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GIS Applications in the Evaluation of Nonpoint Source Pollution Inputs to Inland Lakes

ABSTRACT
The water quality of a lake is a reflection of the condition and types of human activities in the surrounding watershed. Residential development and agricultural practices increase both surface runoff and nutrient sources which influence lake productivity. This report introduces GIS methodologies which can evaluate aspects of land use types in relationship to nonpoint sources of phosphorus loading to lakes. Lake drainage basins were delineated by on-screen digitizing with reference of topographic maps. Distributions of land use types were examined by the watershed boundary. The potential of a land use class to export a nutrient to a lake was represented by applying export coefficients in a GIS. Lake volume and average total phosphorus concentration were calculated by developing a Triangulated Irregular Network (TIN) in a GIS. Lastly as a management scenario, a buffer region was applied to represent riparian zones. The study shows that the occurrence of residential developments along shorelines potentially has a significant impact on lake quality. These areas would be priority targets for practices that decrease nutrient loading to lakes. Modeling Phosphorus (P) inputs to lakes is restricted by the omission of many ecological processes linked to physical land characteristics and lake cycling of P. However, initial examination of significant factors of phosphorus dynamics in a GIS provides insights into the influence of landscape features, and can aid in prioritizing management strategies.

Introduction
Freshwater systems are an invaluable resource for our nation both as sources of our water supply and for the biological integrity of the planet. Inland lakes are a critical component of the aquatic system within the Great Lakes region. However, for decades inland lake ecosystems have been altered by human activity. The leading cause of lake degradation is anthropogenic eutrophication from nonpoint source pollution. Phosphorus (P), a nonpoint source pollutant, reaches inland waters from overland runoff and its availability is intimately tied to land use in the watershed. Little data have been collected to quantify and analyze the effects of excessive phosphorus inputs to the state’s lakes (Goudy 1994). The overall water quality trend for the vast majority of Michigan’s inland lakes, if not for all lakes, is unknown (Goudy 1994). A strategy to understand the multidimensional features of anthropogenic eutrophication entails the recognition and analysis of a lake’s watershed.

Phosphorus enters a lake by surface runoff from the surrounding watershed. The amount of runoff and the physical characteristics in the watershed such as soil type will influence the ecological state of a lake (Wetzel 1983). A watershed, which is large relative to lake surface area, will drive greater interaction between land and water (Wetzel 1983). The amount of P in runoff depends on both soil texture and composition. Phosphorus adheres to finer soil and organic matter (Pierzynski et al. 1994). Therefore, fine, clay and silts and organic debris are easily transported in runoff waters (Pote et al. 1996). By contrast lake basins with sandy soils and high infiltration rates will experience less P loading (Pierzynski et al. 1994).

It is widely recognized that water quality of a lake is an expression of the surrounding watershed (Rast and Lee 1983, Pierzynski et al. 1994). Land use/cover type has been cited as one of
the most significant factors which influences nonpoint source P contributions with agricultural land having the greatest impact on water quality (Sharpley et al. 1994). Residential growth increases nutrient runoff to lakes by increasing impermeable surfaces (Arnell 1983) and fertilizer application (Arnold and Gibbons 1996). Modeling processes such as the influence of land use and soil on runoff can provide an initial evaluation to the specific characteristics of a watershed.

Phosphorus concentrations in lakes vary at different depths and seasons. Highly eutrophic lakes release high concentrations of TP from an anoxic hypolimnion during the summer months (Welch and Cooke 1995). By contrast, the epilimnion TP concentrations will be low in thermally stratified lakes. During spring and fall mixing of lake waters, TP will be distributed throughout the water column and available as a nutrient (Horne and Goldman 1994). Accordingly, lake volume is an important parameter to calculate an average TP concentration from lake sampling data.

Natural vegetated areas called, riparian zones, slow surface runoff by having highly porous and organic soils. Phosphorus, usually limiting in both aquatic and terrestrial ecosystems, is utilized efficiently in riparian ecosystems by storage both in the soil and vegetation (Naiman and Decamps 1997). Shoreline riparian zones can decrease phosphorus loads to lakes and are encouraged as a lake management strategy.

The general objective of the research was to address issues related to land use in association to water quality. A highly adapted tool to analyze these factors is a GIS. In the research we used a GIS to evaluate phosphorus inputs to 6 lakes in Kent County, Michigan. The primary software used in the project was ArcView GIS. Figure 1 is an example of the interface of the system. A GIS is the computer hardware and software used to manage spatial information with an associated database. The system is uniquely suited to address natural resource issues because these problems have a strong spatial basis. Nonpoint sources of pollution are influenced by many factors such as proximity to lakeshores, soil texture, and percentage of undeveloped areas (Rast and Lee 1978). A GIS can represent these factors and many others with the potential to calculate, join, and add additional attributes to an existing database. The specific objectives of the study were to 1) delineate the drainage basins, 2) estimate TP areal loads to the lakes by surface runoff, 3) estimate average lake Total Phosphorus (TP) concentrations, and 4) explore a management strategy to reduce loads. This report highlights different techniques available within a GIS to meet these goals.

Study Sites
The six lakes and watersheds examined in the research are located in Kent County, Michigan. Land uses typical in the watersheds are agricultural, single family homes, mid-successional forest, and fields. Commercial and industrial regions comprise a very small percentage of the total land use. Agricultural activity is mostly row-crops, grains, orchards, and pasture. Lake productivity levels are reported by MDNR (1996) and range from moderate trophic state to eutrophic with atypical symptoms of excessive loading such as algae blooms and low dissolved oxygen levels. Five of the lakes are under annual treatment programs of herbicide application to control algae and macrophyte (Broekstra 1999). For the purpose of this study, four lakes are represented in the illustrations.

Methods
Watershed area (objective 1) was determined by digitizing boundaries and calculating area of 1997 land use types at each site. Watershed boundaries were digitized by referencing USGS Topographic 7.5' quadrangles at 1:24,000 scale (US Geological Survey) and larger hydrologic units from Michigan Natural Resource Information System (MIRIS). Sub-watershed lines were extrapolated by elevation contours from the USGS topographic maps (Figure 2). Field investigation confirmed the presence or absence of drains. This watershed theme was used to clip the corresponding extent of soil and landuse maps (MIRIS). The GIS was used to determine yearly phosphorus contribution of an area by intersecting land use and soil maps (objective 2). Total Phosphorus (TP) coefficients (kg/ha/yr) STWCS. (1999) were applied to the output map and used to estimate yearly mass TP loads (Reckhow and Simpson 1980). The method is widely used to estimate TP loads in lakes for which little background information exists (Dillon and Rigler 1975, Rast and Lee 1983, Vollenwieder 1969).

A number of steps were performed to calculate lake volume (objective 3). Hard-copy lake contour and depth maps (Bright Spot Maps) were scanned as digital images. In ArcView, 8 to 11 coordinate points from digital base maps (MIRIS) were identified by using landmarks such as roads, streams, and shorelines. The coordinate points were used to rectify the image into NAD 23, State Plane Coordinate System in Geographic Transformer (software). The georeferenced image were used as a guide to on-screen digitize each contour (Figure 3). The elevation of the contour line was recorded in the associated table. A separate theme of the lake shoreline was created to be used as the boundary in the TIN function. To execute the TIN function, the hull (boundary theme) entry was a soft clip shape polygon and the contour theme entry was soft breaklines (Figure 4). Lake TP concentrations at various lake depths were used to calculate average TP concentration for each lake. A 3-dimensional model of the lake basin was created from the TIN.
Watershed delineation identifies the land area which interacts with the lake system. For example, Lime Lake has a surface area with a ratio of 19:1. A strategy (objective 5) is to establish a riparian zone (Figure 6 and 7) which was simulated by applying a 30 m buffer around shorelines.

Results and Discussion
Watershed delineation identifies the land area which interacts with the lake system. For example, Lime Lake has a surface area with a ratio of 19:1. A strategy (objective 5) is to establish a riparian zone (Figure 6 and 7) which was simulated by applying a 30 m buffer around shorelines.

The effect of land-use and soil types on nutrient loads is evident from the intersection of soil and land use maps in the Bass Lake watershed (Figure 6 and 7) which revealed that residential areas occurred in regions of rich soils. A high runoff event in association with impermeable surfaces and organic soil create conditions for TP loading to the lake. Estimated TP load for Bass Lake was 184.4 kg/yr in 1997 with the greatest percentage from residential areas (47.8%). Agricultural and residential land use comprise the southern portion of the watershed along with coarse soil texture. Even though these soils may have a low runoff propensity, without effective soil conservation practices these areas will contribute a large portion of TP loads to the lake. TP coefficients applied in the watershed (Figure 8) illustrate the higher contribution of nutrients from residential land use in locales of organic soils and low inputs from undeveloped areas. Research has found an inverse correlation between the percent of natural areas in a watershed and low productivity in a lake (Field et al. 1996). Undeveloped areas are considered to supply a lake system with background nutrient levels while many land use activities contribute to excessive P loading. Residential land use occurring in close proximity to the shoreline will heighten runoff events. Vegetated areas comprise approximately a third of the watershed while agricultural lands are in conjunction with highly impervious surfaces such as residential roads. These are important factors which influence nutrient availability to this lake.

Average lake TP concentration for Big Pine Island lake is 0.020 mg/l. Lakes with these TP concentrations are usually susceptible to algae blooms (ISWCS. 1999). Unfortunately, one average TP analysis is not representative of TP availability throughout the year. A study of monitoring design for water quality by Reckow and Stow (1990) suggests approximately four years of monthly water quality data are needed to detect trends. Therefore, long-term monitoring is a critical element to consider for water quality management. Nevertheless lake volume data remains an important consideration. For example, Big Pine Island Lake is elongated and its volume would be difficult to estimate by conventional means. Lake basin morphology is very diverse from being shaped symmetrically as a kettle lake to being elongated and curved such as oxbow lakes (Wetzel 1984). The GIS function TIN can recognized the variations in lake surface area and depth to approximate lake volume.

It has been recognized for decades that phosphorus loading to lakes accelerates plant growth thereby decreasing water clarity, and degrades aesthetic qualities of lakes. Nutrient loading can change fish communities and narrow recreational usage of a lake. To protect lake ecosystem many states governmental agencies either have zoning ordinances which prohibit disturbance in riparian zones or encourage the practice of protecting riparian zones (Minnesota DNR 2000 and WDNR 2000). Figure 9 shows a 30 m buffer which represents an adequate distance in most circumstances to trap nutrients from entering water bodies (Philips 1989). The land use theme overlaid with the buffer zone identifies a critical region (residential) for lake management.

Clearly, as demonstrated by these examples a GIS is an extremely versatile tool to manage and manipulate spatial information. In addition, an existing GIS can be expanded to incorporate auxiliary data. Parcel information could be merged to identify property owners in critical regions of the watershed such as shorelines and along streams. This would facilitate the distribution of information on their lake and watershed. Watershed analysis using a GIS has an immense potential to communicate, illustrate, and advance the understanding of lake ecosystems and the impact of human activities.
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