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INVESTIGATING THE WATER QUALITY IMPACTS OF FUTURE LAND-USE AND CLIMATE CHANGES IN THE LITTLE MIAMI RIVER WATERSHED

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ABSTRACT: *In this paper, we examine the combined water quality impacts of future land-use and climate changes in the Little Miami River Watershed in southwestern Ohio. It is important to quantify these impacts because this information will allow us to make changes to the current water resource allocations in order to cope with future conditions. To simulate future land-use conditions, we used the existing future land-use development plans of the eleven counties comprising the watershed. Future climate changes were simulated using results from recent Global Circulation Models. By calibrating and validating an integrated watershed-scale hydrological model (Soil and Water Assessment Tool), we were able to quantify the changes in runoff and nonpoint source pollution, which would occur under the projected future environmental conditions. Model results indicate that, under future land-use and climate conditions, average pollutant loads and daily concentrations are reduced. The total phosphorus concentration decreased from 3.0 mg/L to 1.2 mg/L, demonstrating that sound land-use management schemes can work to reduce the eutrophication problem. In the Little Miami River, eutrophication is caused by an overabundance of phosphorus. However, the fact that the new phosphorus concentration level still exceeds EPA's suggested limit indicates that other practices, in addition to land-use changes, will be needed to mitigate the adverse water quality impacts of climate change.*

INTRODUCTION

Sound scientific evidence has shown that the unusual and rapid increase in the concentration of greenhouse gases impacts all aspects of our global environment (National Research Council, 1999). There is a growing concern over the importance of climate change as citizens become more aware of these issues, both nationally and internationally. As the consequences of climate change become more clearly understood, it is critical to investigate possible adaptation measures for reducing the adverse impacts.

Given the complexity of the climate system and the uncertainties, which exist in climate modeling, it is difficult to make an accurate assessment of climate change impacts. However, it is generally accepted that climate change contributes to the occurrence of extreme weather patterns and changes in surface-water runoff. These changes can then translate into reduced water supply for our drinking water and wastewater treatment (Wood et al., 1997). Furthermore, extreme high temperatures and low levels of precipitation can result in low flow conditions in rivers and streams, which in turn, contribute to the toxic concentration of pollutants, such as algae, minerals, and water-borne pathogens. Thus, changes in long-term climatic conditions can drastically alter the quantity and quality of the water that we use.

Implicit in the literature, one strategy that has been used to mitigate the negative effects of climate change is the use of land management techniques (Ferrier et al., 1995; Changnon and Demissie, 1996; Bouraoui et al., 1998). Indeed, land-use is known to have significant impacts on water quality. Many studies have investigated the effects of different land-use types on water quality (Sivapalan et al., 1996; Lorup et al., 1998; Worrall and Burt, 1999). Other studies have investigated the effects of climate changes on water quality in watersheds of different land-use types (Wu and Haith, 1993; Changnon and Demissie, 1996), or implicitly modeled land-use changes with the use of runoff export coefficients (Ferrier et al., 1995). However, none of these studies have explicitly investigated the use of land-use management schemes (such as using existing or future land-use development plans) to reduce the adverse water quality impacts of global climate change.

For practical water resources planning, it is important that we determine what the future land-use conditions will be like. One good indication of these conditions is the future land-use development plans being used by counties to consider future zoning options. Previous studies have quantified the water quality impacts of different land-use types in isolation, without reference to their geographical contexts. This paper examines the water quality impacts of future climate and land-use changes in a watershed that is currently experiencing water quality problems.

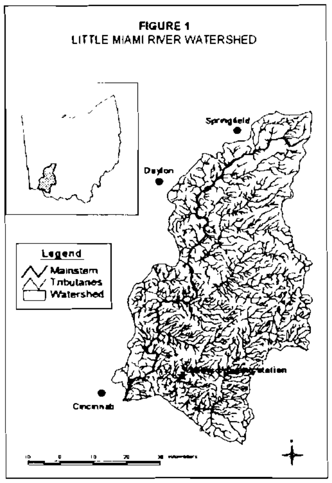
METHODOLOGY

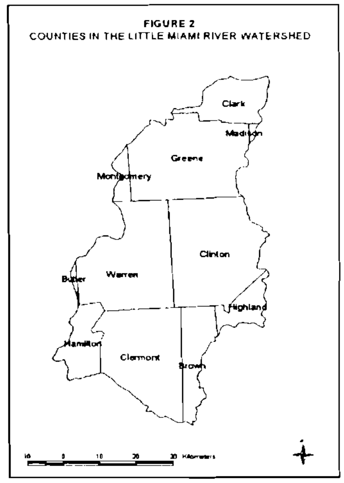
Study Area

The Little Miami River (LMR) watershed (Figure 1) was chosen as a study site for several reasons. First, the LMR is a designated national scenic river with great biological diversity. Designated as a state scenic river in 1969 and a national scenic river in 1973, the LMR "contains some of Ohio's most scenic and diverse riverine habitats" (Ohio EPA, 1995). The LMR is Ohio's largest Exceptional Warmwater Habitat stream (EWH streams only make up about 10% of the total stream miles in Ohio) and is one of the most biologically diverse. It is the home to 84 fish species, some of which are rare and endangered. However, there are indications that the watershed is a system under stress. High levels of fish anomalies and shifts within the fish communities have been noted (Ohio EPA, 2000).

Second, it is a predominantly agricultural watershed that has undergone urbanization and sub-urban sprawl processes in the last 50 years. This major land-use change has prompted the selection of the watershed because the watershed is likely to experience further modifications. This will be of great importance to water resource managers interested in the water quality impacts of mixed land-use watersheds. Major urban areas near the watershed include Cincinnati and Dayton, Ohio. The populations of Cincinnati and Dayton have declined steadily since peaking in the 1960s. This trend reflects a population decline within the city limits; however, the metropolitan areas have been growing. This growth in the metropolitan areas is due to the relocation of residents from the city center to the suburbs, as well as movement of people from other areas. Such migration pattern is usually accompanied by the conversion of agricultural land to residential and commercial areas, resulting in development that can adversely affect water quality and aquatic ecosystems (U. S. Geological Survey, 2000).

The topography of the LMR watershed has been influenced by glaciation, which has left distinctive landforms and thick deposits of silt, sand, and gravel. The northern portion of the watershed is within the Eastern Corn Belt Plains ecoregion, which is characterized by level to gently sloping land, and relatively low gradient streams. For most of its length, the LMR flows atop a buried valley aquifer composed of highly permeable glacial outwash deposits of sand and gravel. Along its course, the LMR drops from an elevation of approximately 350 to 140 meters with an average gradient of 4 meters per kilometer. Average annual precipitation in the watershed ranges from 90 to 110 centimeters and increases towards the south; about one-third of the precipitation becomes surface runoff. Average annual air temperature ranges from 10 degrees





Figures 1 and 2. The Little Miami River Watershed.

Celsius in the north to 13 degrees Celsius in the south. Average snowfall in the watershed is 50 to 75 centimeters per year.

Hydrological Model

The Soil and Water Assessment Tool (SWAT; Arnold et. al, 1993) was chosen to simulate the climatic and hydrological conditions for this study because it is a physically-based and watershed-scale model which uses minimal input data to describe hydrological conditions. Developed by Dr. Jeff Arnold for the USDA Agricultural Research Service, SWAT requires information about weather, soil properties, topography, vegetation, and land management practices occurring within the watershed. SWAT models evapotranspiration, lateral subsurface flow, return flow from groundwater, surface runoff, nutrient cycling, erosion and sediment yield and allows a number of different physical processes to be simulated in a watershed.

Different sets of spatial data were utilized in the model. They include GIS data layers such as land cover maps, a delineated watershed coverage (8-digit hydrologic unit code, from the United States Geological Survey), and digital elevation models (DEMs, from the United States Geological Survey). The land cover maps used are described below (under "Future Land-Use Scenario" and "Model Calibration and Validation"). The soil map (from STATSGO) was obtained at a 30 x 30 meter cell size and used as input into the SWAT hydrologic model. Climatological data for the rain gage and climate station (in Milford, Ohio) were obtained from the National Climatic Data Center. A weather generator (consisting of weather information on 1,112 stations around the United States) was provided with the interface and used to fill in gaps in the climatological data.

For modeling purposes, the watershed can be partitioned into a number of sub-watersheds or sub-basins. The use of sub-basins in a simulation is particularly useful when different areas of the watershed are dominated by land-uses or soils different enough in hydrology to impact hydrology. In the pre-processing, the LMR watershed was delineated into 25 sub-watersheds using the automatic delineation tool in BASINS version 3.0, the DEM grid, and stream characteristics from the Reach File 3 coverage. Parameters for each of the 25 delineated sub-watersheds were estimated using the SWAT interface based on the predominant land-use or soil type described by the GIS map layers. Then, a number of hydrologic response units were created within each sub-watershed. A hydrologic response unit (HRU) is generated, which is a unique land-use/soil combination representing a sub-watershed. Next, the weather and input databases were written, and the SWAT hydrological model was executed. Finally, calibration and validation of the hydrological model were performed to ensure the accuracy of the simulation.

Future Land-Use Scenario

The future land-use scenario for the LMR watershed was developed using future land-use development plans obtained from the counties comprising the watershed. There are eleven counties in the LMR watershed (Figure 2). This future land-use scenario serves two purposes. First, it provides a "snap-shot" of a very possible land development scenario, which will occur in the watershed. As such, it provides water resource managers with a very probable view of what the landscape will be like and its plausible effects on the water supply. Second, the map is necessary to provide information on the combined impacts of future land-use and climate changes in the watershed. This information will eventually provide guidance on how land management plans can be used to mitigate the water quality impacts of climate change.

After the maps were obtained from the county development offices, the maps were screen-digitized into Arc coverages, merged, and then clipped to form the LMR watershed. The digitized land-use maps were then re-classified to preserve uniformity and consistency in the watershed.

Future Climate Scenarios

Because there is some uncertainty concerning the magnitude and direction of the climate change (whether precipitation will actually increase or decrease, and the magnitude of the temperature increase), a number of hypothetical scenarios were used in this study. These scenarios do not offer a prediction on what the climate will be, but show the range of conditions that are possible, and the range of impacts resulting from these conditions (Karl, 1992; USGCRP, 2000). Until the state of climatology is advanced enough to forecast the effects of a doubling of carbon dioxide in the atmosphere, these scenarios act as guidelines to help decision-makers develop adaptive and flexible solutions which will work in a variety of situations.

In total, five climate change scenarios were utilized in this study. The hypothetical climate scenarios are based on projections made by the IPCC and the United Kingdom Hadley Centre's climate model. These scenarios indicate that, by 2010, temperatures in Ohio could increase by 2 to 4 degrees Celsius and precipitation could change by -20% to +20% (Karl et al., 1996; U. S. EPA, 1998). We have chosen these precipitation and temperature extremes to represent "worst-case" scenarios. As a result, it is anticipated that the results from the modeling study will demonstrate the most extreme changes that resource managers would need to make under a changing environment.

In order to examine the combined effects of climate and land-use changes on water quality, it is necessary to execute the hydrologic and water quality model with both the future land-use and future climate change scenarios. To compare these effects, the impacts of the current land-use scenario under the current climate (with no changes) are compared to the impacts of the future land-use scenario under each of the four future climate change scenarios (Table 1). The comparison allows us to examine what happens when both the land-use and climate are altered from current conditions.

Table 1 Current and future land-use and climate scenarios used in this study

Scenario	Land-Use Change	Climate Change
Current	Current	No changes in temperature and precipitation
Future/Wettest	Future	+2 degrees Celsius; +20% precipitation
Future/Wet	Future	+4 degrees Celsius; +20% precipitation
Future/Dry	Future	+2 degrees Celsius; -20% precipitation
Future/Driest	Future	+4 degrees Celsius;

Table 2
Distribution of land-use types (expresses in % of total watershed) in LMR watershed during each time period

Land-Use Types*	1980s	1990s	Future
Agricultural	80.48	71.27	34.81
Residential	7.67	5.91	48.79
Low-density		(5.5)	(47.68)
Medium-density			(0.45)
High-density		(0.41)	(0.66)
Commercial	1.45	1.50**	2.44
Industrial	0.23	0	5.66
Transportation	0.94	0	3.18
Forest	7.60	20.01	2.43
Water	0.68	0.93	1.32

*Not all land-use types are listed.
**1990 MRLC land cover data set classifies industrial and transportation land-uses as commercial.

Model Calibration and Validation

The SWAT hydrological model was calibrated using the 1980s land-use map of the LMR watershed and daily precipitation and temperature data from 1980 to 1984. The 1980s land-use map was obtained from the 1:250,000 scale quadrangles from the U.S. Geological Survey GIRAS data set, and represents information from 1977 to the early 1980s (U. S. EPA, 1994). The distribution of land-use types can be seen in Table 2. The land-use map was re-classified according to the specifications of the SWAT model. A simulation period of five years (with a daily time step) was chosen to provide an adequate time period for the model to simulate the general conditions of the watershed. Multiple hydrologic response units were created. If a particular land-use type or soil type covered at least 18-20% of the subwatershed, a separate response unit was also created.

The calibration procedure was performed on the hydrology (flow), nutrient loadings, and sediment loadings. Relevant parameters for model calibration included the sensitivity of the model to the different land-use/soil combinations, the curve number in the hydrology component, the effective hydraulic conductivity in the main channel alluvium, the main channel cover factor, and the percolation factors for nitrogen and phosphorus. The calibration was performed by trial-and-error, with each of the above input parameters being adjusted until the simulated results were reasonably close to the observed values (obtained from the U.S. Geological Survey). The t-value was used to compare the observed and simulated data. Calibration was done by adjusting some of the parameters to allow a higher degree of variation during model execution. The nitrogen and phosphorus percolation coefficients were adjusted to reflect the applications of chemicals and fertilizer by homeowners and farmers in the watershed. The time step for the hydrological modeling is one day. All of the values of the simulated parameters were close to the observed values ($P > 0.50$).

The calibrated parameters were used in the model validation. The model was validated using the 1990s land-use map and daily precipitation and temperature data from 1990 to 1994. The 1990s land-use map was obtained from the Multi-Resolution Land Consortium and was re-classified according to the specifications of the SWAT model. The classified image used information from 1987 to 1994 (U. S. Geological Survey, 1994). All of the values of the simulated parameters were close to the observed values ($P > 0.50$). Based on these results, it was concluded that the SWAT model is suitable for predicting the impact of climate changes on the hydrology and nutrient loadings in the LMR watershed.

RESULTS AND DISCUSSION

Annual Flow

The greatest increase in annual flow occurred in the future-wet scenario. In this scenario, the hydrologic model is executed with the future land-use map (comprised of future land-use development plans) and the "wet" climate scenario (+4 degrees Celsius, +20% precipitation). Under this scenario, the annual flow is nearly 23% higher than the current conditions scenario (Table 3). In the current conditions scenario, the hydrologic model is executed with the current land-use map and the current climatological data in which no changes were made to the temperature and precipitation. There did not appear to be any significant differences in the timing of the peak flows amongst the different scenarios.

Annual Nitrogen Load

The highest nitrate loads occurred during the wet scenarios, while the lowest loads occurred during the dry scenarios. The wet scenarios produced approximately a 20-25% increase in nitrate load, while the dry scenarios produced a 40-45% decrease in nitrate load (Table 3). When comparing average daily concentrations amongst the scenarios, the lowest concentrations occurred during the wet scenarios, while the highest concentrations occurred during the dry scenarios. However, in most cases, the current scenario usually yielded the overall highest average daily concentrations, suggesting that the cumulative effect of the land-use and climate changes is to decrease the concentrations of the nitrogen species in the streams.

For nitrate, the dry scenarios produced approximately a 5-7% increase in average daily concentration, while the wet scenarios produced a slight decrease (0-2%). As in almost all the nitrogen species, the average daily concentration increased as the degree of dryness increased. The average daily concentrations of nitrate were between 3.0 and 4.0 mg/L, for the different scenarios. This concentration is below the EPA's suggested daily limit of 10.0 mg/L for human consumption (Ohio EPA, 2002).

With ammonia, the highest loads occurred during the wet scenarios, and the lowest loads occurred during the dry scenarios. The wet scenarios resulted in a 40-50% reduction in load, while the dry scenarios produced a 70% decrease in load. The trend was reversed when examining the average daily concentrations, as the highest concentrations were seen in the dry scenarios, and the lowest concentrations were seen in the wet scenarios. Again, on the whole, the current scenario usually yielded the highest average daily concentrations, suggesting that the cumulative effects of the land-use and climate changes is to decrease the concentration of the ammonia in the streams. Overall, the average daily concentrations of ammonia were between 2.0 and 3.0 mg/L for the different scenarios. EPA's ammonia-nitrogen criterion for exceptional warmwater habitats is dependent on the pH and temperature. The maximum limit for ammonia in waters with zero to 25 degrees Celsius and neutral pH waters is 13.0 mg/L (Ohio EPA, 2002).

Table 3
Annual loads of major nonpoint source pollutants and runoff under future conditions
Numbers in parenthesis indicates percent change from the current condition

Scenerio	Annual Runoff (m^3/s)	Annual Nitrate Load (10^5 kg of N)	Annual Phosphorus Load (10^5 kg of P)
Current Condition	9620	9.8	8.9
Future – Wettest	11500 (+19.54%)	11.9 (+20.9%)	4.6 (-47.87%)
Future – Wet	11820 (+22.87%)	12.0 (+22.0%)	4.4 (-50.56%)
Future – Dry	5180 (-46.15%)	5.6 (-42.7%)	2.6 (-71.24%)
Future - Driest	5400 (-43.87%)	5.8 (-41.4%)	2.6 (-71.24%)

Annual Phosphorus Load

The highest total phosphorus loads occurred in the current conditions scenario. All of the future scenarios experienced a decrease in total phosphorus load. The wet scenarios produced approximately a 50% decrease in total phosphorus, while the dry scenarios produced approximately a 70% decrease in total phosphorus (Table 3). This suggests that the cumulative impact of the future land-use and climate changes is to reduce the total phosphorus load. When considering average daily concentrations, the lowest concentrations occurred during the wet scenarios, while the highest concentrations occurred during the current condition scenario. The dry scenarios produced approximately a 50% decrease in average daily concentration, while the wet scenarios produced a 60% decrease. The highest concentrations occurred under the current conditions scenario - again, suggesting that the future land-use and climate changes result in a net reduction of phosphorus concentration.

The average daily concentrations of phosphorus were between 1.0 and 2.0 mg/L for the different future scenarios. This concentration is still above the EPA's suggested daily limit of 0.1 mg/L for rivers and streams (U. S. EPA, 1986).

CONCLUSIONS

The study has shown the possible effects of future land-use and climate conditions in the Little Miami River watershed. The interplay of the climate change and land-use change indicates that, in most cases, future climate and land-use conditions will result in a net reduction in runoff, pollutant load and average daily concentration. Almost all nutrients (except for nitrate) experienced a reduction in both annual load and average daily concentration. In fact, the total phosphorus concentration decreased from 3.0 mg/L to 1.2 mg/L, which shows that sound land-use management schemes can work to reduce the eutrophication problem, which, in this watershed, is attributed to an overabundance of phosphorus.

This information is useful to environmental scientists and watershed managers to develop tools to mitigate the adverse water quality impacts of climate change. Attempts to comply with the Clear Water Act (Sections 208, 303, and 305) and control all sources of pollution in a watershed will require scientists to take into account the possible future changes, such as climate change and land-use change. In addition, to address U. S. EPA's Total Maximum Daily Load process, it will be necessary to investigate watershed management techniques which will address the nonattainment of designated uses of receiving water bodies (U. S. EPA, 1991). This current research has already shown that future, planned land-use changes can work to reduce the eutrophication problem due to phosphorus. These land-use changes were broad-scaled and covered several counties. By using 1 square meter DEMs and SSURGO soils data, it would be interesting to study how smaller-scale changes, such as riparian buffer zones, filter strips and constructed wetlands, can affect water quality (Gustafson, 1998; Gelbrecht et al., 1996; Fleischer, 1994). Additional strategies will need to be employed, because this current research demonstrates that existing future land-use development plans will not completely solve the eutrophication problem that is exacerbated by the future climate change. Therefore, investigations into other strategies, such as crop tillage techniques, detention ponds, and buffers, will be necessary.

The significance of this study lies in the fact that it is one of a very few studies to explicitly model both land-use changes and climate changes. As such, it can be regarded as a study of the potential interplay between future climate and land-use changes and how they affect water quality. Hence, the results from this research have many potential applications. First, they can serve as a guideline to policy makers and water resources managers for the possible impacts of future environmental changes in the watershed. Since this study employed existing future land-use development plans, it provides useful information to resource managers on what is very likely to happen to the water quality in the watershed, as such additional changes in the infrastructure of current water treatment facilities and reservoirs could be made (Argue, 1995). However, caution must be used in interpreting these results. Although these results indicate that low-density residential developments result in a reduction of most nonpoint source pollutants, these land-use changes may have many implications on other water quality variables not explicitly modeled in this study. Many other effluents, such as pathogens, heavy metals, and toxic materials are likely to be affected by the proposed land-use changes. Hence, this research is not a prescription for county planners to begin converting agricultural lands to low-density residential developments. Rather, it suggests that land-use management schemes can be used to adapt to the water quality impacts of climate change. The precise placement and size of the land-use changes must be studied in greater detail.

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