArcView as triangular shapes with a calculated area of ~600 m^2. Almost half (43%) of the features are $< 10^3$ m^2 (i.e. essentially the limit of resolution); 90% are $< 10^4$ m^2.

The DLG data do not provide comprehensive coverage across the entire United States, but they do provide higher resolution of features than the modified NLCD. Based on the size distributions of the water features, we estimate that the nominal lower size limit on these features is ~5 m (25 m^2). There is substantial variation in the lower size limits of mapped features from one DLG to another, not surprising inasmuch as the original maps were prepared over a 40-year time span (1950s to 1990s). Extrapolating from the quadrangles examined, there could be as many as 9×10^6 water bodies > 25 m^2 in area across the conterminous United States.

The US Census Bureau TIGER data provide the most comprehensive and detailed digital coverage of water bodies other than the modified NLCD data. This dataset includes approximately 75 000 water bodies in the conterminous United States. However, in marked contrast with the modified NLCD and DLG databases, fewer than 1% of the TIGER features are $< 10^3$ m^2 in area, and only ~6% are $< 10^4$ m^2.

The National Inventory of Dams (NID) dataset, as we modified it, has approximately 43 000 features in the conterminous United States; features

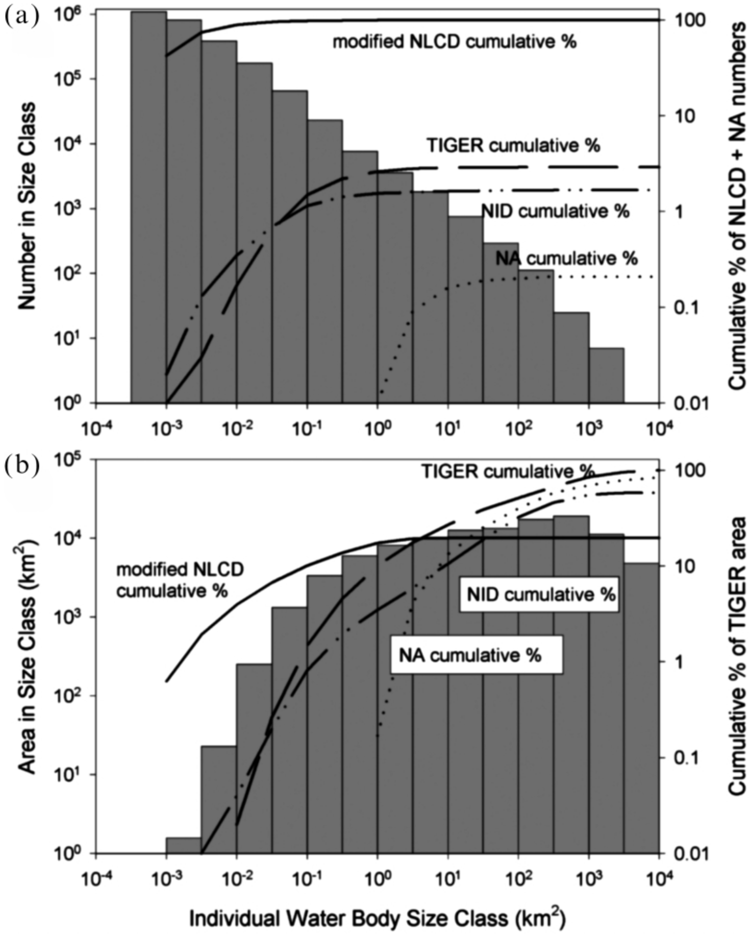

Fig. 1. Comparisons of numbers and areas of water bodies among NLCD, NA, TIGER and NID data sets. (a) Total numbers of water bodies identified in the modified NLCD+NA data (bars), compared with cumulative percentages by number for each data set. No data set other than the modified NLCD accounts for a significant fraction of the total number of water bodies. (b) Areas of TIGER water bodies (bars), compared with cumulative percentages by area for each data set. The modified NLCD (uncounted in the other surveys) accounts for approximately 20% of the total water area.

Table 2
Number, total area, mean area, and minimum reported area of water bodies in various data sets

Data set	Number of water bodies (thousands)	Total surface area (thousand km^2)	Mean water body area (thousand m^2)	Minimum water body area (m^2)
Mod. NLCD	2600	21	8	600
NID	43	62	140	80
NA	5	89	1700	120 000
TIGER[a]	75	107	143	–[b]
DLG	9000	–	–	25

[a] Includes streams.
[b] Many of the smallest features are slivers; 94% of the features in the TIGER data are $>10^4$ m^2 in area.

Table 3
Number and area of water bodies in the modified NLCD data set by two-digit hydrologic region

HUC-2	Name	HUC-2 area (thousand km^2)	Water body area (km^2)	Percent water	Number of water bodies (thousands)	Water bodies per km^2
01	New England	160	1240	0.78	66	0.41
02	Mid Atlantic	278	1048	0.38	101	0.36
03	South Atlantic-Gulf	711	3011	0.42	448	0.63
04	Great Lakes	305	1802	0.59	143	0.47
05	Ohio River	423	690	0.16	130	0.31
06	Tennessee River	106	95	0.09	21	0.20
07	Upper Mississippi	493	2672	0.54	184	0.37
08	Lower Mississippi	265	1445	0.55	232	0.88
09	Souris-Red-Rainy	151	1113	0.74	54	0.36
10	Missouri River	1324	2893	0.22	459	0.35
11	Arkansas-White-Red	643	1910	0.30	368	0.57
12	Texas-Gulf	471	1368	0.29	214	0.45
13	Rio Grande	342	104	0.03	9	0.03
14	Upper Colorado	288	142	0.05	11	0.04
15	Lower Colorado	375	80	0.02	5	0.01
16	Great Basin	355	82	0.02	7	0.02
17	Pacific Northwest	714	672	0.09	81	0.11
18	California	420	373	0.09	27	0.06
	Total	7824	20 740	0.27	2605	0.33

are listed in that database specifically because they represent potential flood hazards. While some features as small as approximately 80 m^2 are included in the NID, only approximately 21% are $<10^4$ m^2 in area.

The NA database, which has the lowest resolu-

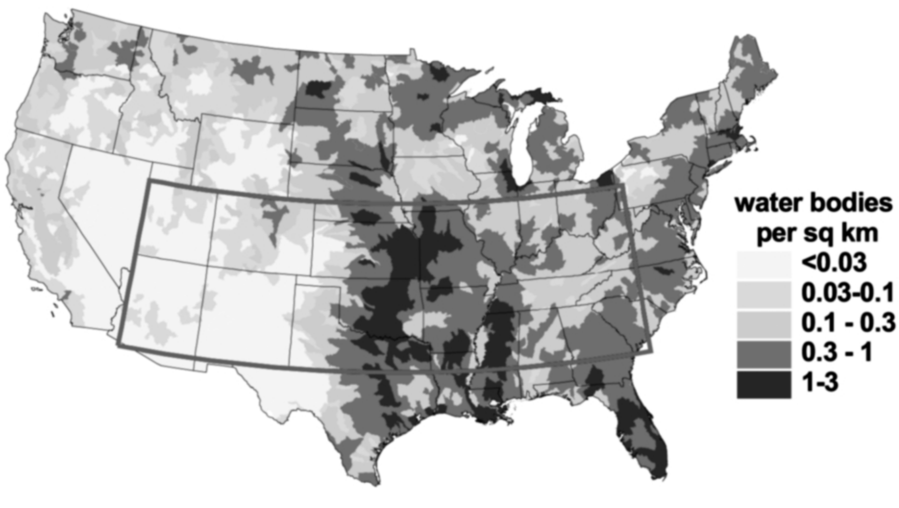

Fig. 2. Map of impoundment density (number km^{-2}), mapped by HUC-8 cataloging unit. The outline box is the 32–41 degree transect with data summarized in Fig. 3.

tion of the databases examined but which represents the most widely available database of water bodies across the United States, has only ~5000 features in the conterminous United States, the smallest of which is ~120 000 m^2.

The pattern that emerges from this comparison is that small water bodies are, numerically, overwhelmingly dominant across the conterminous United States; the available datasets differ widely in representing those features. The modified NLCD dataset records 35 and 60 times as many features as the TIGER and NID databases, respectively, and ~500 times as many features as the NA database. The DLG dataset apparently records more than three times as many features as the modified NLCD. The estimated average water body density across the United States area of 7.8×10^6 km^2, based on the satellite-derived modified NLCD data, is 0.33 water bodies km^{-2}. If these features were evenly distributed across the US landscape, this would be equivalent to an average net catchment area (excluding areas tributary to upstream impoundments) of 3 km^2. If the sampled DLG map data are representative, the density may be >1.0 water bodies km^{-2} (average catchment <1 km^2).

It has long been recognized that the lengths of coastlines and other complex geographic boundaries are dependent upon the scale at which the calculations are made (e.g. Mandelbrot, 1967). It can be demonstrated that estimates of area are less susceptible to measurement scale than estimates of boundary length. The topological analogy is evident in the case of water body number, but not area. A gross difference in the estimated number of small water bodies across the landscape apparently makes relatively little difference in the estimated area.

3.2. Spatial patterns of water body distribution

3.2.1. Number of water bodies

Fig. 2 is a map of 'impoundment density' across the conterminous United States, based on the modified NLCD data. Densities range from <0.03 water bodies km^{-2} in much of the south-west to >1 in the mid-west. In the more familiar notation of catchment areas, these would range from average catchment areas of <1 km^2 in the mid-west to >30 km^2 in the south-west.

The highest concentration of water bodies is in agricultural regions, especially eastern portions of the Great Plains and the lower Mississippi Valley. On a state-by-state basis Texas leads the list, with approximately 10% of the total. Other restricted areas of high density occur in the glacial terrain of northern Minnesota, Michigan and New England, and in the wetlands of southern Louisiana, southern Georgia, and Florida. If the data are examined by a two-digit hydrologic region (HUC-2; Table 3), impoundment density varies from ~0.9 water bodies km^{-2} in Region 08 (Lower Mississippi) to 0.01 km^{-2} in Region 15 (Lower Colorado).

There are clear east-to-west gradations in these features. In order to gain insight into the distribution, a 9-degree (latitude) by 34-degree (longitude) transect is presented for much of the conterminous United States (Fig. 3a). This transect trims hydrological complications associated with extensive wetlands near the coasts and in the northernmost portion of the country. Except for the DLG data, which are insufficient for such detailed analysis, the transect data are presented as 1-degree longitudinal averages (each longitudinal strip being ~90 000 km^2 in area). The more sparse DLG data are expressed as 2-degree averages. This transect incorporates approximately 40% of the area of the conterminous United States.

Although differing in magnitude, the databases show much higher numbers of water bodies in the eastern half of the United States than in the west. Most of the east-to-west decrease occurs between 95° and 103° W, approximately the width of Kansas and other states in that north-south tier. To the east of 95° W, the modified NLCD and DLG data give comparable estimates of impoundment density (~1 km^{-2}). The DLG densities are slightly higher, consistent with their greater resolution (25 vs. 900 m^2). To the west, the estimates diverge, as the DLG estimate decreases to 0.1 km^{-2} and the modified NLCD estimate decreases to 0.01. The divergence probably largely arises because the modified NLCD estimates represent estimates of

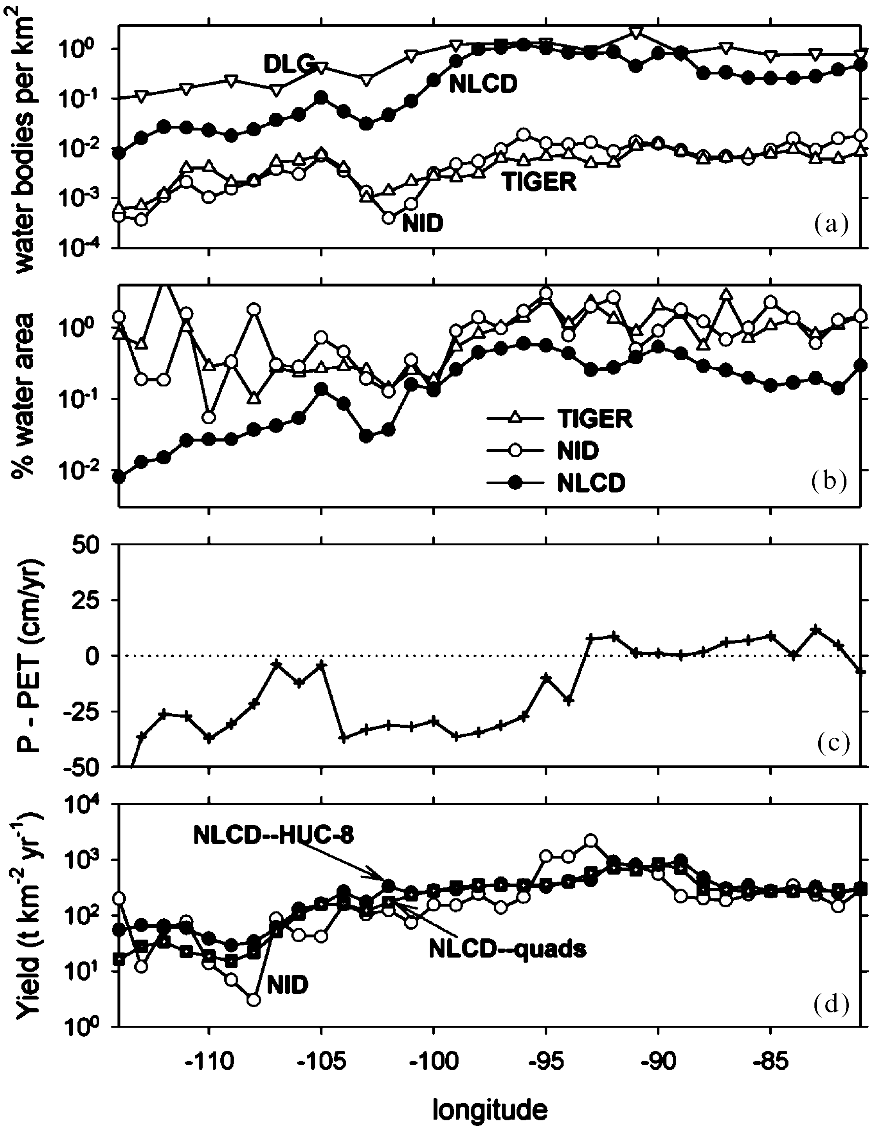

Fig. 3. Summary of water body numbers in 32–41 degree transect (Fig. 2). (a) Average number of water bodies per km^2 in each longitudinal strip. (b) Percent of total area covered by water as identified from each database. (c) Water balance (precipitation minus potential evapotranspiration). (d) Large water body sediment yields (NID) compared to two estimates of small water body sediment yields in the same longitudinal strip.

actual water as identified from satellite images, while the DLG coverage includes topographic lows that may contain water only on an ephemeral basis. If this explanation is generally correct, then analysis of the DLG data overestimates the water body abundance. The NID and TIGER data are in close agreement with one another on water body numbers, but well below the modified NLCD. The NA data give yet lower numbers and are not shown. Based on the TIGER and modified NLCD numbers, the number of small water bodies exceeds the number of large water bodies by a factor of ~70 along the transect.

3.2.2. Area of water bodies

When water surface areas are examined (Table 2; Fig. 3b), the results are quite different. Large water bodies account for most of the water area across the transect. The NID represents artificial reservoirs (or lakes that have been significantly manipulated artificially), while TIGER represents any water body large enough to have been mapped at a scale of 1:100 000. The agreement in total area between these two data sets—one that is entirely artificial and the other that is natural plus artificial—is persuasive evidence that unaltered natural lakes other than the Great Lakes account for only a small percentage of water area across the conterminous United States. The NA data (not shown) record a roughly similar area as NID and TIGER, despite having far fewer features. An interesting characteristic of the NA data is that most (~90%) of its features are identified as 'lakes,' apparently because of their proper names (Lake Powell, Franklin D. Roosevelt Lake, etc.) even though the NID—TIGER comparison would suggest that most of these 'lakes' are artificial. The only significant large natural lake on the transect is the Great Salt Lake, which is a prominent spike in the TIGER area (but not in the NID) at 112° W. The NID and TIGER data each show the transect area to be approximately 1.0% water. For comparison, the modified NLCD small water bodies have an area of approximately 0.2% of the transect, or ~17% of the total water area.

4. Discussion: importance of small water bodies

4.1. Origin of small water bodies

The dataset we use in this analysis does not allow explicit identification of small water bodies as natural or artificial. Natural lakes and ponds can be found throughout the conterminous United States. The majority of natural lakes are almost certainly of glacial origin. Numerous lakes are also found in karst landscapes such as central Florida. Lakes of aeolian origin occur in many areas, including the high plains of Texas and New Mexico and the southeastern coastal plain. Oxbows and swales occur on the floodplains of large rivers, although most of these have been eliminated from our dataset. Lakes of tectonic origins (most of them dry or ephemeral) are common in the western United States.

Nonetheless, it is evident from the geographic distribution of water bodies that most of the small water bodies we have identified are of human origin. One argument is based on land use. Across agricultural areas, thousands of water bodies dot the landscape where there were apparently virtually no such features a century or less ago. The average density of water bodies in Oklahoma (0.88 km^{-2}) is nearly double that of Minnesota (0.46 km^{-2}), although on a percent area basis Minnesota has more than double the water of Oklahoma.

Various citations (Holland, 1971; Oklahoma Water Resources Board, 1990) and numerous documents found on the World Wide Web provide estimates of the numbers of artificial farm ponds in various States (AL, GA, IA, IN, KS, MO, OK, TN, TX). For these nine states, the 'published' total number of constructed farm ponds is approximately 1.9 million; our estimate of water bodies for these states is 1.1 million (i.e. 42% of the features mapped in the modified NLCD data). With two prominent and puzzling exceptions (MO: 500 000 published vs. 137 000 NLCD; TN: 190 000 published vs. 35 000 NLCD), the agreement between the published number of farm ponds and our estimate for total small water bodies is good (1.2 million published vs. 0.9 million NLCD) ($r^2=0.45$ including MO, TN; $r^2=0.87$ excluding those states). Various web publications give the statewide addition of new ponds as 1–3% per year. Due to differing and unstated criteria for the published estimates of farm pond numbers, as well as differing and unstated dates for when those estimates were made, some of this evidence might be considered anecdotal; however, the agreement is adequate to conclude that most of the small water bodies we have recorded are artificial, and that their abundance is increasing dramatically. As

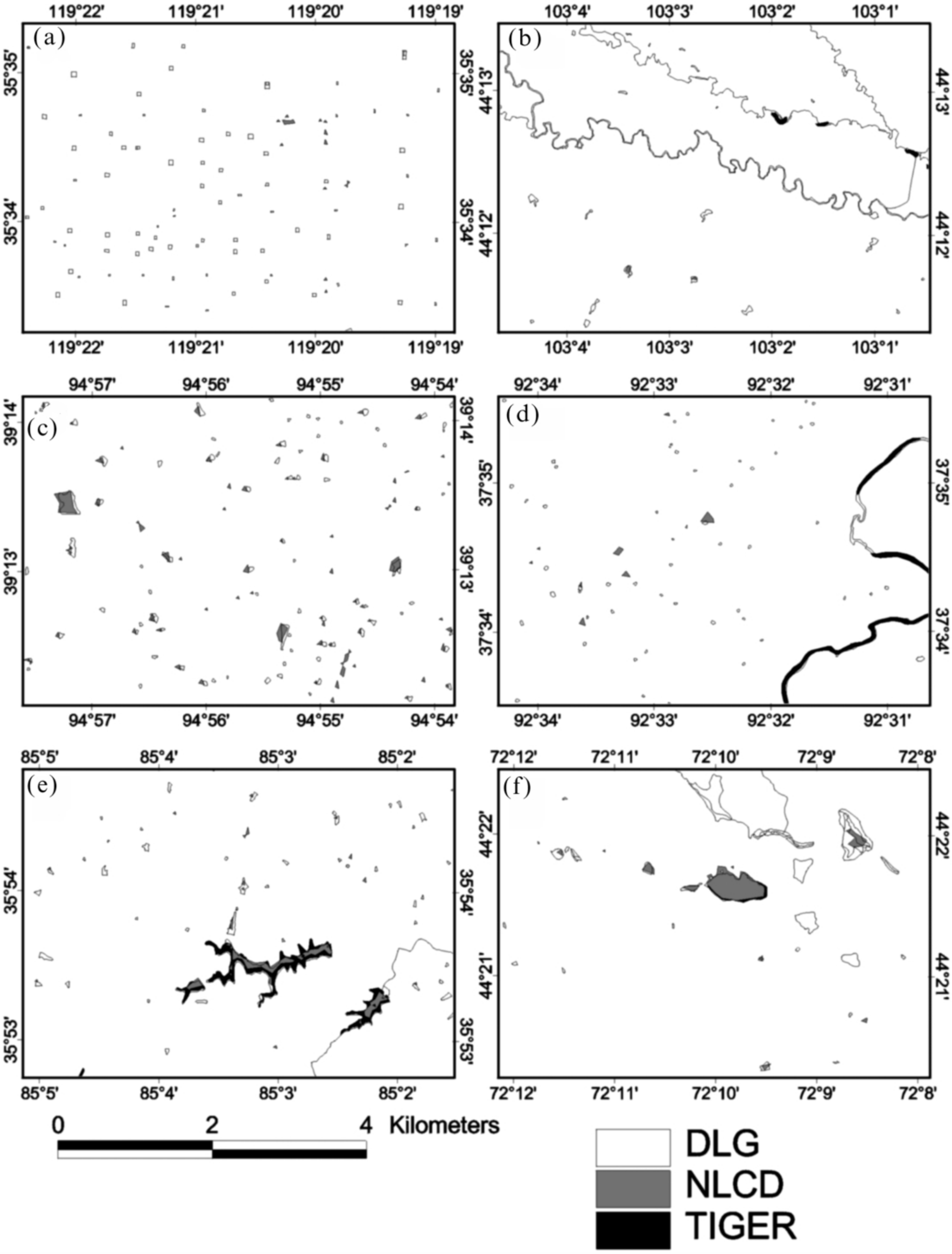

Fig. 4. Examples of water bodies in selected USGS 1:24 000 quadrangles. Comparison of DLG, modified NLCD, and TIGER water bodies. (a) Wasco, CA. (b) Bend, SD. (c) Basehor, KS. (d) Russ, MO. (e) Crossville, TN. (f) Peacham, VT.

such, these features constitute a fundamental human transformation of the landscape.

Selected examples of water bodies in various environments are shown in Fig. 4. In every case many features appear in the DLG data that do not appear in the NLCD or TIGER coverages. In semiarid regions such as California and South Dakota (Fig. 4a,b), surface water as detected in the NLCD layer is less extensive. The area shown in Fig. 4a is a flat, agricultural landscape in the San Joaquin Valley. The water bodies appear to be holding ponds for irrigation water. Only a few of them show up in the modified NLCD coverage; perhaps some have filled in or were dry at the time the satellite data were collected. ArcView's conversion of single-pixel water bodies to triangular units is clearly visible. The mid-west is represented in Fig. 4c,d. In both of these, the landscape is rolling and agricultural. Virtually all the water bodies shown are small ponds constructed for soil conservation and/or agricultural water supply purposes. Many of those in this image are too small to show up on the modified NLCD coverage, or were dry or have subsequently filled in. The Gasconade River visible in the TIGER data at the right-hand portion of Fig. 4c is an example of a river that is included as a water body in the total listed in Table 2. Two small reservoirs large enough to appear in TIGER data are visible in Fig. 4e, an example from Tennessee, while Fig. 4f is a glaciated landscape in northern Vermont. The NLCD layer identifies a few small, apparently natural, water bodies. The larger of these also appear in the TIGER coverage. Most of the water bodies in Fig. 4f that appear on the DLGs but not on the modified NLCD layer are vegetated wetlands.

4.2. Hydrological significance of small water bodies

Much of the explanation for both the area and number distribution of water bodies can be derived from simple hydrological considerations. A transect of precipitation minus potential evapotranspiration (P-PET) (Fig. 3c) demonstrates that the mid-continent peak in numbers and then the westward decline in both numbers and area occur along the transition from positive to negative water balance. The large number and area of the water bodies in the mid-continent in large part represent local human attempts to compensate for natural 'loss' of water. This management strategy may work at the site of the impoundment; water remains locally available. However, the larger-scale aggregate effect of this local water trapping will be to elevate evaporation, rather than allowing this water to flow downstream or percolate.

Evaporation is commonly parameterized as a function of wind speed (u, m/s), the water vapor pressure of the surface water and the overlying air (e_w, e_a; expressed here in mbar), and a mass transfer coefficient (N) (Sverdrup et al., 1942; Hutchinson, 1957; Harbeck, 1962). It is useful to express e_a explicitly in terms of saturation vapor pressure at the air temperature and the relative humidity (h). Harbeck (1962) further observed that N is a function of the area A (m^2) of the water body in question. Converting Harbeck's formulations to metric units yields the following:

$$E = 0.30A^{-0.05}u(e_w - he_{as}) \tag{1}$$

Specifically, the product $0.3(A)^{-0.05}$ in Eq. (1) equals the transfer coefficient, N. Evaporation goes to 0 as the quantity $(e_w - he_{as})$ goes to 0. e_o and e_{as} are a function of temperature; in the presence of any wind, evaporation will occur if either a temperature differential or relative humidity below 1 drives $e_w > he_{as}$.

Harbeck (1962) attributed the decrease of evaporation as a function of size in large part to changing surface roughness of the water body. A second consideration that may particularly elevate evaporation in small water bodies is higher summer heating in shallow systems.

The smallest systems considered by Harbeck were approximately 4000 m^2. The median size of the modified NLCD water bodies in this study is $\sim$1000 m^2, and the mean is approximately 8000 m^2. The mean of the water bodies in the TIGER and NID databases is approximately 140 000 m^2 (Table 2, Fig. 1). N for these systems would range from 0.21 (NLCD median) up to 0.16 (TIGER mean). Large reservoirs ($>10^7$ m^2) would have $N < 0.13$. Based on Eq. (1) evaporation from small water bodies will be decidedly elevated above that from large water bodies.

These small water bodies will induce other hydrological effects as well. For example, percolation and groundwater recharge will be affected, in ways reflecting the local hydrology. While we have not yet undertaken detailed continent-scale analysis of the locations of these water bodies in relation to drainage networks, analysis in selected localities suggests that they are located primarily on small streams with small catchment areas. For example, 80 ponds inventoried in two studies in southwestern Ohio have an average surface area of 2800 m^2 and average catchment areas of 0.13 km^2 (L. Theis, unpublished data; Hayes-Bohanan, 1989). The position of these water bodies in upland catchments with small drainage areas has the effect of increasing the residence time of water in upstream areas relative to downstream areas. In areas of relatively permeable subsurface materials, this may result in increased groundwater recharge in upland areas. A similar analysis of position has not been carried out in the transitional and water-deficit areas to the west of the (water-excess) Ohio location, so we do not know how generalizable the observation will be.

4.3. Sedimentological significance of small water bodies

Sediment yield provides an index of the relative importance of the small and large water bodies. Dendy and Champion (1978) tabulated the sediment accumulation rates in ~1600 impoundments across the United States. The drainage areas for the impoundments in their survey range from < 0.02 km^2 to > 400 000 km^2. Approximately half of these impoundments had drainage areas < 6 km^2 (Fig. 5 in Dendy and Champion, 1978), thus are similar in magnitude to catchment areas in the modified NLCD. We used these data to calculate sediment yield ($m^3\ km^{-2}\ year^{-1} \approx t\ km^{-2}\ year^{-1}$) as a function of catchment area (km^2) for each of the 18 HUC-2 regions across the conterminous United States (Table 4). The equations are of the form:

$$\text{Yield} = a \times \text{Area}^b \tag{2}$$

Table 4
Results of regression analyses of sediment yields derived from Dendy and Champion (1978), by two-digit hydrologic region

HUC-2	N	R^2	Slope (b)	Intercept (a)	P
01	8	0.39	−0.80	2.42	0.10
02	47	0.01	−0.06	1.99	0.55
03	55	0.12	−0.15	2.57	0.01
04	47	0.06	−0.18	2.10	0.10
05	157	0.17	−0.18	2.57	0.00
06	41	0.05	−0.06	2.51	0.16
07	109	0.04	−0.08	2.62	0.05
08	38	0.59	−0.30	3.18	0.00
09	18	0.02	−0.06	1.63	0.57
10	290	0.23	−0.25	2.67	0.00
11	218	0.02	−0.06	2.51	0.03
12	115	0.02	−0.06	2.52	0.13
13	51	0.10	−0.17	2.51	0.02
14	35	0.24	−0.78	2.03	0.00
15	74	0.02	−0.06	1.93	0.27
16	21	0.01	−0.06	2.13	0.66
17	101	0.09	−0.29	1.60	0.00
18	196	0.05	−0.15	2.76	0.00

The coefficient, a, represents the average yield ($m^3\ km^{-2}\ year^{-1}$) for a catchment with a drainage area of 1 km^2. The exponent, b, describes the change in yield as a function of catchment size. In all of the HUC-2 regions the exponent b is negative, implying that specific yield decreases as a function of catchment area. If a is constant over any area, then decreasing yield with increasing area implies that an increasing amount of eroded sediment is retained outside of the receiving water body within progressively larger catchments.

In simplified notation for this paper, we assign total erosion products (E_T) into three categories: (1) products than can be assigned to inventoried water bodies with explicitly known catchment areas (E_{NID}); (2) products that are trapped in the heretofore un-inventoried small water bodies discussed in this paper (E_{NLCD}); and products that are deposited in other alluvial and colluvial deposits across the landscape (E_O). Thus:

$$E_T = E_{NID} + E_{NLCD} + E_O \tag{3}$$

We analyze two components of these products, E_{NID} and E_{NLCD}. The third component, E_O, is characterized by difference (see also Smith et al., 2001).

Tabulated catchment areas of the individual NID water bodies are used to calculate E_{NID} according to the regression equations. From consideration of water area (above and Fig. 3b), these calculations represent sediment accumulation in the majority of water area across the conterminous United States. The sediment yield to NID reservoirs along the transect is 317 ± 447 t km^{-2} year^{-1} (mean ± standard deviation of data for the 1-degree longitudinal strips on the transect) (Fig. 2d). Scaled to the water surface areas of the reservoirs, the vertical accretion rate is 4 ± 4 cm year^{-1}.

The NID reservoir inventory includes only a few of the small water bodies recorded in the modified NLCD, because the larger NID water bodies have been removed from the modified NLCD. That modified dataset has >50 times as many features as NID along the transect. We can therefore calculate E_{NLCD} with essentially no duplication of water bodies with E_{NID}. This use of the regression equations is appropriate, because they are based on the gross—not net—catchment areas upstream of the impoundments. The regression equations are applied to the estimated mean catchment size associated with groups of impoundments, the inverse of the modified NLCD impoundment density. Initially, impoundment density is based on the number of impoundments in each of the HUC-8 cataloging units. This provides an estimate of E_{NLCD} as an addition to E_{NID} for each of the HUC-8 areas. This estimated yield along the transect (308 ± 239 t km^{-2} year^{-1}) is almost identical to the NID-based estimate. As the water area of the modified NLCD impoundments is much smaller than the water-body area of the NID data, the estimated vertical accretion rate in the small water bodies is faster (22 ± 19 cm year^{-1}).

This calculation based on the HUC-8 units is an overestimate of E_{NLCD}, because it assumes the modified NLCD features are evenly distributed within these units. If, instead, the modified NLCD features are heterogeneously distributed within the HUC-8 units, then areas with locally high water body density would have high local yield, but the entire cataloging unit (the summation of high-density areas and low-density areas) would be characterized by lower total sediment accumulation. In order to evaluate the degree of this overestimate, the modified NLCD was re-sampled to calculate impoundment density within 7.5 minute quadrangles maps. Because there are approximately 55 000 7.5 minute quadrangles across the conterminous United States, in comparison with 2100 HUC-8 units, this represents >25-fold decrease in the average aggregation area for calculating impoundment density. In effect, this analysis imposes the homogeneity constraint for calculating impoundment density onto much smaller areas than the HUC-8 units. Along the transect, $\sim 21\%$ of the quadrangles have no NLCD water bodies. This recalculation lowers estimated sediment accumulation into modified NLCD water bodies by only approximately 10% (from 308 to 278 ± 218 t km^{-2} year^{-1}). We conclude that explicit resolution of catchment areas for NLCD feature would produce only modest decreases in estimated yield. In specific local studies for which the small water bodies are mapped onto the local topography, the yield equations could be applied explicitly to the catchment areas of the modified NLCD features, but that is presently impractical for the entire United States.

The conclusion that there is similar sediment yield from the landscape into the NID and modified NLCD water bodies therefore appears robust. While the results might be different if the exponential slopes in Table 4 were varied dramatically, the most important point to emphasize here is that negative slopes force the conclusion that yield decreases as a function of catchment size. Examination of more intensive 'gray literature data' for specific locations (Ohio and Kansas), as well as the summary by Walling (1983) and the basin-scale analyses by Milliman and Syvitski (1992) emphasizes that this general negative log–log relationship is widespread in the United States, if not necessarily universal. We use the Dendy and Champion summary, because it is the most comprehensive, readily available summary for the United States. The conclusion is that approximately 600 t km^{-2} year^{-1} is being trapped along the transect in large plus small water bodies. Approximately half is being trapped in small water bodies not counted in standard inventories. Contemporary erosion across the United States is estimated to be ~ 900 t km^{-2} year^{-1} (Smith et al., 2001). Therefore accumulation in small plus large water bodies apparently accounts for approximately two-thirds of total erosion products, with small and large water bodies accounting for roughly equal amounts of accumulation. The remaining third would be assigned to E_O according to this continental-scale analysis.

4.4. Geochemical and ecological significance of small water bodies

Both the difference in sedimentation rate between the large and small water bodies (discussed above), and the effects of small water bodies in changing the residence times and distributions of water and erosion products (sediments) within a watershed, have further ramifications. The rapid build-up of the water-body sediments (primarily eroded topsoil) not only buries organic matter deeply in topographic depressions (which will be less subject to exhumation and erosion even when ponds are no longer present), but also causes a systematic shift in redox conditions in the deeper sediment that substantially slows oxidation of organic matter (Schlesinger, 1997; pp. 244, 253–254). The rapid sediment burial in the small water bodies (E_{NLCD}), in combination with their typical proximity to human and agricultural sources of nutrient loading, will result in eutrophication and high organic input causing suboxic or anoxic conditions and diagenetic reactions which are very different than in larger water bodies with slower sedimentation (E_{NID}).

The effect of burial is reinforced by hydrologic conditions. Rice (2002) observed that, with regard to carbon sequestration, 'Soil water content also is important. Optimal microbial activity occurs at or near field capacity-the maximum amount of water that soil can hold against gravity. As soil becomes waterlogged, decomposition slows and becomes less complete…Decomposition also slows as soils dry.'

The effect of artificial ponds is to maintain the rapidly accumulating sediments in a permanently saturated condition. Even when ponds are dredged to extend their lifetimes, practices in the central part of the USA are to use the spoil to extend the earthen dam creating the pond, or to leave the excavated sediments piled nearby (R. Sleezer, personal communication), which creates a drier environment than that of undisturbed soil. Either fate retards the oxidation of organic matter. Decomposition of organic matter will be greatly slowed and organic preservation will be enhanced under the combined conditions found in small, artificial water bodies. In addition to carbon cycle effects, small water bodies may also be expected to have significant effects on local- and landscape-scale budgets and fluxes of nitrogen and phosphorus.

Ecological and biological effects of small water bodies are also important. The closest natural analog to the density and spacing of pond in the central USA is probably the 'prairie pothole' environment, which Sorenson et al. (1998) found to be both critical habitat and highly sensitive to climate variation. While artificial ponds will not fill exactly the same roles for a variety of reasons, the existence of a high spatial density of permanent aquatic microenvironments across the landscape will be important to the survival, migration, and range extension of a wide variety of species, both natural and invasive.

Our findings pointing to the addition of millions of artificial water bodies with a total area of tens of thousands of km^2 can also be viewed in the context of the loss of natural wetlands; Mitsch and Gosselink (1993) report that the 48 conterminous states of the USA have lost approximately 500 000 km^2 of wetlands. Of the wetlands remaining, of over half are forested or salt-water wetlands, which are in general not the types of water bodies addressed in this study (Dahl et al., 1991).

Although there is a large difference between the wetland areas lost and the artificial water bodies added, we suggest that there are two aspects of the comparison that call for further study: (1) the disparity of numbers of water bodies lost and gained will not be as great as the difference in area, and the result of human intervention may be a more uniform distribution of smaller but more reliably saturated aquatic microenvironments than the pre-existing natural situation; and (2) there are profound qualitative differences between natural wetlands and artificial ponds in terms of not only size, but cover (open water vs. marsh vegetation), seasonal and interannual variability, placement on the landscape, and proximity and response to adjacent human land use. We expect that these water bodies have significant environmental impacts on the biota. The presence of large numbers of constructed water bodies in landscapes that otherwise had few or no lakes or wetlands constitutes a qualitative change in the environment with major potential ecological consequences.

5. Conclusions

Human influence on hydrological and sedimentological processes across the landscape is well recognized at large scales, a point that has been made by various authors (e.g. Dynesius and Nilsson, 1994; Graf, 1999; Vörösmarty and Sahagian, 2000; St. Louis et al., 2000). We have demonstrated that this human influence is quantitatively important well below the scales of the large, inventoried features. Local water balance and sedimentation are affected out of proportion with the area and volume of the small features, and geochemical and ecological impacts of small water bodies differ both quantitatively and qualitatively from the impacts of large water bodies.

These distributed effects are difficult to deal with at large (regional) scales by using routing models that are targeted to pinpoint specific features at specific locations. As the features are ephemeral on time scales of years to a very few decades, are too numerous to be explicitly inventoried, and are changing (largely increasing) in numbers, it is not apparent that explicit routing models are the best way to quantify their impacts. Yet we have demonstrated that the features *are* important. It therefore follows that, models, inventories and other analyses at these larger scales need to incorporate the aggregate effects of these features across the landscape.

Among the consequences of small water bodies are:

- elevated evaporation, decreased downstream flow, and altered groundwater recharge;
- significant sediment trapping; more rapid vertical accretion and infilling than large water bodies;
- stronger redox gradients than in large water bodies, hence different diagenetic reactions (e.g. of organic material); because of rapid infilling, more ephemeral storage (decades vs. centuries) than in large water bodies; and
- severely modified aquatic habitats that may at least partially compensate for—but spatially redistribute—anthropogenically lost natural wetlands.

Does the enumeration of the number of water bodies really matter? One can suppose that small, ephemeral mud puddles can be legitimately ignored in any reasoned inventory of water body distribution across the landscape. Their presence across the landscape can be viewed as brief, local transition phenomena as water soaks into the ground and enters some more persistent hydrological feature. Farm ponds and other water bodies at scales of hundreds to thousands of square meters cannot be so readily dismissed. These aggregate modifications of the landscape represent highly visible features that persist over periods ranging from seasons or years to decades. As they fill with sediment, they tend to be replaced. And their numbers across many landscapes are increasing. Their presence appears to be significant; and their distribution, abundance, and function are relatively easy to assess.

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