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LAKES, WETLANDS, AND STREAMS AS DYNAMIC DRIVERS OF LAND USE/COVER PATTERN AND CHANGE: A UNIQUE VIEW OF AQUATIC ECOSYSTEMS IN THE LANDSCAPE

By

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ABSTRACT

LAKES, WETLANDS, AND STREAMS AS DYNAMIC DRIVERS OF LAND USE/COVER PATTERN AND CHANGE: A UNIQUE VIEW OF AQUATIC ECOSYSTEMS IN THE LANDSCAPE

By

Sarah E. Walsh

Most research linking aquatic ecosystems to their surrounding environment has focused on how terrestrial processes affect lakes, wetlands, and streams. However, it is equally as important to examine how aquatic ecosystems alter terrestrial systems. I examined spatial patterns of rural residential development and land use/cover around lakes, nonforested depressional wetlands, and streams in the Huron River watershed in southeast Michigan, USA. Specifically, I found that urban land use/cover occurs closer to lakes than depressional wetlands or streams compared to the watershed. Agriculture occurs proportionally less around lakes and streams, but more around depressional wetlands than in the watershed. Additionally, forested land is found proportionally more often around all three types of aquatic ecosystems than watershed average. These patterns are not static and show changes between 1938 and 1992. This research has revealed that a more complete understanding of how aquatic ecosystems drive patterns in landscape patterns is important and could potentially be useful to incorporate into predictive models of land use/cover change.

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Lakes, wetlands, and streams as dynamic drivers of land use/cover spatial pattern and change: a unique view of aquatic ecosystems in the landscape

Introduction

Aquatic ecosystems are strongly linked to the surrounding landscape and cannot be studied in a vacuum set apart from their environmental setting (Hynes 1975; Karr and Schlosser 1978; Malanson 1993; Allan and Johnson 1997). Over the past several decades, scientists from many different disciplines have increasingly studied how human modification of the landscape affects aquatic ecosystems. For streams, land use/cover has been correlated to many chemical (Osborne and Wiley 1988; Johnson et al. 1997, Herlihy 1998), physical (Kuhnle et al. 1996), and biological (Steedman 1988, Schlosser 1995) factors. In lakes, land use/cover has been shown to cause physical (Christensen 1996; France 1997), chemical and nutrient (Eilers et al. 1989; Field et al. 1996; Siver 1996), and possibly biological (Stemberger and Lazorchek 1994; Allen et al. 1999) changes. The little research that has been done on wetlands has mainly examined effects of land use/cover on biological features of wetlands (Mensing 1998; Euliss 1999; Anderson and Vondracek 1999). However, despite these examples, the major focus of research on land-water interactions has been on how land use/cover affects streams and far fewer studies have been conducted on wetlands or lakes with the exception of those studies focusing on nutrient loading in lakes (Dillon and Kirchner 1975).

In addition, few studies have examined a specific function or process in lakes, wetlands, and streams together (Gorham 1996). Although some studies have linked two systems, for example when examining the effects of wetlands on water quality in lakes (Detenbeck et al. 1993) or streams (Johnston et al. 1990; Weller et al. 1996), rarely have all three been examined. Examining how land use/cover affects multiple aquatic systems together might greatly improve our understanding of the complex interaction between terrestrial and aquatic ecosystems.

To fully understand the interactions between aquatic and terrestrial ecosystems, aquatic ecosystems must also be seen as more than receptors of human modification of the landscape, but also as potential drivers of these modifications. The distribution and location of aquatic ecosystems may actually influence how humans use the land. For example, forested riparian buffers are often left around streams to filter upland sediment and nutrients before they reach streams (Peterjohn and Correll 1984; Osborne and Kovacic 1993). Because human use of the landscape has been shown to be so important to aquatic ecosystems it is important to examine how aquatic ecosystems might in turn affect human use of the land.

Researchers have examined the pattern of rural residential development and land use/cover change for some time (Burgess 1967, Hart 1976), but they have generally come from disciplines such as geography, rural sociology, and urban and regional planning. Only recently have ecologists begun to include human modifications in research on ecological systems at larger scales (Vitousek 1994; Dale et al. 1998). From an ecological point of view, there is still more to learn about land use/cover pattern and change. In particular, we have gained many new insights from studies that describe land use/cover pattern and change at specific places around the country (Simpson et al. 1994; Silbernagel et al. 1997). These studies have revealed some broad generalizations about land use/cover change (Medley et al. 1995; Bradshaw and Muller 1998). For example, the conversion of agricultural land to other land use/cover types (i.e. converted to residential uses or left to return to forest land cover) has been seen as a problem for decades in the U.S. (Furuseth 1982). The loss of American farms is a very complex phenomenon that we do not yet completely understand (Galston and Baehler 1995). Another general pattern in land use/cover change is increased urbanization, which can be found throughout the country (Befort et al. 1998).

Human utilization of the land does not occur randomly across the landscape. There are social, economic, political, and physical drivers of land use/cover change that range from the reigning political party to local landscape features (Cronon 1983). For example, land cover change has been found to depend on the land ownership in the southern Appalachian highlands and the Olympic peninsula (Turner et al 1996). Similarly, natural features on the landscape have the potential to affect land use/cover change (Pan et al. 1999) or rural population growth (McGranahan 1999). Pan et al. (1999) found that the physical landscape in Quebec, Canada constrained land use changes which were triggered by socioeconomic forces. Other studies have found a weaker relationship between landscape attributes and land use change (Iverson 1988; LaGro 1998). This relationship may be weaker in some areas due to specific conditions in the region. For example, Iverson (1988) found that in southern Illinois most soils are suitable for crop production so changes in agriculture were unrelated to physical conditions of the landscape. LaGro (1998) found little relationship between development and physical landscape attributes because improved technology in private on-site sewage systems allowed their placement in areas that used to be constrained by slope, soil permeability, depth to bedrock, or depth to water. The results of all of these studies suggest that including natural features may be important variables to consider when trying to predict how land use/cover is going to change in a region.

Several models have been developed to predict future land use/cover in various areas of the country (Pijanowski et al. 1995, Turner 1996) and have included predictor variables such as distance to employment, land use regulations, elevation, and age of farmer. The extent to which natural features are included in the models varies, but very few studies have explicitly included aquatic ecosystems. Lakes, wetlands, and streams are sometimes mentioned (for example the Great Lakes shoreline or stream riparian buffers in Pijanowski et al. (1995)), but rarely included as key parameters in land use/cover change models, suggesting that they do not play important roles in land use/cover pattern and change. However, other studies that found correlations between landscape features and development show this assumption may not be valid (Orr 1997; McGranahan 1999; Pan et al. 1999).

Aquatic ecosystems may not have been included in many models simulating future land use/cover scenarios because we do not know the role that lakes, wetlands, and streams play in influencing land use/cover in the immediate region surrounding these important ecosystems. Nonetheless, we do know that lakes attract people for their aesthetic and recreational values (Orr 1997). In some regions, especially in the Upper Great Lakes region, this relationship is due to retirement communities or second home growth (Hunt et al. in press; Green et al. 1996). Streams have been included as a variable in some land use/cover change models by leaving a buffer around streams where development is not allowed to occur (Pijanowski et al. 1995). This conservation of stream riparian zones is opposite that of lakes (where people tend to build in riparian zones rather than preserve them) and is supported in some literature on perceptions and urban growth in river corridors. For example, Ryan (1998) and Bollens (1990) state that it is important to maintain natural corridors around streams. Bollens (1990) examined the effect of floodplain management programs on the development of river floodplains and Ryan (1998) examined preferences and attitudes of rural residents toward riparian landscapes. In both studies, the goal was to maintain natural vegetation near rivers. This conservation attitude appears to not have not been transferred to lakes or wetlands.

Given the importance of aquatic ecosystems, coupled with our lack of knowledge of how they drive human modification of the landscape, a basic question that needs to be addressed is whether the presence of aquatic ecosystems on the landscape predictably alters land use/cover in surrounding land. The specific questions I address are:

1) Do aquatic ecosystems correlate to spatial patterns of rural residential development and land use/cover?
2) How has both the total amount and spatial pattern of riparian land use/cover changed through time?
3) Does lake or wetland area affect riparian land use/cover?
4) How do different indicators of human use/development compare (i.e. land use/cover and well density)?

I answer the above questions by analyzing spatial patterns in rural residential development and land use/cover around lakes, depressional wetlands, and streams using a conceptually simple buffer analysis. I conducted this research in the Huron River watershed in southeastern Michigan using data from five time steps between 1938-1992. I examined whether the location of aquatic ecosystems are correlated to spatial patterns on the landscape by using land use/cover and well density as indicators of human modification of the landscape. To assess spatial pattern, I compared well density and land use/cover percent in several buffers around aquatic ecosystems to the average watershed well density and land use/cover percentage. The location of drinking water wells were chosen as an indicator of rural residential development in that they represent a single household. Although I am not aware of any other research that has used wells as an indicator of development, septic tanks have been effectively used in a similar fashion (LaGro 1998) and wells are likely to be highly correlated to septic tanks. I hypothesized that the location of aquatic ecosystems would influence the spatial patterns of how humans use the land in the Huron River watershed.

Study site description

The Huron River watershed drains 2300 km^2 in southeast Michigan (Figure 1). The river and its tributaries flow approximately 800 km into the northwest corner of Lake Erie, carrying a mean annual discharge of approximately 90 m^3/s. The surface topography of the watershed is characteristic of a glaciated landscape. The northern region makes up the majority of the watershed area and contains a dendritic pattern of tributaries, lakes connected by the rivers, and extensive wetland areas (Figure 2). Geologically, the watershed is largely comprised of glacial moraines, till plains, and outwash deposits (Hay-Chmielewski et al. 1995). Both outwash and moraine geologies contain sand and gravel deposits that are conducive to groundwater – surface water exchanges, however, the till plains consist of sorted fine sediments that are more conducive to surface runoff (Hay-Chmielewski et al. 1995).

European human settlement began in the 1700's and by the 1800's agriculture was the dominant land use in the watershed (Hay-Chmeilewski et al. 1995). Since then however, extensive land conversion within the watershed has produced a mixture of urban, agricultural, and natural land use/covers today (Figure 1). Urban growth and development extending from the Detroit metropolitan area (southeast of the Huron watershed) and Ann Arbor (in the southeast portion of the watershed) drive much of the land conversion in the watershed. The watershed used in all of my analyses in Figure 1 is a subset of the entire watershed (see below for details). The large urban center in the southern corner of the watershed is the city of Ann Arbor, around which occurs extensive agricultural development. By 1992, approximately 25% of the watershed was classified as urban land use/cover, 28% as agricultural land use/cover and 18% as forested land (Figure 1; data sources given in methods). These land use/cover percentages within the watershed subset have not been constant throughout time however (Figure 3a). Over the last 55 years, there have been marked decreases in agriculture and increases in urban land use/cover, but little change in the area covered by forests (Figure 3a). The average annual rates of change in ha/year of all six land use/cover types between each timestep for this watershed subset are shown in Figure 3b. Although the wetland loss occurred through all 5 timesteps in the Huron River watershed, the rate of change is much lower in recent timesteps than it was between early timesteps (Figure 3b). This result is to be expected given legislation that has been passed to prevent wetland loss (Zedler et al. 1998). The majority of wetland loss in Michigan occurred before 1930 and was the result of installing drains to create agricultural fields (Fretwell et al. 1996).

Methods

Landscape and aquatic ecosystem data

All data were compiled in a geographic information system (GIS) database. The landscape and aquatic ecosystem data were obtained from the Michigan Resource Information Service (MIRIS). These data included coverages of land use/cover, county boundaries, watershed boundaries, waterways, and water well locations. The land use/cover data is classified in a hierarchical 5-step scheme using the Anderson Classification scheme (Anderson et al. 1976). The most general level of classification used in this study includes the following land use/cover types: urban, agricultural, nonforested vegetation (i.e. scrubs and shrubs), forest, water, and wetlands. Land use/cover data for the watershed are based on a 1985 digital base map (note that the rest of the state of Michigan in the MIRIS database are based on 1978 data). Historical land use/cover coverages were created from aerial photographs taken in three timesteps previous to 1985. The aerial photographs were taken for the following years for each timestep: Step 1 (1937, 1940), Step 2 (1955, 1957), Step 3 (1969, 1970, 1972, 1973), and Step 4 (1985). I will refer to each timestep by the average year of the aerial photos (1938, 1956, 1971, 1985, and 1992). The digital 1938, 1956, and 1971 land use/cover coverages were created chronologically going back through time beginning with the 1971 layer. The 1971 layer was created by overlaying the 1985 land use/cover data layer on the 1971 photographs and editing the land use/cover data layer to match the photos (D. Rutledge, unpublished data). The same methods were used to create the 1938 and 1956 land use/cover layers overlaying the preceding data layer on the photos for each timestep.

The 1992 land use/cover coverage was obtained from the Huron River Watershed Council, which was created from classification of color aerial photographs in addition to ground truthing. All coverages were edited to obtain maximum accuracy and continuity between the five timesteps (D. Rutledge, unpublished data). The minimum resolution of the original MIRIS land use/cover data is approximately 1 hectare. For the purpose of this research, I reduced the watershed's extent (Figure 1). I excluded areas where there was not enough information on wells, where there was a low number of wells, or a known public water supply in an area not within town boundaries (as determined from public water supply maps and personal communication with township public works departments).

The drinking well coverage contains the location of each well indicated by a point (Figure 4). The original drinking well data were compiled from the Water Well and Pump Records of the Michigan Department of Public Health. Because wells were chosen as an indicator of rural residential development, any wells located within the boundary of towns were excluded from analyses. The rationale for this decision is that if public drinking water supply became available to a town after private wells had been drilled, they would have remained in the dataset, but would be no longer in use. Only 200 out of over 17,000 wells were located in towns and subsequently removed from the analysis. The town coverage was obtained by selecting the delineated towns from the county coverage (as shown by the dark polygons in Figure 4). Figure 5 shows the distribution of wells around lakes, nonforested wetlands, and streams for a subset of the watershed.

Creating the GIS coverages of the aquatic ecosystems involved several additional steps of data manipulation. All of the aquatic coverages came from the 1992 land use/cover coverage and were assumed not to change through time. In building a lake coverage, any body of water coded as a lake and greater than 1 ha was included in the lake coverage because 1 ha is the minimum resolution of the data of the original MIRIS database. The final lake coverage contained 453 lakes (Table 1).

The wetland coverage created for all spatial analysis includes a subset of the total number of polygons classified as wetlands in the 1992 land use/cover coverage. In the wetland coverage I only included wetlands classified as nonforested wetlands because they are more likely to have standing water. Nonforested wetlands made up 75% of the total wetlands in the watershed (Table 2). Similar to lakes, all nonforested wetlands under 1 ha in area were not included in the wetland coverage. In addition, I removed those nonforested wetlands that were directly contiguous to lakes and streams (riparian wetlands), which ended up being 29% of the nonforested wetlands. Thus, I restricted my analysis to those nonforested depressional wetlands that would not be confounded by the presence of a lake or stream immediately adjacent to that nonforested wetland. The same was not done for lakes and streams because approximately 40% of lakes and 60% of streams had wetlands adjacent to them. Reducing the number of lakes and streams by that much would have lowered the sample size too much. Because keeping the lakes and streams with adjacent wetlands in the final coverages confounds the interpretation, my analysis is likely to be conservative. The final depressional wetland coverage contained 1296 waterbodies (Table 1).

The 1985 MIRIS land use/cover coverage served as the starting point for the creation of the stream coverage rather than the 1992 coverage. The land use/cover coverage was edited using an additional stream layer from MIRIS and aerial photographs from the first three timesteps to include small order streams (down to approximately 3rd order (Strahler 1964)) than were available in the original coverage. Very short stream segments that were not ultimately connected to the tributaries or the mainstem of the river were deleted from the stream coverage, but not the land use/cover coverage. I divided the stream coverage into 110 segments following an approximate stream order classification (Table 1).

These three aquatic ecosystem coverages were used for analyses in all timesteps. Thus, I assumed that there were no changes in the location and the spatial pattern of aquatic ecosystems across the 55 years. There were only minor changes in the number, size, and distribution of lakes and streams relative to overall land use/cover (Figure 3b). Overall, the total area of depressional wetlands decreased by 32% from 1938 to 1992. For the depressional wetlands, it is important to note that only the depressional wetlands remaining in 1992 were included in the spatial pattern analyses. I examined how depressional wetlands correlated to land use/cover change around them, but the total extent of all wetlands in the land use/cover coverage also changed due to the conversion or creation of new wetlands through time (Table 3). For all three aquatic ecosystems it was important to use a consistent set of waterbodies throughout the analysis that were present in all timesteps.

Data analysis

Creating Buffers: For all analyses, I created 20 concentric 100 meter buffers around the separate coverages of lakes, depressional wetlands, and streams. Using ArcView the following operations were performed to make three coverages that each contained twenty 100 m buffers around each aquatic ecosystem type. First, for the lake coverage a 100 m buffer was created around each lake (Figure 6). If lakes were closer than 200 m to each other, the overlapping area of the two buffers was randomly assigned to one of the two lakes. This step was necessary as there was no analytical way to split the overlapping buffer area in two. By assigning the overlapping area randomly, there should have been no systematic bias introduced into the analysis, only extra variation, or noise. After the 100 m buffers were created, the 200 m buffers were added as a 100 m wide buffer beginning at the end of the first 100 m buffer. As with the 100 m buffer, if the 200 m buffer intersected another 200 m buffer, then the same rules were applied as for the 100 m buffer. The 200 m buffer of one lake was not allowed to overlap a 100m buffer around another lake. Thus, buffers with the shortest distance from a lake were always given preference over buffers further away. This buffer creation continued until 20 buffers were made around each lake (Figure 7). Lake identification numbers were assigned to each buffer so that buffers could be connected with lake attribute information (i.e. surface area). The final data file contained buffers, buffer areas and the lake that they were assigned to. These steps were repeated for streams and wetlands, resulting in three separate coverages used to describe the spatial pattern of rural residential development and land use/cover patterns around lakes, depressional wetlands, and streams. Because of the complexity of the spatial patterning of lakes, wetlands, and streams, it was not possible in this study to examine the possible correlations among all ecosystems types and land use/cover pattern combined.

Spatial pattern: I examined the spatial pattern of rural residential development and land use/cover by analyzing both the well density (as an indicator of rural residential development) and 1992 land use/cover data (urban, agriculture, and forest) in buffers around lakes, depressional wetlands, and streams. Urban land use/cover is a composite of many types of development, but is dominated by residential use (70%) in the Huron River watershed. I calculated the weighted mean well density and land use/cover percentages for each buffer and compared it to the average watershed value. I weighted each observation (buffer polygon) by buffer area because there was a wide range of buffer areas. Using 95% confidence intervals (based on an estimate of variance for ratio data (Cochran 1953; Lockwood et al. 1999)), I determined if there was a significant difference between each buffer mean and the overall watershed average value by determining whether the watershed value was found outside the 95% confidence interval. If, for example, the percentage of urban land use/cover was significantly higher in a buffer near lakes compared to the watershed average, I concluded that lakes attract human development. If, on the other hand, the percentage of urban land use/cover was significantly lower than the watershed average, I concluded that lakes repel human development. These words (attract and repel) do not necessarily claim a causal relationship, but only a positive or negative correlation between the location of aquatic ecosystems and rural residential development or land use/cover. For the well analysis I used all twenty concentric 100 meter buffers, and for the land use/cover analysis I used a subset of ten of the buffer distances (100-400, 700, 1000, 1100, 1500, 1800, 1900).

Riparian land use/cover changes: To examine if the spatial patterns in land use/cover changed through time I also analyzed urban, agricultural, and forested land use/cover for 1938 in the same subset of buffers around lakes, depressional wetlands, and streams as the 1992 analysis. In addition, I examined the changes in patterns of the riparian zone in more detail because I expected this area to show the greatest difference from the overall watershed. To address how riparian land use/cover spatial pattern changed through time, I analyzed land use/cover percentage for three land use/cover types (urban, agriculture, and forest) in the 100 m buffer around lakes, depressional wetlands, and steams for the five timesteps (1938, 1956, 1971, 1985, 1992). I define riparian as the first 100 meters away from a water body. Although this definition is not hydrologically accurate because it is not based on hydrology or topography, it was selected because of the limitations of data resolution, to ensure that at least one entire property width was included in the riparian buffer, and because many previous studies define it as such. The spatial pattern in riparian land use/cover was analyzed through time for lakes, depressional wetlands, and streams by comparing weighted means to the estimate of watershed land use/cover percentage as described above.

Effects of lake and wetland area: To test for the effects of lake and wetland area on the spatial patterns of well density and land use/cover percentage, I created groups (bins) of lakes and wetlands based on area, using of 10 and 5 ha intervals, respectively (Figure 8). I performed regression analyses on the binned data to examine whether there was a significant relationship between area and either well density or land use/cover percentage. For these analyses, I did not weight the data by buffer area because it was necessary to treat the lakes as individual sample points of a population (each with their own area), therefore I used traditional statistical methods in my regression analysis instead of using the estimate of variance for ratio data. The regressions were done on the full group of data, not the mean value for each buffer distance because of the large amount of variance in well density and land use/cover percentage. These data do not have a normal distribution partly due to the large number of zeros (for both land use/cover percentage and well density). To improve the normality of the data, I performed power and log transformations on the well density and lake or wetland areas, and I transformed the land use/cover percentages with an arcsine transformation (Wilkinson 1996).

Indicators of human use: I used the riparian well density and percentage of riparian urban land use/cover for each lake, depressional wetland, and stream to compare the similarity of two different indicators of human use and residential development. I plotted the riparian well density for each waterbody against the percentage of riparian urban land use/cover and calculated the significance of the regression and correlation coefficients. This analysis was performed independently for lakes, depressional wetlands, and streams.

Results

Buffers

Creating 20 concentric 100 meter buffers around separate coverages of lakes, depressional wetlands, or streams results in three buffer coverages. The area that each buffer distance represents varies with distance from the water body and aquatic ecosystem type (Figure 9). The total buffer area for each distance increases further away from lakes and wetlands for the first three to five 100 m buffers (as would be expected from basic geometric properties of the area of circles). However, after the first 3-5 buffers, the area of each buffer decreases as you move away from the lakes or wetlands. This spatial pattern occurs because the buffers begin to overlap other buffers that are closer to another lake or are at the edge of the watershed. Unlike lakes and wetlands, streams do not show an initial increase in buffer area because they are more linear in shape and thus do not share the same geometric properties. Stream buffers show a steady decrease in area as they increase in distance from the stream and overlap buffers that are closer to another stream or reach the edge of the watershed. Because the analyses are corrected for area I expect these buffer area patterns will not influence the following results. The twenty 100 m buffers around each aquatic ecosystem type cover approximately 80% of the total watershed for lakes, 90% for depressional wetlands, and 75% for streams (Figure 9). I analyzed the proportion of urban, agriculture, and forest land use/cover in these buffers and found that these three land use/cover types make up between 60 and 80% of the total area for each buffer distance around all systems. Although they were not analyzed, the other land use/cover types do not change much through time in the watershed (Figure 3b) and should not have much of an influence on other land use spatial patterns observed in this study.

Spatial pattern

It appears that aquatic ecosystems are strongly correlated to spatial patterns in rural residential development and urban, agricultural, and forested land use/cover (Figure 10-13). The confidence intervals presented in these figures are very small because of the high number of individual waterbodies in each group. In general, the first two to four 100 m buffers around lakes, depressional wetlands, and streams are most dramatically influenced by the presence of the aquatic ecosystem. The buffers farther away from the lake, depressional wetland, or stream often show significant differences from overall watershed well density or land use/cover (dotted line). Additionally, buffers further away from waterbodies typically show the opposite relationship to the watershed average as buffers close to the system, possibly because if the well density is higher than average near lakes it has to be lower than the watershed average somewhere else.

Well density in the first 2-3 buffers around lakes, depressional wetlands, and streams, and therefore rural residential development, differs from the overall watershed well density (Figure 10). Lakes show the greatest difference from the overall watershed well density in the first 100m buffer where the density of wells is 2.5 times greater than the watershed as a whole (Figure 10a). Although lakes appear to attract rural residential development, depressional wetlands do the opposite and repel development (Figure 10b). Streams attract rural residential development beyond the first 100 meter buffer (Figure 10c). The first 100 meters adjacent to streams and the first 300 meters around wetlands have less development than the watershed as a whole and show similar degrees of development repulsion in the first 100 meters.

Land use/cover percentages show attraction and repulsion (i.e. positive and negative correlations) from aquatic ecosystems similar to spatial patterns of wells. Urban land use/cover shows trends almost identical to rural residential development trends, which I expected since they measure similar human modifications. Urban land use/cover is attracted to lakes and repelled from depressional wetlands and streams in the first few 100 m buffers (Figure 11). Lakes and streams strongly repel agricultural land use/cover, whereas wetlands attract it (Figure 12). All aquatic ecosystems have higher percentages of forest near them compared to the rest of the watershed (Figure 13). Streams only have an increase in forest in the first 100 meters, whereas lakes and depressional wetlands have higher percentage of forest in the first four to five 100 m buffers. Lakes also show a smaller attraction of forest compared to wetlands and streams, especially in the first buffer. Overall, lakes, depressional wetlands, and streams do alter the spatial pattern of development and land use/cover on the landscape.

Riparian land use/cover changes

This study shows that there have been some changes in the spatial patterns of rural residential development and land use/cover over 55 years. By comparing the most recent to the oldest coverage, I found the magnitude of the difference between riparian and watershed urban land use/cover percentage was more extreme for all systems in 1992 than it was in 1938 (Figure 14). The spatial pattern of agriculture around lakes does not change much with time, streams show a little less repulsion, and depressional wetlands show attraction more distinctly in 1992 than in 1938 (Figure 15). Forested land use/cover shows different changes in spatial pattern depending on the aquatic ecosystem. In 1992, there is slightly more forest in the watershed, but the amount of forest in the 100 m buffer around lakes decreased from 1938 to 1992 (Figure 16a). The other lake buffers increase in forest at a rate similar to the increase in forest in the watershed as a whole. Depressional wetlands show an overall increase in the magnitude of the difference between forest in the proximate buffers and entire watershed (Figure 16b). Stream buffers show little change in the spatial pattern of forested land use/cover over time, except an overall increase in percent forest in all buffers (Figure 16c).

Because riparian areas showed the most change, I examined the first 100 m buffer in greater detail. Spatial patterns in lake, depressional wetland, and stream riparian land use/cover percentages in the Huron River watershed have changed over the five timesteps between 1938-1992. In general, the percentage of urban in the riparian buffer increased in all timesteps for all systems (Figure 17a) and the percentage of agriculture decreased

(Figure 17b). Forest land use/cover in the riparian buffer showed less absolute change (Figure 17c). Because the confidence intervals are actually smaller than the data point in almost all cases, almost all of the observed changes are significant.

Riparian urban land use/cover around lakes changed from under 7% to over 35% over the 55 years, with the highest rate of increase between 1956 and 1971 (1265 ha/year) (Figure 17a). The percentage of urban land use/cover around streams is much smaller than around lakes and slightly less than is in the watershed for every timestep (except 1956 when there was a slightly higher amount of urban around streams than there was in the watershed) (Figure 17a and Table 4). Although depressional wetlands repel urban land use/cover even more than streams do, the difference between watershed and wetland riparian land use/cover percentages has been decreasing over the 55 year period (Figure 17a and Table 4). As was the case at the watershed scale, the urban land use/cover category is mainly comprised of residential uses in the areas riparian to lakes, depressional wetlands, and streams (64-76%). Other types of urban uses that were common (10-15%) around the waterbodies were extractive, industrial, and openland/outdoor recreation urban land use/cover classes.

Agricultural land use/cover has been decreasing around lakes, depressional wetlands, and streams and at the watershed scale across the study period. In 1938, the percentage of riparian area around lakes that was agricultural land use/cover was very similar to the percentage around streams (Figures 17b). Through time, the amount of riparian agriculture around streams decreased at a rate very similar to the watershed's decrease, but lakes lost much more agricultural land from their riparian zones. Depressional wetlands had slightly more agriculture in their riparian zones than found at

the watershed scale and the difference increased over the five timesteps (Figure 17b and Table 4).

Overall, forested land use/cover increased in the watershed from 1938 to 1992, with the peak of the increase between 1938 and 1971 (Figure 17c). Since 1971, forest area has been decreasing in the watershed. Riparian forest shows similar trends of peaking in the middle of the five time periods and then showing some decreases more recently (Figure 17c). During the first time period, lakes had more riparian forest than streams or wetlands (which were all higher than the percentage in the watershed), but by 1971 lakes had the least amount of riparian forest of the three systems. Wetlands started out with the least amount of forest around them and in 1992 had the highest percentage. In the last three timesteps, lakes show a faster rate of forest loss than the watershed. Riparian forests around streams have mirrored the changes in forest at the watershed scale very closely and the magnitude of the difference between watershed and riparian has changed very little over time (Table 4).

Effects of lake and wetland area

Lake area (in 10 ha bins) had a very small, but significant and positive relationship with riparian well density (Figure 18a; $p < 0.001$, $R^2 = 0.079$). Wetland area (in 5 ha bins) also had a significant and positive relationship with well density using a log transformation on well density and a power transformation on wetland area (Figure 18b; $p = 0.037$, $R^2 = 0.003$).

The percentage of each land use/cover type in the riparian zone around lakes and wetlands showed that some land use/cover types correlated with lake and wetland area (Figure 19). Lake area had a significant relationship with both urban (positive, $p = 0.005$,

$R^2 = .018$) and agriculture land use/cover (negative, $p = 0.065$, $R^2 = 0.008$). Wetland area had a significant positive relationship with agricultural land use/cover ($p = 0.043$, $R^2 = 0.003$). However, all relationships explain a very small amount of the variation between lakes in riparian well density and land use/cover percentages.

Indicators of human use

Comparing the percentage of urban land use/cover to well density in the riparian areas around each lake, depressional wetland, and stream showed that these two indicators of human use or residential development are not highly correlated although the regressions for lakes and depressional wetlands were significant ($p = 0.001$ and 0.005 respectively). The regression of riparian well density and urban land use/cover percentage for each stream was not significant after removing one outlier ($p = 0.253$). Although the regressions were significant, very little of the variation in riparian well density for each waterbody is explained by the percentage of the riparian buffer classified as urban land use/cover.

Discussion

The goal of this research was to gain a better understanding of land use/cover spatial pattern and change in relation to aquatic ecosystems and to help improve our understanding of aquatic-terrestrial linkages. Riparian areas play a proportionally greater role in influencing aquatic ecosystems than any other part of the watershed and yet also appear to be highly valued areas by humans. Therefore, understanding more about riparian land use/cover and the spatial pattern of land use/cover to aquatic systems should be important for land use/cover planning and management. We measured spatial pattern by measuring the magnitude of the difference between the land use percentage in buffers around each type of waterbody and the watershed. There are two important outcomes of this research. First, the presence of lakes, depressional wetlands, and streams are correlated to spatial patterns in rural residential development and urban, agricultural, and forested land use/cover. Second, the area closest to waterbodies (up to 500 m away) is most dramatically affected by the presence of the aquatic ecosystem.

Predicting land use/cover change is useful, but inherently difficult. One way to improve our understanding of land use/cover change is to ensure that the most significant variables are included as predictors of future land use/cover. Typically, natural features on the landscape, especially aquatic ecosystems, have not been used to predict land use/cover change. This study has revealed that lakes, depressional wetlands, and streams may be useful to include in predictive models because they are highly correlated to some spatial patterns of human use of the landscape.

Spatial pattern

Using well density as an indicator of rural residential development, I found rural residential development was strongly attracted to lakes and repelled (less strongly though) from depressional wetlands and streams (in the first 100 meters). I found strong correlations between the location of aquatic ecosystems and rural residential development and land use/cover supporting my hypothesis that in fact lakes, depressional wetlands, and streams may drive spatial patterns on the landscape. The percentage of urban land use/cover showed very similar spatial patterns to well density (attraction to lakes and repulsion from depressional wetlands and streams in the riparian buffer). Beyond 100 meters, streams did attract urban land use/cover, which suggests that depressional wetlands may be the only type of aquatic ecosystem that truly repels urban development. Depressional wetlands were also the only aquatic ecosystem to attract agriculture and showed the largest difference in the percent of forest compared to the entire watershed. For depressional wetlands, as well as lakes and streams, the attraction or repulsion of certain land use/cover types may be due in part to the spatial distribution of other land use/cover types. Specifically, depressional wetlands may have had more agriculture and forest around them because the percent of urban land use/cover in the first several buffers away from depressional wetlands was lower than for lakes or streams.

The increase in proportion of urban land use/cover around aquatic ecosystems is ecologically important. The processes through which land use/cover affects aquatic ecosystems likely occur at different scales for different variables and are still not well understood. These relationships have been examined mainly for streams (Roth et al. 1996; Allan et al 1997). Although there is still some debate over what scale aquatic ecosystems respond most closely to human modifications, it is clear that the spatial pattern of land use/cover on the landscape is important to ecosystems. These discrepancies are due in part to the scale and focus of each study (Lammert and Allan 1999). Depending on the study, either the entire watershed (Omernik et al. 1981; Hunsaker and Levine 1995; Roth et al. 1996) or only riparian land use/cover (Richards et al. 1996; Soranno et al. 1996; Lammert and Allan 1999) has been found to be a better predictor of aquatic conditions. The importance of the spatial pattern of land use/cover to aquatic ecosystems makes it more important that we understand how lakes, wetlands, and streams drive those spatial patterns.

The strong attraction of human residential development to areas around lakes, and to a lesser extent streams, may mean that urban land use/cover may be influencing the relationship with other land use types around lakes. Lakes attract urban land use/cover within the first three hundred meters which likely raises property values and decreases the likelihood of agriculture and forests occurring in this area (Orr 1997). Land use/cover in the first 100 m buffer around streams may be driven in part by the hazard of occasional flooding (Bollens 1990) and because of public education on the importance of forested riparian buffer strips around streams. The increase in urban proportion in the near-stream buffers (beyond the first 100 m buffer) may be indicative of a general trend of rural residential development that is occurring in southeastern Michigan (Erickson 1995). For example, in the River Raisin watershed between 1968 and 1988 there was an overall increase in urban land use/cover and decrease in agriculture. Erickson (1995) expected forested land to also decrease in this time period, but actually found that it in fact increased.

Similar to the potential effects of floods on streamside development, the geomophology that creates wetlands most likely has an effect on how the land is modified by humans. The lower percent urban land use/cover near depressional wetlands may lead to the higher percentage of forest around depressional wetlands than in the watershed as a whole. I found that wetlands slightly attract agriculture, but I had not expected to see a positive correlation between the location of wetlands and agricultural land use/cover. However, because agricultural land in southeastern Michigan is often created by draining wetlands (Erickson 1995), these two land use/cover types may be more likely to occur in close proximity to each other.

Riparian land use/cover changes

The spatial pattern of land use/cover around aquatic ecosystems in the Huron River watershed has not changed between 1938 and 1992. For example, in all timesteps urban land use/cover was attracted to lakes and forest was attracted to all three types of aquatic ecosystems. The absolute amount of each land use/cover type has changed through time. One of the components of land use/cover spatial pattern that has changed around aquatic ecosystems in the magnitude of the difference between each land use/cover type in the riparian zone and at the watershed scale. For example, for wetlands the magnitude of the difference of urban land use/cover was higher for the first three to four 100 meter buffers in 1992 than in 1938, but in both timesteps, depressional wetlands repelled urban land use/cover. This change in magnitude may indicate a change in the way wetlands are viewed by society (i.e. less likely to build within 100 meters of them in 1992). Lakes showed an increased magnitude of urban attraction through time. This result suggests that lakes increasingly attract people to develop in the riparian area as both the population in the watershed increases and possibly as lakes become more developed. From 1938 to 1992, there was an increase in the number of buffers around lakes (beginning from the shoreline) with higher percentages of urban land use/cover than the watershed average, as well as an increase in the magnitude of the difference. This result is likely due partly to the overall low percentage of urban land in the watershed in 1938, but could also show that the distance from lakes that attracts development is growing. In 1938 it was only in the first 100 meters that had a higher percentage of urban than the watershed, but in 1992 four 100 meter buffers showed an increase in human residential development.

One of the more extreme changes in land use/cover around aquatic ecosystems that has occurred in the Huron River watershed is the change in the total percentage of urban land use/cover around lakes through time. In 1938, ~6% of the 100 m riparian buffer around lakes was urban. In 1992 the percentage was ~35%. Urban land use/cover also increased around depressional wetlands and streams, but neither increase was as extreme as lakes. There are important implications for lake ecosystems of the increase in the percent of urban land use/cover around lakes from 6% to 35% (NRC 1992; Smith 1998). On average increasing the percentage of urban land in a watershed increases nitrogen and phosphorus load to aquatic ecosystems (Omernik 1976). This can have dramatic impacts on chlorophyll concentrations and percent of nuisance algae species in lakes (Smith 1998).

We can also examine trends in individual lakes through time to understand how changes in land use/cover affects an individual lake, wetland, or stream. Of the 453 lakes in this study, 324 increased in the percentage of urban from 1938 to 1992, 128 remained the same, and only 1 decreased (the decrease was a 5% reduction in urban percentage which is within the possible measurement error) (Figure 20). Sixty percent of depressional wetlands and 106 of the 110 stream segments had an increase in the percentage of riparian urban land use/cover. These relationships between percent urban in 1938 and 1992 show that it is unlikely that any waterbody will become less developed through time. For example, the lakes with very low urban land use/cover percentages in 1938 showed the full range of development in 1992 which suggests that lakes with low development are not likely to remain that way in the future unless zoning or other planning measures are put into place. In addition, there were very few lakes with high development in 1938 (Figure 20). In 1938 there were very few lakes with more than 50% of their riparian zone classified as urban land use/cover, however, by 1992 many lakes had more than 50% of their riparian buffer in urban land use/cover. This result can have important implications for lake ecosystems because lakes with changes in residential development have been shown to have larger changes in conductivity, alkalinity, calcium, and pH over a 50 year period (Eilers et al. 1989).

It is interesting to note that while most of the research on the effects of land use/cover on aquatic ecosystems has focused on streams, while my study revealed there is proportionally less urban development in the 100 meters closest to streams than in the watershed as a whole. Notably, there is also much less urban riparian land use/cover around streams compared to lakes. This result is supported by other reports of riparian land use where urban land use/cover was also found to be proportionally less in riparian buffers around streams (Tufford et al. 1998). Tufford et al. (1998) also found smaller percentages of agriculture and higher percentages of forest around streams that an the watershed scale. Similarly, a study in the River Raisin watershed, just south of the Huron River watershed, found that between 1968 and 1988 there had been an increase in riparian forests next to streams (Kleiman and Erickson 1996). In the River Raisin the number of acres being farmed and the number of farms have both decreased resulting in the removal of marginal land from farming which may have influenced the increase in riparian forest in both their and my studies. The majority of research on the effects of riparian buffers has also been conducted primarily on streams. These studies have shown that forested buffers are important in streams ecosystems because they help regulate water quantity and quality. Presently, many studies have shown an increase in the percentage of stream channel lined by riparian forest, suggesting a conservation of land to preserve streams. There has been less focus on the use of riparian areas around lakes and wetlands however, and in fact lakes attract development into the riparian areas. A thorough and complete understanding of why these spatial patterns occur and why they change was beyond the scope of this research, but it is likely that legislative, social, and economic factors interact to change both human behavior and the role that lakes, streams, and wetlands play in determining land use spatial pattern.

Effects of lake and wetland area

Because strong relationships were found between aquatic ecosystems and land use/cover spatial patterns, I examined how this relationship varied across lakes and depressional wetlands with different surface areas. My results show that both depressional wetland and lake area have positive and significant relationships with well density which means that larger bodies of water have higher well densities around them, although the variance in well density explained by lake or wetland area was very low. Intuitively, this relationship makes sense for lakes because larger lakes may attract more people for the increased opportunities for recreation. The relationship with wetland area is less intuitive, no relationship was expected to be found between well density and wetland area. The percentage of urban land use/cover was also significant with lake area which corroborates the finding of a significant relationship with well density and lake area. Urban land use/cover percentage was not found to have a significant relationship with depressional wetlands, although well density was significant, suggesting that this is not a strong relationship. In addition to urban land use/cover, agricultural land use/cover was found to be significant to both lake (negative) and depressional wetland area (positive). A possible explanation of these results is that because of the positive relationship with urban land use/cover, larger lakes are less likely to have agriculture around them. The positive relationship between depressional wetlands and agriculture is more difficult to explain and may be specific to this watershed. However, the topography and hydrology around depressional wetlands may vary with wetland size and result in better-suited conditions around larger depressional wetlands for agriculture.

For all of the surface area analyses, it is important to keep in mind that although these relationships were found to be significant, a very small amount of the variance in well density and land use/cover percentage is explained by surface area. These relationships may be weak partly because the range in lake and depressional wetland surface area is not very wide. The smallest waterbodies (< 2 ha) were removed from the analysis and the upper range was not very large (maximum: ~400 ha lake and ~80 ha depressional wetland). A wider range in sizes may have resulted in stronger relationships.

One of the factors not explicitly examined in this study that may affect the percent of riparian urban land use/cover around a lake is the distribution of lakes on the landscape and the relative locations of large urban centers. In the Huron River watershed, the natural distribution of lakes results in an uneven scattering of lakes and lake sizes within the watershed. The northern part of the watershed has more and larger lakes than the southern portion. Figure 22 shows that lakes with higher percentages of urban land use/cover in the 100 m riparian zone are somewhat clumped together in 1992. This suggests that the distance from one lake to another may be important in determining how developed a lake will become. In 1938, there also seems to be some spatial pattern between distance to other lakes and shoreline development. Therefore, the distribution of lakes on the landscape appears to play a role in determining urban riparian development, although it would be necessary to analyze this pattern more quantitatively in a variety of watersheds to conclude if this is an ecologically significant spatial pattern.

Indicators of human use

I examined how aquatic ecosystems drive spatial patterns on the landscape by using well density and land use/cover as indicators of human modification of the landscape. I expected to find a similarity between the spatial pattern of well density and urban land use/cover because they indicate similar human modification of the landscape. However, they result in slightly different conclusions about the magnitude of the difference between the riparian and watershed averages. For example, for lakes the first 100 m buffer had a well density 2.5 times higher than the watershed, while the urban percentage in that buffer was only 1.3 times higher. Urban land use/cover indicates when an area of land is being used for residential, commercial, or industrial purposes. It does not reveal anything about the intensity of that use. Well densities can only be used in areas without public water supplies (i.e. rural) and is therefore most useful for examining rural residential development. Unlike urban land use/cover, wells can give you information about the density of development which may be ecologically important (Dillon and Rigler 1975; Hutchinson et al. 1991). In fact, well density and the percent of urban land use/cover for the first 100 m buffer around each lake, depressional wetland, and stream are not strongly correlated, although the regression is statistically significant ($p < 0.001$) (Figure 22). As the percent of urban land use/cover increases in the buffers, there is an overall increase in well density, but there is a great deal of variation around this relationship. In fact, eighty percent of the wells were in land use/cover classified as urban, 6% in agriculture, 5% in forest, and 9% in other land use/cover types, suggesting that there is also slight variation in the land use/cover category associated with a given well. This result suggests that well density and urban proportion reflect different features of human use and that well density can provide more of an indicator of the intensity of human use. Depending on the question, it is important to carefully choose which indicator of development is used.

Conclusions

In this study, I examined if rural residential development and land use/cover showed any spatial patterns in relation to aquatic ecosystems in the Huron River watershed. My results show that urban, agricultural, and forested land use/cover types have different distributions in riparian zones than in the watershed as a whole and show different rates of change through time. My results may be typical for the North temperate glaciated landscapes in regions with a large human population, but warrant further research in other watersheds and regions.

A complete understanding of how natural features on the landscape affect land use/cover spatial pattern and change will add to our ability to predict land use change in the future and help better manage land use in environmentally sensitive and highly valued areas such as riparian zones. Although riparian areas do play a proportionally greater role in influencing aquatic ecosystems than other parts of the watershed, riparian areas cannot be expected to mitigate the effects of uncontrolled modification of the landscape, especially when they are also under development pressure.

APPENDIX 1

TABLES AND FIGURES

Table 1. Summary characteristics of aquatic ecosystems in the Huron River watershed.

	Lake	Wetland	Stream
Number of polygons	453	1296	110 segments
Total area or length	6249 ha	5455 ha	553 km
Area or length range	1 – 412 ha	1-77 ha	0.6 – 24.7 km
Mean area or length	13.8 ha	4.2 ha	5.0 km
Median area or length	3.4 ha	2.4 ha	4.0 km

Table 2. Summary of wetlands in the Huron River watershed classified into forested and nonforested classes. The number of wetlands that were removed from the nonforested wetland group to create the depressional wetland group are also described.

	Area (ha)	Number
Forested wetlands	3296	662
Nonforested wetlands	8796	1840
Depressional	5574	1312
Nonforested riparian	3222	528

Table 3. Wetland area and number of wetlands classified to nonforested and forested wetland types. The percent change is reported for a timestep from the previous timestep.

Wetland area	**Nonforested**		**Forested**		**Total**	
	Wetland area (ha)	% change	Wetland area (ha)	% change	Wetland area (ha)	% change
1938	13199		4534		17733	
1956	10072	-24%	3534	-22%	13606	-23%
1971	9063	-10%	3376	-4%	12439	-9%
1985	8912	-2%	3336	-1%	12248	-2%
1992	8796	-1%	3296	-1%	12092	-1%

Number of wetlands	**Nonforested**		**Forested**		**Total**	
	Number	% change	Number	% change	Number	% change
1938	4296		1386		5682	
1956	2598	-40%	850	-39%	3448	-39%
1971	2061	-21%	742	-13%	2803	-19%
1985	1979	-4%	716	-4%	2695	-4%
1992	1840	-7%	662	-8%	2502	-7%

Table 4. Difference in percent of watershed land use from percent of riparian land use

URBAN	Year	Lake	Wetland	Stream
	1938	2.1	-2.9	-0.6
	1956	7.4	-4.6	1
	1971	11.3	-7.9	-1.2
	1985	11.7	-8.3	-2.3
	1992	9.8	-9.0	-3.3
AGRICULTURE		Lake	Wetland	Stream
	1938	-24.8	0.1	-23.9
	1956	-24.3	3.1	-21.4
	1971	-23.7	3.0	-16.3
	1985	-22.6	3.8	-14.4
	1992	-20.7	4.5	-13.3
FOREST		Lake	Wetland	Stream
	1938	6.8	2.3	4.8
	1956	6.3	4.0	7.1
	1971	3.7	6.2	5.0
	1985	3.2	6.3	5.1
	1992	2.5	5.9	5.1

LIST OF FIGURES

Figure 8. Frequency distribution of lake (a) and depressional wetland (b) areas placed in 10 and 5 hectare bins, respectively.

Figure 9. Area of land included in each buffer around lakes (a), depressional wetlands (b), and streams (c) and the cumulative percent area of all buffers to a given distance.

Figure 10. Weighted mean well density (wells/km^2) and 95% confidence intervals for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed line is the average well density in the watershed after removing lake, wetland, stream, and towns from the area of the watershed.

Figure 11. Weighted means and 95% confidence intervals of the percentage of urban land use/cover in 1992 for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed line is the percentage of urban land use/cover in the entire watershed.

Figure 12. Weighted means and 95% confidence intervals of the percentage of agricultural land use/cover in 1992 for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed line is the percentage of agricultural land use/cover in the entire watershed.

Figure 13. Weighted means and 95% confidence intervals of the percentage of forest land use/cover in 1992 for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed line is the percentage of forest land use/cover in the entire watershed.

Figure 14. Weighted means and 95% confidence intervals of the percentage of urban land use/cover in 1938 (grey bars) and 1992 (black bars) for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed lines are the percentages of urban land use/cover in the entire watershed in 1938 and 1992.

Figure 15. Weighted means and 95% confidence intervals of the percentage of agricultural land use/cover in 1938 (grey bars) and 1992 (black bars) for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed lines are the percentages of agricultural land use/cover in the entire watershed in 1938 and 1992.

Figure 16. Weighted means and 95% confidence intervals of the percentage of forest land use/cover in 1938 (grey bars) and 1992 (black bars) for each buffer distance around lakes (a), depressional wetlands (b), and streams (c). Dashed lines are the percentages of forest land use/cover in the entire watershed in 1938 and 1992.

Figure 17. Weighted mean percentage of urban (a), agricultural (b), and forest (c) land use/cover in the 100 meter buffer around lakes, depressional wetlands, and streams for each timestep. 95% confidence intervals are presented with the means, but are not visible

because they are smaller than the data points. Note that forest (c) has a different scale on the y-axis.

Figure 18. Box plots of well density in the 100 meter buffer around lakes (a) and depressional wetlands (b) grouped into 10 and 5 hectare bins, respectively.

Figure 19. Box plots of percentage of urban, agriculture, and forest land use/cover in the 100 meter buffer around lakes (a) and depressional wetlands (b) grouped into 10 and 5 hectare bins, respectively.

Figure 20. Percentage of urban land use/cover in the 100 meter buffer around each lake in 1992 as compared to 1938.

Figure 21. Lakes are shaded to represent the percentage of urban land use/cover in the 100 meter buffer around each lake in 1938 (a) and 1992 (b) in a subset of the watershed. Images in this figure are presented in color.

Figure 22. Percentage of urban land use/cover in the 100 meter buffer around each lake (a), depressional wetland (b), and stream (c) in 1992 compared to the well density (wells/km^2) in the 100 m buffer around each lake. The R^2 and p-value reported for streams were calculated after removing one outlier.

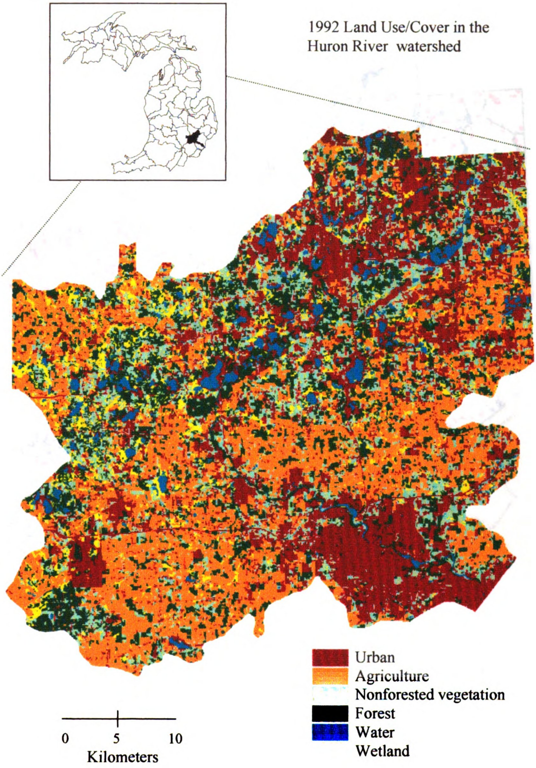

1992 Land Use/Cover in the
Huron River watershed
Urban
Agriculture
Nonforested vegetation
Forest
Water
Wetland
0
5
10
Kilometers

Figure 1

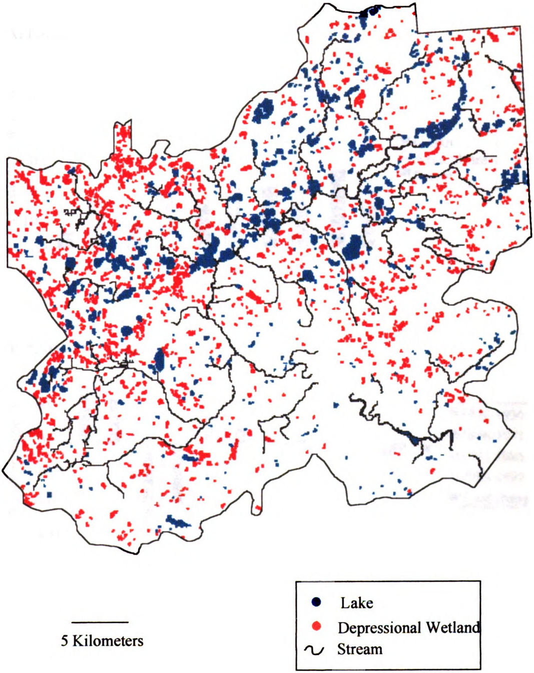
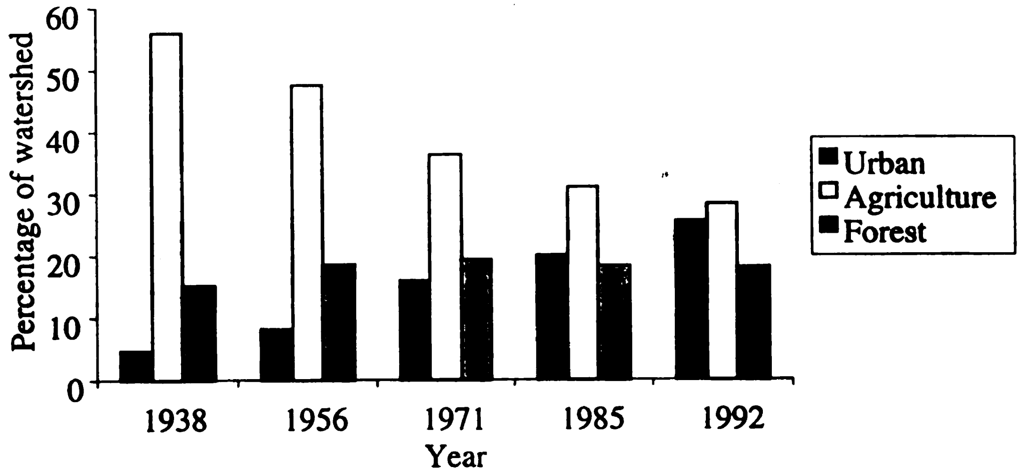


Figure 2

A. Land use percentages



B. Rate of land use change

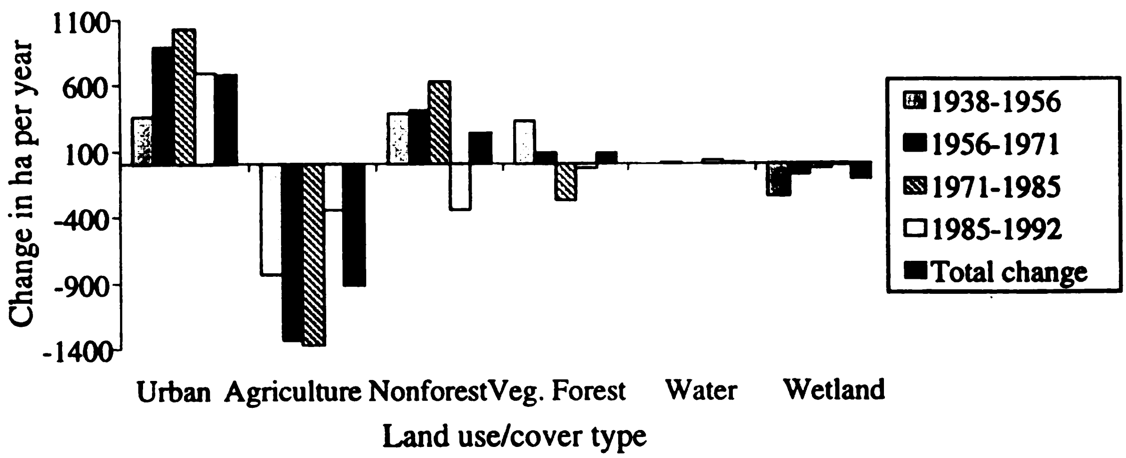


Figure 3

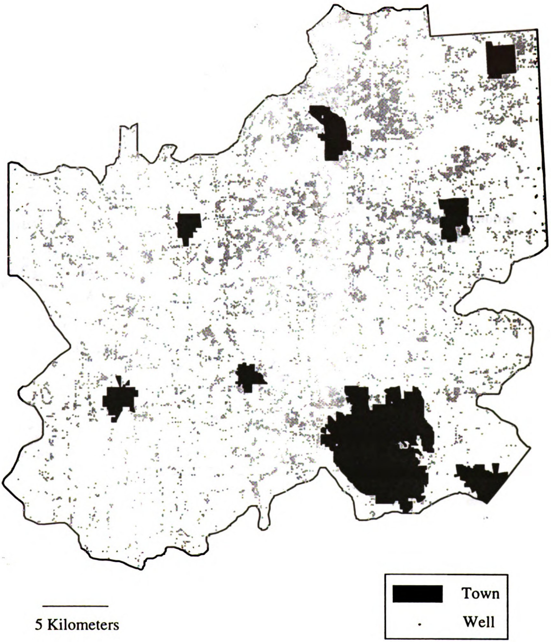


Figure 4

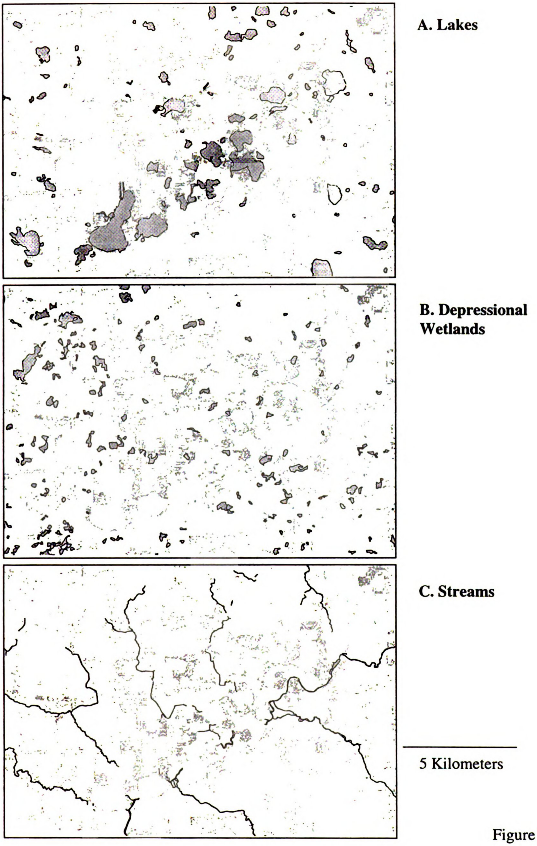


Figure 5

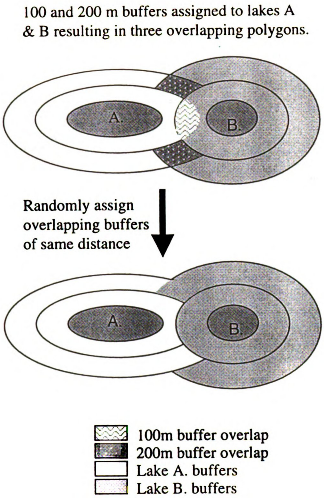
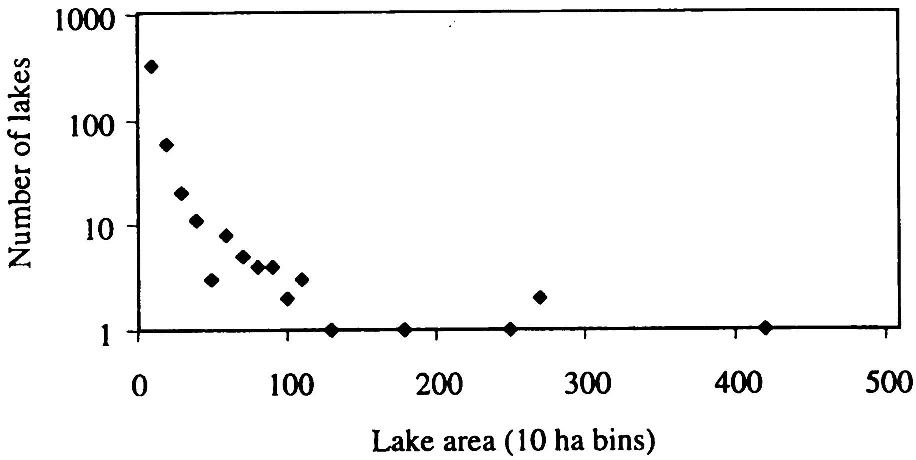

100 and 200 m buffers assigned to lakes A
& B resulting in three overlapping polygons.
A.
B.
Randomly assign
overlapping buffers
of same distance
A.
B.
100m buffer overlap
200m buffer overlap
Lake A. buffers
Lake B. buffers

Figure 6

5 Kilometers

Figure7

A. Lake areas



B. Depressional wetland areas

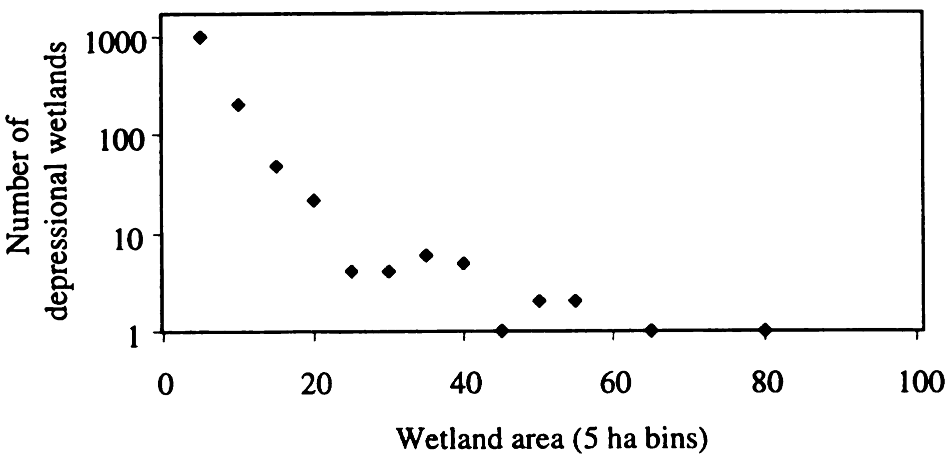


Figure 8

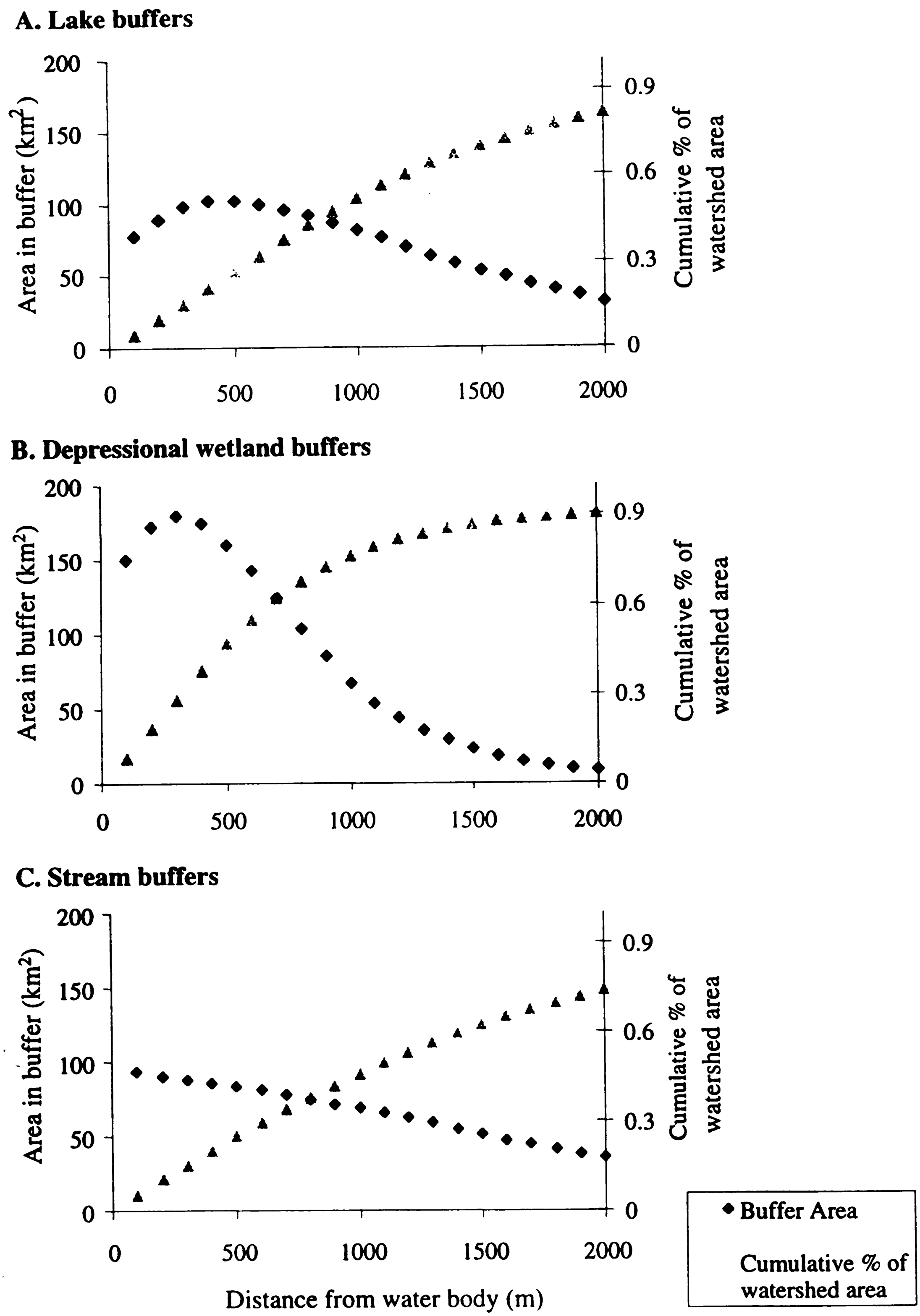

A. Lake buffers
B. Depressional wetland buffers
C. Stream buffers
Area in buffer (km2)
Cumulative % of watershed area
0
50
100
150
200
0.3
0.6
0.9
500
1000
1500
2000
Distance from water body (m)
Buffer Area
Cumulative % of watershed area

Figure 9

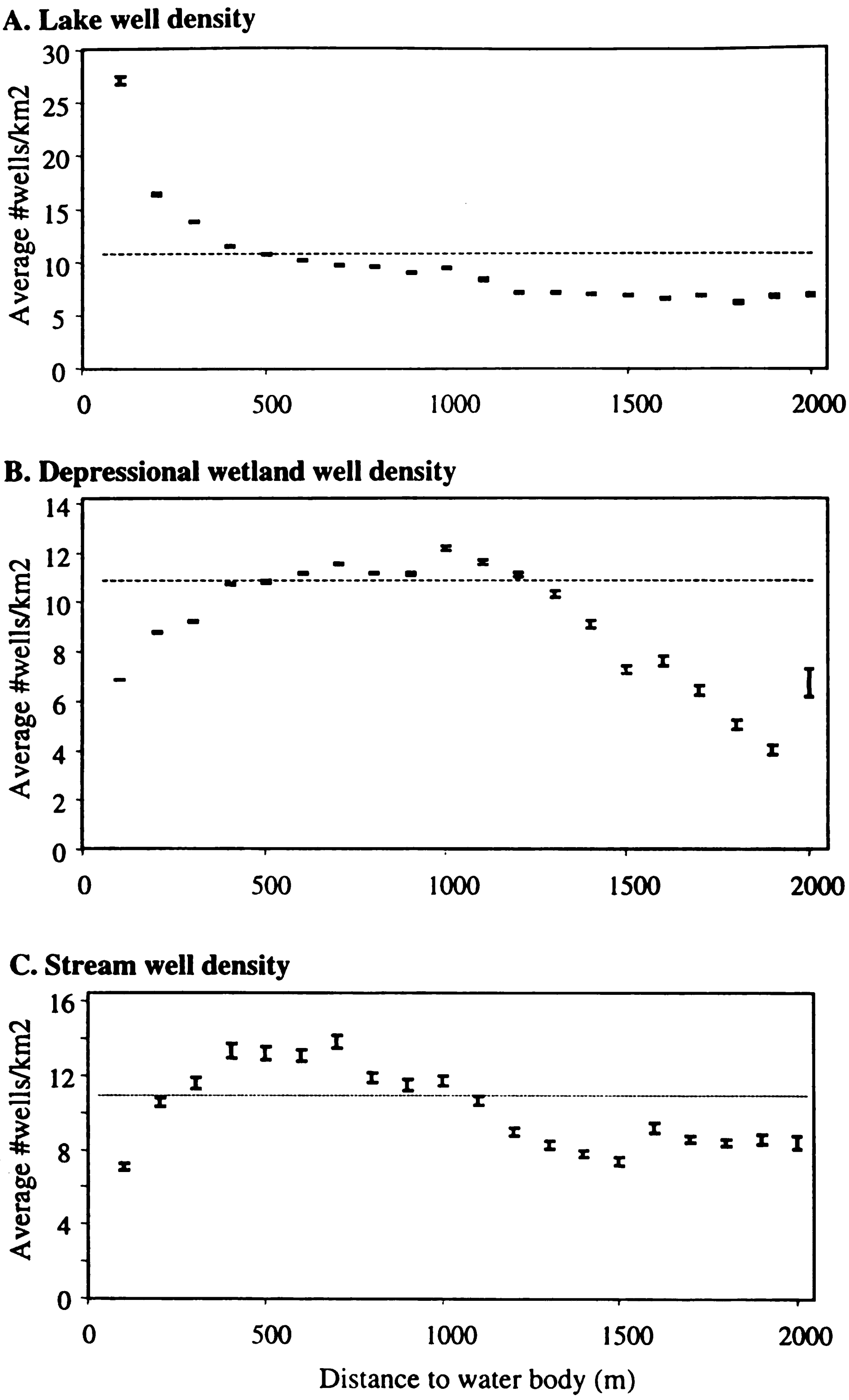

A. Lake well density
Average #wells/km2
0
5
10
15
20
25
30
0
500
1000
1500
2000
B. Depressional wetland well density
Average #wells/km2
0
2
4
6
8
10
12
14
0
500
1000
1500
2000
C. Stream well density
Average #wells/km2
0
4
8
12
16
0
500
1000
1500
2000
Distance to water body (m)

Figure10

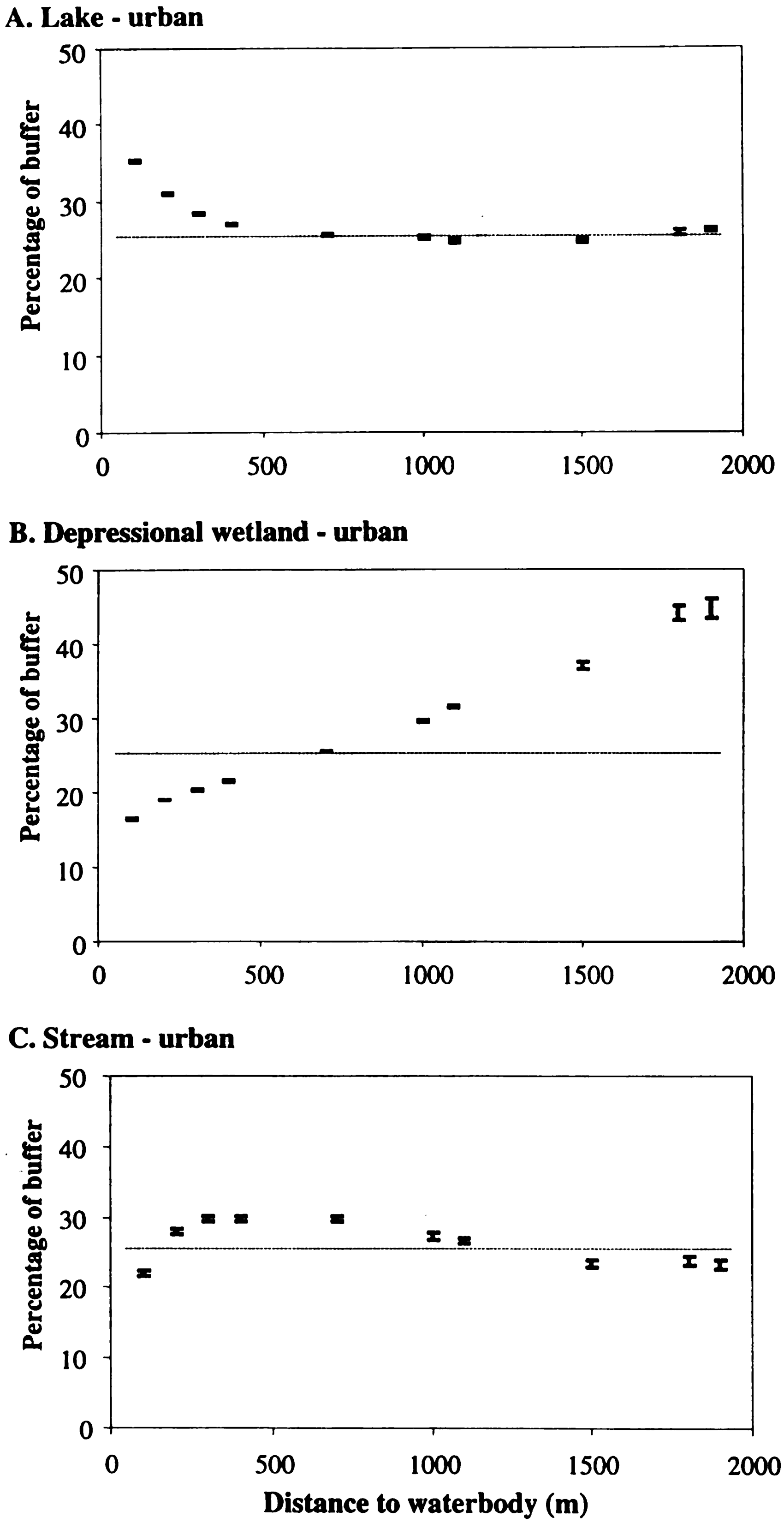

A. Lake - urban
B. Depressional wetland - urban
C. Stream - urban
Percentage of buffer
0
10
20
30
40
50
0
500
1000
1500
2000
Distance to waterbody (m)

Figure 11

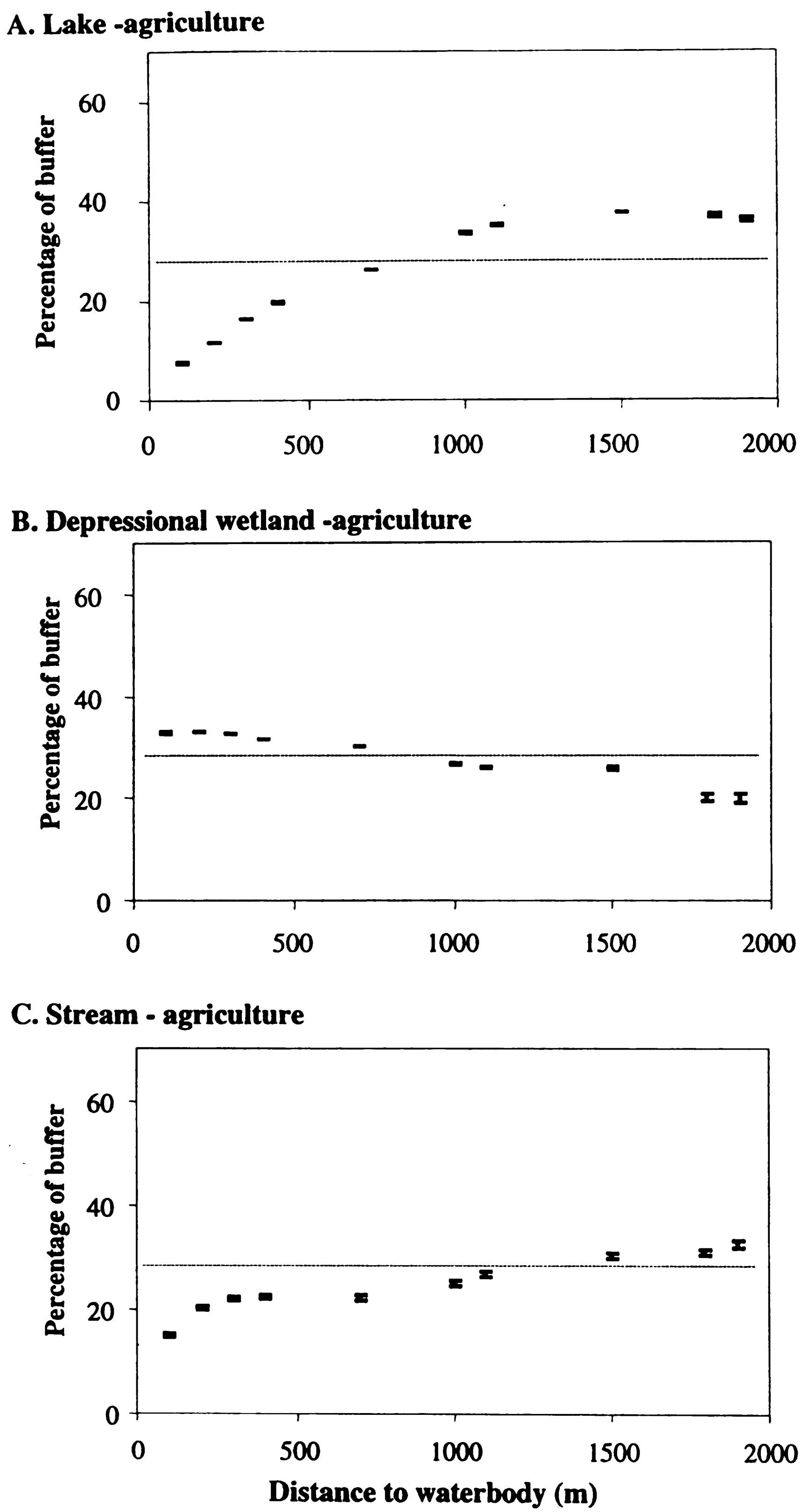

A. Lake -agriculture
Percentage of buffer
60
40
20
0
0
500
1000
1500
2000
B. Depressional wetland -agriculture
Percentage of buffer
60
40
20
0
0
500
1000
1500
2000
C. Stream - agriculture
Percentage of buffer
60
40
20
0
0
500
1000
1500
2000
Distance to waterbody (m)

Figure 12

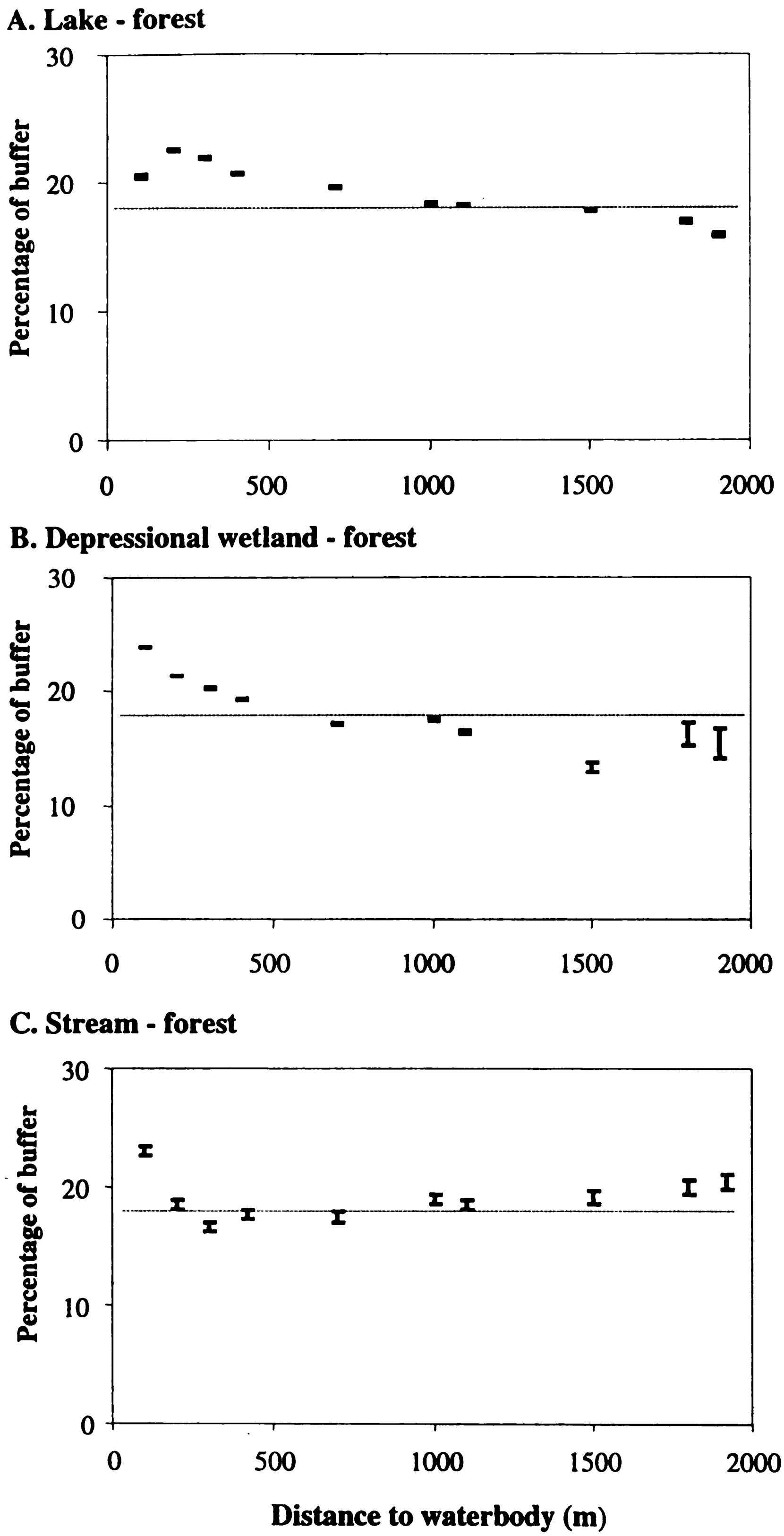
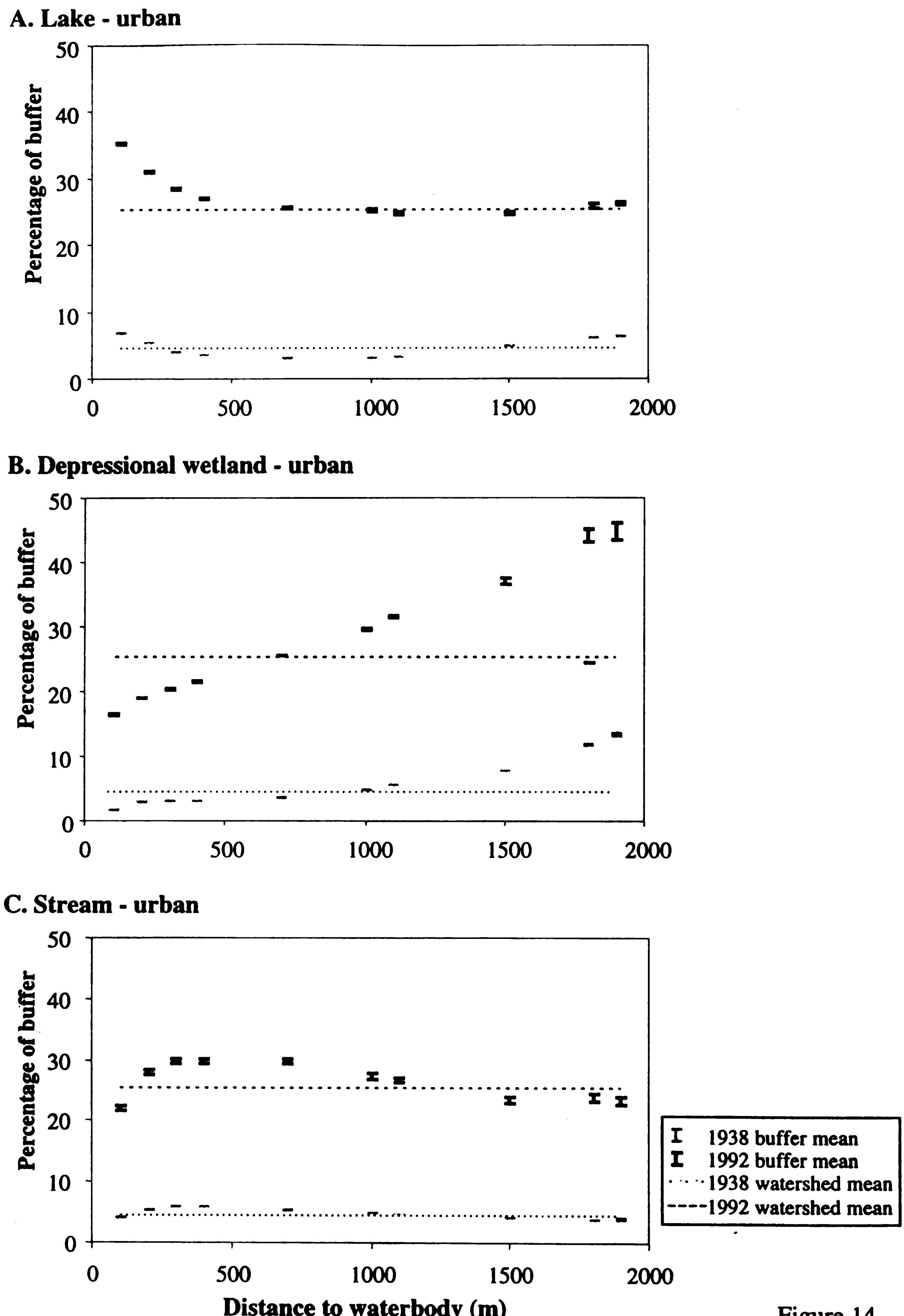

A. Lake - forest
B. Depressional wetland - forest
C. Stream - forest
Percentage of buffer
0
10
20
30
0
500
1000
1500
2000
Distance to waterbody (m)

Figure 13



A. Lake - urban
Percentage of buffer
B. Depressional wetland - urban
Percentage of buffer
C. Stream - urban
Percentage of buffer
Distance to waterbody (m)
1938 buffer mean
1992 buffer mean
1938 watershed mean
1992 watershed mean

Figure 14

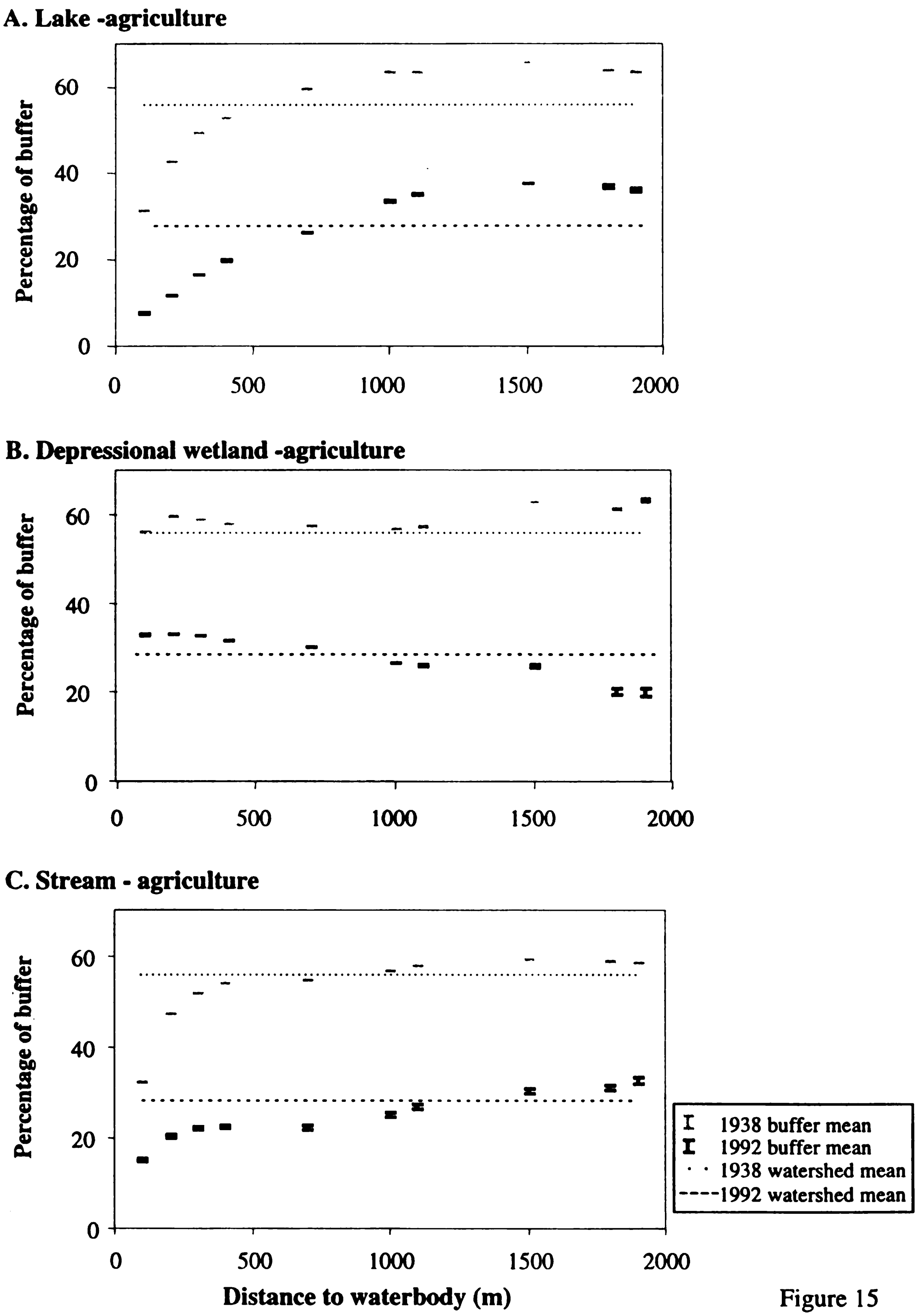
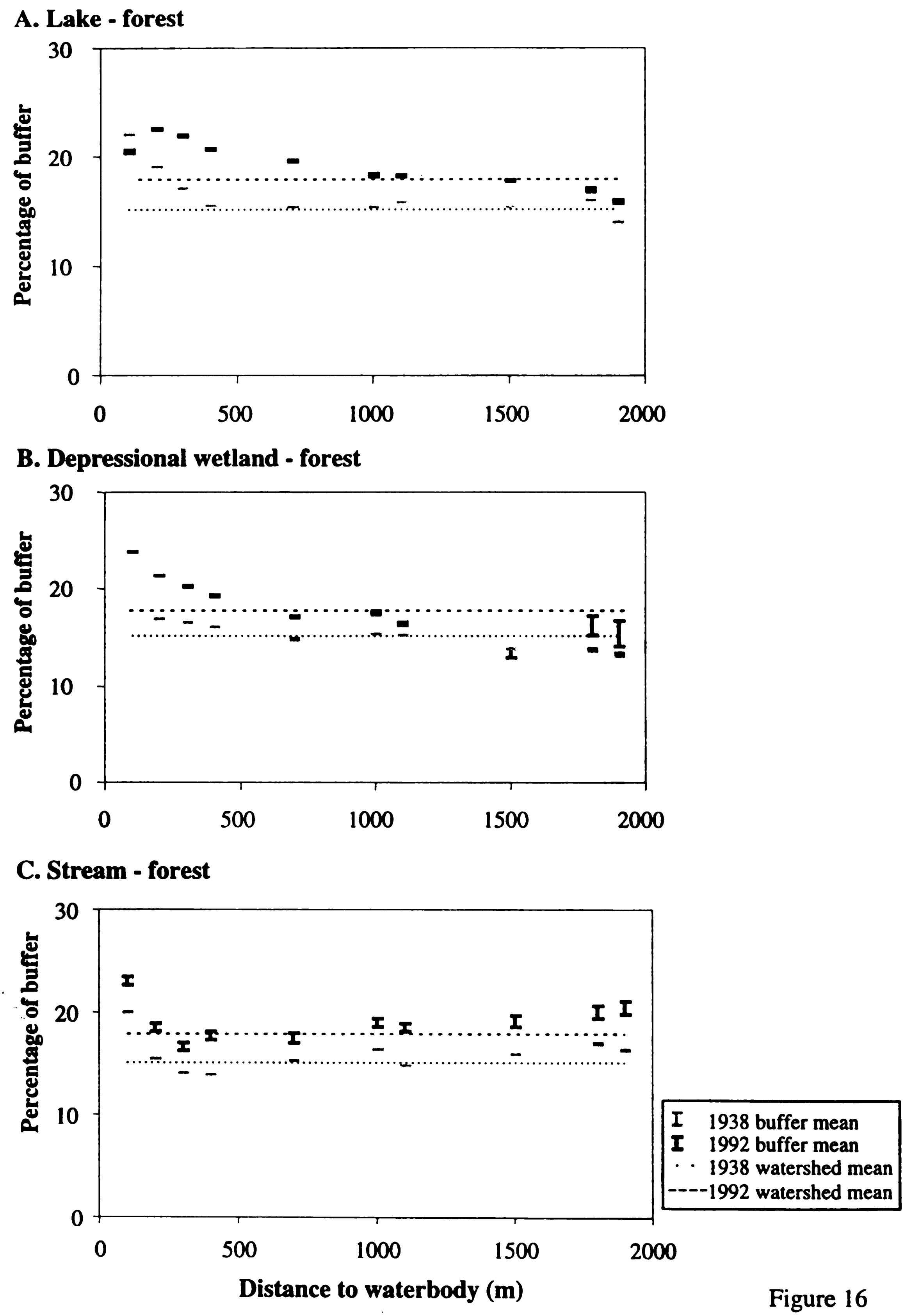

A. Lake -agriculture
Percentage of buffer
0
20
40
60
0
500
1000
1500
2000
B. Depressional wetland -agriculture
Percentage of buffer
0
20
40
60
0
500
1000
1500
2000
C. Stream - agriculture
Percentage of buffer
0
20
40
60
0
500
1000
1500
2000
Distance to waterbody (m)
1938 buffer mean
1992 buffer mean
1938 watershed mean
1992 watershed mean

Figure 15



A. Lake - forest
B. Depressional wetland - forest
C. Stream - forest
Percentage of buffer
30
20
10
0
0
500
1000
1500
2000
Distance to waterbody (m)
1938 buffer mean
1992 buffer mean
1938 watershed mean
1992 watershed mean

Figure 16

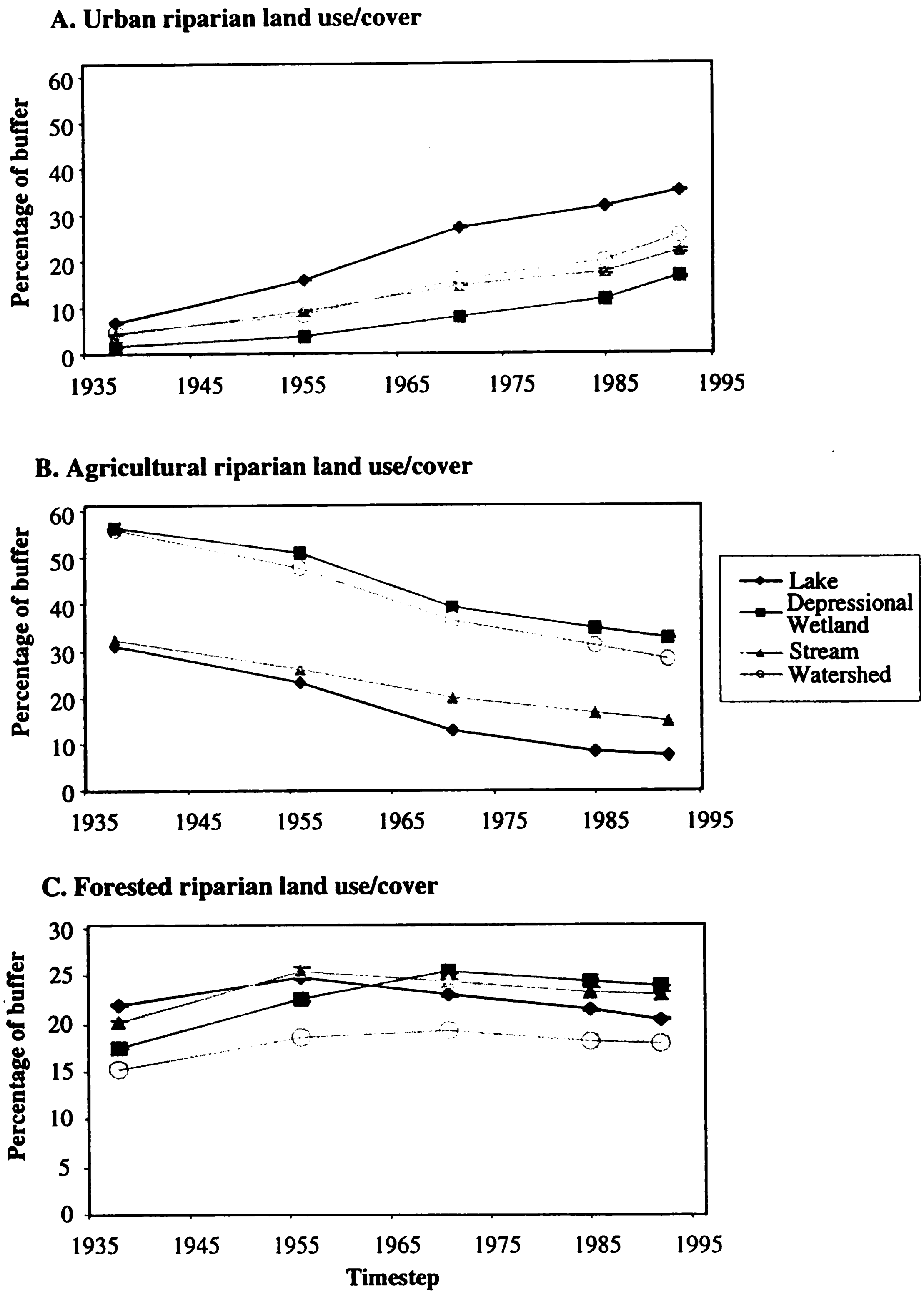
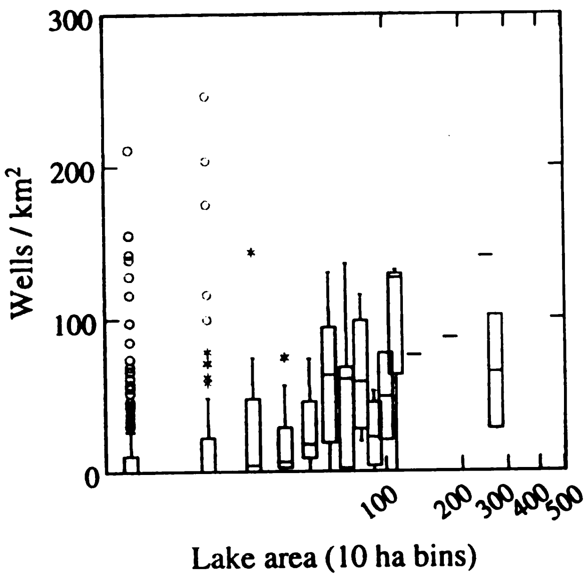

A. Urban riparian land use/cover
Percentage of buffer
0
10
20
30
40
50
60
1935
1945
1955
1965
1975
1985
1995
B. Agricultural riparian land use/cover
Percentage of buffer
0
10
20
30
40
50
60
1935
1945
1955
1965
1975
1985
1995
Lake
Depressional Wetland
Stream
Watershed
C. Forested riparian land use/cover
Percentage of buffer
0
5
10
15
20
25
30
1935
1945
1955
1965
1975
1985
1995
Timestep

Figure 17

A. Lake area - well density



B. Depressional Wetland area - well density

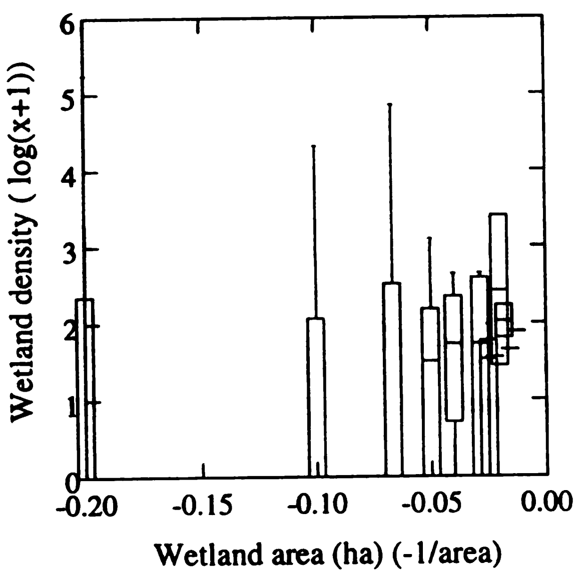
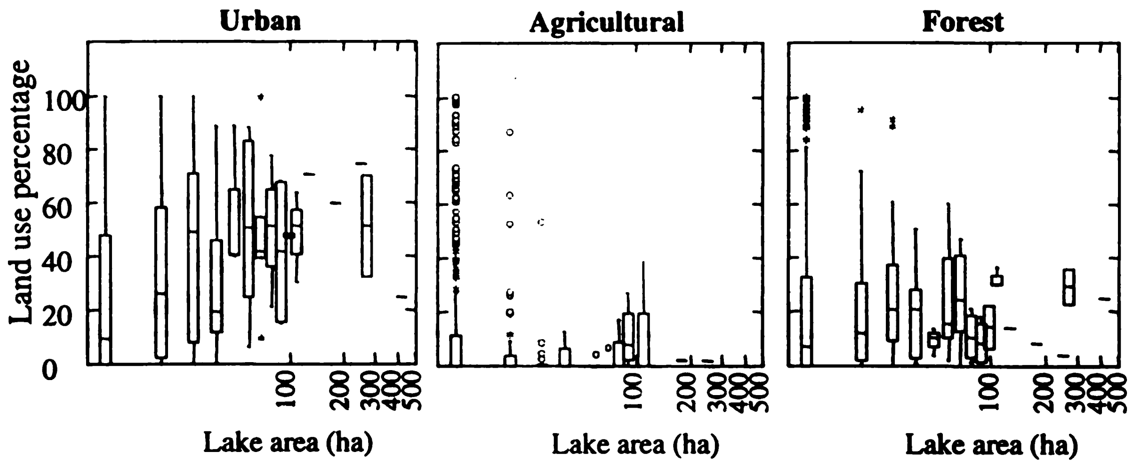


Figure 18

A. Lake area - land use percentage



B. Depressional Wetland area - land use percentage

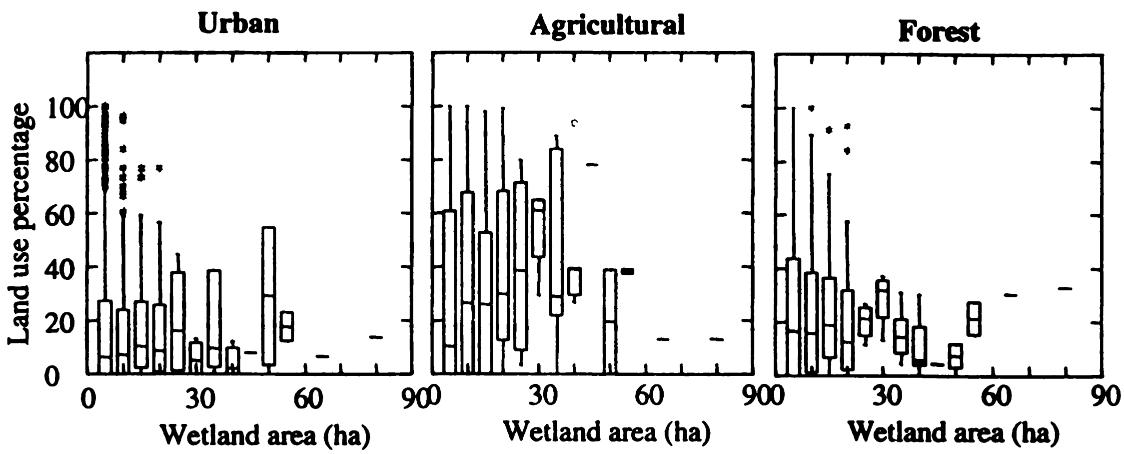
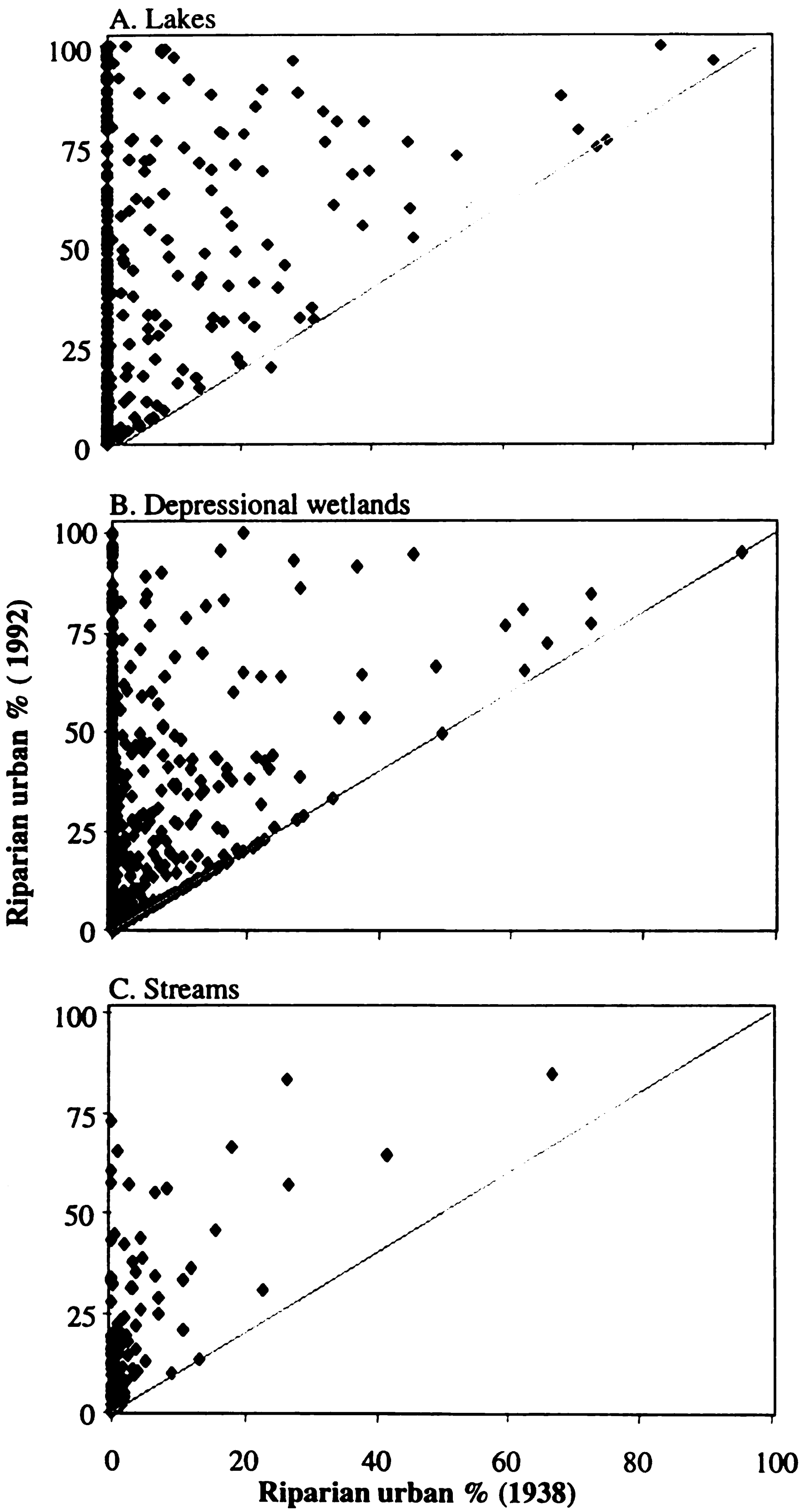


Figure 19



A. Lakes
B. Depressional wetlands
C. Streams
100
75
50
25
0
0
20
40
60
80
100
Riparian urban % (1992)
Riparian urban % (1938)

Figure 20

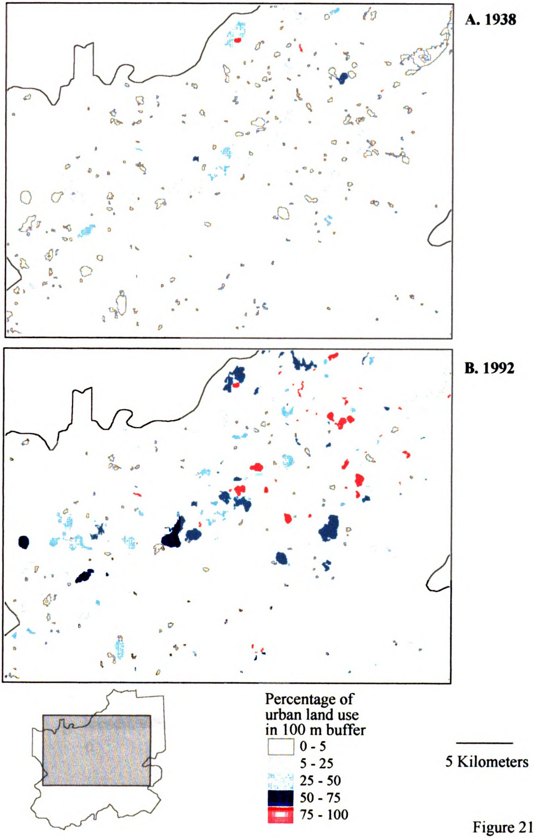

A. 1938
B. 1992
Percentage of
urban land use
in 100 m buffer
0 - 5
5 - 25
25 - 50
50 - 75
75 - 100
5 Kilometers

Figure 21

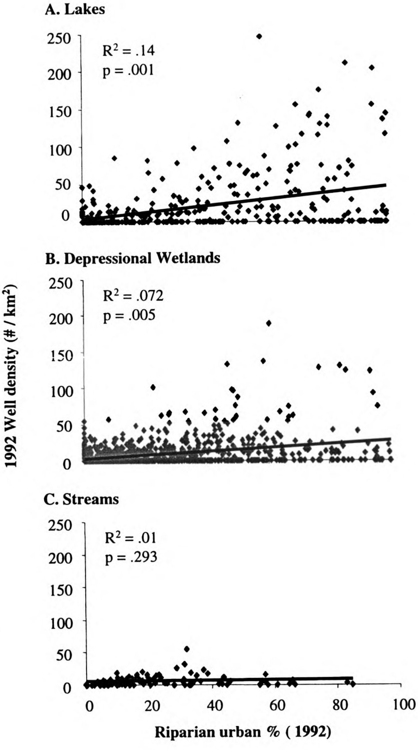

A. Lakes
250
200
150
100
50
0
R² = .14
p = .001
B. Depressional Wetlands
250
200
150
100
50
0
R² = .072
p = .005
1992 Well density (# / km²)
C. Streams
250
200
150
100
50
0
R² = .01
p = .293
0
20
40
60
80
100
Riparian urban % (1992)

Figure 22

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Literature Cited

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