Detection and Characterization of Small Water Bodies

A Final Technical Report for the NASA-EPSCoR/KTech- funded project, "Landscape-Scale Detection and Classification of Small Water Bodies: Temporal Integration of Diverse Types of Data"

Compiled by Robert W. Buddemeier (PI), with contributions from F. J. deNoyelles, S. Egbert, R. O. Sleezer, D. P. Young, X.-Y. Zhan, Z. Andereck, M. Houts, B. Mosiman, P. Taylor, J. Vopata, Wilson, W. H. Renwick, and S. V. Smith. 1. Introduction

1 Introduction

1.1 Scientific Background.

The 48 contiguous United States contain at least 2.6 x 10^6 small water bodies ($\geq$ 600-900 m^2), and possibly as many as 9 x 10^6 ($\geq$ 25 m^2) (Smith et al. 2002). These water bodies are termed 'small' not only because of their size distributions, but also to emphasize the distinction between the water bodies discussed here and the much smaller number (a few percent of the total at most) of relatively well-documented lakes, reservoirs, and large impoundments found in the available US databases of water bodies.

Based on the smaller number cited above, the densities of small water bodies (ponds) in the coarsest US Hydrologic Units (HUC-2: water.usgs.gov/GIS/huc.html) range from 0.1 to 0.88 per km^2; however, when densities are examined on the basis of the more highly resolved HUC-8 units significant areas are seen to have densities of 1-3 ponds per km^2 (see Figure 1a). In coastal lowlands, forests, and the glaciated northern prairie regions the ponds may be largely of natural origin, but over most of the populated and developed portions of the US, the overwhelming majority are man-made. The high present density of ponds seen in the central US is superimposed on a landscape that had virtually no permanent water bodies other than streams and marshes prior to European settlement.

Man-made ponds represent a systematic fine-grained alteration of the landscape that has large cumulative effects on the hydrologic and biogeochemical cycles and ecology of a region. They play a substantial role in modifying the environment, both directly and through the broader land use changes which they support or represent. They increase water residence time and thus evaporation and percolation; they trap sediment, thereby affecting biogeochemical cycles (Nixdorf and Deneke, 1997; Renwick et al., in press); and they can function as distributed riparian zones in modifying water quality (Whigham, 1995). They can create habitat diversity and may provide both a partial counterbalance to lost wetlands; they also can provide pathways or habitats for invasive species (Edminster, 1964). Many of the hydrologic and biogeochemical effects of water bodies have been well documented for large streams and water bodies, and a substantial literature has developed that addresses the environmental and biogeochemical impacts of large dams and river flow regulation (Dynesius and Nilsson, 1994; Stallard, 1998; Vörösmarty and Sahagian, 2000). However, similar studies have not been extended to the cumulative effects of small ponds.

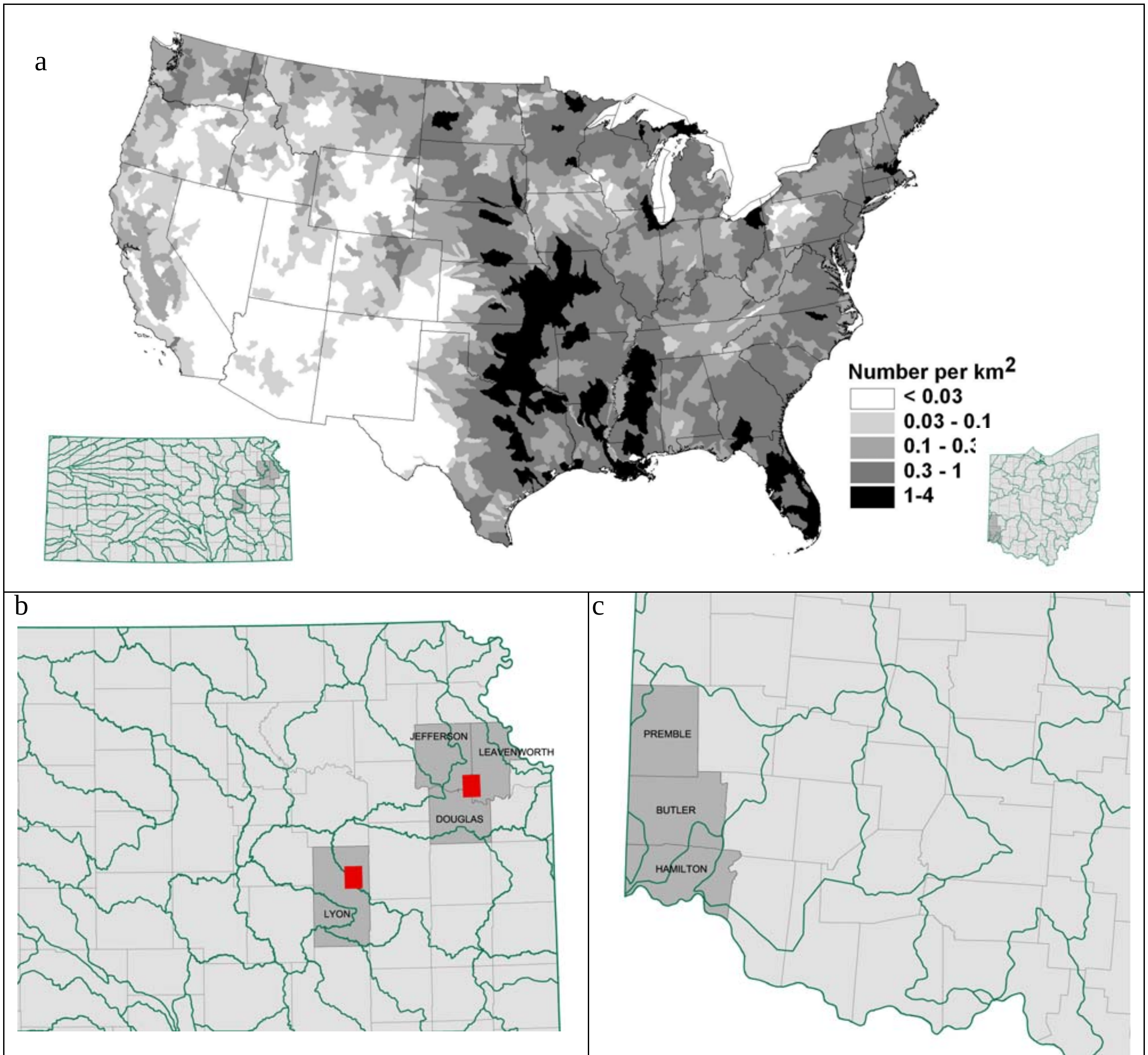


Figure 1: (a) pond densities as estimated by Smith et al. 2002 and Renwick et al in press; insets of Kansas and Ohio show the general locations of the study sites depicted in more detail in (b) and (c).

Small ponds constitute about 20% of the standing water surface area of the 48 contiguous United States, but their cumulative effects on ecosystems and biogeochemical cycles are disproportionately far larger (Smith et al. 2002, Renwick et al. in press). Assessing those effects over a variety of scales is important, but is a major challenge. Ponds are small, they are located primarily on private property, their numbers and locations vary over time, and they are typically missing from or underrepresented on the digital map products and databases normally used for hydrologic and ecological analyses. Detailed analysis of individual ponds and watersheds is clearly impractical as a path to large-scale assessments; equally clearly, it is a critical component of calibrating approaches based on remote sensing or other means of landscape characterization.

1.2 Objectives and Products

This project had three objectives in furthering the investigation and understanding of small water bodies and their biogeochemical and ecological roles. The technical results are derived from a pilot study of pond detection, characterization, distribution, history, and impacts on landscape alteration, carried out in eastern Kansas, USA. The initial results of this study are integrated with comparable results from an ongoing study in southwestern Ohio (USA), as well as previous results and additional findings. Figure 1bc shows both specific study areas. Presentation of the results of these studies, and their discussion in the context of the findings of other, larger-scale studies, addresses two of the three objectives:

1. To examine, evaluate, and start the process of calibrating some of the more promising tools and methods for small pond inventory, functional characterization, and determination of their landscape-scale effects; and,

2. To analyze and present detailed results for the intensive study areas, both as case studies in general and as possible indicators of the characteristics of other regions.

The third objective is to facilitate the assembly of information and expertise to address the integrated study of these important but elusive landscape features. Pond distributions, uses, and characteristics are strong functions not only of climate, terrain, and land use, but also of cultural and economic factors, and although much relevant information is potentially available, it is very widely distributed in variety of technical journals (often in applied fields), “gray literature,” websites, etc. Characterizing effects of small water bodies thus requires both diverse local or regional expertise, and access to the variety of data sources. We hope that presenting the following results from two pond-rich regions of the U.S. will stimulate comparisons and collaborations from other areas that will more rapidly expand our overall understanding of the roles of these features in earth surface processes.

2 Data and Methods

2.1 Data Sources

Detailed information on the data types and sources used in this study is tabulated in Appendix A. Appendix Table A-1 describes the sensors and data used for the primary study. The primary data used were from:

- Archived aerial photographs from a variety of sources, including both black and white and color images. Resolution varies slightly, but is generally one meter or better. A high-resolution scanner was used to convert film images to digital form.
- Multispectral (3-band) images obtained by locally-conducted air photo flights using the DuncanTech MS3100 digital camera system. Taken from an elevation of 3300 m, the images provide one meter resolution.
- Terra ASTER satellite images (15 m resolution, 3 spectral bands)
- Landsat Enhanced Thematic Mapper (ETM+) satellite images (30 m resolution, 3 spectral bands)

2.2 Procedures

2.2.1 Site selection and data acquisition

A hierarchy of sampling regions was identified in the eastern Kansas study region. Target counties (political jurisdictions with areas on the order of 3000 km^2) were identified based on scientific criteria, data availability, and access to study sites; locations are shown in Figure 1. Within each of two Kansas counties, a USGS map quadrangle (~150 km^2) was selected for comprehensive assessment of pond occurrence and characteristics over both space and time. Some watershed units located entirely within the counties and largely within the quadrangles were also selected for surface hydrology study applications.

The Midland quadrangle in SE Jefferson County, Kansas, is the site of an ongoing study that produces composite multispectral air photos several times per year; it is close to the University of Kansas (KU), and contains the Nelson Environmental Study Area, a field research site containing both watershed ponds and arrays of experimental water bodies. The study area is covered by 44 DuncanTech images which have been rectified, georegistered, and assembled into a mosaic. This imagery overlaps rectified imagery from the ASTER sensor as well as Landsat ETM+. The Midland Quandrangle is in an area of mixed and changing land use – agricultural with wooded areas, and an accelerating transition from rural to “exurban” residential.

Lyon County, Kansas, is the site of Emporia State University (ESU); the Allen SE quadrangle was selected as representative of that primarily agricultural region, and was surveyed once with DuncanTech camera overflights in November, 2003, to provide imagery comparable to the Midland quadrangle. The Allen SE quadrangle is in an area of stable, long-trerm agricultural land use.

For both counties, Digital Ortho Quarter Quadrangle (DOQQ: URL) air photos were acquired, and film images of various ages were acquired from the photoarchives of research institution collections, county offices, and the regional offices of state and federal agencies.

In southwestern Ohio, Hamilton, Preble and Butler counties surround the location of Miami University (MU), and have been the focus of ongoing studies of pond distributions and histories. The three counties form a transect from relatively hilly, urban, and forested Hamilton

County in the south (dominated by the Cincinnati metropolitan area) through rolling and mixed-land-use Butler County, to relatively flat, agricultural Preble County in the north. We identified all ponds visible in black & white aerial photography for three time periods: 1930s, 1950s, and 2000.

2.2.2 Data processing and analysis

Data processing techniques are discussed in more detail in Appendix A. Remotely sensed digital images were clustered and classified using ERDAS Imagine software; ESRI GIS (ArcView, ArcMap, ArcInfo, ArcObjects) software was used to register, rectify, measure, and overlay the water bodies. The computer model TOPAZ (Topographic Parameterization) was applied to a 30 m DEM to derive the drainage-related topographic parameters needed to apply existing watershed models to a HUC-14 watershed within the drainage basin of a large impoundment (Lyon County State Lake, LCSL). In addition to subwatershed definition and the surface flow network, this produced for each subwatershed a value for the LS (Length-Steepness) Factor, an indicator of erosion potential. We then used spatial analysis techniques in GIS to determine the runoff curve number (CN; SCS, 1972) based on precipitation, soil type, and land cover. Combining these factors permits determination of the most likely major sediment producing areas within a drainage basin based, and comparing these with the spatial distribution of small ponds to help determine the cumulative effects of ponds on runoff and sediment yield. The derived model parameters can also be compared to water quality estimated from remote sensing for selected small ponds within the watershed to determine the relationship of these parameters to pond conditions.

Images from three different satellite and airborne sensors were compared to see how accurately they could locate and inventory ponds in areas of Jefferson county for which satisfactory images of all types could be acquired. Landsat (ETM+) 30m multispectral imagery, ASTER 15m multispectral imagery, and 1m multispectral imagery from the DuncanTech digital camera were used to create maps of water impoundments. For areas sampled, we computed the number of water bodies, their size classes, and the total water surface area. Based on our assumption that the maps derived from the 1m airborne digital imagery would provide the most detailed and accurate estimate of the actual number of ponds in the study areas, we used them as the basis for comparison with the maps derived from Landsat and ASTER imagery. Since it is generally impractical (due to cost and time considerations) to manually map small ponds from detailed imagery, our objective was to determine by how much the number of ponds in the Kansas landscape is underestimated using satellite imagery. In addition to comparing results of the digital airborne camera inventory to maps from the two satellite sensors, we also compared them to two inventories of water bodies that were previously created, the Kansas Surface Water Database (KSWD), and the Surface Waters Information Management System (SWIMS). See Appendix A.

3. Results

3.1 Detection and inventory– Conventional aerial photography

We take the numbers and areas of ponds determined by visual analysis and digitization of the aerial photographs as the standard against which to compare the satellite and spectral imagery. Although these determinations are undoubtedly not completely error-free, a number of factors convince us that the error rate is low, and insignificant with respect to the interpretations presented here: (1) we have used and compared multiple images of various types (black and white, conventional color, and multi-spectral), some closely spaced in time and at various times within the year; (2) all images have been checked by at least one person other than the primary analyst, and some have been subject to independent replicate analysis; and (3) the study areas are in familiar terrain, and generally accessible for ground truth comparison.

The results of the quadrangle analyses are presented in Table 1 and Figure 2. Both quandrangles have experienced major increases in pond numbers, although Allen SE clearly has a longer history of pond development. The pond densities corresponding to the most resent inventories are 3.7 km^{-2} for Allen SE and 4.6 km^{-2} for Midland. The cumulative pond water area in both quadrangles corresponds to slightly more than one percent of the total surface area, compared to essentially none prior to human modification. Size frequency distributions of the ponds are discussed in the following section, where the results of satellite detection are compared with the aerial photography.

Table 1: Results of pond inventory in two map quadrangles

	Total number of ponds		**Total pond area (km^2)**	
Year	**AllenSE**	**Midland**	**AllenSE**	**Midland**
1941		25		0.03
1945	254		1.09	
1954		123		0.08
1959	479		1.30	
1966		351		0.78
1976		420		1.21
1979	496		1.52	
1980	499		0.68	
1991	472	600	1.27	1.13
1993	475		1.57	
1997	493		1.94	
2002		683		1.67
2003	546		1.57	

The 1979-1980 data in Allen SE illustrate climatic effects: 1980 was an extremely dry year, following a period of normal precipitation. The results of a single-year drought were a reduction of >50% in total pond area, with essentially no change in pond numbers. This illustrates both the effect of climate on small water bodies, and the role of those water bodies in maintaining water availability under variable conditions.

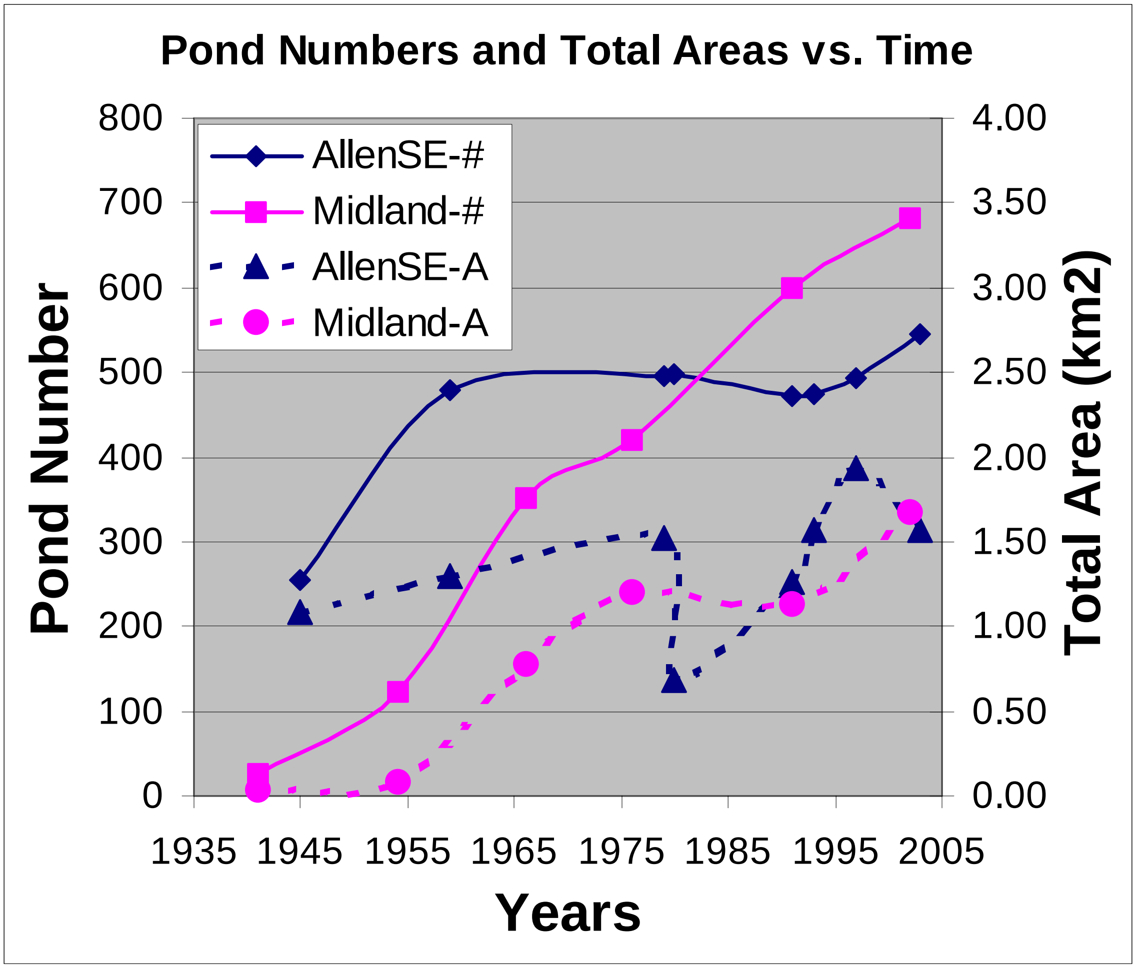


Figure 2: Pond numbers (#; solid lines) and cumulative pond area (A; dashed lines) over time for the Midland (purple) and Allen SE (blue) quadrangles. Data are based on hand-digitized pond inventories in historical aerial photographs. Note the fluctuations in total area in the Midland quadrangle in or after 1980 (a drought year) and 1993 (a flood year).

The values shown in Table 1 and Figure 2 are net inventories, with no indication of the balance between new pond construction and loss due to destruction or infilling and abandonment. A study addressing the life cycle of ponds was conducted in the three SW Ohio counties. Tables 2 and 3 shows the results of a multi-decadal assessment, indicating the number of ponds lost over each interval as well as the currently existing totals. The average lifespan of a pond in this area is clearly on the order of several decades; a more detailed analysis would be complex because the ponds are subject to both human destruction and maintenance as well as loss to natural processes such as sedimentation.

Table 2: History of pond development and survival in 3 SE Ohio counties

County	1930s	1950s	2000	1930s only	1950s only	2000 only	1930s and 1950s only	1950s and 2000 only	1930s and 1950s and 2000	Area km^2	2000 Density, ponds/ km^2	Percent of 1950s gone by 2000
Preble	5	80	684	2	77	456	0	225	3	1105	0.62	96.25
Butler	9	405	1988	2	398	1176	0	805	7	1217	1.63	98.27
Hamilton	84	350	885	28	294	541	9	297	47	1069	0.83	86.57
Total	98	835	3557	32	769	2173	9	1327	57	3391	1.05	93.17

Table 3: Longitudinal analysis of pond cohorts by county

Preble	1930s	1950s	2000	fraction disappeared
Disappeared	0	2	79	0.103
Existing	5	80	684	
Total	5	82	763	
Butler	1930s	1950s	2000	
Disappeared	0	2	400	0.168
Existing	9	405	1988	
Total	9	407	2388	
Hamilton	1930s	1950s	2000	
Disappeared	0	28	331	0.272
Existing	84	350	885	
Total	84	378	1216	
Total	1930s	1950s	2000	
Disappeared	0	32	810	0.228
Existing	98	835	3557	

In the three southwest Ohio counties, 93% of ponds existing in the 1950s had disappeared by 2000. Two factors contributed to the disappearance of ponds from the landscape: sedimentation and replacement by other land uses. Sedimentation is the dominant cause for pond disappearance in rural areas. Sedimentation rates are highly variable, with some ponds filling in only a few decades and others appearing unchanged over 50 or more years. Some ponds are dredged periodically, prolonging their lives. In urbanizing areas many ponds disappear because they are replaced by residential, commercial, or industrial facilities.

3.2 Detection and identification -- Spectral and satellite-based data

Subregions of the Midland quadrangle for which cloud-free ASTER and ETM+ images were available were identified, and the inventory of ponds obtained from the digitized DuncanTech images was compared with the automated spectral detection of water-dominated pixels in the satellite images. Figure 3 shows images of the same scene as recorded by the DuncanTech, ASTER and ETM+ sensors, and three copies of the DuncanTech image comparing overlays of the water body analysis from the three different sensors.

Figure 4 shows the size frequency distribution of the water bodies detected by the three different techniques, and a similar plot for the entire Midland quadrangle for comparison. The DuncanTech sample of the test region is clearly representative of the overall distribution, but the other sensors miss, or misidentify, the smaller water bodies, causing a shift in the apparent frequency distributions. Table 4 summarizes the results in terms of numbers and areas, and also compares the results of the remotely sensed determinations with pond inventories for the same areas from the two surface water databases (KSWD and SWIMS – see Appendix A).

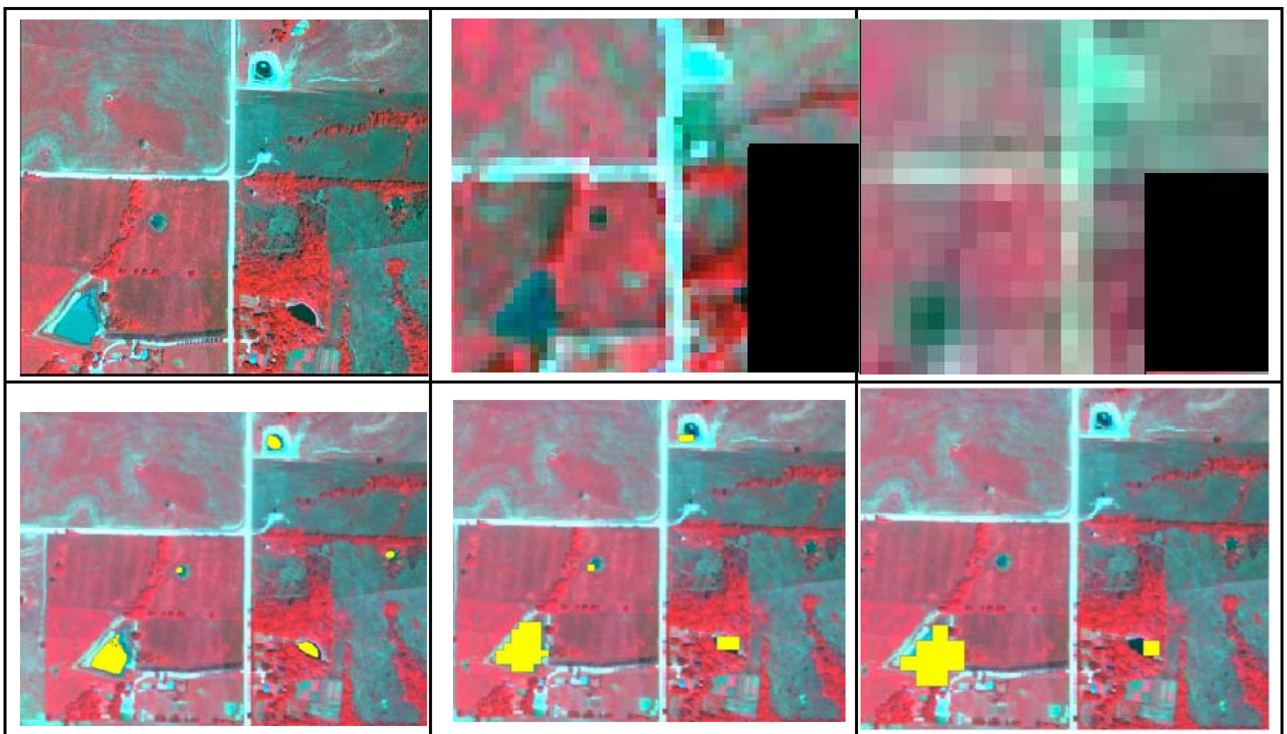
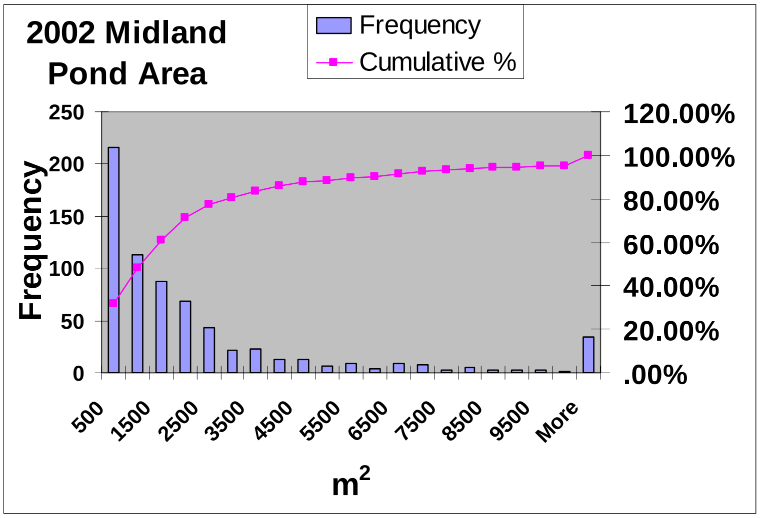


Figure 3: Satellite-air photo comparisons. Top, actual image sof the same scene – (a) DuncanTech MS3100 (1 m resolution); (b) ASTER (15 m); (c) ETM+ (30 m). Bottom, Duncan Tech photo image with superimposed pond identifications – (d) digitized from photo; (e) ASTER water mask; (f) ETM+ water mask.



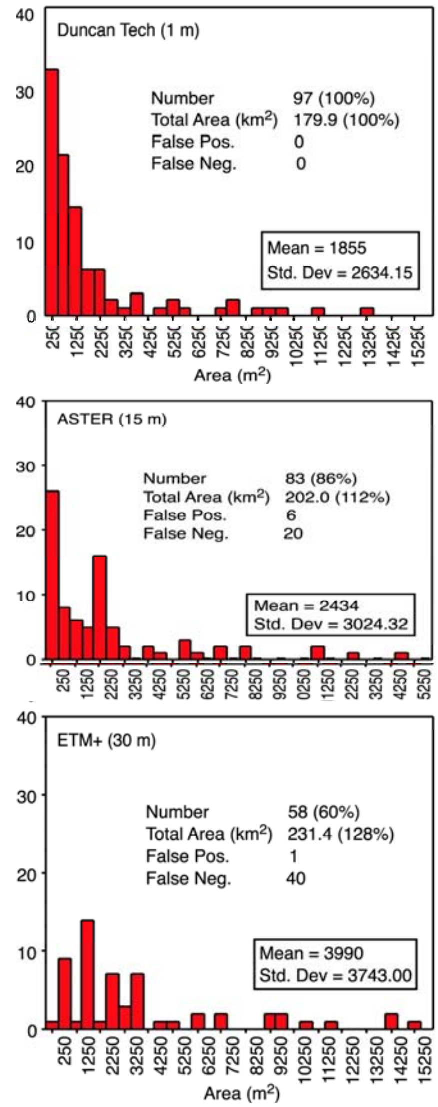


Figure 4: (a) Size distribution of ponds in the entire Midland quadrangle (683 ponds), determined from digitization of the DuncanTech aerial photos. (b) Size distribution of 97 ponds in an area selected to compare photo and satellite images (a subset of the ponds in figure 4a). (c) The same scene as b, with the inventory and sizes as detected by automated procedures using ASTER imagery. (d) As in c, but with Landsat ETM+ imagery used.

Table 4: Comparison of sensor and database pond detection in part of the Midland quadrangle.

Data Set	*# Water Bodies*	*% of Number*	*Total Sfc. Area (km^2)*	*% of Area*	*Commission Error*	*Omission Error*
DuncanTech (1m)	***97***	***100%***	***179.9***	***100%***		
ASTER (15m)	***83***	***86%***	***202.0***	***112%***	***6***	***20***
ETM+ (30m)	***58***	***60%***	***231.4***	***128%***	***1***	***40***
KSWD	***3***	***3%***	***26.1***	***15%***		
SWIMS	***1***	***1%***	***23.6***	***13%***		

As expected, the number of ponds identified by each of the three multispectral sensors (ETM+, ASTER, and DuncanTech) varied directly with spatial resolution, with the greatest number of ponds being identified by the sensor with the highest spatial resolution (DuncanTech digital aerial camera). In particular, it is noteworthy that imagery from Landsat's ETM+ sensor, which is the most widely available low-cost multispectral imagery source, successfully mapped only 60% of the actual ponds in the study sample. An interesting, and somewhat unexpected, result was that the total estimated surface area actually increased with poorer (i.e., coarser) spatial resolution. This is undoubtedly attributable at least in part to the large relative size of the coarser pixels and the tendency of the image processing methodology to identify mixed water pixels as belonging to the water class. The two surface water databases grossly underestimated the number of water bodies, although, to be fair, neither database was designed to be an inclusive map of all water bodies. It does underscore, however, the potential danger of using databases for purposes for which they were not designed – in this case the identification and mapping of small, but environmentally important, farm ponds.

3.3 Characterization and classification

Beyond the basic characterization of size, shape, and location available by conventional image analysis and the use of spectral signals for water detection, the multispectral signals offer opportunities for both qualitative and quantitative environmental classification. In addition, the combination of data on pond types and locations with other datasets and geospatial modeling tools offers opportunities for exploring the mechanisms of pond-environment interactions and predicting their effects in detail. This section presents the results of initial explorations of qualitative ecological characterization (pond vegetation and water quality types), quantitative water quality assessment (turbidity), and a test of the ability of simple topographic models to predict water quality classifications.

3.3.1 Pond vegetation and water quality

The near infra-red bands provide sensitivity to vegetation density and characteristics, and the combination of the three color bands can be used to assess water clarity (presented in more detail below). DuncanTech images were examined and compared with ground truth observations and classifications, both at the NESA and in neighboring farm ponds. The aerial images are capable of distinguishing not only degrees of water clarity, but also the amount, locations, and types of both terrestrial and riparian vegetation (trees, shrubs, grasses) and aquatic vegetation (emergent or shallow submerged rooted vegetation and floating algae).

Figure 5 illustrates several combinations of water clarity and vegetation that can be distinguished readily by visual inspection of the images. At present these classification techniques are qualitative or semi-quantitative and require scene-by-scene examination, but in principle the classification techniques could be automated and quantified in ways analogous to (but more complicated than) the turbidity assessment described below.

3.2.2 Water quality (turbidity) determination

Small pond water clarity is generally homogeneous over the central part of the water body, and can readily be evaluated using spectral information. Figure 6 displays the spectral data and corresponding images for transects across three water bodies in the Allen SE quadrangle with significantly different water clarity. Systematic differences in both pond appearance and the corresponding reflectances are readily apparent. Three scenes were selected from a specific watershed (see following section) in the Allen SE quadrangle, to include ponds of various sizes, shapes, and levels of turbidity, and turbidities were estimated using an initial calibration based on these findings illustrated in Figure 6. Figure 7 shows the scenes and the derived turbidity classifications. In addition to being reasonable in terms of visual inspection, several of the ponds classified have been tested against a model indicator of watershed erosion potential (see below), with results that support the applicability of both the modeling approach and the water quality classification.

3.2.3 Environmental models and correlations

Figure 8 illustrates the results of applying the TOPAZ model to a HUC-14 watershed. The subwatershed units are color-coded to show the classes of LS Factor values, an indicator of erosion potential. Numbered ponds correspond to the detailed images and estimated turbidity values shown in Figures 6 and 7; actual LS Factor values are given in Table 5 along with pond ID and turbidity class.

Table 5: Comparison of pond turbidity with watershed Length-Slope Factor

Pond number (Figure 8)	Turbidity Class (1 = low, 4 = high)	LS Factor
1	1	0.584
2	2	0.620
3	3	0.830

4. Integrated Discussion

The results of this study confirm the motivating hypotheses – that small, artificial water bodies are widely distributed features of the landscape that are temporally dynamic, diverse in terms of their settings and ecological or biogeochemical functions, and poorly characterized by the most widely used mapping and inventorying techniques. Our findings both indicate needed areas of research and suggest some methodological approaches and developments.

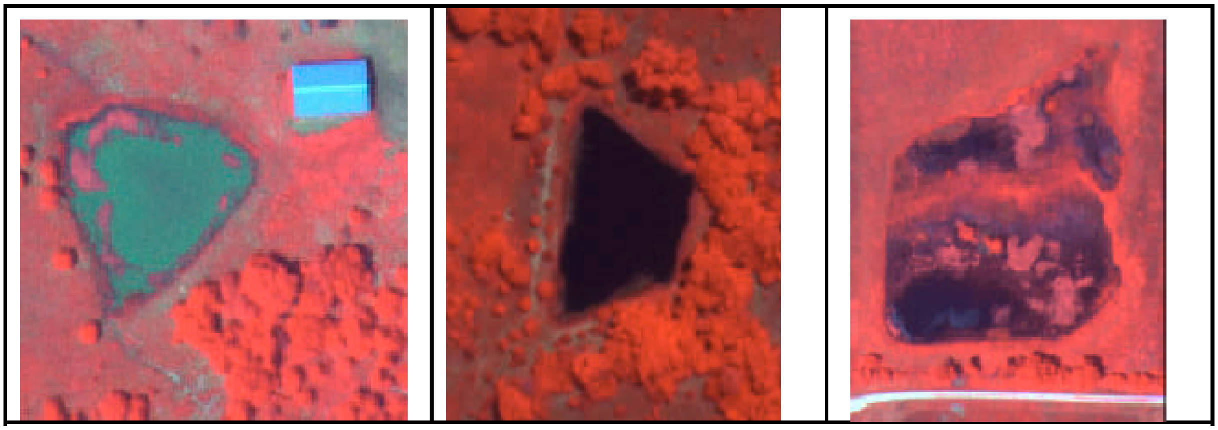


Figure 5: False-color images of NE Kansas farm ponds taken with the MS3100 multispectral camera: (a) moderately turbid water, some vegetation at edges; (b) clear water, little vegetation; (c) pond clogged with vegetation and sediment, but with moderately clear water in places.

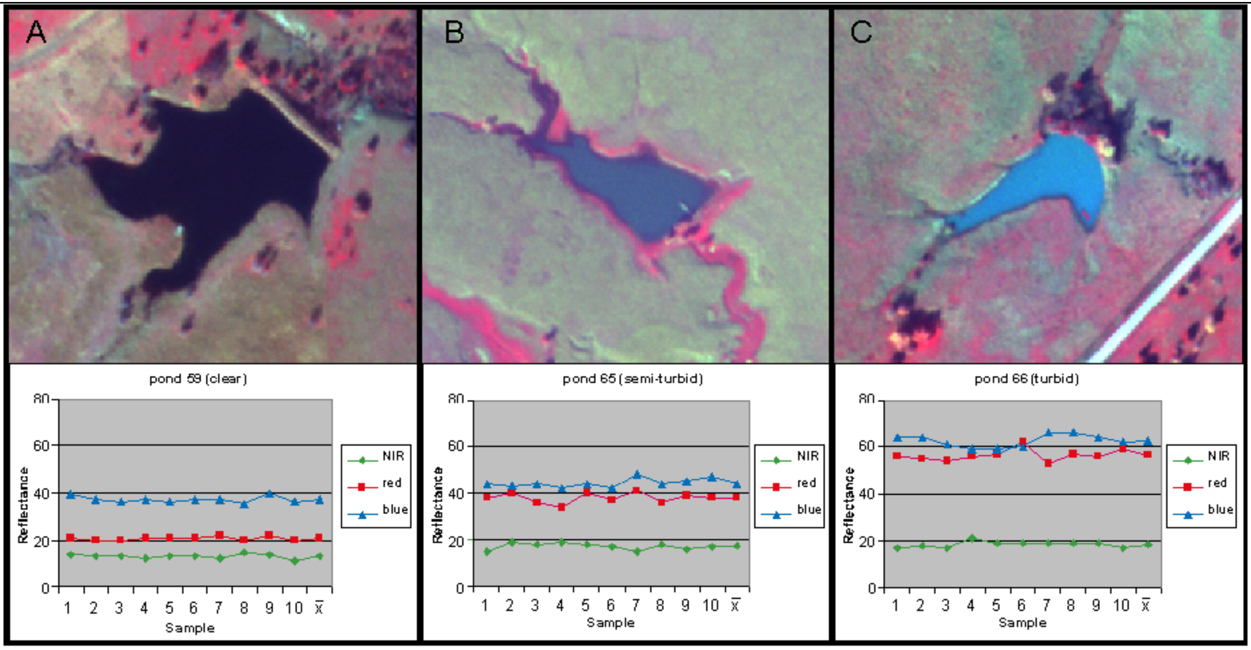


Figure 6: Spectral analysis of transects across three ponds in the Allen SE quadrangle, illustrating that the relative and absolute reflectance values of the three bands shows a strong relationship to water clarity – an indicator of turbidity, or total suspended solids. See also figure 8 and section 3.2.3.

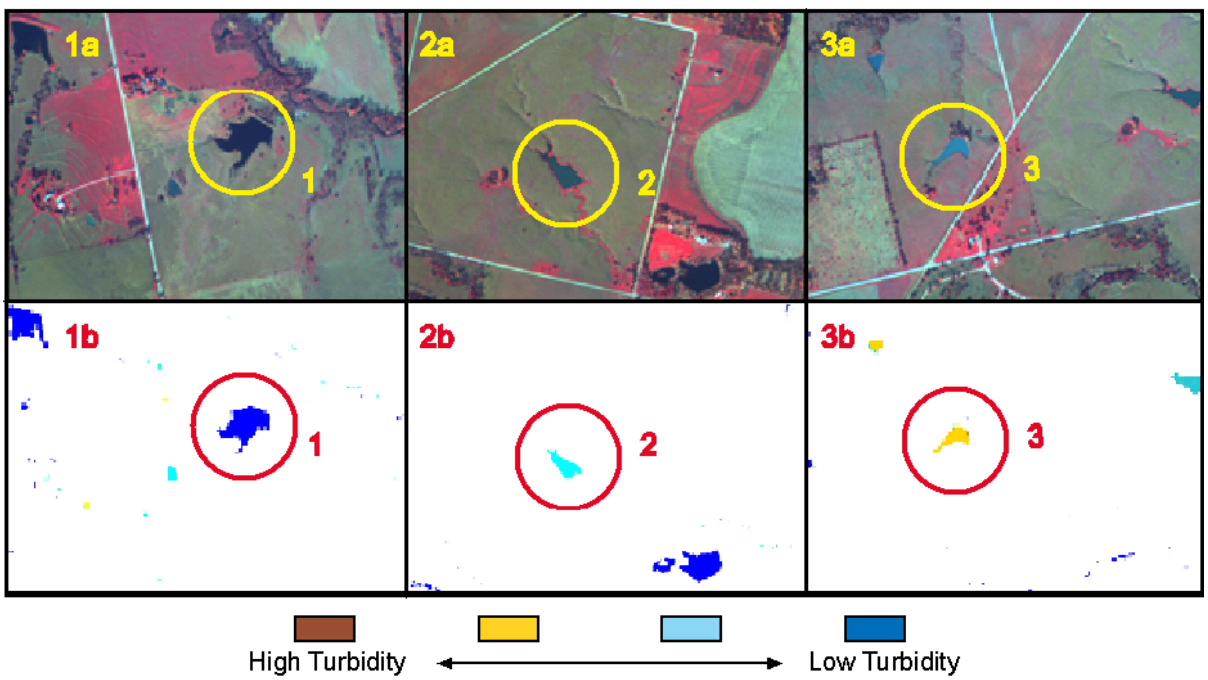


Figure 7: Turbidity classifications based on the spectral results illustrated in Figure 7. Panels 1a, 2a, and 3a show DuncanTech images of ponds with various apparent turbidity levels. Figures 2a, 2b, and 2c show the corresponding pond overlays, color-coded to indicate spectrally derived turbidity class. Circled and numbered ponds are discussed in section 3.2.3.

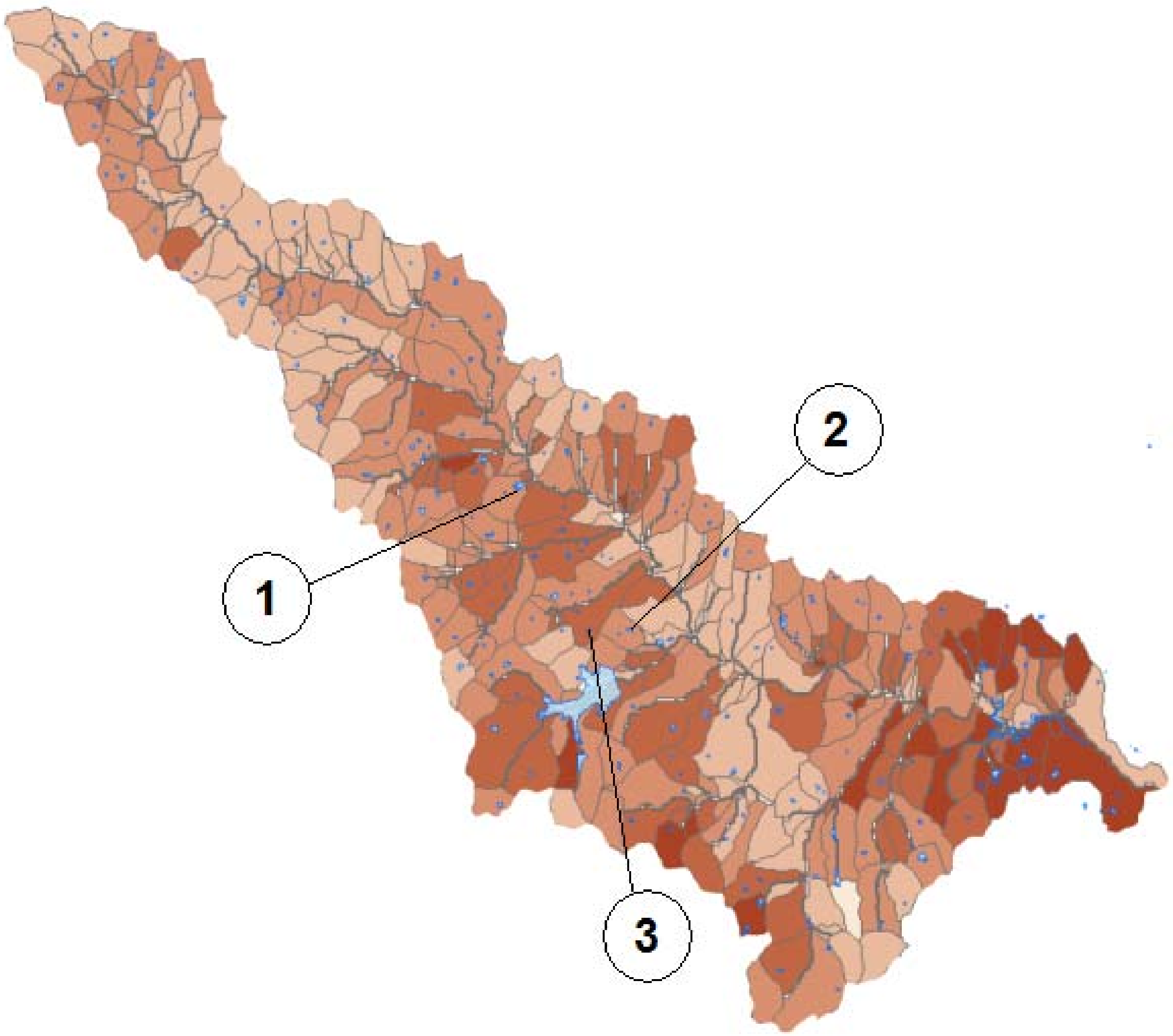


Figure 8: A watershed in the Allen SE quadrangle, with pond inventory superimposed and the subwatersheds classified according to their Length-Slope (LS) factor as determined by the TOPAZ model (see text). Darker areas have higher LS factors. Numbered locations correspond to Figure 7, and show locations of ponds used to compare remotely estimated turbidity with LS factors.

4.1 Detection, inventory, and characterization

The ideal situation for studying the distribution and effects of small water bodies would be to have access to images or coverages of adequate resolution and spectral detail to determine number, size, and pond and watershed characteristics as well as position, and to do so in a somewhat automated fashion. We have found that aerial photographs are often available – but they must be obtained individually and processed manually, and they lack spectral information from which environmental characteristics and water quality might be determined. Satellite data, by contrast, may be available over wide areas from a single source, and typically offers the possibility of spectral analysis. In the US, there is a growing inventory of centralized high-resolution imagery available, but the most readily available large-area images are still of relatively low resolution.

Based on our results, it appears likely that multispectral imagery with spatial resolution on the order of 4 meters (such as imagery from the Ikonos and Quickbird satellites) would permit automated mapping of small ponds with sufficient accuracy without incurring the storage and processing overhead and expense entailed in using 1-meter imagery. In principle, such images could also assess vegetation and water clarity as can be done with the multispectral DuncanTech MS3100 digital camera, which is a very useful tool for assessing riparian and water characteristics. Visual analysis provided reliable insights into the characteristics of vegetation and turbidity levels, and the use of more elaborate and quantitative methods showed differences in the spectral properties of ponds with different vegetation and turbidity levels. These spectral differences proved consistent enough to permit classification of ponds into different turbidity categories. It remains to be seen whether extension of these classifications to satellite imagery is practical, in view of the potential problems associated with signals from pixels that combine land and water.

Initial results suggest that it may be possible to develop calibration factors to improve the estimates of pond numbers and areas derived from satellite images of lower resolution, but considerably more work is required to develop this. Preliminary data suggest that pond sizes and positions on the landscape are strong functions not only of topography and land use, but also of climate, and it remains to be seen how many different environmental classes of calibration factors might be required to make significant corrections to (for example) Landsat-derived pond inventories.

4.2 Spatial distribution

Findings of this study support the contention that the pond density estimates of Smith et al. (2002) may be conservative; in an area of figure 1 classified at the HUC-8 level as having 1-3 ponds/km^2, the Allen SE and Midland quadrangles had approximately 3.6 and 4.5 ponds/km^2, respectively. This reinforces the arguments supporting the overall biogeochemical and landscape significance of these water bodies. More accurate estimates of pond densities and their variations (see section 4.1) would not only permit better estimates of pond potential impacts, but would also set the stage for an improved understanding of their relationships to topography, land use and climate, and for distinguishing between natural and artificial water bodies.

One of the more exciting directions of research is indicated by the very preliminary results of the topographic and hydrologic modeling efforts. Integration of pond locations with topography permits evaluation of the fraction of watershed runoff intercepted by small water bodies, which in turn permits modeling the effects on streamflow and water budget (Burns and McDonnell, 1998; Van Liew et al., 2003), as well as on sediment retention and soil organic carbon sequestration (Smith et al., 2002; Renwick et al., in press; Smith et al., submitted). With the further addition of data on land use/land cover and agricultural practices, the role of ponds in nutrient cycling and runoff can be modeled.

4.3 Temporal distribution

The results shown in Table 1 and Figures 2 and 3 indicate that most of the artificial pond building in the study areas occurred in the past 50-75 years. Eastern Kansas has been settled by people of European stock for 150 years, Ohio for about 200 years. Although historical and anecdotal evidence suggest that some ponds were constructed by hand or with draft animals by the earliest settlers, three successive factors have been identified (J. Koelliker, pers. commun.) as contributing to the onset of rapid growth in the pond inventory: (1) availability of steam-powered tractors, beginning in the 1920s; (2) the "Dust Bowl" drought years of the 1930s, which led government agencies to advocate watershed dams as a means of erosion control; and (3) the widespread availability of military surplus heavy equipment following World War II. In Ohio pond-building began somewhat later than in Kansas because water needs were not as acute, but like Kansas was greatly accelerated by government agencies and equipment availability after World War II (Helms, 1988).

The results also suggest that the actual rate of pond construction is higher than indicated by the present inventory, since the net inventory includes the loss of some ponds to destruction or abandonment and infilling. The idea of defining a meaningful lifetime for features that are artificially created, maintained, and sometimes destroyed is probably not realistic, but the available data suggest that in the areas studied, longevities on the order of several decades are common.

In the three southwest Ohio counties, 93% of ponds existing in the 1950s had disappeared by 2000. Two factors contributed to the disappearance of ponds from the landscape: sedimentation and replacement by other land uses. Sedimentation is the dominant cause for pond disappearance in rural areas. Sedimentation rates are highly variable, with some ponds filling in only a few decades and others appearing unchanged over 50 or more years. Some ponds are dredged periodically, prolonging their lives. In urbanizing areas many ponds disappear because they are replaced by residential, commercial, or industrial facilities.

4.4 System-level and large-scale considerations

4.4.1 Ecological issues

As in many countries, the US has experienced a substantial net loss of natural wetlands over the past few centuries, and one question of interest would be whether the pond construction has to some extent compensated for that. We suspect that such compensation would be very limited;

most of the ponds are constructed in settings distant and different from the ones in which wetlands originally occurred. Although some organisms may be able to use either type of water body, the two trends probably have little connection – one class of environments loses water bodies to human intervention, while a different class gains them, and the natural biota of both are stressed.

In addition to concerns about habitat preservation and biodiversity, a major contemporary issue is that of introduced, invasive, or pest species. The proliferation of small ponds in areas previously lacking them is an issue of concern in this regard. Not only do they provide habitat for pest organisms with aquatic life stages (mosquitoes are a classic example), but the dramatic reduction in distances between water bodies also means that aquatic or semi-aquatic organisms with limited range or mobility have much greater opportunities for range extension. To the best of our knowledge, the dramatic change in water body density has not been factored into models of either indigenous or invasive species distributions.

4.4.2 Hydrologic and biogeochemical issues

With reference to the US patterns of pond construction and occurrence, one of the most striking features is the rate of change in pond numbers and densities. Ponds and their cumulative effects have changed rapidly and are continuing to do so on time scales that are rapid compared with the 30-year periods used for climate and streamflow norms, and comparable to rates of anthropogenic change in aspects of the C, N, P and hydrologic cycles. Because this dynamic landscape alteration has gone largely unnoticed by the biogeochemical community, there is the potential for significant distortion of some budgets and modeling efforts, as exemplified by recent discussions of the soil organic carbon cycle (Renwick et al., 2004; Smith et al., 2002).

The degree to which the US model is applicable elsewhere is, we feel, a very important question to be resolved. We suspect that Australia may show similar patterns, but in much of Eurasia and parts of Africa, settled agricultural communities have been modifying the hydrologic cycle for millennia rather than decades, and in parts of the developing world the transition to mechanized landscape alteration has still not occurred at the level of the individual farm or community. Given the importance of water to human activities, we are confident that artifical ponds will be created and used wherever they are advantageous, but the temporal and spatial patterns of those uses may differ greatly around the globe.

One factor that is likely to remain relatively consistent across cultures and economies is the relationship between pond utility and water balance. Figure 9 reproduces for comparison the US pond density map of Figure 1, and adds two other comparison figures: a plot of precipitation minus potential evapotranspiration along a transect across the central US, and a map of pond evaporation as a percent of runoff. Net evaporation from lakes and reservoirs is defined as the added evaporation that takes place as a result of the presence of an open water surface, beyond what would occur from a terrestrial surface. Net evaporation, D_R, as a percent of mean annual runoff, is calculated as

$$D_R = \frac{(E_L - (P - R)) \times A_P \times 100}{R}$$

where E_L = lake evaporation (Environmental Sciences Service Administration, 1968); P = precipitation (Daly and Taylor, 1998); R = runoff (Gebert Graczyk, and Krug, 1987); and A_P = pond area (Smith et al, 2002), expressed as a fraction of total area. The location of the nearly N-S belt of high pond densities in the middle of the country straddles the transition zone from water surplus to water deficit, and is substantially to the east (the wet direction) of the maximum in pond evaporation relative to runoff.

The explanation seems straightforward – in the water-surplus east, rainfall and runoff are more reliable and there is less need for artificial storage of water. In the transition zone, there is enough water on average, but reliability is reduced and potentially damaging dry periods occur. Here, small ponds can retain enough water to last through most dry periods, and they are an inexpensive water reserve, especially for livestock (See Table 1 and Figure 2). Farther to the west the rainfall is so unreliable and evaporation rates so high that a water body must be relatively large to survive the dry periods, and here the density of small ponds drops off sharply. We suggest that this climatic control on pond distribution, particularly when combined with population and land use data, should have considerable predictive power on a much larger scale.

5. Summary and Conclusions

The results presented here support and extend the previously published analyses suggesting that small, man-made water bodies can significantly alter landscape functions, including biogeochemical fluxes, at scales ranging from the local watershed to the regional and potentially global. In part because of lack of an adequate database or inventory of such features, they commonly have been ignored in both ecological and biogeochemical studies

We examine and illustrate a number of approaches to identifying and characterizing ponds and their functional characteristics, and illustrate their use with case study results. These results provide some insights into pond distribution and function in a significant part of the US, and suggest some relationships with climate and land use that are probably generalizable. However, it is clear that there are historical, cultural, and economic factors affecting the use and effects of small water bodies, and data concerning both the water bodies and the factors controlling their occurrence are most likely to be found (with some effort) at local to regional levels and in a variety of sources.

We therefore return to the third objective stated in section 1.2. We hope that presentation of the results of this study will stimulate not only discussion, but also research in other settings, so that we can begin to piece together the role that local-scale human alteration of the hydrologic cycle may play in various regions and at the planetary level.

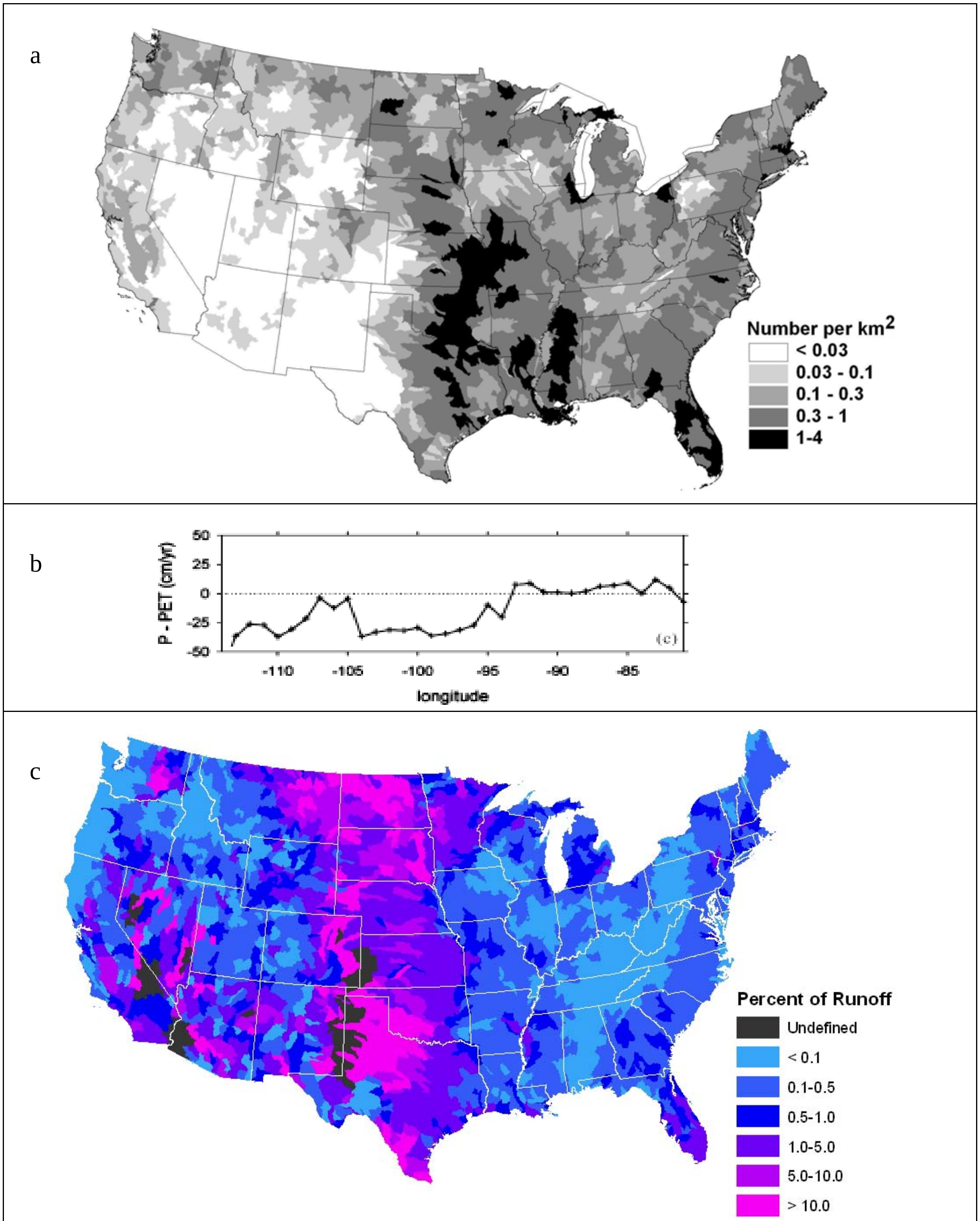


Figure 9: Water-balance and pond density comparisons. (a) Estimated pond density (same as Figure 1). (b) Average annual water balance along an E-W transect approximately centered on Kansas. (c) Estimated pond evaporation expressed as a function of runoff.

Appendix A

Data used and available:

The most recent is the Kansas Surface Water Database (KSWD), which was derived from 2000 and 2001Landsat ETM+ imagery at a minimum mapping unit of 1.5 acres and became available for use in 2003. The second inventory of water bodies is the Surface Waters Information Management System (SWIMS). This database was created using the Environmental Protection Agency's (EPA) River Reach Files (RF3). The RF3 files were developed from 1:500,000-scale NOAA aeronautical charts and 1:100,000-scale digital line graphs developed by USGS.

Table A-1: Sensor characteristics

	Detector Wavelengths (µm)					
Color	**Band**	**DuncanTech**	**Band**	**ASTER**	**Band**	**ETM+**
Blue Green	1	0.45-0.52			1	0.45-0.52
Green			1	0.52-0.60	2	0.52-0.60
Red	2	0.63-0.69	2	0.63-0.69	3	0.63-0.69
Near IR	3	0.76-0.90	3	0.76-0.86	4	0.76-0.90
Mid IR					5	1.55-1.75
Mid IR					6	2.08-2.35

ASTER

The ASTER image (August 6, 2001) was processed using an unsupervised classification procedure in ERDAS Imagine. Using the ISODATA clustering algorithm, 100 spectral clusters were defined. The clusters that represented water were then combined into a 'Water' class and the remaining classes were combined into a class called 'Non-Water.' The result was a raster data set with two classes: water and non-water, that was then brought into ArcMAP and converted to a polygon shapefile. Using the Editor extension, all polygons were visually confirmed to represent actual water bodies. If a polygon did not represent a water body (typically edge polygons), it was deleted. The result was a vector-format estimate of the water bodies. The reason for converting from raster to vector format was to be able to calculate the surface area of each polygon. To facilitate extracting surface area, a tool was developed using ArcObjects to extract each polygon area from the "shape" field within the shapefile.

Landsat Enhanced Thematic Mapper (ETM+)

The ETM+ image (July 21, 2001) was processed in the same manner as the ASTER image, first using an unsupervised classification procedure in ERDAS Imagine. Using the ISODATA clustering algorithm, 100 spectral clusters were defined. The clusters that represented water were then combined into a 'Water' class and the remaining classes were combined into a class called 'Non-Water.' The result was a raster data set with two classes: water and non-water, that was then brought into ArcMAP and converted to a polygon shapefile. Using the Editor extension, all polygons were visually confirmed to represent actual water bodies. If a polygon did not represent a water body (typically edge polygons), it was deleted. The result was a vector-format estimate of the water bodies.

DuncanTech Digital Aerial Imagery

Forty-four scenes from three different dates (12 April 2003, 9 May 2003, and 9 June 2003) were mosaicked together using ERDAS Imagine. All water bodies were then digitized into a vector layer using standard heads-up digitizing procedures. The resulting vector layer was then saved as a polygon shapefile, which was then brought into ArcMap for calculation of the number of water bodies and their surface areas. In addition a polygon layer was created that represented the extent of all the 44 DuncanTech images. This layer constituted the extent of the study sites within the study area and was used to clip all other map layers.

Kansas Surface Water Database (KSWD)

The KSWD was clipped to the extent of the 44 Duncan Tech images. It was converted from a raster layer to a polygon shapefile. The number of ponds and their surface area were then calculated.

Surface Water Information Management System (SWIMS)

This dataset was downloaded from DASC in shapefile format. The polygons were clipped to the extent of the 44 DuncanTech scenes and the resulting shapefile was added to ArcMap, where the number of ponds and surface area were calculated.

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