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Modeling the relationship between land use and surface water quality

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It is widely known that watershed hydrology is dependent on many factors, including land use, climate, and soil conditions. But the relative impacts of different types of land use on the surface water are yet to be ascertained and quantified. This research attempted to use a comprehensive approach to examine the hydrologic effects of land use at both a regional and a local scale. Statistical and spatial analyses were employed to examine the statistical and spatial relationships of land use and the flow and water quality in receiving waters on a regional scale in the State of Ohio. Besides, a widely accepted watershed-based water quality assessment tool, the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), was adopted to model the plausible effects of land use on water quality in a local watershed in the East Fork Little Miami River Basin. The results from the statistical analyses revealed that there was a significant relationship between land use and in-stream water quality, especially for nitrogen, phosphorus and Fecal coliform. *The geographic information systems (GIS) spatial analyses identified the watersheds that have high levels of contaminants and percentages of agricultural and urban lands. Furthermore, the hydrologic and water quality modeling showed that agricultural and impervious urban lands produced a much higher level of nitrogen and phosphorus than other land surfaces. From this research, it seems that the approach adopted in this study is comprehensive, covering both the regional and local scales. It also reveals that BASINS is a very useful and reliable tool, capable of characterizing the flow and water quality conditions for the study area under different watershed scales. With little modification, these models should be able to adapt to other watersheds or to simulate other contaminants. They also can be used to study the plausible impacts of global environmental change. In addition, the information on the hydrologic effects of land use is very useful. It can provide guidelines not only for resource managers in restoring our aquatic ecosystems, but also for local planners in devising viable and ecologically-sound watershed development plans, as well as for policy makers in evaluating alternate land management decisions.*

Keywords: BASINS, ArcView, GIS, watershed hydrologic modeling, water quality, flow.

Introduction

As water drains from the land surface, it carries the residues from the land. Surface runoff, especially under the first flush phenomena, is an important source of non-point source pollution. Runoff from different types of land use may be enriched with different kinds of contaminants. For example, runoff from agricultural lands may be enriched with nutrients and sediments. Likewise, runoff from highly developed urban areas may be enriched with rubber fragments, heavy metals, as well as sodium and sulfate from road deicers. Moreover, through evapotranspiration, interception, infiltration, percolation and absorption, different types and coverages of vegetative surfaces can modify the land surface characteristics, water balance, hydrologic cycle, and the surface water temperature (LeBlanc *et al*., 1997). As a result, the quantity of water available for runoff, streamflow and ground water flow, as well as the physical, chemical and biological processes in the receiving water bodies can be affected. It is therefore conceivable that there is a strong relationship between land-use types and the quantity and quality of water (Gburek and Folmar, 1999).

In a study of the effects of forested, agricultural and urban areas on water quality and aquatic biota in the Piedmont ecoregion of North Carolina, Lenat

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and Crawford (1994) found that the agricultural lands produced the highest nutrient concentrations. Fisher *et al*. (2000) also noted a higher amount of nitrogen, phosphorus and *Fecal coliform* bacteria in the poultry production areas in the Upper Oconee Watershed in Georgia. In another study of Coweeta Creek in western North Carolina, Bolstad and Swank (1997) observed that there were consistent changes in water quality variables, concomitant with land-use change. Similarly, in an earlier study of the Little Miami River Basin, Tong (1990) found that urban development in the watershed had caused substantial modification on flood runoff and water quality. Changing land use and land management practices are therefore regarded as one of the main factors in altering the hydrological system, causing changes in runoff (Mander *et al*., 1998), surface water supply yields (Wu and Haith, 1993), as well as the quality of receiving water (Changnon and Demissie, 1996).

Although there have been some studies on the impacts of land use on water flows and quality (see for example, the work of Hanratty and Stefan, 1998; Rai and Sharma, 1998; and Bhaduri *et al*., 2001), the complex intrinsic relationships of land use, water yields and water quality in different geographical areas under different scales are yet to be elucidated. Current methods on predicting water quality in river catchments based on land-use patterns are still developmental. Most existing research is confined to field studies. Some studies are very specific to a locality at one geographical scale. Many focused on either statistical, or spatial, or modeling analyses. Others examined the impacts of land use on only the quantity or the quality aspect of runoff. Examples of such work include those performed by Meissner *et al*. (1999), Ferrier *et al*. (1995), Tsihrintzis and Hamid (1998), Mattikalli and Richards (1996), Wu and Haith (1993), Hulme *et al*. (1993), Henderson-Sellers (1994), and Bouraoui *et al*. (1998). Only a few studies have employed an integrated approach involving the use of statistical and spatial analyses, as well as hydrologic modeling to examine the hydrologic effects of land use in both a regional and a local scale.

Study objective

The objective of this study was to use a watershed-based approach to examine the plausible statistical and spatial relationships of land use on the quantity and quality of the surface water under a broad regional scale in the State of Ohio, and to model the relative impacts of different types of land use in a local watershed. The aim is to further our understanding of the hydrologic effects of land use.

Methods and materials

Both statistical (such as non-parametric correlation analysis and analysis of variance) and geographic information system (GIS) analyses were adopted in this study. They were used to examine the general association of land use and flow and water quality, and locate the watersheds that are enriched with contaminants and with strong relationships with land use. GIS is a powerful data integration and spatial analysis tool. In this research, ArcView GIS is used to aggregate, synthesize and analyze large databases, and to identify spatial relationships.

Based on the correlation results and the availability of data, a watershed was chosen for detailed modeling of the relative hydrologic impacts of different types of land use in a local watershed scale. A sophisticated and widely used assessment tool, the Better Assessment Science Integrating Point and Nonpoint Sources, BASINS, (US Environmental Protection Agency, 1998) was utilized in this study. BASINS is a physical-process-based analytical system developed by the US Environmental Protection Agency (USEPA) as an assessment tool for watershed-based and water-quality-based studies. Version of BASINS 2·01 was used in this paper to characterize the flow and water quality conditions in the watershed. Several water quality parameters (nitrates, phosphates, and *Fecal coliform*) were examined in detail. The models were calibrated and validated using flow and water quality data from historical records retrieved from US Geological Survey (USGS). The efficacy of the models in representing the real world runoff and water quality conditions under different geographical scales was also assessed.

The approach to the analyses entailed first of all the establishment of whether there are any statistical and spatial relationships between land use and water quality at a regional scale. If such relationships exist, the second task was to model the water quality from a local watershed with different types of land use.

The State of Ohio was selected in this project for the broad scale regional study due to the availability of historical data on flow, water quality, land use, elevation, and climate. In the hydrololgic modeling, a watershed from the Little Miami River Basin, the East Fork Little Miami River Basin, was chosen.

Statistical and spatial analysis

Statistical analyses were utilized to test the null hypothesis that water quality is not related to the surrounding land-use types at a regional scale. They were also used to determine the quantitative associations, if any, of land use and water quality in the State of Ohio. The GIS spatial analyses were employed to map the areas that have a high contamination level and to examine the spatial relationships of land use and water quality.

Data preparation

The map of the 11-digit Hydrological Units (HUCs) for the State of Ohio was obtained from USGS. It was used as the base map for the analyses. The water quality data for the period of 1990–1998 in Ohio were obtained from the USEPA's Storage and Retrieval computerized environmental data system (STORET). STORET is a repository for water quality, biological, and physical data. The data are in database (DBF) format. There are 243 water quality variables. Each monitoring site is referenced in latitude and longitude. To spatially locate these monitoring stations, an Arc Avenue program was developed to extract the water quality information using the longitude and latitude values of each monitoring station. Using the spatial location function of ArcView, a shape file was created for all the monitoring stations. The original water quality table was then joined to this spatial map by station; as such queries on the data could be performed and the water quality data could be geo-referenced spatially by each station. The map was projected into Albers map projection to match the 11-digit HUCs base map. By employing the spatial selection in ArcView, all the stations in each HUC were obtained. The mean values of each water quality variable in each 11-digit HUC were then calculated. These constituted the water quality data for statistical and spatial analyses.

Land-use data for the State of Ohio in 1994 were obtained from Landsat Thematic Mapper dataset acquired by the Multi-Resolution Land Characterization Consortium (MRLC). The MRLC data are in a grid format, with land-use types listed for each pixel. Since the HUCs are displayed in a vector format, file conversion was performed. The 'add' function in ArcView GIS was used to combine the two files. The percentages of each type of land use in each HUC were then calculated.

Prior to the statistical analyses, the normality and linearity of the water quality and land-use data were tested. Only pH and sulfate water quality variables and forest land-use variable exhibited some form of normal distribution. Scattergrams also revealed that the relationships of land use and water quality might not be linear. This latter result conforms with other researchers, such as Nikolaidis *et al*. (1998), who suggested a non-linear response of nutrient loadings to different land-use types due to the nature of hydrogeochemical processes in a watershed. Moreover, in the data sets for total phosphorus, total nitrogen, lead, manganese and *Fecal coliform*, there are a few outliers (in the form of extremely high values). These outliers as well as missing data and 'zero' values were deleted from the data set for further analyses. Only those HUCs containing water quality data were used in the statistical analyses.

The analyses

Since most of the variables did not distribute normally, the statistical analyses were confined to non-parametric statistical tests. Spearman's rank correlation analyses were used to explore the relationships between land use and water quality in the State of Ohio. Analysis of variance on the ranked values of a few selected water quality variables was also performed to test if there were any significant differences between land-use categories.

Water quality variables that were significantly related to land use were chosen for further GIS spatial analyses. Based on the frequency distribution, and the mean and median values of each water quality variable, the HUCs were classified into three arbitrary categories, the 'High', 'Medium', or 'Low', depicting the HUCs with a high, medium, or low value of that water quality variable. Similarly, for the land-use variables, the HUCs were classified into 'High', 'Medium', or 'Low', representing the HUCs with a high, medium, or low percentage of certain land-use type. According to the rank correlation results, pairs of water quality and land-use variables that were significantly related were selected. Each pair of water quality and land-use variables was superimposed using ArcView GIS. For example, if nitrogen was positively related to agriculture land use, the HUCs with high nitrogen values were overlaid with the HUCs with a high percentage of agriculture land use. The resultant map denoted the spatial relationships of that water quality variable with that land-use type.

Hydrologic modeling on the East Fork Little Miami River watershed

The selection of a hydrologic model

There are different types of hydrologic models in use today. They range in capability, complexity, scale and resolution. With various theoretical assumptions and mathematical algorithms, these models may have different data requirements. Moreover, the accuracies of the resulting simulation may vary (Singh, 1995). The most common full-scale simulation models for urban areas are L-THIA (Bhadhuri *et al*., 1997), Sacramento Soil Moisture Accounting Model (Burnash *et al*., 1973), SWAT (Arnold *et al*., 1994), SWIM (Krysanova and Luik, 1989), HYDROTREND (Syvitski *et al*., 1988), System Hydrologique Europeen Model (Abbott *et al*., 1986), and the Hydrological Simulation Program-FORTRAN (Johanson *et al*., 1984; Donigian *et al*., 1984). Other models for non-point source pollution include CREAMS (Knisel, 1980), GLEAMS (Leonard *et al*., 1987), SWRRB (Arnold *et al*., l990), MATSALU (Krysanova *et al*., 1998), ANSWERS (Beasley *et al*., 1980), and AGNPS (Young *et al*., 1989).

A number of hydrologic models were considered in this research. The main criteria for choosing the model were: model accuracy, model capabilities, model flexibility, data requirements, and ease of use. Based on extensive literature searches for models in use today and communications with other model users, BASINS was chosen to model the quantity and quality of the runoff from different types of land use.

BASINS

BASINS is a flexible, yet valuable watershed-based multipurpose integrated water-quality analysis system. Using the familiar Windows environment and an ArcView-based GIS as an integrating framework, BASINS incorporates commonly used environmental data, a variety of proven and robust analytical hydrologic, point and non-point loading, and water quality stream models, assessment and planning tools, statistical analytical tools, data mining, organizing, evaluating and management technologies, as well as reports and graphics display and visualizing capabilities into one system. Accordingly, it can support analysis at a variety of scales and can integrate and display a wide range of information in various formats.

There are two stream models (QUAL2E and TOXIROUTE) and a Nonpoint Source Model (NPSM) in BASINS. The NPSM is a planning-level watershed model. By incorporating both point and non-point sources, NPSM is capable of simulating non-point source runoff and associated pollutant loadings, point source discharges, flow and water quality routing through stream reaches and well-mixed reservoirs. NPSM uses most of the simulation capabilities of the Hydrological Simulation Program—FORTRAN (HSPF) hydrologic model (US Environmental Protection Agency, 1984). HSPF is a very robust, high resolution, flexible, reliable, and comprehensive hydrologic model for simulation of watershed hydrology and water quality (Bicknell *et al*., 1996). As a physical-process-based model, HSPF uses minimal input data to describe hydrological conditions in a watershed. As a time series management system, it can simulate continuously the hydrologic and associated water quality processes on pervious and impervious land surfaces as well as in streams and well-mixed impoundments. Derived from the Stanford Watershed Model (SWM), HSPF considers all streamflow components (runoff, interflow, and baseflow) and their pollutant contributions. In addition, it has incorporated many non-point source models, such as ARM and NPS. By integrating the chemical, biological, and contaminant runoff processes on land surfaces and in the soil profiles with in-stream hydraulic, water temperature, sediment transport, and nutrient and sediment-chemical interactions, it simulates hydrolysis, oxidation, photolysis, biodegradation, volatilization and sorption. Based on a continuous record of precipitation and evaporation data, it computes a continuous hydrograph of streamflow at the basin outlet and produces a time history of the runoff, sediment load, and nutrient and pesticide concentrations (Donigian and Huber, 1991). Indeed, it is an integrated and comprehensive model for runoff, erosion, fate and transport of pollutants. It has been widely-used for simulating watershed hydrology and water quality, and has been applied to support various watershed and water quality modeling studies.

HSPF is a continuous simulation program. It requires continuous records of rainfall, evapotranspiration, temperature, and solar intensity to drive the simulations. Thus, only those watersheds which are close to a meteorological station with reliable long-term climate data can be used in the study. Moreover, for calibration purposes, the watershed has to have USGS gauge stations that have historical discharge, flow and water quality information.

The East Fork Little Miami watershed

In this project, the East Fork Little Miami River, a tributary of the Little Miami River in southwestern Ohio, was chosen for further hydrological modeling. This was mainly because the Little Miami River has been monitored by the USGS since 1920. Continuous records of stream flow are available for many areas in the river. In addition, there are historical climate, land use, flow, permitted point source discharge and water quality data. The land-use types in the river basin are diversified. Besides, the preliminary statistical and GIS analyses found that there were strong relationships between land use and water quality in this river basin. After calibration and validation, the models were used to characterize the flow and water quality conditions in the watershed.

The Little Miami River is a major tributary of the Ohio River. It flows from northeast to southwest and joins the Ohio River near Cincinnati, Ohio. Its watershed covers more than 5840 sq. km and 3970 stream km. The dominant parent materials of the region consist of shale, limestone and dolomite from the Upper Ordovician or Silurian (Ohio Department of Natural Resources, 1964). Most of the soils belong to Genesse-Williamsburg Association and have their origins from alluvial, glacial outwash, residual and glacial till plains. They are deep, moderately well drained and highly productive (Lerch *et al*., 1975). The sand and gravel deposits provide aquifers with fair yield potentials for groundwater supplies.

Containing some of Ohio's most scenic and diverse riverine habitats, the Little Miami River was designated a state scenic river in 1969 and a national scenic river in 1973. In addition, the river is one of the largest 'exceptional warmwater habitat stream' in Ohio, supporting a very rich aquatic community of flora and fauna (Debrewer *et al*., 2000). Notwithstanding the fact that most lands in the river basin are agricultural, there has been a steady increase of residential and commercial land use due to recent suburban sprawls. Natural forests and agricultural lands are gradually replaced by developed areas. The river system is now under stress. Any change in stream flow caused by land-use modification will undoubtedly aggravate the situation, reducing the water availability for municipalities, degrading water quality, and increasing the potentially toxic algae (Ohio Environmental Protection Agency, 1996). In order to conserve the area, it is of paramount importance to have a better understanding of the hydrologic consequences of land use. This type of knowledge will be invaluable not only to academia, but also to the resource managers and local government.

The East Fork Little Miami River is the eastern branch of the Little Miami River. The watershed used in this simulation study is the southern most HUC in the Little Miami River watershed. There are eleven reaches in this HUC. In this East Fork Little Miami watershed, agriculture is the predominant land use, although there are more forest and urban areas in the western part.

Database construction and model preparation

Since BASINS is a watershed-based model, the watershed for the analyses had to be delineated first. This was done by using the delineation tool in BASINS. The watershed for the East Fork Little Miami Rivers was delineated according to the Reach Files Version 1 and Version 3 (RF1 and RF3, respectively) from the USEPA and digital elevation data (DEM) from USGS. To examine the efficacy of BASINS in simulating watersheds at different scale, the East Fork Little Miami River Basin was further partitioned into eleven smaller subwatersheds according to the eleven reaches in the Reach File Version 1 (Figure 1). Each of these smaller subwatersheds is identified using its reach identification code. The use of smaller subwatersheds is helpful because there are subwatersheds in the study area that are dominated by different types of land use, which might impact the hydrology differently. By comparing the output of flow, nitrogen, phosphorus, and *Fecal coliform* from different land-use types in different subwatersheds, the relative impacts of land use on water quantity and quality could be ascertained.

Once the subwatersheds were delineated in BASINS, then GIS data were prepared, the NPSM files were created, and a NPSM model specific for the study area was built. The GIS data were extracted from the BASINS database using the 'Data Extraction' tool in BASINS. These data included connection and topological relationships, water quality observation data, permit point source pollution data, and information on river flow and HUCs. Furthermore, the 1970–1990 land-use coverages were obtained from the MRLC. Meteorological data were obtained from the National Climatic Data Center. Soil data were acquired from the National State Soil Geographic (STATSGO) database produced by the U.S. Department of Agriculture—National Resources Conservation Service. All of these additional data were compiled

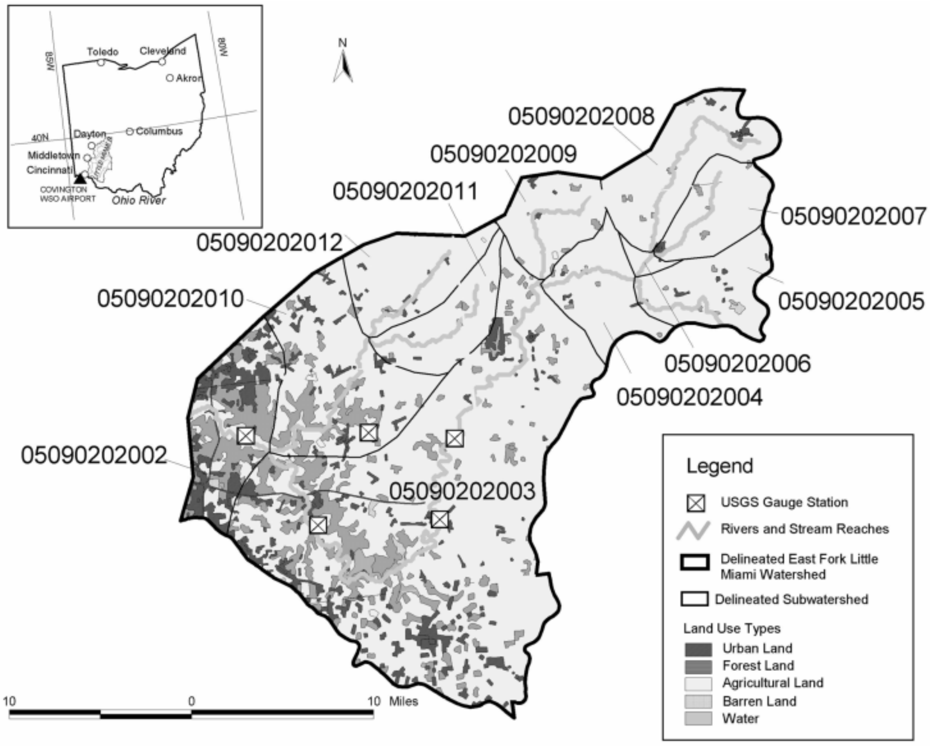

Figure 1. Delineated East Fork Little Miami watershed.

and managed in a GIS database. Spatial coverages were merged and clipped using Arc/Info. They were then imported into the NPSM project. Next, the *.uci file (user input file) was generated and the most appropriate meteorological station and the Watershed Data Management (WDM) file selected. The NPSM was run for the subwatersheds at the lowest pour point.

Hydrologic simulation

The simulation was performed in two steps: the simulation of the hydrology and the simulation of the water quality parameters. This is because water quality simulation is based on the general hydrologic model. Simulation was based on January 1, 1988 to December 31, 1994 meteorological data from the Covington WSO Airport Weather Station in Northern Kentucky, and 1990s land-use data from MRLC. By default, BASINS assumes all built-up areas to have a 50% pervious and a 50% impervious land surface. To reflect the actual percentages of pervious and impervious areas in the urban areas, a land-use report for the study area was generated from BASINS. The information was then used to adjust the % of perviousness and % of imperviousness in the watershed.

A basic hydrologic model for the East Fork Little Miami River Basin was then built by first running the HSPF module in NPSM for each smaller subwatershed using the default parameters. According to the connection relation among the reaches, the simulated flow from the subwatershed at the upper reaches was added to the HUC downstream as a point source flow. After simulating all the subwatersheds in the basin, a hydrologic model for the East Fork Little Miami River Basin was created.

Model calibrations

The simulated flow results for the East Fork Little Miami River, in terms of total rate of outflow of reaches, were then compared with the observed daily discharge records during the simulation period from existing USGS monitoring data. It was found that by using the default parameters, the simulated flow was very close to the actual monitored flow rate, with an error rate of about 8·12% reduction, meaning that the simulated flow was 8·12% lower than the actual observed USGS flow data (Figure 2). The error rate is calculated as: (Simulated value−Monitored value) ÷ Simulated value. Generally, if the error rate is less than 10%, the model is regarded to be good. The model is still

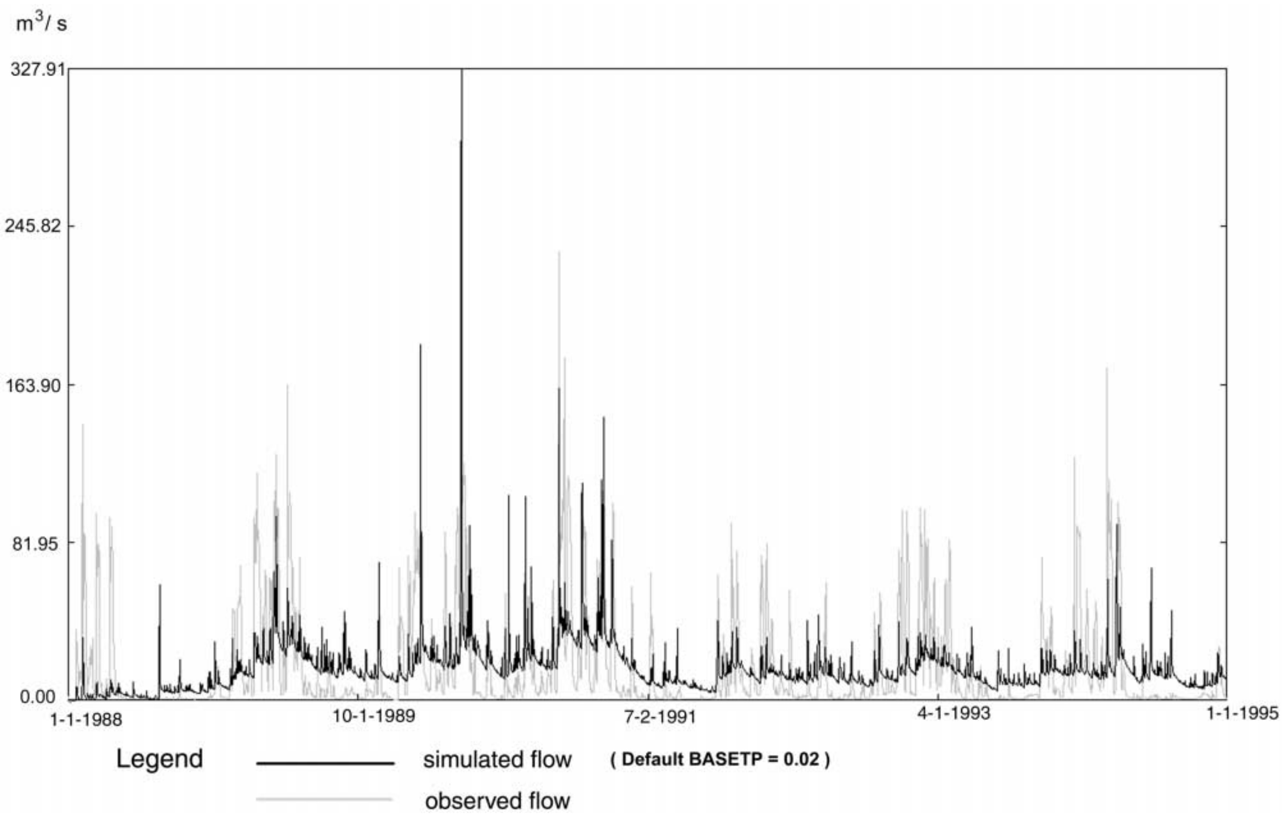

Figure 2. Simulated flow with default input parameters compared with observed flow, East Fork Little Miami River.

acceptable if the rate ranges from 10–20% (Bicknell *et al*., 1996).

In order to better reflect the real world conditions, the HSPF model parameters were calibrated until there was a satisfactory agreement between the simulated flow rate and the observed monitored flow data. There are different methods for calibration. BASINS provides some parameter estimates and the users can adjust the input parameters manually. In addition, computer programs like Annie, Parameter Estimation (PEST 2000), and the Expert System for the Calibration of the Hydrological Simulation Program—Fortran (HSPEXP) can be used to help estimating the parameters. Since the error rate was so low, calibration was done manually using the HSPF Parameter Database (HSPFParm). The 'input data editor' in BASINS was used to modify the input parameters. In the original hydrologic model, the base flow was too low. Thus, the parameters in the 'pervious land hydrology' algorithm were modified. According to BASINS Technical Notes (US Environmental Protection Agency, 2000), the 'fraction of remaining evapotranspiration for base flow' (BASETP) was reduced. This decreased the evapotranspiration by riparian vegetation. The default setting for BASETP was originally 0·02. After several iterations, it was finally adjusted to 0·001. Under this parameter setting, the error rate for streamflow was reduced to 0·1% reduction. It implies that the simulated results for the watershed are almost the same as the actual monitored values and the hydrologic model for the East Fork Little Miami River Basin can realistically simulate the actual flow conditions.

Simulation under a subwatershed scale

The simulated flow conditions for five smaller subwatersheds in the river basin were further evaluated. These subwatersheds were selected because each of them is located very near to a monitoring gauge station. The simulated flow results from these subwatersheds were compared with the observed flow records. The results indicated that the flow values were very close to the monitored values and all of them were within acceptable limits. Moreover, when the flow values for each reach were examined, it was observed that the combined flow values in the upper reaches were found to be approximately the same as the flow rate in the lower reach. For example, the simulated flow rate for Reach

05090202002 on January 1,1993 was 10·93 cu m/s. It was approximately equal to the sum of the flow in the two upper reaches, Reach 05090202003 (8·22 cu m/s) and Reach 05090202010 (2·37 cu m/s). These results provided insights into the efficacy of the models in representing the real world conditions under different geographic scales. Apparently, the model can effectively simulate the flow conditions in the smaller subwatersheds as well as the larger watershed. Consequently, this hydrologic model was accepted and was used for further water quality simulation.

Water quality simulation

In simulating the water quality conditions, modeling was confined to total nitrogen, total phosphorus and *Fecal coliform*. This is mainly because the earlier correlation analysis showed that these three variables had strong correlations with land-use types. Besides, there is a lack of available historical monitoring date on other water quality parameters for the watershed and available parameter estimates for calibration purposes.

Three water quality models (nitrogen, phosphorus, and *Fecal coliform*) were built through the pollution related routines in NPSM. In each of the models, the information on the point source discharges from the BASINS database was compared with existing Permit Compliance System metadata set from the Office of Water of the USEPA. There were four point sources of nitrogen and phosphorus that were not included in the BASINS database. Consequently, the BASINS data were edited by using the 'point source editor' in NPSM. The new information was imported manually to the project. Then, each model was run for each smaller subwatershed. As in the hydrologic modeling, the simulated results for each water quality parameter were compared to the monitored values from USGS and calibration and validation were performed as described earlier.

Results and discussion

Statistical and GIS analyses

Results from the statistical analyses indicated that land-use types were significantly correlated to many water quality variables in the watersheds in the State of Ohio at a probability level of $<0{\cdot}0001$ (Table 1). For example, total nitrogen, total phosphorus, and *Fecal coliform* had strong positive relationships with commercial, residential, and agricultural lands. They were also negatively related to forest land use. In addition, agriculture land use was strongly related to conductivity and pH. It was negatively related to zinc, cadmium, lead, and manganese. Residential and commercial lands were related to sodium, cadmium, lead, conductivity, BOD, and zinc.

The analysis of variance on the ranked values of nitrogen and phosphorus showed that both variables exhibited significant differences (with $P = 0{\cdot}0001$ level) between the land-use classes (Table 2). The mean ranked in-stream total nitrogen and phosphorus values were much higher in the agricultural watersheds (mean of nitrogen = 407, mean of phosphorus = 426) than the urban

Table 1. Results of the Spearman's rank correlation analysis on water quality variables and land-use types in all subwatersheds in the State of Ohio[a]

Water quality variables	Land-use types			
	Residential	Commercial	Forest	Agriculture
Conductivity	0·2266*	0·2094*	−0·3757*	0·2854*
BOD	0·2078*	0·2088*	−0·2073*	0·0938
pH	0·0318	0·0070	−0·2181*	0·2266*
Total nitrogen	0·2265*	0·2054*	−0·3279*	0·1913*
Total phosphorus	0·3379*	0·2905*	−0·2850*	0·1563*
Sodium	0·3654*	0·3988*	−0·0607	−0·2276
Cadmium	0·2504*	0·2596*	0·0240	−0·1891*
Lead	0·2345*	0·2538*	0·0294	−0·1995*
Manganese	−0·1822	−0·1677	0·4602*	−0·3579*
Zinc	0·1915*	0·1893*	0·0315	−0·1444*
Fecal coliform	0·2660*	0·2541*	−0·3295*	0·1768*

[a]Only significant relationships are listed.
*Denotes significant relationships at a probability level of $<0{\cdot}0001$.

ones (mean of nitrogen = 372, mean of phosphorus = 388). Forested areas had a much lower nitrogen and phosphorus rankings (mean of nitrogen = 239, mean of phosphorus = 252).

GIS analyses identified a few watersheds that were contaminated. Watersheds in the Lower Great Miami River, Lower Little Miami River, and the Upper Middle Ohio Laughery River Basins had high levels of nitrogen and phosphorus. Watersheds around Cincinnati, Cleveland, and Akron had high levels of nitrogen, whereas watersheds around Cincinnati and Dayton had high levels of phosphorus, and watersheds around Columbus, Akron, Toledo and Cleveland had high *Fecal coliform* bacteria (Figures 3–5). These are the watersheds that should warrant our restoration efforts. Such information would be useful to land-use planners, resource managers and regulatory agencies for assessing the current conditions and prioritizing restoration efforts.

Table 2. Results of the analysis of variance on the ranked values of total nitrogen and phosphorus among different land-use classes in all subwatersheds in the State of Ohio

Water quality variables	F-values	Probability level
Nitrogen	33·39	0·0001
Phosphorus	33·77	0·0001

Figures 6–9 depict some examples of the spatial relationships of land use and water quality in Lower Great Miami River, Lower Little Miami River, and the Upper Middle Ohio Laughery River Basins by overlaying the maps of high % of agricultural and urban land use with nitrogen, phosphorus and *Fecal coliform*. These maps showed that for agricultural lands, the spatial relationship with total phosphorus was very prominent. The watersheds just northwest of West Carollton City and northeast of Lebanon had both high % of agricultural land and nitrogen and phosphorus loadings (Figures 6 and 7). Regarding the urban lands, phosphorus again exhibited a more apparent spatial relationship. Watersheds in the northern and eastern Upper Middle Ohio Laughery River Basin and the western Lower Little Miami River Basin around Lebanon and Mason had both a high % of urban land use and high values for phosphorus and nitrogen (Figures 8 and 9). This result is very useful as it reveals that the relationships of phosphorus with agriculture and urban land use are very strong. This association is often neglected, as most of our current restoration and

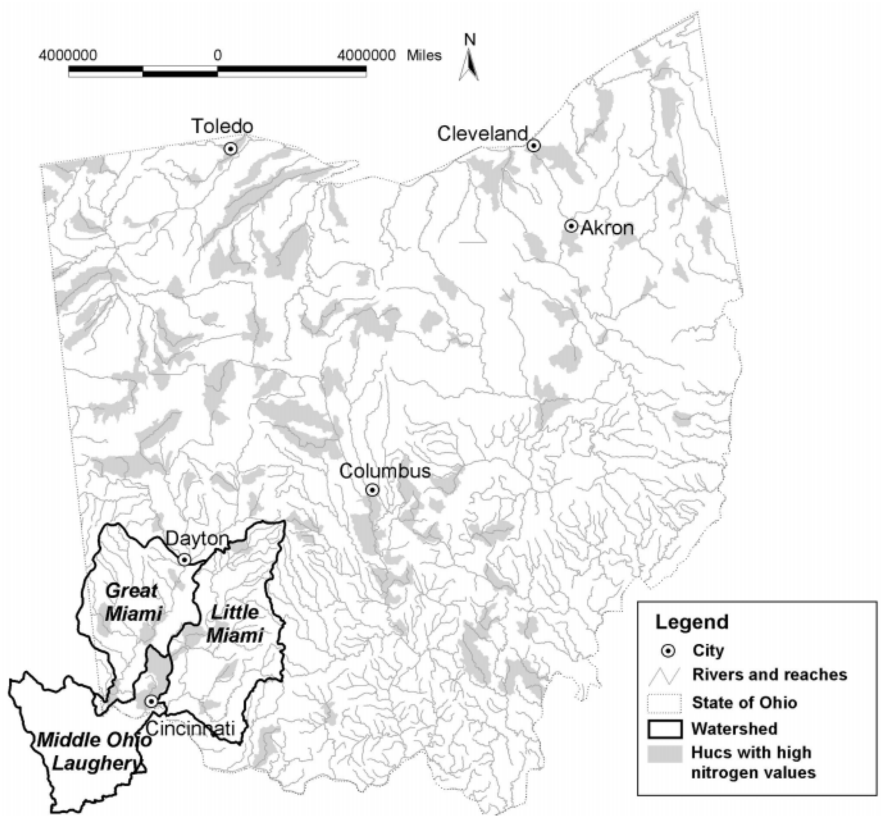

Figure 3. HUCs with high in-stream nitrogen values in the State of Ohio.

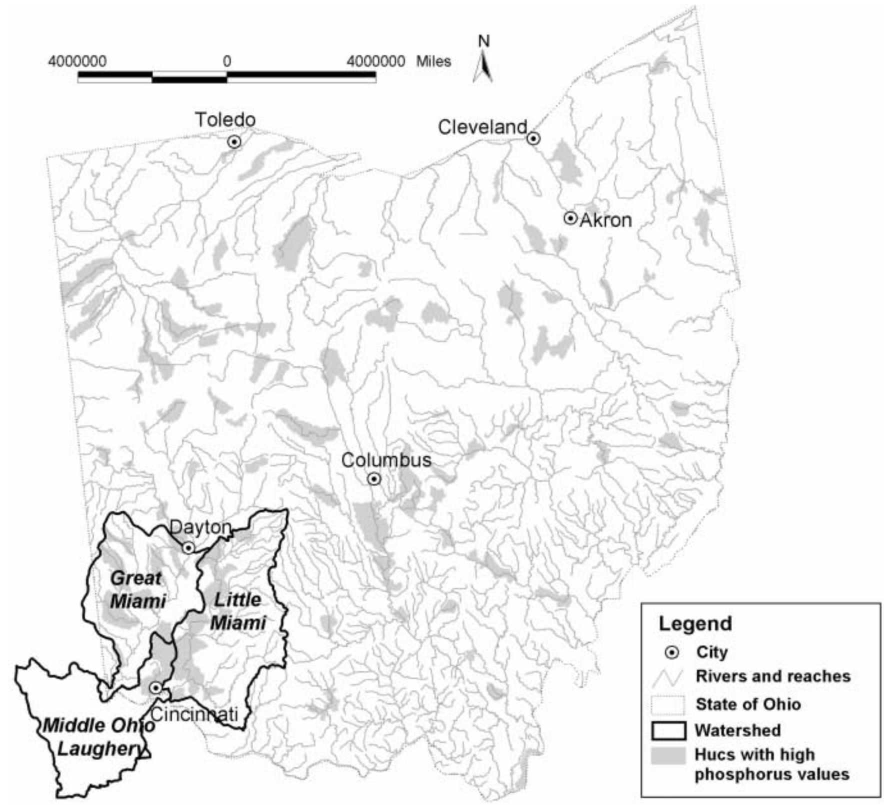

Figure 4. HUCs with high in-stream phosphorus values in the State of Ohio.

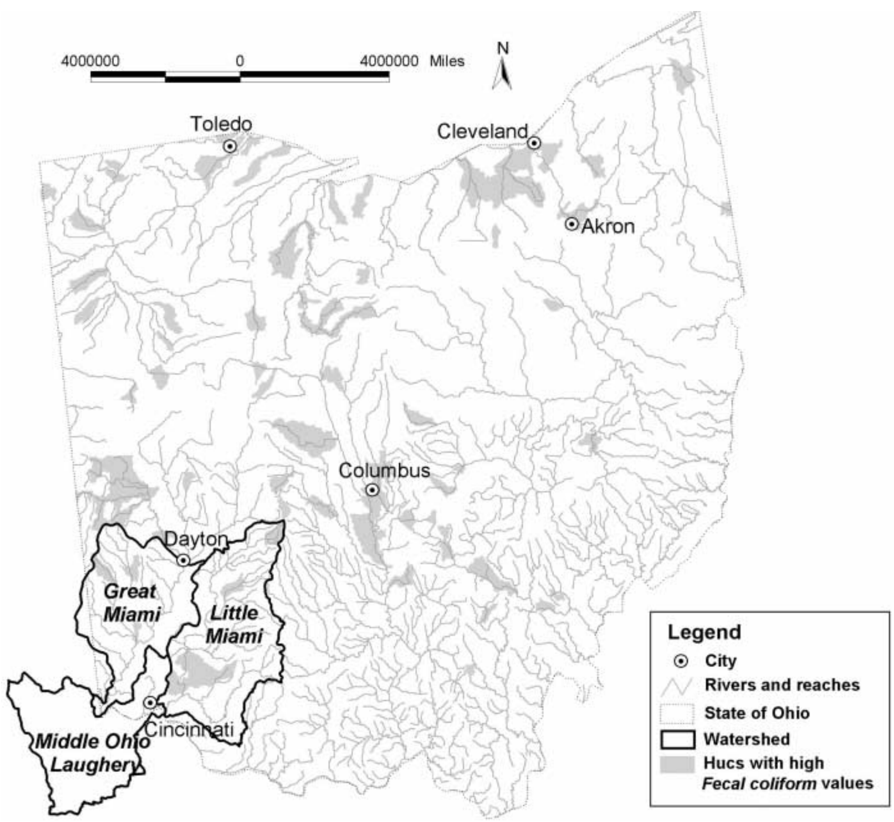

Figure 5. HUCs with high *Fecal coliform* counts in the State of Ohio.

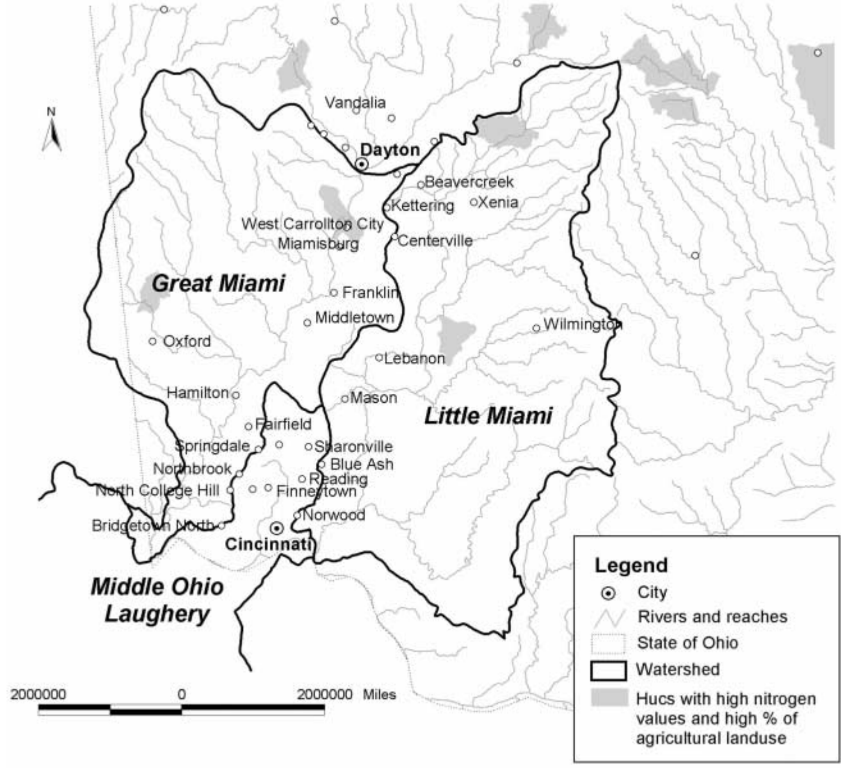

Figure 6. HUCs with high in-stream nitrogen values and high % of agricultural land use in three watersheds in Ohio.

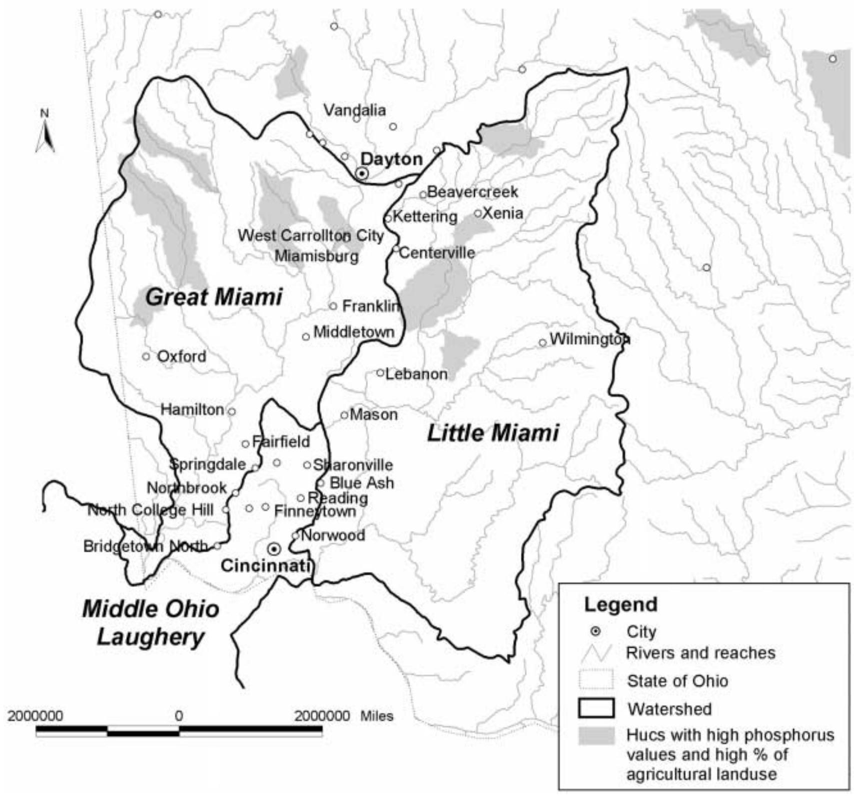

Figure 7. HUCs with high in-stream phosphorus values and high % of agricultural land use in three watersheds in Ohio.

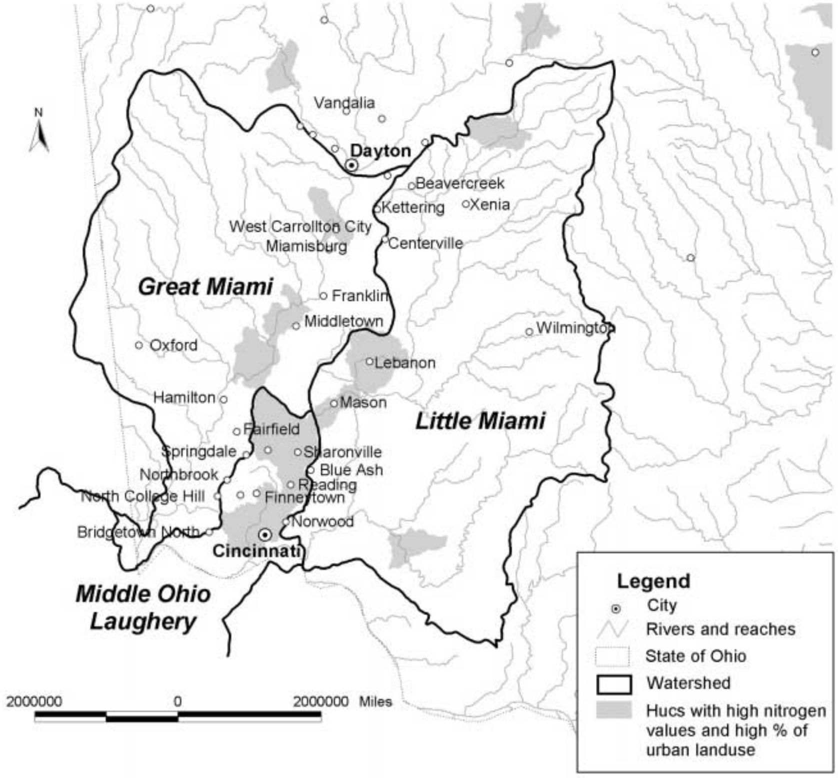

Figure 8. HUCs with high in-stream nitrogen values and high % of urban land use in three watersheds in Ohio.

conservation efforts are directed toward the reduction of nitrogen levels, especially from agricultural lands. To protect our watersheds, considerations should be made to lower not only the amount of nitrogen, but also phosphorus, in both the agricultural and urban areas. An example is by implementing nitrogen and phosphorus removal and treatment facilities in our sewage treatment plants.

Hydrologic and water quality modeling

The outputs for the simulation were plotted as graphs. An examination of the graphs for the eleven subwatersheds revealed that they portrayed very similar hydrologic patterns. The simulation results also disclosed that the impervious lands produced more than 55 times as much runoff as the pervious lands. For example, in subwatershed 05090202002, the arithmetic mean of surface flow generated from the impervious urban lands was 26·59 cm per day. The surface runoff from agricultural lands was only 0·46 cm per day. Moreover, the surface flow and pollutant graphs for the impervious lands for all subwatersheds approximated that of the precipitation curves. This may be due to the lack of infiltration and water storage capacities of the impervious land surface. Any rainfall will be readily converted to storm-water discharge. The increased amount of surface flow also will wash away more contaminants from the land surface. Even small rain is capable of washing the pollutants from the impervious surfaces into the receiving waters. Stream flow and, to a certain extent, water quality is therefore primarily determined by rainfall. Figure 10 shows an example of the nitrogen loading generated from impervious urban lands from subwatershed 05090202002.

To examine the relative effects of different types of land use on water quality, the output curves from different types of land use were superimposed. Figure 11 is an example of such curves. This figure compares the loadings of nitrogen between the agricultural and pervious urban land use. The relative contributions of pollutants from different types of land use were also expressed in terms of the amount of pollutant per unit area of each type of land use. Results showed that agricultural land use produced the highest and barren land use the least amount of contaminants.

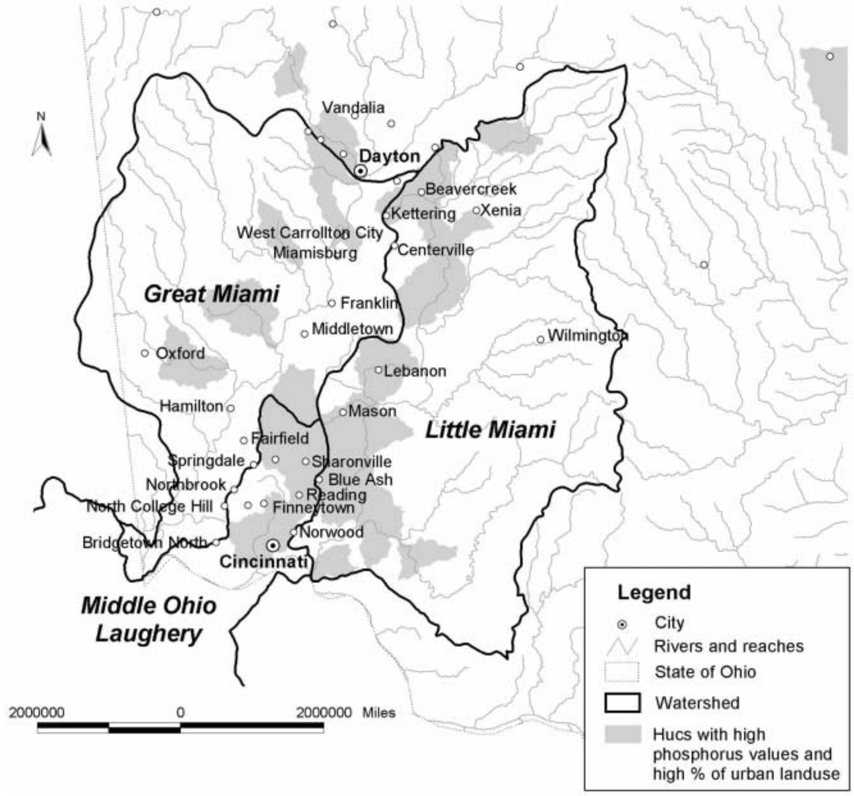

Figure 9. HUCs with high in-stream phosphorus values and high % of urban land use in three watersheds in Ohio.

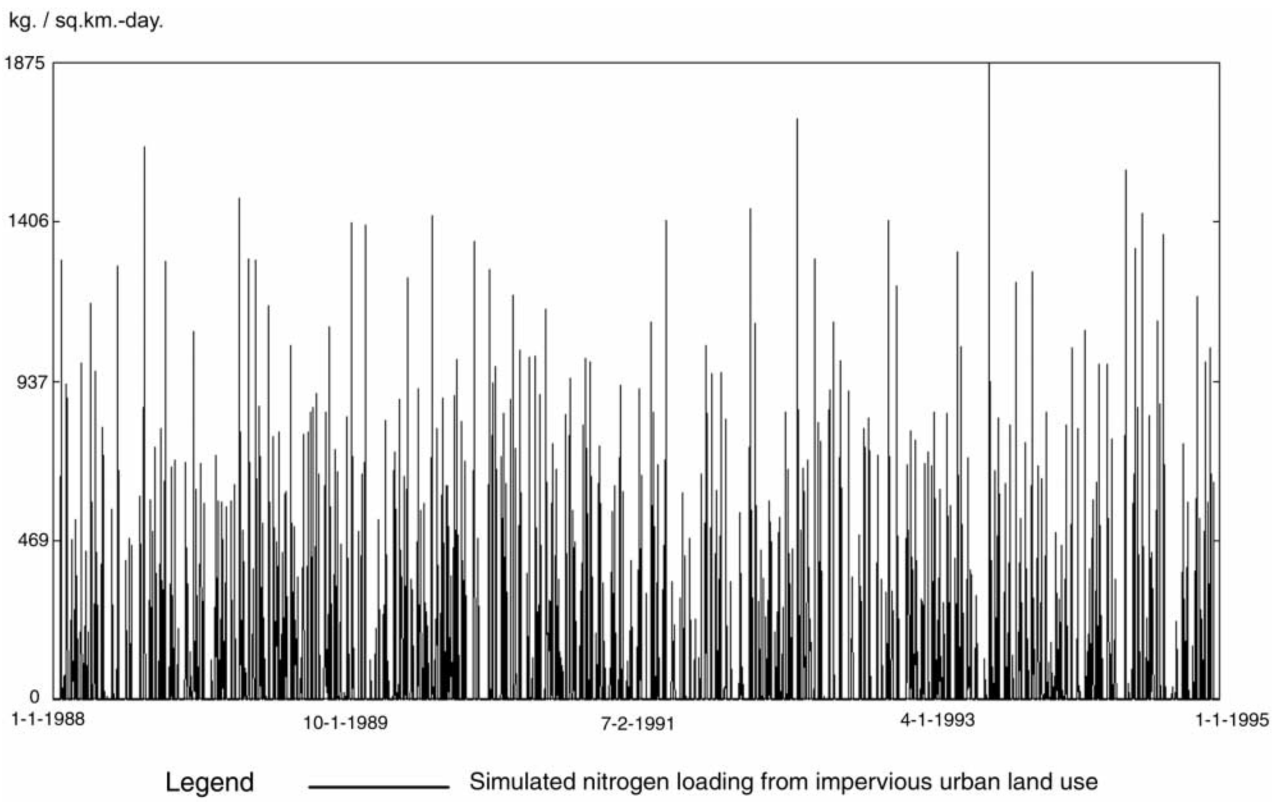

Figure 10. Simulated nitrogen loading from impervious urban land use in subwatershed 05090202002.

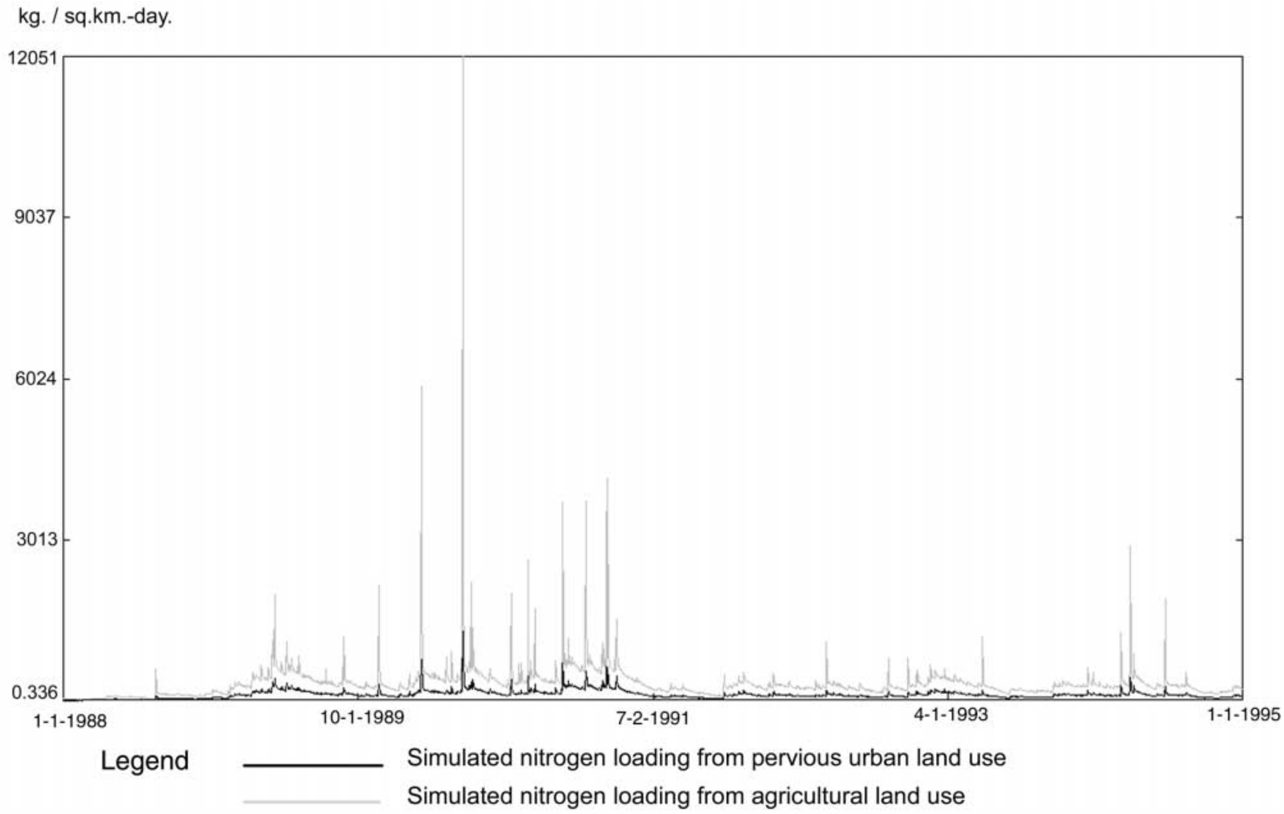

Figure 11. Comparison of the simulated nitrogen loading from agricultural land use and pervious urban land use in subwatershed 05090202002.

Most nitrogen loading was produced from agricultural lands. This finding can be illustrated by examining the simulation from June 1, 1992 to June 30, 1992 in subwatershed 05090202008. In this agricultural watershed, each acre of agricultural land produced 2·5 to 4·5 kg of nitrogen each day. In general, the amount of nitrogen produced from agricultural lands was about seven times than those produced from impervious urban. It was more than nine times as much as pervious urban land. Pervious urban land use yielded a slightly higher level of nitrogen, about 1·2 times, than the forest lands. But, it produced 24 times that of the barren lands. In terms of the total amount of nitrogen produced per unit area, the order for the different types of land use was: agriculture > impervious urban > pervious urban > forest > barren. However, an examination of the simulation curves during storms revealed a slightly different pattern. The order for nitrogen output in different land-use types during storms was: agriculture > impervious urban > forest > pervious urban > barren. That means, agricultural, impervious urban and forested areas produce more nitrogen in times of storms and heavy rainfall.

The simulated model results for phosphorus were very similar to nitrogen in terms of the overall output pattern. Nevertheless, the amount of phosphorus output was much smaller than nitrogen. It was about 10 times less than nitrogen. As an example, in the small subwatershed 05090202002, from July 1, 1992 to July 31, 1992, the nitrogen output for this subwatershed was about 216 kg/sq km-day, whereas the phosphorus output was 20 kg/sq km-day. The order for the amount of phosphorus loadings generated from different land-use types was: agriculture > impervious urban > pervious urban > forest > barren. Agricultural land use commonly produced more than six times as much phosphorus than impervious urban, 10 times more than pervious urban, 20 times more than forest, and 154 times that of barren land use.

The *Fecal coliform* counts produced from agriculture land use were about five times greater than that from pervious urban areas, seven times than that of forest, and more than 16 times that of impervious land and 46 times that of barren land. The order for the amount of *Fecal coliform* counts for different land-use types was: agriculture > pervious urban > forest > impervious urban > barren.

There was also a tendency for *Fecal coliform* counts to increase in winter and spring seasons and decrease during the summer and fall.

Conclusions

In this paper, the analysis involved statistical, GIS, as well as hydrologic modeling. The results showed that, unequivocally, land use was related to many water quality parameters. This relationship was evident in a regional scale (the State of Ohio), both statistically and spatially. In smaller watersheds, the impacts of land use on water quality could be modeled effectively using BASINS. From the model results, it was apparent that runoff from agricultural as well as impervious urban land use had much more nitrogen and phosphorus. This was the case especially after rain storms. These results are in accordance with an earlier finding where the subwatersheds of Cincinnati and Columbus in the Ohio River Basin were modeled using L-THIA hydrologic model (Liu *et al*., 2000).

If land use changes in the future, the levels of contaminants will be changed accordingly. Hence, future land development and management should be considered with care. This is especially the case if the land is going to be changed to agriculture or impervious urban lands. With a better land-use planning, we may be able to curtail some of the water quality problems. Using an analytical tool such as BASINS would help us to predict the plausible hydrological consequences of such changes in land use.

BASINS has many advantages. It is a very comprehensive water quality analysis tool. As demonstrated from this study, it is capable of modeling the water quantity and water quality conditions under different geographic scales with an acceptable degree of accuracy. All of the simulated values were very close to the actual monitored values. It seems likely that with little calibration and validation, the model can be used to characterize the current discharge and water quality conditions in another watershed under a different geographical scale, in a different region with various landscapes, soils, and vegetative environments. The model also can be employed to predict the future hydrological conditions in times of global environmental change, such as land-use change, climate change, or changes in total mass discharge loads (TMDLs), point source discharge or permit discharge conditions. Other contaminants can also be simulated easily.

The present study integrates different techniques to investigate the impacts of land use, as such, the models and the methodology can provide a simple, but effective, management tool for policy makers. In addition, the information derived from this study can have direct application values to state and local agencies, city planners and government resource managers for defining the impacts of land use on water resources and for implementing long-term water planning and management schemes. The research findings can also contribute to the existing knowledge of the plausible hydrologic implications of land use.

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