INDICATORS AND DRIVERS OF HABITAT QUALITY AND WATER QUALITY IN INLAND MICHIGAN LAKES

by

Zach Hecht-Leavitt

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Thesis Committee:

Adjunct Professor Kevin Wehrly
Adjunct Professor Lizhu Wang (co-chair)
Professor David Allan (co-chair)

Abstract

Water quality and habitat quality are important components of lake ecosystems and are controlled by natural and anthropogenic factors operating at multiple spatial scales. Understanding the relative importance of these factors and the scales at which they operate is therefore critical for identifying threats and developing effective lake management strategies. Through a series of models, I evaluated the factors that influence water quality and habitat quality in 263 inland lakes located throughout Michigan. I defined water quality and habitat quality as latent, conceptual variables indicated by measures of water chemistry, clarity, and lakeshore development. I then developed structural equation models (SEMs) to test hypothesized, causal linkages between natural and anthropogenic drivers of lake water quality and habitat quality. Models were parameterized for multiple combinations of spatial scale and lake hydrologic type. Overall model fit was significant at every combination of scale and lake type and data at the cumulative scale explained the most variation in water quality and habitat quality. The strongest driver of habitat quality was residential development, which occurred preferentially on larger lakes. Residential development also mediated the indirect effects of urbanization and wetland cover. Agricultural land use was the strongest driver of water quality through its indirect effect on forest cover. Modeling results also suggested that the current suite of indicators used by resource agencies are relatively robust measures of water quality and habitat quality. There was no significant correlation between water quality and habitat quality, suggesting these two concepts are fundamentally different components of lake health.

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Introduction

Eutrophication and habitat loss are widespread problems affecting lakes worldwide (Smith, 2003; Dudgeon et al., 2006). In the United States, the U.S. Environmental Protection Agency (EPA) named nutrient enrichment and shoreline degradation as the top stressors impairing the nation's lakes (EPA, 2002; EPA, 2009). Elevated inputs of nutrients such as phosphorous and nitrogen increase primary production (Conley and Malone, 1992; Schindler, 2006), which can decrease transparency, reduce hypolimnetic oxygen, change biotic composition, and cause fish die-offs (Bachmann et al., 1996; Heiskiary and Wilson, 2008). Homogenization of near-shore habitats can alter sediment erosion and deposition, reduce carbon inputs, modify biological production, and change community structure (Engel and Pederson, 1998; Schindler et al., 2000; Hunt and Annett, 2002; Roth et al., 2007, Francis and Schindler, 2009; Reed and Pereira, 2009). Understanding the factors regulating water quality and habitat quality is therefore critical to the development of effective lake management strategies.

Both water quality and habitat quality are controlled by a variety of natural and anthropogenic factors operating at multiple spatial scales. For example, lakes may receive nutrient inputs from farmland located upstream in the watershed as well as from residential lawns bordering the lake itself (Graczyk et al., 2003; Chen and Driscoll, 2009). The amount of nutrients ultimately reaching the lake may be mediated by natural factors such as rainfall and forest land-cover that influence nutrient mobilization and absorption (Lowrance, 1992; McFarland and Hauck, 1999). Lakeshore residential development replaces native forests with houses, lawns, and docks, drastically reducing riparian habitat quality and inputs of woody debris (Christensen et al., 1996; Francis and Schindler, 2006). Lakeshore development, however, may stem from patterns of urbanization operating at larger spatial scales (So et al., 2001; Gustafson et al., 2005).

Despite the multivariate, multiple-spatial scale nature of habitat quality and water quality, relatively few studies have evaluated the influence of multiple factors and scales across broad geographic regions. However, Wang et al. (2010) used relationships between in-lake indicators and landscape-scale variables to assess the condition of lakes throughout Michigan, Detenbeck et al. (1993) regressed lake water quality variables on a variety of land use/cover variables for a region of Minnesota, and Dodson et al. (2005) linked land use to water chemistry, morphology, vegetation, and zooplankton community for lakes in southeast Wisconsin. Also in Wisconsin, Riera et al. (2000) examined the relationship between lake landscape position and various chemical, optical, biological and anthropogenic variables.

The majority of these studies, however, do not explicitly examine the causal pathways through which the associations between landscape variables and in-lake and lakeshore variables manifest themselves. The objective of this study was to develop a modeling framework to test hypothesized, causal linkages between drivers of lake water quality and habitat quality, and to identify proximate and ultimate drivers of lake health. By including habitat quality and water quality in the same analysis framework, this study helps determine if similar or different variables control them, and if they provide similar information about lake health. Finally, by using a representative sample of Michigan lakes spanning natural and anthropogenic gradients, this study will improve the generalizabilty of its results and their applicability to broad-scale management strategies.

Methods

Study Sites

Water chemistry and littoral habitat data were compiled from surveys conducted from 2001 – 2009 by the EPA National Lake Assessment (http://water.epa.gov/type/lakes/web_data.cfm), the U.S. Geological Survey (USGS) and Michigan Department of Environmental Quality (MDEQ) Michigan Lake Water Quality Assessment program (http://waterdata.usgs.gov/mi/nwis/qw), and the Michigan Department of Natural Resources (MDNR). Lakes sampled by each monitoring program were randomly selected and therefore representative of the spatial distribution and types of lakes in Michigan. An additional set of 40 lakes were sampled in 2010 by the author. Data from 263 lakes 4 ha and larger were used in this study. These lakes were distributed throughout Michigan (Figure 1) and exhibited a broad range of chemical, physical, and landscape characteristics (Table 1). Lakes differed in their hydrologic connectivity, with 181 lakes having an upstream tributary connection (“inline”) and 82 lakes having no upstream tributary (“non-inline”).

Water Quality, Littoral Habitat, and Residential Development

Water quality, littoral habitat, and residential development were measured during the summer stratification period (July, August, September). Water samples were collected from the epilimnion over the deepest area and analyzed for total dissolved phosphorus, total dissolved nitrogen, and chlorophyll a. Secchi depths were also collected. Details of sampling methods can be found in EPA (2007), Fuller and Minnerick (2008), and Wehrly et al. (in press-a).

Habitat conditions and lakeshore development were visually assessed from a boat travelling approximately 30 meters offshore. The entire shoreline was surveyed for the number of dwellings adjacent to the water, number of docks, number of pieces of large woody debris ≥ 7.6 cm in diameter, and proportion of shoreline armoring to the nearest 10 percent. Armoring was defined as sheet piling, concrete, rip rap, and other materials intentionally placed to reduce erosion. Survey data were recorded on each 300 m segment for the entire shoreline. Density of dwellings, docks, and large woody debris were calculated by dividing lake-wide counts of each variable by lake perimeter. Extent of armoring in each lake was calculated as the average shoreline armoring for all 0.3 km segments of shoreline.

Lake Catchments and Landscape Data

Polygons for natural and manmade lakes 4 ha or larger were identified from the 1:24,000 National Hydrography Dataset (NHD) for the entire state of Michigan using a geographic information system (GIS, ESRI 2002). Tributary and local catchment boundaries were delineated for all lakes and a 100-meter buffer was created around each lake polygon (Figure 2). Tributary catchments were defined as the land area where surface water drains directly into rivers and then into a lake. Local catchments were defined as the land area where surface runoff drains directly into a lake. The cumulative catchment was defined as the sum of the tributary and local catchments. Catchment boundaries were delineated using GIS algorithms to identify runoff directions based on a 30-m resolution Digital Elevation Model and to restrict the outmost catchment boundaries using 12-digit Hydrological Units (HUs) or aggregated HUs that were developed by the Michigan Department of Environmental Quality.

Percentage land use/cover, surficial geology texture, and precipitation data within the tributary, local, and cumulative catchments of the lakes as well as the 100-meter buffer were computed. Land cover types were measured from 2001 Michigan Land Use/Cover Data (http://www.mcgi.state.mi.us/mgdl) and surficial geology texture was calculated from the Michigan Quarternary geology geographic theme (http://www.mcgi.state.mi.us/mgdl/?rel=ext&action=sext). Mean annual precipitation data were obtained from the Oregon State University Spatial Climate Analysis Service for the conterminous United States (www.climatesource.com/us/fact_sheets/fact_tmean_us.html). Lake surface area was derived from GIS measurements, and residence times were calculated according the following equation (Lindhurst et al., 1986):

$$RT = \frac{LA * Zm}{[RO * (WA\text{-}LA)] + (LA * PRECIP)}$$

where RT = residence time, LA = lake area (ha) measured from the NHD, Zm = mean depth (m) calculated from lake bathymetric maps, RO = runoff (m/yr), WA = watershed area (ha), and PRECIP = precipitation (m/yr).

Model Specification

The influence of natural and anthropogenic variables on lake water quality and habitat quality were evaluated using structural equation modeling (SEM). SEM is a framework that can be used to describe and decompose causal relationships among variables (Kenney, 2009; Grace, 2010). Linear equations specify both direct and indirect relationships, and the relative strength of these relationships is described using standardized path coefficients, which are analogous to regression coefficients. Because SEM is a confirmatory method, the researcher develops an *a priori* model that is then tested against the data. The goal is to accept the null hypotheses as a plausible representation of the system, meaning that there is not a significant difference between the model-implied covariance structure and the data-implied covariance structure.

I developed an inland lake health model that included measures and predictors of water quality and habitat quality (Figure 3). Following SEM drawing conventions, squares represent observed variables and circles represent latent variables. The ability to specify latent variables is one of the primary strengths of the SEM framework. They may be thought of as "theoretical constructs" that are indicated or reflected by what we can actually observe. Causation is presumed to flow from the latent cause to the manifest indicators (Grace, 2010). Specification of a latent variable and its indicators is sometimes referred to as the "measurement model."

Water Quality Component

I specified water quality as a latent variable indicated by Secchi disk transparency (a measure of water clarity), chlorophyll a concentration (a surrogate for phytoplankton biomass), and P and N concentrations. This suite of indicators is typically used by water resource agencies to monitor and assess lake trophic status (Whittier et al., 2002).

Urban and agricultural land use were specified as having a direct effect on water quality, because catchments with greater proportions of agricultural and urban land use receive greater amounts of nutrients (Knoll et al., 2003; Houlahan and Findlay, 2004; Dodson et al., 2005; Chen and Driscoll, 2009). Sources of nutrient input include animal waste and fertilizer application in agricultural fields (McFarland and Hauck, 1999) and increased runoff from urban, impervious surfaces (Corbett et al., 1997; Wang et al., 2001).

In addition to a direct effect, I also included an indirect effect for agricultural land use on water quality, through its effect on forest cover. In the Great Lakes region of the US, humans have converted forests and prairies to cropland (Cole et al., 1998). This alters the hydrology of the catchment such that denitrification potential decreases (Verchot et al., 1997; Mao and Cherkauer, 2009) and runoff of inorganic nutrients increases (Lowrance, 1992; Hopkins and Vallino, 1995; Correll and Weller, 1997).

The transport mechanism for these nutrients is rainfall (McFarland and Hauck, 1999), and one might expect watersheds with more precipitation to export more nutrients, all else equal. Precipitation can also add nitrogen to lakes through atmospheric deposition (Lajtha et al., 1995). Therefore, I included precipitation as having a direct effect on water quality.

Residence time is defined as the time it takes for a parcel of water to enter and exit, or "flush," through the lake. Lakes with longer residence times may accumulate more nutrients and experience greater eutrophication (Schindler, 2006; Baker et al., 2008; Koiv et al., 2011), although longer residence times may also allow more time for nutrient removal (Meals et al., 2010). In any case, I included a direct effect for residence time in the model.

Since surficial geology texture affects ease of tillage, water infiltration, and water movement within the soil (Eliasson et al., 2010), I specified an indirect effect for percent coarse geology texture, through its effect on percent agriculture. Soils with lower proportions of coarse material are generally more suitable for cropland.

People are attracted to lakes for their recreational value, and larger, clearer, cleaner, more accessible lakes close to urban centers tend to attract more development (Kooyoomjian, 1974; Smith and Mulamoottil, 1979; Butler and Redfield, 1991; Reed-Anderson et al., 2000; Riera, 2000; So et al., 2001; Schnaiberg, 2002; Gustafson et al., 2005; Wehrly et al., in press-b). Lakes in the Midwest have seen a substantial increase in primary and seasonal housing development in the past few decades (Marcouiller et al., 1996; Hammer et al., 2004). The lawns and septic systems of these lakeshore homes can export nutrients to the lake (Robertson et al., 1998; Graczyk, 2003; Baker et al., 2008). Therefore, I specified urban land use and lake surface area as having indirect effects on water quality through their effect on the number of lakeshore housing units.

Wetlands had direct and indirect effects on water quality in the model. The presence of wetlands around a lake may inhibit housing development (Wehrly et al., in press-b), as special permits are required for construction on wetlands in Michigan (MDEQ, 2011). Wetlands may also have a direct effect through humic and fulvic acid inputs that decrease water clarity (Detenbeck, 1993).

Habitat Quality Component

Habitat quality was specified as a latent variable indicated by number of partially submerged trees, percentage of shoreline armoring, and number of docks. Fallen tree serves as an important refuge, food source, and spawning habitat for fish (Schindler et al., 2000; Hunt and Annett, 2002; Roth et al., 2007). They also provide food and shelter for amphibians, waterbirds, and mammals (Engel and Pederson, 1998). Additionally, boat hulls and propellers may cause physical damage to emergent vegetation that provides fish nesting habitat (Reed and Pereira, 2009) and may stir up sediments sufficient to hamper photosynthesis (Yousef et al., 1980; Murphy and Eaton, 1983; Asplund, 2000). Finally, erosion control materials destroy shoreline plants that provide food and cover for invertebrates which are in turn consumed by fish (Engel and Pederson, 1998). These materials may also reduce habitat heterogeneity, thereby reducing fish species richness (Jennings et al., 1999).

I specified houses as having a direct effect on habitat quality. As in the water quality component, urban land use, wetlands, and surface area exerted indirect effects through houses. Surface area also exerted a direct effect, since larger lakes have longer fetches and hence stronger waves (Allan and Kirk, 2000) which may lead to increased shoreline erosion (Elci et al., 2007; Lim et al., 2011) and the need for more armoring. Forest cover exerted a direct effect on habitat quality in the model because lakes with more forested land in their catchment are likely to have a greater source of large woody debris input (Jennings et al., 2003). As in the water quality component, percentages of coarse geology and agricultural land use exerted indirect effects through forest cover. As in the water quality component, percent coarse geology and agricultural land use exerted indirect effects through forest cover.

Scale and Lake Type

The drivers of water and habitat quality may act differently depending on spatial scale (Wang et al., 2010; Wehrly et al., in press-b) and lake type (Sorrano et al., 1999; Martin and Sorrano, 2006; Sass et al., 2008). Consequently, I developed models using land use/ cover, surficial geology texture, and rainfall data at the buffer, local, tributary, and cumulative scales. I also developed separate models for inline, non-inline, and all lake types. Thus, there were four geographic scales and three lake types for a total of 10 combinations. Note that the number of combinations is not 12 because inline lakes are the only ones that have tributary scale data. Also, in the buffer model, a direct relationship was not specified between percent urban land use and number of shoreline houses, since they measured essentially the same thing.

Covariation, Significance, and Sample Size

Error terms and covariance arrows, both typical features of an SEM diagram, were omitted for clarity. Variables were allowed to co-vary where appropriate. For example, percent urban and percent agriculture, while not causally related in the diagram, spatially co-varied in the dataset. Coefficients were estimated using maximum likelihood, and coefficients were standardized to allow for direct comparisons between effect sizes. If X is the coefficient, then

$X_{standard} = (X_{raw} - \overline{X}_{raw}) / SD(X)$, where SD = standard deviation. All variables were transformed prior to modeling to improve normality and linearity of relationships.

Overall model significance was determined by a chi-square statistic greater than 0.05, a comparative fit index (CFI) greater than 0.9, and a root mean square error of approximation (RMSEA) index of less than 0.1. Significance of the standardized path coefficients, referred to as the direct and indirect effects, as well as significance of the latent variable indicator coefficients (loadings) were determined by constructing 95-percent bias-corrected bootstrapped confidence intervals. Structural equation models were developed using AMOS v19 (Arbuckle, 2010).

Although there is no absolute rule for sample size, some researchers suggest that models with three or more indicators per latent variable should have at least 150 observations (Anderson and Gerbing, 1984). In this analysis, the number of inline lakes exceeded this criterion (181), but the number of non-inline lakes did not (82). While models with only 50 – 100 samples can perform well (Iacobucci, 2010), I erred on the conservative side and specified separate, simplified models for water quality and habitat quality for the non-inline subset of lakes (Figure 4). All other models followed Figure 3.

Results

Overall model fit was significant at every combination of scale and lake type (Tables 2 and 3). P-values were all greater than 0.05, suggesting no significant departure from the covariance structure implied in the data. CFIs were all greater than 0.9, suggesting the model was not overly complex and fit the data better than a model with no paths specified. RMSEA indices were less than 0.05, suggesting that differences between data predictions and model predictions (residuals) were not significantly large.

When all lake types were included, the cumulative scale data had the most explanatory power (water quality R^2 = 0.237, habitat quality R^2 = 0.899). The non-inline subset model at the direct scale had the highest R^2 for water quality (0.377), and the inline subset model at the cumulative scale had the highest R^2 for habitat quality (0.931). The model did a consistently better job of explaining variation in habitat quality than water quality. Correlations between habitat and water quality were not significant at any combination of scale or lake type.

Indicators of Habitat Quality and Water Quality

All indicator coefficients were significant, and all signs were as expected (Table 4). To facilitate interpretation, some indicators were rescaled so that all the resultant indicator coefficients had the same sign. "Good" water quality was reflected by decreased P, N, and chlorophyll *a* concentrations and increased Secchi depth. "Good" habitat quality was reflected by decreased armoring and docks and increased woody debris. Standardized coefficients for water quality indicators were within 0.3 standard deviations of one another in all but a few cases, suggesting that each indicator is reflective of the same, underlying concept. For habitat quality, standardized coefficients for docks and armoring were within 0.3 standard deviations of one another, but trees were consistently lower by about 0.5 standard deviations.

Drivers of Habitat Quality

Surface area had significant negative direct, indirect, and total effects on habitat quality across most spatial scales and lake types (Table 5). Urban land use had a significantly negative indirect and total effect at the cumulative scale, through its effect on houses. Coarse-textured surficial geology had a significant positive indirect and total effect at the watershed scale, mediated by agriculture and then forest cover. Wetlands had a significantly positive indirect and total effect, through houses, at the buffer and cumulative scales. Agricultural land use had a significant negative indirect and total effect through forest cover across almost all spatial scales and lake types. Houses (negative) and forest land cover (positive) both had significant direct and total effects across scale and lake type. Boxplots corroborated the direction of these relationships (Figure 5).

Drivers of Water Quality

The most consistent significant effect on water quality was by agriculture, with negative effects at all spatial scales, although not necessarily for all lake types (Table 6). The agricultural effect was primarily indirect (and total) through its influence on forest land cover, although it was direct at the tributary scale. Forests had a significantly positive direct and total effect at certain scales and lake types. Coarse geology had a significant negative effect on habitat quality through agriculture and then forests. Surface area and wetlands had occasional significant positive indirect effects through houses, and houses were positively associated with water quality at the buffer and local scales. Residence time had a positive direct and total effect on water quality for non-inline lakes at the cumulative catchment scale. Boxplots corroborated the direction of these relationships (Figure 6).

Discussion

Indicators of Habitat Quality and Water Quality

All indicators of habitat quality and water quality were significant at all combinations of scale and lake type, and standardized indicator coefficients were generally within 0.3 standard deviations of each other. Correlation signs were also in the expected directions. This suggests that model structure was correctly specified, the selected indicators were appropriate, and the model is robust for answer my research questions.

Other studies generally point to the utility of these indicators, with some caveats. For example, TN was found to agree well with a diatom-based indicator of water quality (Weckstrom et al., 2004) and chlorophyll *a* was found to agree well with other water quality parameters (Stanley et al., 2003). Peeters et al. (2009) found that Secchi depth alone was a good predictor of ecological quality as judged by a panel of experts for a set of shallow lakes, although it is most sensitive to eutrophication and less useful where other forms of pollution are the primary stressors. Salmaso et al. (2006) found that Secchi depth alone tended to underestimate lake trophic state compared to TP and chlorophyll *a*. Thus, it should be used in conjunction with other indicators, as I have done here. Sondergaard et al. (2005) cautioned that indicators may not change synchronously, though, and Meals et al. (2010) noted that there may be significant lags in the response of in-lake N and P to changing land use practices in the catchment. Finally, the relationship between chlorophyll *a* and algal biomass is known to vary depending on species and radiation intensity (Vollenweider and Kerekes, 1982). The mixed results in the literature and the results of my analysis suggest that a suite of indicators may be appropriate for water quality monitoring programs as recommended by the EPA.

There has been less research on habitat quality indicators, but the ones chosen for this study are fairly well-supported. Goforth et al. (2005) suggested that lakeshore development provides a terrestrial indicator of nearshore ecological integrity, and Radomski et al. (2010) noted that number of docks serves as a reasonable proxy for human impact on in-lake and near-shore habitats. Trial et al. (2001) found that non-vegetated and armored shorelines had fewer species of fish compared to vegetated and unarmored shorelines, and Sass et al. (2006) found maintenance of coarse woody debris to be crucial in sustaining lake fish populations. However, Roth et al. (2007) noted that relationships between prey fish density and coarse woody debris may be masked by fishing activities.

Drivers of Habitat Quality

Our measures of habitat quality behave mostly as expected. Larger lakes seem to require more armoring against stronger wave action, resulting in a negative association between surface area and habitat quality. Larger lakes also appear to be more attractive for residential development, which in turn reduces riparian forest cover, adds docks, and adds armoring. Surface area was significant across most combinations of scale and lake type, and housing development was significant across all combinations. Thus, it appears the strongest driver of habitat quality is residential development, which occurs preferentially on larger lakes. This relationship between development and shoreline integrity is well-supported (Christensen et al., 1996; Roth et al., 2007; Gaeta et al., 2010; Wehrly et al., in press-b), as is the increased likelihood of development on larger lakes (Smith and Mulamootil, 1979; Reed-Anderson et al., 2000; Schnaiberg et al., 2002).

Increased forest cover was associated with improved habitat quality across almost all combinations of scale and lake type, suggesting lakes with more forest cover in their catchment receive more inputs of coarse woody debris (CWD). Christensen et al. (1996) and Francis and Schindler (2006) found a strong positive relationship between CWD and forest cover at the riparian scale, although Marburg et al. (2006) did not, suggesting past disturbances may be as important as present land uses.

Agriculture appears to have a negative, indirect effect on habitat quality through its influence on forest land use. Agricultural practices clear land for farming and reduce forest land cover. There was no effect of percent coarse geology on agriculture and hence habitat quality, however, except for inline lakes at the tributary scale. The reason for this is not immediately apparent, although it may be that percent coarse geology alone is a poor measure of agricultural suitability. Temperature, drainage, rooting depth, salinity, moisture balance, and slope are also important (Eliasson et al., 2010).

Both percent urban and percent wetland had significant effects on habitat quality through their effect on houses, at certain spatial scales. It appears the presence of wetlands at the buffer scale inhibits development due to building restrictions (MDEQ, 2011), whereas lakeshores close to existing urban amenities at the cumulative scale are more attractive for development.

Drivers of Water Quality

Agriculture emerged as a significant driver of water quality through its effect on forest land cover. This effect was most pronounced at the buffer scale, where it appears that the interception and denitrification ability of forests were strongest. Indeed, riparian forest has been shown to be an effective control of nonpoint source pollution (Lowrance et al., 1997;

Verchot et al., 1997). Except for at the tributary scale, however, agriculture did not have a significant direct effect on water quality. This runs counter to my expectation that agricultural land use in a catchment exports nutrients to a lake. It may make sense, however, that this direct effect exists only at the tributary scale, where, by definition, all lakes must be connected to a stream network. Similarly, percent coarse geology only had a significant effect on water quality at the tributary scale, through its effect on agriculture. Sass et al. (2008) found that lakes with no inflowing streams had lower chlorophyll *a* compared to connected lakes, perhaps reflecting enhanced delivery of nutrients to networked lakes.

Urban land use did not have a significant effect on water quality. This is somewhat surprising, as one might expect runoff from urban surfaces to carry nutrients to lakes. It appears that forest land cover and agricultural land use are more important in determining water quality. It may also be that overall urban land use is a poor proxy for connected imperviousness. Wang et al. (2001) found that connected imperviousness explained substantially more variation in stream fish communities than general urban land use.

We also expected the lawns and septic systems of lakeside houses to export nutrients to the lake, resulting in higher N, P, and chlorophyll *a* levels and lower Secchi depth. Paradoxically, houses were associated with better water quality at two combinations of scale and lake type. This may reflect the fact that people prefer to live on clearer, less eutrophied lakes (Kooyoomjian et al., 1974; Smith and Mulamoottil, 1979). In effect, the causation may run in the opposite direction from that specified in the model. This leads surface area and percent wetland, through houses, to have a spurious, positive indirect effect on water quality at certain scales. It is also interesting to note that this positive association between houses and water quality was only present at the buffer and local scales. At the larger tributary and cumulative scales, it may be that land use activity outside the shoreline area outweighs any effect houses have, positive or negative. Baker et al. (2008) found that in lakes with large catchment area to lake area ratios, catchment land use, particularly agriculture, was more important in determining Secchi depth than shoreline development.

Residence time was significantly associated with water quality at only one combination of scale and lake type, and precipitation seemed to have no effect on water quality at any combination. This may be because precipitation can transport nutrients to a lake, but also dilute those same nutrients, resulting in no significant net effect. It is unclear why residence time was so rarely significant, although it may be that longer residence times result in more time for suspended substances to settle and degrade (Hakanson, 1995), increasing water quality, but less flushing, lowering water quality. The net effect, then, is weak.

Comparison of Habitat and Water Quality

The models did a consistently better job of explaining variation in habitat quality than water quality. This may be because water quality is a highly dynamic variable, changing with season, mixing state, and amount of catchment runoff. Habitat quality, however, is fairly static. Water quality is also a more complex variable, and the measurement model may do a poorer job of capturing the necessary indicators. I have chosen to focus on nutrients, but dissolved oxygen, salinity/conductivity, metals, bacteria, and many other variables are also important for water quality. Water quality may also be highly influenced by spatial variation in groundwater recharge to Michigan lakes, a process not captured by the model. Because a goal of this study was to develop a model that could be applied statewide, certain variables were not included because they are available for only a small number of Michigan lakes.

Management Implications

While some variation in habitat quality was due to natural factors (e.g. surface area, soil texture), the strongest driver appeared to be residential development, which ostensibly removed riparian trees in favor of docks and lawns and required armoring to prevent property loss. Thus, supplemental logs may be a useful management tool to improve shoreline habitat (Hunt and Annett, 2002), and regulations might include minimum house setback distances from lakeshore to minimize habitat alteration and the need for erosion control.   When erosion control is necessary, riprap may be preferable to retaining walls (Jennings et al., 2003).

Similarly, while some variation in water quality was due to natural factors (e.g. surface area, residence time), the strongest drivers were agriculture and forest land cover. Managers may want to consider reforestation at the catchment scale and vegetation buffer strips at the riparian scale to improve nutrient absorption and rainwater interception. Such actions may also increase coarse woody debris inputs (Jennings et al., 2003). For the full set of lakes, cumulative-scale variables explained the most variation in water quality and habitat quality. This points to the need to consider the entire hydrological system, including tributary drainage, direct drainage, and near-shore processes, when examining lake health.

There was no significant correlation ($p<.05$) between water quality and habitat quality at any combination of scale and lake type. This suggests that they are fundamentally different measures of lake health. Thus, it seems unlikely that the overall status of a lake can be inferred from one or the other alone. Biological indices (e.g. Harman, 1997; DeSousa et al., 2008) which are sensitive to variation in water quality and habitat quality should continue to be refined and developed.

Conclusion

SEMs are a powerful tool for studying ecological systems. By developing measurement models, specifying a variety of causal pathways across different scales and lake types, and comparing effect sizes, I was able to determine that residential development and forest land cover were the strongest drivers of habitat quality and water quality, respectively, in Michigan lakes. That said, my representation of this system is but one of many possible representations. Future work should continue to explore these relationships in an effort to better understand and improve the health of inland lakes.

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Tables

Table 1. Chemical, physical, landscape, and climatic attributes of the lakes. Range and mean for landscape variables are averaged across all scales.

Variable	Abbreviation	Units	Range	Mean	Source
Water quality					
Total Nitrogen	N	micrograms/liter	0.12 - 1.8	0.67	field
Total Phosphorous	P	micrograms/liter	0 - 0.24	0.02	field
Chlorophyll a	chl. a	micrograms/liter	0 - 70.8	4.9	field
Secchi depth	Secchi	feet	0.3 - 8.5	3.1	field
Shoreline					
Houses	none	number per km of shoreline	0 - 50.7	15.9	field
Trees	none	number per km of shoreline	0 - 396.6	15.1	field
Docks	none	number per km of shoreline	0 - 51.4	12.0	field
Armor	none	% of shoreline armored	0 - 93	23.9	field
Landscape					
% Agriculture	% ag	% of catchment/buffer	0 - 82	11.8	GIS
% Urban	none	% of catchment/buffer	0 - 76	8.2	GIS
% Forested	none	% of catchment/buffer	0 - 93	41.2	GIS
% Wetland	none	% of catchment/buffer	0 - 95	17.5	GIS
% Coarse-Class Soil	% coarse	% of catchment/buffer	0 - 100	72.5	GIS
Physical					
Residence Time	none	index, see appendix	0.01- 46.1	5.7	GIS
Precipitation	ppt	mean annual inches, 1961-90	28.1 – 79.0	38.3	GIS
Surface Area	none	km^2	0.014 - 20.1	0.71	GIS

Table 2. Fit and explanatory power of models parameterized for all lakes and inline lakes using data at buffer, local, tributary, and cumulative catchment scales.

Spatial scale Model set	Water Quality R^2	Habitat Quality R^2	P-value	CFI	RMSEA
Buffer					
All lakes	0.154	0.870	0.366	0.998	0.015
Inline lakes	0.149	0.909	0.485	1.000	0.000
Local					
All lakes	0.149	0.865	0.179	0.995	0.027
Inline lakes	0.192	0.923	0.274	0.996	0.026
Cumulative					
All lakes	0.237	0.899	0.202	0.997	0.027
Inline lakes	0.228	0.931	0.190	0.995	0.034
Tributary					
Inline lakes	0.144	0.881	0.111	0.990	0.038

Table 3. Fit and explanatory power of models parameterized for non-inline lakes using data at buffer, local, tributary, and cumulative catchment scales. Water and habitat quality models were separated and simplified for these lakes due to sample size limitations.

	R^2		P-value		CFI		RMSEA	
Spatial scale Model set	Water Quality	Habitat Quality	Water Quality	Habitat Quality	Water Quality	Habitat Quality	Water Quality	Habitat Quality
Non-Inline								
Buffer	0.144	0.788	0.473	0.638	1.000	1.000	0.000	0.000
Local	0.377	0.836	0.170	0.415	0.984	0.999	0.068	0.020
Cumulative	0.310	0.839	0.488	0.595	1.000	1.000	0.000	0.000

Table 4. Standardized coefficients for latent variable indicators. To aid interpretation, P, N, chl. a, armor, and docks have been rescaled such that all coefficients read positive.

	Water Quality				Habitat Quality		
	P	N	chl. a	Secchi	armor	trees	docks
Buffer							
Full	0.57	0.67	0.77	0.72	0.64	0.40	0.93
Inline	0.61	0.72	0.83	0.73	0.67	0.41	0.94
Non-inline	0.56	0.90	0.59	0.70	0.64	0.42	0.91
Direct							
Full	0.57	0.66	0.69	0.84	0.68	0.43	0.93
Inline	0.57	0.61	0.72	0.91	0.81	0.42	0.94
Non-inline	0.62	1.05	0.58	0.63	0.95	0.36	0.86
Cumulative							
Full	0.56	0.61	0.50	0.81	0.92	0.41	0.91
Inline	0.54	0.83	0.47	0.64	0.95	0.41	0.93
Non-inline	0.64	0.73	0.81	0.72	0.97	0.37	0.86
Watershed							
Inline	0.52	0.54	0.70	0.87	0.68	0.40	0.95

Table 5. Effects on habitat quality. Significant effects are in green (+) or red (-). Effect sizes have been standardized. Total effect = direct + indirect effect.

	Standardized Effects on Habitat Quality																				
	surface area			% urban			% coarse			% wetlands			% ag			% houses			% forests		
	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T
Buffer																					
Full	**-.118**	**-.07**	**-.188**	-----	-----	-----	-.001	-----	-.001	**.382**	-----	**.382**	**-.037**	-----	**-.037**	-----	**-.907**	**-.907**	-----	**.103**	**.103**
Inline	-.07	-.05	-.119	-----	-----	-----	.001	-----	.001	**.356**	-----	**.356**	-.017	-----	-.017	-----	**-.943**	**-.943**	-----	.045	.045
Non-inline	**-.308**	-.088	**-.396**	-----	-----	-----	-----	-----	-----	**.313**	-----	**.313**	**-.051**	-----	**-.051**	-----	**-.773**	**-.773**	-----	**.136**	**.136**
Local																					
Full	-.098	**-.08**	**-.178**	.097	-----	.097	.002	-----	.002	.109	-----	.109	**-.128**	-----	**-.128**	-----	**-.852**	**-.852**	-----	**.184**	**.184**
Inline	**-.126**	**-.066**	**-.192**	.597	-----	.597	.01	-----	.01	.156	-----	.156	**-.112**	-----	**-.112**	-----	**-.887**	**-.887**	-----	**.174**	**.174**
Non-inline	**-.266**	-.104	**-.371**	**-.336**	-----	**-.336**	-----	-----	-----	.091		.091	**-.167**		**-.167**		**-.789**	**-.789**		**.207**	**.207**
Cumulative																					
Full	**-.154**	**-.069**	**-.223**	**-.360**	-----	**-.360**	.005	-----	.005	**.121**	-----	**.121**	**-.11**	-----	**-.11**	-----	**-.877**	**-.877**	-----	**.134**	**.134**
Inline	**-.145**	**-.066**	**-.211**	**-.330**	-----	**-.330**	.01	-----	.01	.078	-----	.078	**-.089**	-----	**-.089**	-----	**-.889**	**-.889**	-----	**.110**	**.110**
Non-inline	**-.253**	-.078	**-.331**	**-.363**	-----	**-.363**	-----	-----	-----	.049	-----	.049	-.124	-----	-.124	-----	**-.822**	**-.822**	-----	.152	.152
Tributary																					
Inline	-.101	**-.057**	-.158	-.068	-----	-.068	**.009**	-----	**.009**	.052	-----	.052	**-.062**	-----	**-.062**	-----	**-.906**	**-.906**	-----	**.085**	**.085**

Table 6. Effects on water quality. Significant effects are in green (+) or red (-). Effect sizes have been standardized. Total effect = direct + indirect effect.

	Standardized Effects on Water Quality																										
	ppt			surface area			% urban			% coarse			% wetlands			% ag			res. time			houses			forests		
	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T	I	D	T
Buffer																											
Full	-----	-.044	-.044	**.037**	-----	**.037**	-----	-.075	-.075	-.003	-----	-.003	**-.121**	.090	-.032	**-.104**	-.046	**-.151**	-----	.085	.085	-----	**.288**	**.288**	-----	**.292**	**.292**
Inline	-----	-.089	-.089	.019	-----	.019	-----	-.018	-.018	.012	-----	.012	-.099	.241	.142	**-.122**	-.081	**-.202**	-----	.064	.064	-----	.262	.262	-----	**.333**	**.333**
Non-inline	-----	-----	-----	-----	-----	-----	-----	.217	.217	-----	-----	-----	-.018	-.107	-.125	**-.116**	-.009	-.125	-----	-.058	-.058	-----	.040	.040	-----	.317	.317
Local																											
Full	-----	.344	.344	.045	-----	.045	-.044	-.257	-.302	.006	-----	.006	-.05	-.055	-.105	-.186	-.143	-.329	-----	.105	.105	-----	**.391**	**.391**	-----	.267	.267
Inline	-----	.186	.186	.054	-----	.054	-.256	-.285	-.541	.023	-----	.023	-.067	.016	-.051	-.128	-.141	-.269	-----	.051	.051	-----	.380	.380	-----	.200	.200
Non-inline	-----	-----	-----	-----	-----	-----	.287	.099	.385	-----	-----	-----	-.030	-.007	-.037	**-.863**	.606	-.258	-----	-.049	-.049	-----	.367	.367	-----	**1.073**	**1.073**
Cumulative																											
Full	-----	-.068	-.068	**.031**	-----	**.031**	.072	-.019	.053	.013	-----	.013	-.024	-.161	-.185	-.264	-.005	**-.269**	-----	.138	.138	-----	.175	.175	-----	.322	.322
Inline	-----	-.100	-.100	.017	-----	.017	.039	-.188	-.148	.030	-----	.030	-.009	-.227	-.236	.009	-.289	-.280	-----	.151	.151	-----	.106	.106	-----	-.012	-.012
Non-inline	-----	-----	-----	-----	-----	-----	.085	-.372	-.287	-----	-----	-----	-.018	-.258	-.276	-.130	.053	-.077	-----	**.330**	**.330**	-----	.175	.175	-----	.152	.152
Tributary																											
Inline	-----	.106	.106	.017	-----	.017	.011	-.132	-.120	**.050**	-----	**.050**	-.009	-.164	-.173	.120	**-.470**	**-.349**	-----	.053	.053	-----	.152	.152	-----	-.166	-.166

Figure Captions

Figure 1. Locations of the lakes, grouped by lake type. Lake sizes on the map are not to scale.

Figure 2. Scales at which land use/cover, surficial geology, and precipitation data were aggregated in a GIS.

Figure 3. SEM diagram. Error terms were estimated for all endogenous variables.

Figure 4. Simplified, separate SEM diagrams for the non-inline subset of lakes.

Figure 5. P and N concentrations as a function of various land use types at the cumulative catchment scale. Land use types are grouped as median, 25^{th}, and 75^{th} percentiles.

Figure 6. Habitat quality measures as a function of various explanatory variables, which are grouped as median, 25^{th}, and 75^{th} percentiles

Figures

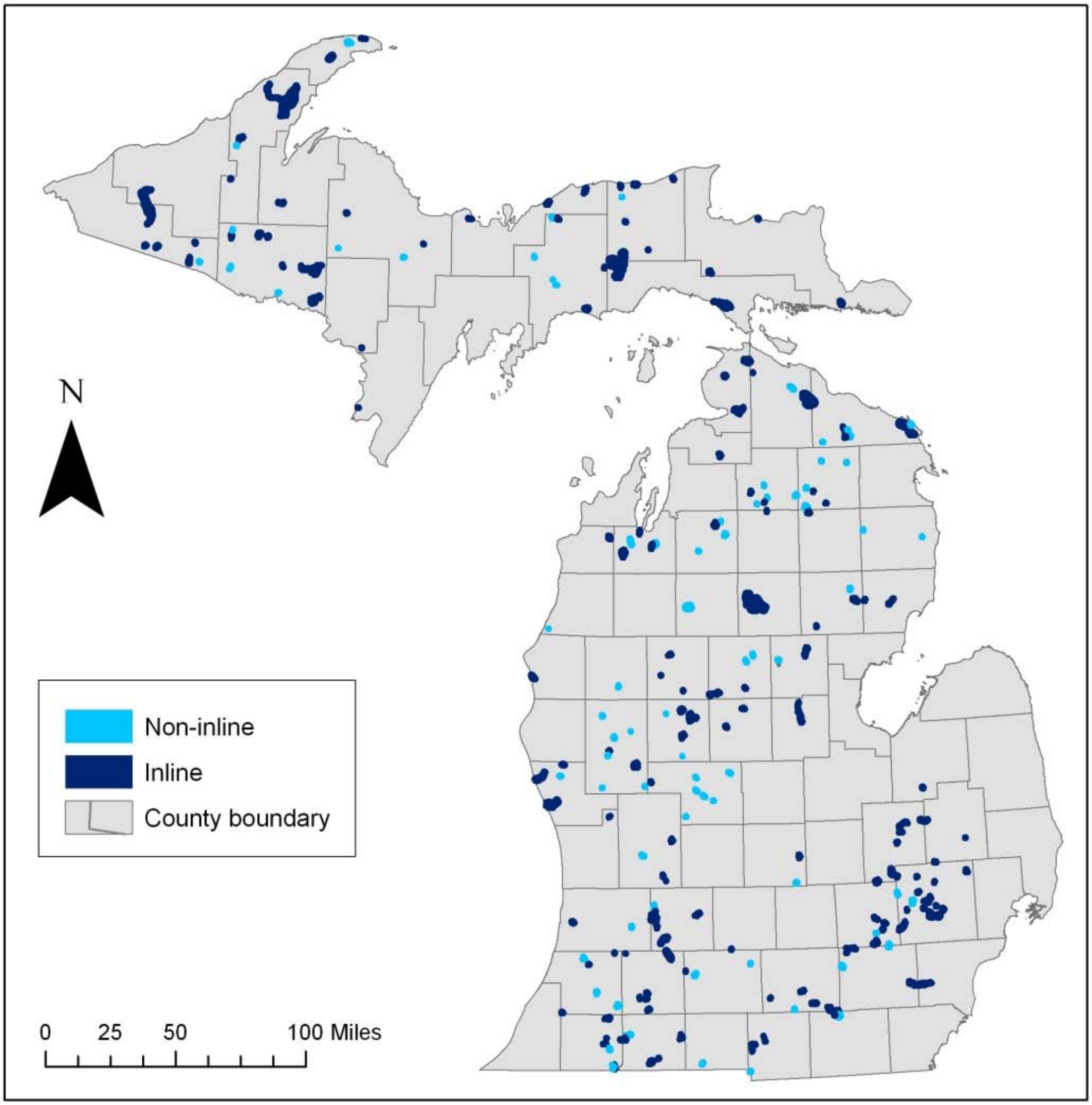


Figure 1.

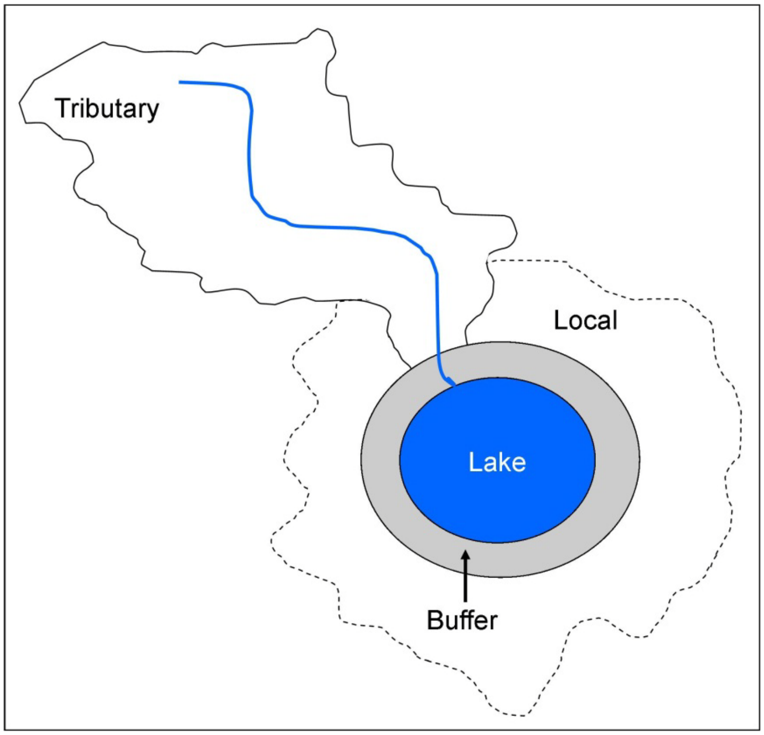


Figure 2.

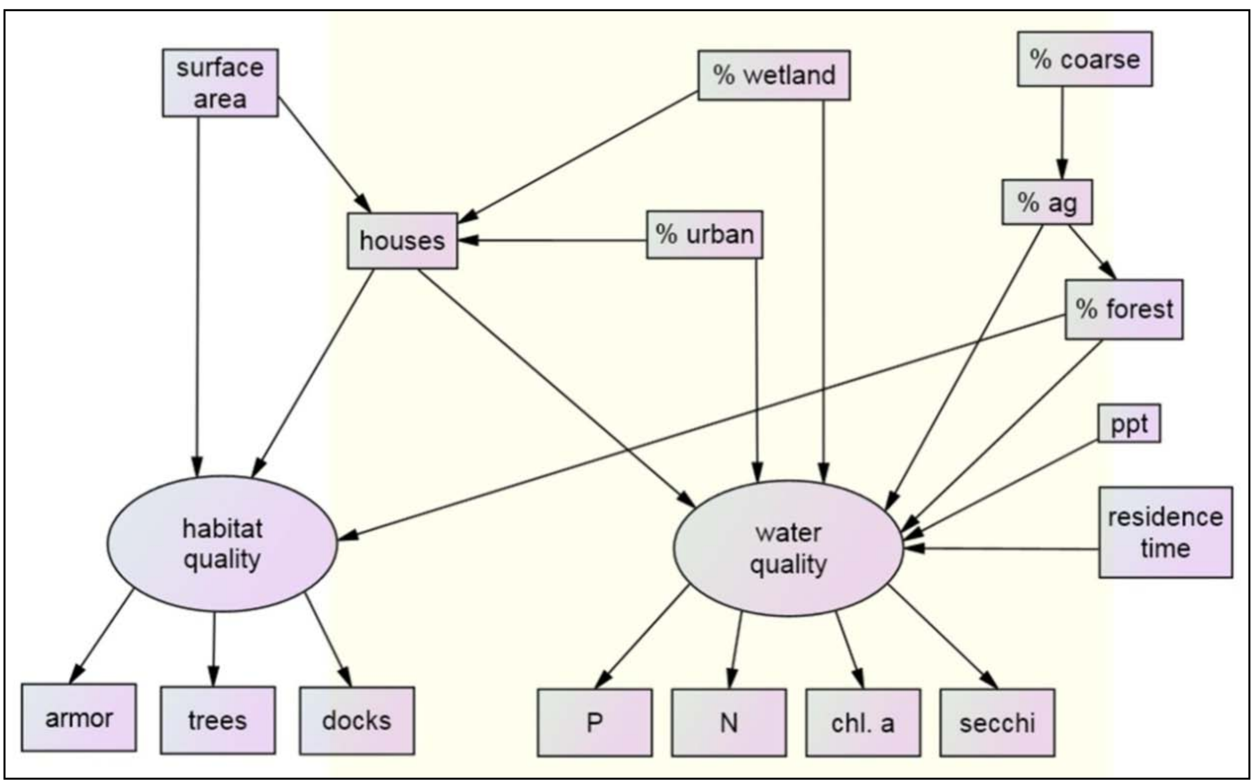
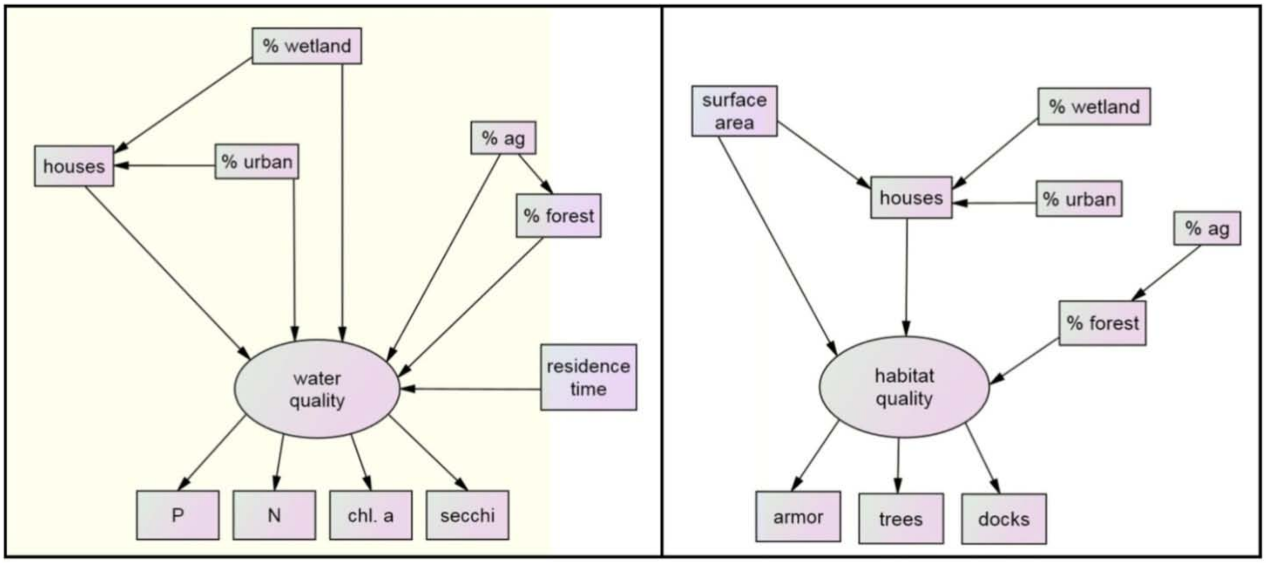
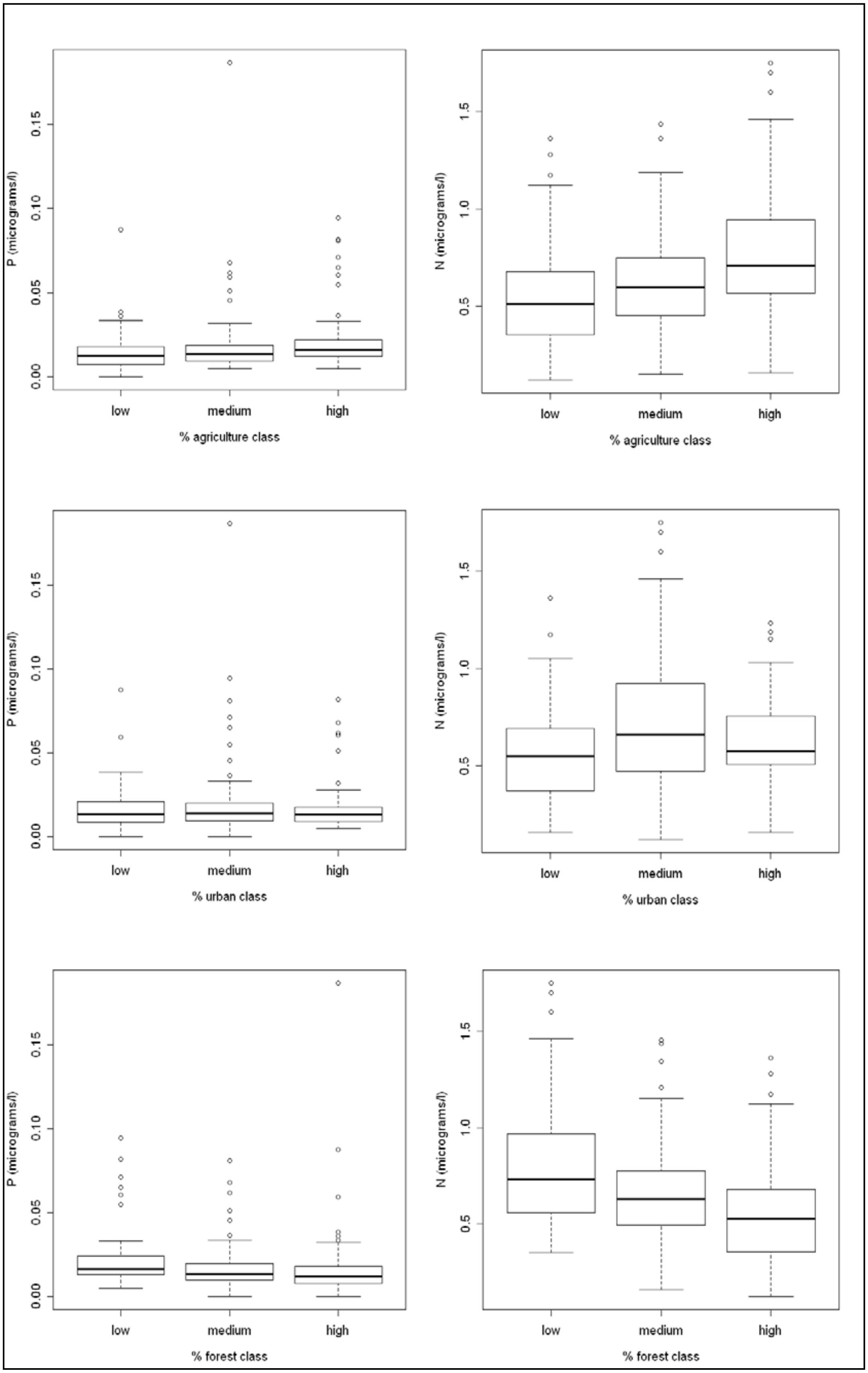


Figure 3.


% wetland
houses
% urban
% ag
% forest
water quality
residence time
P
N
chl. a
secchi
surface area
% wetland
houses
% urban
% ag
% forest
habitat quality
armor
trees
docks
Figure 4.


P (micrograms/l)
N (micrograms/l)
0.00
0.05
0.10
0.15
0.5
1.0
1.5
low
medium
high
% agriculture class
% urban class
% forest class
Figure 5.

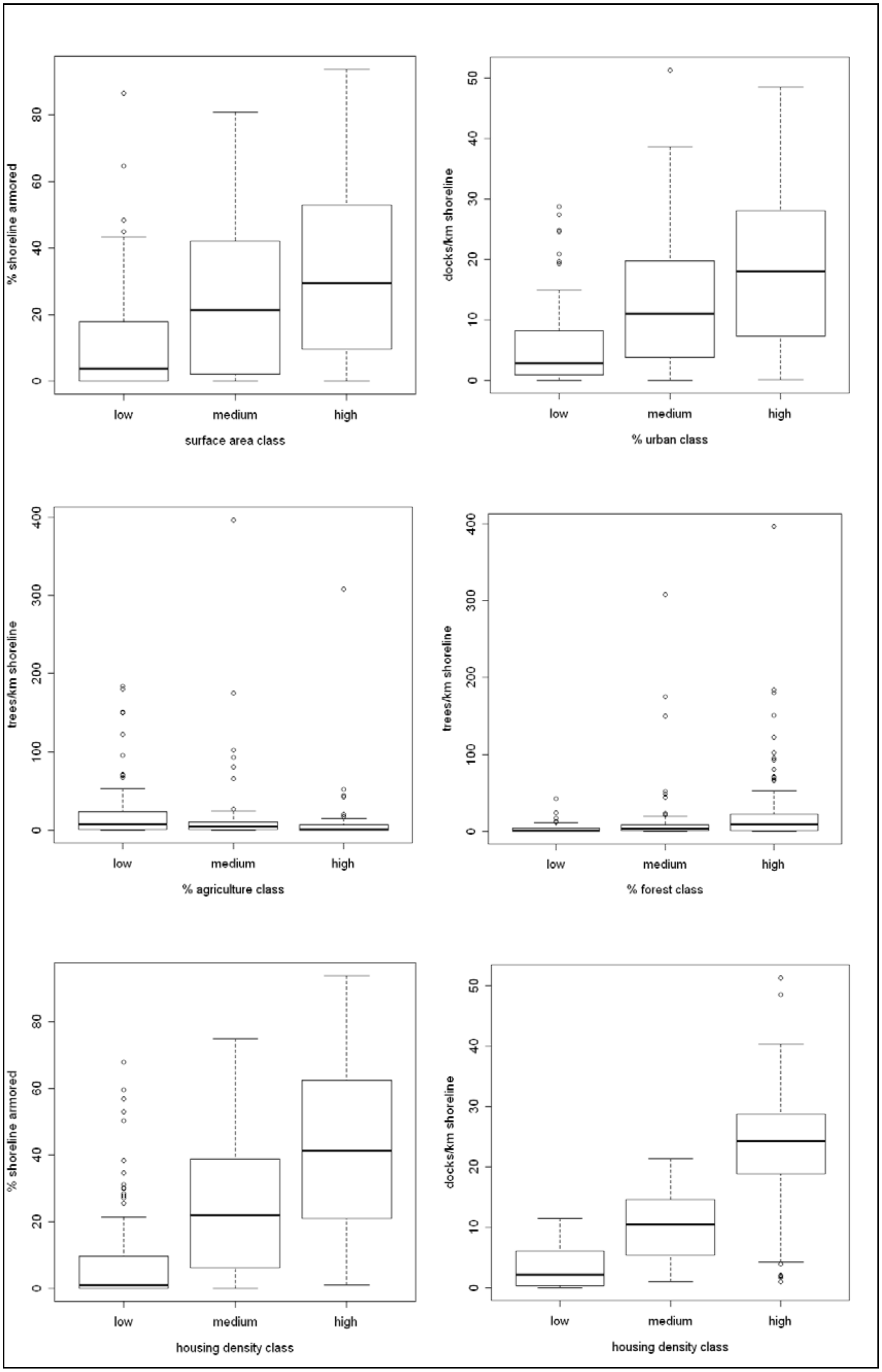

% shoreline armored
low
medium
high
surface area class
docks/km shoreline
low
medium
high
% urban class
trees/km shoreline
low
medium
high
% agriculture class
trees/km shoreline
low
medium
high
% forest class
% shoreline armored
low
medium
high
housing density class
docks/km shoreline
low
medium
high
housing density class

Figure 6.