The role of GIS in assessing the relationship between water quality and land use

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Currently, a study of water quality trends over the past few decades has been initiated in Rhode Island. This project will combine three data sets to quantify and understand the relationships between water quality trends, land use change, and demographic changes in the state. Water quality in some Rhode Island watersheds has declined significantly as pesticide and herbicide use, lawns, impervious surfaces, and groundwater withdrawal has increased. This study will incorporate water quality data collected by the URI Watershed Watch since 1988. The RIGIS database at the URI Environmental Data Center will provide a comprehensive assessment of land use change during the same period. Data from the U.S. Census Bureau will be used to assess the changes in population distribution. The integration, analysis, and interpretation of this data will help identify sources and flows of pollutants and the relationship of water quality to demographic and developmental changes. This will be of great value to policy makers, hopefully ensuring that our freshwater systems are not further damaged by future changes in land use and development.

This project will pose a considerable challenge for a few reasons. First, although the Watershed Watch has amassed a considerable amount of water quality data, there has not yet been a comprehensive spatial or temporal analysis of this data. Second, in order to establish some sort of causal relationship between water quality and land use or population changes, it is necessary to integrate data from different databases. It is anticipated that GIS will play a large role in this study. The papers that were reviewed here deal with GIS applications to analysis of water quality and assessment of contributing factors such as land use.

The water quality data that we have for Rhode Island includes water clarity (Secchi depth); water depth; temperature; dissolved oxygen; pH; alkalinity; chlorophyll; total and dissolved phosphorus; total, nitrate, and ammonium nitrogen; chloride; fecal coliform and enterococci bacteria. Some of these water quality factors can be related to characteristics of land use; for instance, chloride concentrations due to use of road salt, or nitrogen from waste-water treatment plants. Much of the literature deals with one or a couple of water quality indicators. For instance, Bel Hassen and Prou (2001) examined nitrogen as a consequence of aquaculture, and Soranno et al (1996) were concerned with phosphorus loading in a lake watershed. In other studies, such as Costanza et al (2002), an overall view is taken of all contributing factors to the health of a watershed.

Many of the assessments of water quality are watershed-based. That would seem to make sense, particularly when considering nonpoint sources of pollution. The methodologies differ in how they encompass watersheds- whether it's a top-down approach, as in Johnson et al (1990) where a cumulative impact assessment considers the entire watershed at once; or a bottom-up approach, as in Swaney et al (1996) where eight individual watersheds were considered individually and the results aggregated in the assessment of the entire river basin. GIS is useful for studies of watersheds, as hydrologic unit maps are available from USGS, and point sources can be plotted within watershed boundaries.

It would seem to be common sense to assert that land use has a great impact on water
quality, and in fact that is the conclusion of many of these studies. For instance, Swaney et al (1996) concluded that human activity has had an enormous effect on carbon loading in the Hudson River. Over the last few decades, the overall trend in the U.S. has been to move out of cities and traditional suburbs, and “exurbs” have been established in regions that were rural not long ago. Hence, many watersheds have been subjected to significant changes in their impact from human activity. It is preferable to predict outcomes and manage activity, and many of these water quality studies are done for the purpose of providing a tool to policy makers and a means for the public to gauge the impact of their actions on the quality of their drinking water. Two aspects of this problem are apparent- how to characterize land use, and how to convincingly determine its effect on water quality. GIS has a means of characterizing different categories of land use, i.e., the Anderson classification scheme. Some studies (Nilsson et al, 2003) suggest that this scheme does not have sufficient resolution to capture all of the detail in a landscape that is constantly changing. Yet other studies find this scheme too complex, and reduce the level of information to only a few categories (Swaney et al, 1996). If a large set of land use (or other watershed data) classes are considered, the problem of land use/water quality correlation becomes intractable. Thus some sort of multivariate statistical analysis is required to reduce the dimension of the problem, and assess which factors have the most impact. Principal components analysis, a statistical technique of reducing datasets to a lower dimensional space in a way that explains the variance in the data, is often used for this purpose.

Much of the water quality/land use literature wrestles with the issues of scale and complexity. If the data is too sparse, or the models are too simplified, the information contained may be insufficient to lead to a valid conclusion. If the model becomes too complex or the data grows in dimensionality, the problem either may become impossible, or the results might be determined by data that is not significant. The models become even more complex when other factors are introduced, such as geography, socio-economics, or population density. GIS can be a valuable tool for retrieving and displaying information, but it can also provide too much of it. On the other hand, while the capability of systems to provide high-resolution data has improved, some (for example, Nilsson et al, 2003) believe that GIS still has too much inherent approximation to be a valid tool for making these assessments.

The literature on GIS applications on water quality and land use run the gamut from simple models to complex systems; hierarchical or holistic schemes; varying temporal and spatial scales. Yet, there are a few conclusions that most of these studies lead to:

1. Land use and human activity have a great impact on water quality.
2. There are a multitude of approaches to studying this problem.
3. GIS is a useful tool for measuring water quality, for interpreting land use, and for assessing the impact of the latter on the former.
Nutrient loading resulting from agricultural practices is an issue with many of our estuaries. Likewise, aquaculture, which in the west coast of France is generally conducted in earthen ponds, acts as a nonpoint source (NPS) of nitrogen. These ecosystems are coupled with intertidal salt marshes which act as nutrient sinks. Estimating NPS loading using detailed hydrologic and nutrient budgets based on field sampling is a labor-intensive task. Thus there was a need to develop a spatial analysis tool to link upland characteristics to NPS nutrient loading, so that consequences of changes in land use and management practices could be evaluated. GIS was deemed to be of value here for its capability to store, display, integrate, and analyze spatially explicit information. This paper focuses on the methodology used to assess surface dissolve inorganic nitrogen and ortho-phosphorus loadings to intertidal salt marshes, based on the spatial pattern of land use and topography. The regional distribution of stream flows and nutrient loading was interpolated in the bay, using gage stations as known sources. Geostatistical kriging was used because of its capacity to deal with irregularly distributed samples.


A continual theme in discussions of ecological management is scale. Ecological scientists maintain that environmental management is often done on scales that are too small to be effective, with too narrowly defined goals. This is particularly the case now with issues such as global warming and degradation of water quality in coastal ecosystems far from the sources of pollution. The trend has been toward ecosystem-based and watershed-based management. The research described here addresses the need, which is established by the EPA, to assess the effect of stressors on the environment over a range of scales. The Patuxent River is one of most-studied tributaries in the Chesapeake Bay and is often used as a model of the Bay itself. The authors have developed a spatially explicit model of the Patuxent River watershed that integrates data over several spatial, temporal, and complexity scales. The model facilitates the assessment of the impacts of spatial patterns of land use over a range of environmental indicators, thus providing decision makers with insight into the consequences of land use patterns. While these models are site-specific, one aspect that the authors emphasize is the modularity of the model and the adoption of models that were developed for other regions; here, for instance, incorporating models that were developed for the Everglades and New Orleans. The ability to successfully adapt models that were developed for other regions would be of encouragement to those who are charged for developing models for new ecosystems.


This paper is concerned with the cumulative effect of wetlands loss on water quality. The
notion of an incremental effect of an impact on other impacts is emphasized here, as well as the nonlinear relationship between wetlands abundance and cumulative wetland function, i.e., the cumulative function of all wetlands in a watershed is different than the additive function of the individual wetlands themselves. This is another way of looking at the issue of scale. In this study, a GIS was used to measure and record 33 watershed variables that were derived from aerial photos in the region surrounding Minneapolis-St. Paul. Principal components analysis was used to determine which of these variables had the most significant effect on water quality. The authors stress that the importance of this study is to validate the position that cumulative impact assessment is a better tool for evaluating the condition of a watershed than the traditional method of starting with individual wetlands. This landscape-scale approach over long time scales is the product of advances in ecological theory and is only possible as a consequence of GIS.


As the title suggests, the authors describe a highly interdisciplinary approach to predicting the effect of changes in land use on stream ecosystems. Because many of these ecosystems are in areas where population densities have increased due to spreading of suburban regions and the establishment of exurbs, the quality and quantity of drinking water is threatened. This paper is concerned with the complexity of predicting changes in land use as well as assessing what effect these changes will have on rivers and streams. The focus is on using all available resources—ecological models, economic data, geographic and hydrological data, etc. Various approaches to modeling are discussed, with a view of how they might be incorporated into an overall holistic methodology. This paper is included here as an example of the limitations of GIS. The authors acknowledge the contribution that GIS has made to enabling ecological research that was unimaginable only 20 years ago. However, they assert that GIS is not well suited to dealing with smaller scale patterns and processes; for instance, a single, small stream. The linear nature and narrow width of stream channels makes it difficult, in terms of resolution, to document land use changes. The generally used methods for characterizing land use, such as the Anderson classification scheme, are, in the view of the authors, inadequate for capturing a continually varying landscape. Also, they consider the confusion in land use descriptions that result from automated interpretation (for instance, attributing forest land cover to residential areas with well-developed tree canopies) to be a serious problem. The authors do recognize the ongoing technological advances in GIS and remote sensing and suggest that these technologies will be more useful in the future.


This is another paper that deals with nonpoint sources of pollution. In this case, as the subject watershed is around a lake (Lake Mendota in Wisconsin), the concern is phosphorus (P) loading. Modeling a pollutant from land to surface waters can be very complex and data-intensive. The goal of this study was to develop a simple (the authors emphasize “simple”) model to account for spatial patterns in topography and land use using a GIS. After reading some of these papers that revel in complexity, an approach that seeks simplicity is
refreshing. I am not sure if the approach here has been too simplified; it seems to me that some of the assumptions about P fluxes might be broad. The model disregards atmospheric deposition- I don't know how important that is when measuring input of P to lakes. However, the model seems to account for factors such as attenuation, while estimating P loading using only a few parameters. The model estimates the volume of P that is transported over a certain distance, with a few parameters that account for area of land use, amount of P attenuated, etc. The model calculates the flux of P from one pixel to the next; the pixel size is determined by the GIS.


The goal of this study is to estimate the loading of carbon into the Hudson-Mohawk Basin, and to assess how it would be effected by alternative land use scenarios. GIS was used to determine watershed areas and areas of different land use within the watersheds; to map the location of organic carbon point sources within the watersheds; to investigate several different schemes for incorporating weather data; and for mapping the intersection of watershed boundaries and county lines. Level 2 land use categories from NASA high-altitude photographs were aggregated into four land uses, and the land use map was overlayed on USGS hydrologic units for the Hudson-Mohawk Basin. Two alternative land use scenarios were considered- one where the entire watershed region is forested; another where it is entirely agricultural. The model found that sediment flux changed dramatically in these scenarios, from 10% of its present value in the forested scenario to 200% in the agricultural scenario. The model found that variability in total organic carbon (TOC) loading is strongly coupled to land use. The conclusion is that human activity has had an enormous impact on sediment and TOC loading in the Hudson.