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MINIMIZING THE IMPACT OF URBANIZATION ON LONG TERM RUNOFF[1]

*Zhenxu Tang, Bernie A. Engel, Kyoung J. Lim,
Brayn C. Pijanowski, and Jon Harbor*[2]

ABSTRACT: Increasing concern about the problems caused by urban sprawl has encouraged development and implementation of smart growth approaches to land use management. One of the goals of smart growth is water resources protection, in particular minimizing the runoff impact of urbanization. To investigate the magnitude of the potential benefits of land use planning for water resources protection, possible runoff impacts of historical and projected urbanization were estimated for two watersheds in Indiana and Michigan using a long term hydrological impact analysis model. An optimization component allowed selection of land use change placements that minimize runoff increase. Optimizing land use change placement would have reduced runoff increase by as much as 4.9 percent from 1973 to 1997 in the Indiana study watershed. For nonsprawl and sprawl scenarios in the Michigan watershed for 1978 to 2040, optimizing land use change placement would have reduced runoff increase by 12.3 percent and 20.5 percent, respectively. The work presented here illustrates both an approach to assessing the magnitude of the impact of smart growth and the significant potential scale of smart growth in moderating runoff changes that result from urbanization. The results of this study have significant implications for urban planning.

(KEY TERMS: smart growth; urbanization; runoff; optimization; land use; planning.)

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INTRODUCTION

Urbanization has become a significant environmental issue in the United States. New development often results in losses of forest, pasture, range, and crop lands (USDA, 1997). Between 1982 and 1997, the United States lost almost 500,000 acres (202,347 hectares) of prime farmland to development annually (USEPA, 1999). One of the major direct environmental impacts caused by the conversion of open spaces to impervious urban and suburban areas is the degradation of water resources and water quality (USEPA, 2001). The impact of urbanization on water resources is typically reflected in the alteration of the natural hydrological systems in terms of increasing the runoff rate and volume and decreasing infiltration, ground water recharge, and base flow (Carter, 1961; Lazaro, 1990; Harbor, 1994; Moscrip and Montgomery, 1997) and degradation of water quality in both streams and shallow ground water (USGS, 1999).

Concerns about these environmental impacts as well as other negative social and economic effects of urban sprawl have resulted in a widespread movement toward more intelligent, planned forms of future development, referred to as "smart growth" in recent years (Moglen *et al.,* 2003). Smart growth changes the terms of the development debate away from the traditional growth/no growth question to "How and where should new development be accommodated?" (USEPA, 1999). To meet the needs of smart growth within current development patterns, the focus of research on hydrologic impact must be adjusted from identifying and quantifying the impact of land use change to reducing the impact.

In recent decades, numerous researchers have investigated and quantified the impact of urbanization on surface runoff in urbanized watersheds, using

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[2] Respectively, Research Assistant, Professor, and Post-Doctoral Research Associate, Department of Agricultural and Biological Engineering, Purdue University, 225 South University Street, West Lafayette, Indiana 47907-2093; Associate Professor, Department of Forestry and Natural Resources, Purdue University, 195 Marsteller Street, West Lafayette, Indiana 47907-2033; and Professor, Department of Earth and Atmospheric Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051 (E-Mail/Engel: engelb@ purdue.edu).

both monitoring and modeling methods (e.g., Anderson, 1970; Tong, 1990; Bhaduri *et al.,* 1997; Kim *et al.,* 2002; Im *et al.,* 2003). The existing literature concentrates on impact assessment, and approaches to reducing or minimizing the runoff impact of urbanization have received relatively little attention (Zheng and Baetz, 1999; Moglen *et al.,* 2003). Zheng and Baetz (1999) evaluated design alternatives and found that sustainable design with smaller total development areas can effectively reduce the increase of peak flows and total runoff volumes due to development, when compared with less sustainable designs. Moglen *et al.* (2003) suggested a framework for quantitative smart growth in land development in which the runoff impact was optimized by minimizing the total area change in imperviousness. Both studies revealed that the impact of development can be reduced by limiting the total impervious area, which is a straightforward and predictable conclusion. No previous study has evaluated whether the objective of reducing runoff increase can also be achieved by optimizing land use placement without restricting the total area for development. The magnitude of the potential benefits of land use planning that considers impacts on water resources, in particular on runoff processes and systems affected by runoff processes, is largely unknown.

The aim of the work presented here is to investigate the potential benefits of optimizing land use placement patterns to minimize impacts on water resources. The specific objectives of this study are: (1) to quantify possible runoff reductions of historical and projected urbanization by optimizing the placement of land use change within representative watersheds, and (2) to evaluate actual and projected development plans in terms of the potential minimum and maximum runoff impact of the development.

METHODS

Study Areas

This study was conducted in two watersheds: Little Eagle Creek (LEC) and Little Muskegon River (LMR), which represented actual and projected urban development, respectively. The LEC watershed, 70.4 km^2 in area, is on the northwest side of Indianapolis, Indiana, and its suburbs (Figure 1). Because of its proximity to the city, this watershed has experienced rapid and extensive urbanization over the past three decades, which constitutes a potential threat to the water resources of the watershed. Land uses ranging from nonurban natural grass, forested areas, and agricultural areas to typical urban residential and commercial categories exist in the LEC watershed. In 1973, the land use distribution was 48.3 percent urban, 15.3 percent agriculture, 19.5 percent forest, and 15.5 percent grass, with the remainder (0.4 percent) in open water (Grove *et al.,* 2001).

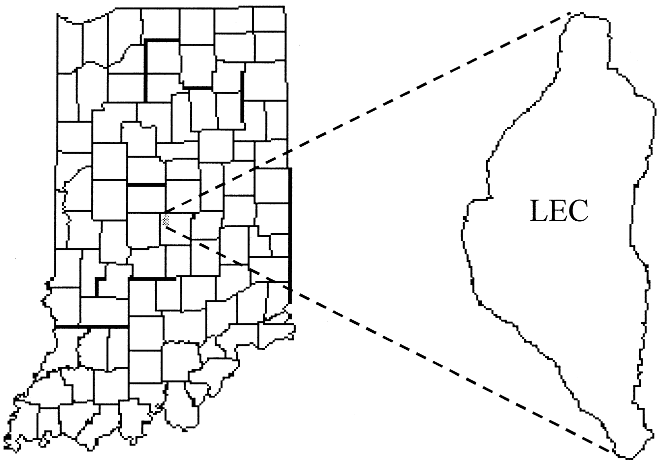


Figure 1. The Location of the Little Eagle Creek Watershed.

The LMR watershed is part of the Muskegon River watershed on the east side of Lake Michigan in north central Michigan. The Muskegon watershed consists of 40 subwatersheds defined by the U.S. Geological Survey's 14-digit hydrologic unit codes (HUCs). The three HUCs 38, 39, and 40 along the coast of Lake Michigan were grouped and named LMR by the authors to simplify the explanation for the rest of the paper (Figure 2). Surface water from HUC1 and HUC2 drains into HUC3. The LMR watershed covers an area of 332 km^2. HUC3 accounts for half of the total LMR watershed area; the other half is shared by HUC1 (37 percent) and HUC2 (13 percent). The City of Muskegon is partially located in HUC3. In a parallel study (Tang *et al.,* 2005), LMR was predicted as the most urbanized watershed, with significant runoff impact, among the 40 subwatersheds of the Muskegon River watershed. In 1978, the land use distribution of LMR was 24.1 percent urban, 13.3 percent agriculture, 42.4 percent forest, 8.8 percent grass, and 10.8 percent water, with the remainder (0.6 percent) in bare soil.

Enhancement of the Long Term Hydrologic Impact Assessment (L-THIA) Model

The Long Term Hydrologic Impact Assessment model, L-THIA (Harbor, 1994; Pandey *et al.,* 2000), was enhanced and then employed for runoff

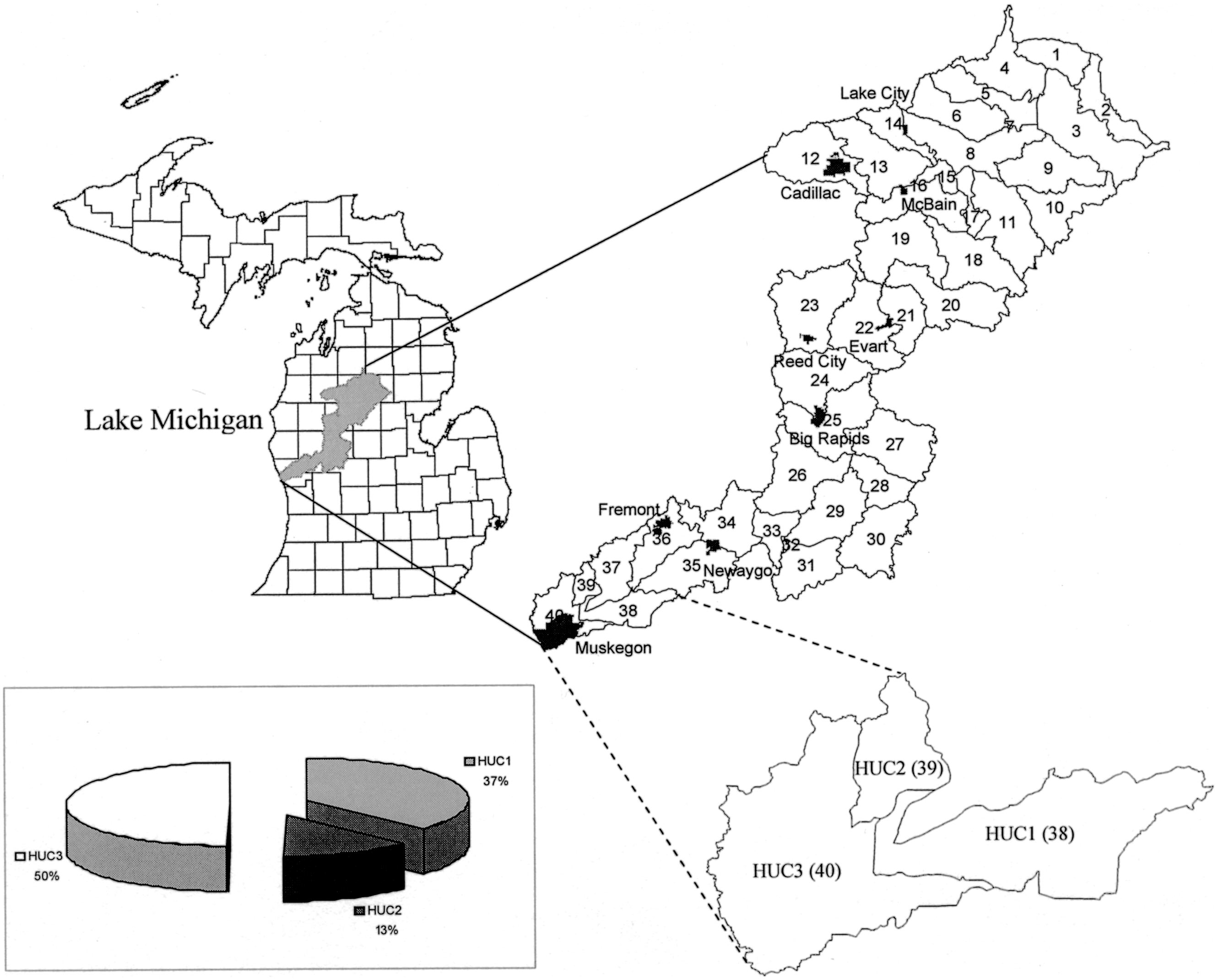


Figure 2. The Location of the Little Muskegon River Watershed and the Area Distribution of HUCs. The dark areas shown in the Muskegon River Watershed are cities.

optimization in this study. The L-THIA model is a straightforward assessment tool that provides estimates of changes in runoff, recharge, and nonpoint source (NPS) pollution resulting from past or proposed land use changes (Harbor, 1994). It gives long term average annual runoff and NPS pollutants for a land use configuration based on actual long term daily climate data, soils, and land use data for an area (Figure 3). The core of the model is based on the Curve Number (CN) method (NRCS, 1986), a widely applied technique for estimating the change in discharge behavior as a watershed undergoes urbanization. Pollutant loading rates combined with runoff estimates are used to quantify NPS pollutants (Pandey *et al.,* 2000). By applying the method to actual and proposed urban developments, the long term effects of past, present, and future land use can be assessed (e.g., Minner *et al.,* 1998; Leitch and Harbor, 1999; Bhaduri *et al.,* 2000). A detailed description of the model structure and approach can be found in Harbor (1994), Bhaduri *et al.* (2000), and Pandey *et al.* (2000). L-THIA works on two platforms, Web-based (Basic L-THIA) and geographic information system (GIS)-based (GIS L-THIA), and it is freely accessible (Purdue University, 2002).

Making use of data that are readily available to the public, the L-THIA model can be used to assess the relative impacts of past, present, and alternate future land management decisions. However, the L-THIA model is not capable of evaluating a development plan with respect to its potential minimum and maximum levels of impact. This research extended the capabilities of the existing and widely used Web version of the L-THIA model by developing a runoff optimization component called RunOff MINimization (ROMIN; Tang, 2004).

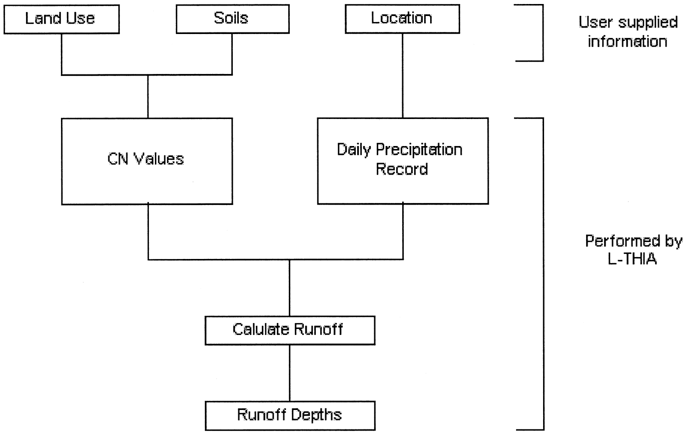


Figure 3. Basic Data Requirements and Components for Analysis in the L-THIA Model (adapted from Pandey *et al.,* 2000).

Structure and Capability of ROMIN. The overall data processing flow of ROMIN is depicted in Figure 4. The input data require basic watershed parameters, including land use, hydrologic soil groups, areas and location (state and county), and the user's proposed urban land uses and areas. The optimization model and algorithm use the input data to identify the optimal and worst case locations for an actual or user proposed land use change. The former produces the minimum runoff increases, and the latter produces the maximum runoff increase for this specific land use change. The land use and soil data of the identified location along with proposed land use data are then passed to L-THIA for estimating runoff and NPS pollutants. Development can be restricted from occurring on specified land uses, such as wetlands. Users also have the option to provide their own plan for placing the proposed land uses within their watershed or area of interest. The resulting output from the integrated L-THIA and optimization system provides land use modifications that result in minimal and maximum changes in runoff. The output also includes runoff depth and volume and NPS pollutant masses for the following cases: minimum runoff increase (optimal development), maximum runoff increase (worst case development), and user proposed land use change plan if provided. Runoff and NPS pollutants for the existing watershed conditions (without the land use change) are estimated as well. Hereafter, optimal development and worst case development are used to refer to minimum and maximum runoff increases.

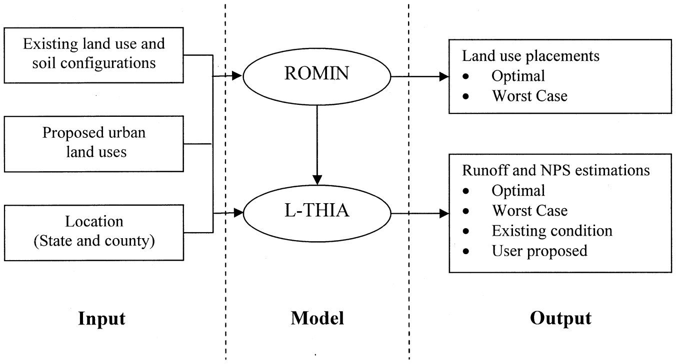


Figure 4. The Data Processing Flow of the Enhanced L-THIA Model Integrated With ROMIN.

Optimization Model and Algorithm. The ROMIN tool was developed using a simple optimization model. ROMIN assumes that urban development only occurs in nonurban land uses. The optimization model is mathematically described as

$$\text{Minimize} \quad Z = \sum_{\substack{i \in Np \\ j \in Ne}} RO_{pi} - RO_{ej} \tag{1}$$

$$\text{Subject to} \quad \sum_{j \in Ne} A_{ej} \geq \sum_{i \in Np} A_{pi} \tag{2}$$

where RO_{pi} is the runoff (m^3) from the ith proposed urban land use, RO_{ej} is the runoff (m^3) from the jth existing land use, A_{ej} is the area (m^2) of the jth existing nonurban land use, A_{pi} is the area (m^2) of the ith proposed urban land use, N_e is the number of existing nonurban land use categories, and N_p is the number of proposed urban land use categories.

This is a simple continuous optimization model with only area constrained. The objective function minimizes the runoff increases between proposed and existing land use and soil configurations. The area constraint states that the total areas of existing nonurban land use have to be larger than or equal to the total proposed urban areas.

A heuristic solution algorithm for this optimization model was also developed with detailed steps shown in Figure 5. The algorithm is essentially based on runoff change between predevelopment and postdevelopment. Daily based long term runoff is calculated for existing land use and soil combinations and each proposed land use and all existing soils, because all soils are potentially possible for the proposed land uses. The runoff differences between proposed and existing land use for the same soils are further calculated. The algorithm assigns existing land use and soils with minimum runoff difference to each corresponding proposed land use. To ensure minimum runoff difference between predevelopment and postdevelopment, the proposed land uses are assigned in the order of minimum to maximum runoff potentials, such as in the order of commercial, high density residential, and low density residential. The algorithm ends when all proposed land uses are assigned.

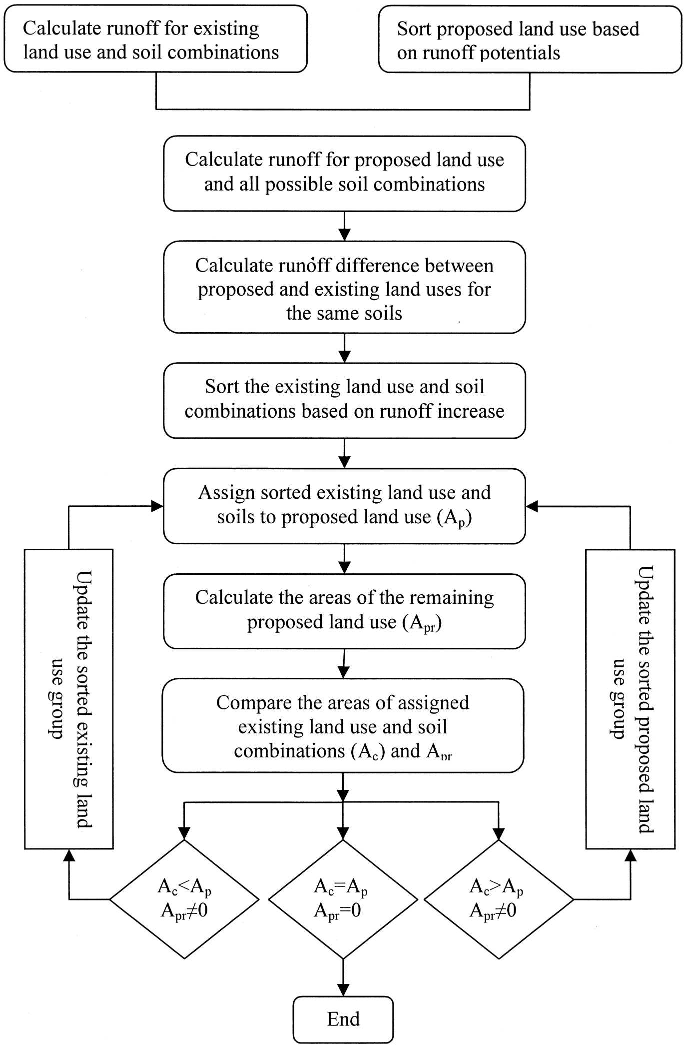


Figure 5. Flow Chart of the Solution Algorithm for the ROMIN Component.

The model and algorithm are capable of assigning proposed land uses to existing land use and soil patterns to achieve the minimum possible runoff increases. Estimation of the maximum runoff increases is easily achieved by modifying the model and its algorithm. The objective function was modified to obtain maximum runoff increases, and the solution algorithm was modified correspondingly.

Data Preparation

The LEC Watershed. Digital land use data for LEC were generated from satellite imagery (80 m resolution Landsat multispectral scanner (MSS) imagery) for 1973, 1984, 1991, and 1997 in previous studies that are part of a long term hydrologic impact assessment (Grove *et al.,* 2001; Muthukrishnan, 2002). These four images represent land use change experienced in the LEC watershed over time. Hydrologic soil group data were obtained from Soil Survey Geographic (SSURGO) maps (NRCS, 2005a) provided by the U.S. Department of Agriculture (USDA). Only Hydrologic Soil Groups B and C are present in the watershed.

Urbanization and its impact on runoff in LEC were evaluated for the following periods using the enhanced L-THIA model: 1973 to 1984, 1984 to 1991, 1991 to 1997, and the entire time span of 1973 to 1997, which summarized the overall development. The land use and soil combinations with areas for each starting year of the time periods served as base year parameters requested by ROMIN (Figure 4). The area increases of urban categories, requested for proposed development in ROMIN, were derived from the land use data of the starting and ending years of each time period. For example, to evaluate the development for 1973 to 1984, the land use and soil combinations in 1973 were used as base year parameters. The area increases of urban categories from 1973 to 1984, including commercial, high density residential, and low density residential, were provided to ROMIN as proposed land uses. The enhanced L-THIA model performed analysis for the above four time periods. A GIS tool was used to manipulate and process hydrologic soil group and land use data for the watershed.

The LMR Watershed. In a parallel study (Tang *et al.,* 2005), land use data for LMR were forecast using a neural net-based land use change model called the Land Transformation Model (LTM). Using 1978 as a baseline, the LTM forecast the land uses to 1995 in nonsprawl condition and 2020 and 2040 in both nonsprawl and sprawl conditions for the entire Muskegon River watershed (see Pijanowski *et al.,* 2002a,b, for details). These projected land uses for the LMR watershed were used in this study. The nonsprawl and sprawl conditions are differentiated by using different urban expansion indices in the model forecasting (Tang *et al.,* 2005). The urban expansion index is defined in LTM as a ratio of the percentage increase of urban areas and the percentage increase of urban populations over the same time intervals. The nonsprawl condition had a lower development rate than the sprawl condition. Hydrologic soil group data were obtained from Soil Survey Geographic (STATSGO) maps provided by USDA (NRCS, 2005b). Hydrologic Soil Groups A, B, and C are present in the watershed.

The enhanced L-THIA model was used to evaluate the projected development in the LMR watershed for the following periods: 1978 to 1995, 1995 to 2020, 2020 to 2040, and the entire time span of 1978 to 2040, which summarized the overall development. The land use and soil data used for the model were prepared using the same method as for the LEC watershed.

RESULTS AND ANALYSIS

The LEC Watershed

Urban areas expanded dramatically in the LEC watershed over the past three decades. In 1973, urban uses accounted for 49 percent of the total watershed area. This number increased to 63 percent in 1984 and 68 percent in 1991. The most rapid development occurred from 1991 to 1997. By 1997, almost the entire watershed was urbanized, with an urban proportion of 95 percent. There were significant changes in average annual runoff volumes as a result of these land use changes (Figure 6). However, changes in runoff volume did not simply map to changes in urban proportion. For example, estimated average annual runoff volume increased 3.5 million cubic meters from 1973 to 1984, an increase of 44 percent, in contrast to the period of most rapid development, 1991 to 1997, during which the increase of runoff volume was only 1.4 millions cubic meters, or 11 percent. This apparent paradox can be attributed to the nonhomogeneous urban growth and runoff contribution potentials of various urban subclasses (Table 1). From 1973 to 1984, urban growth was dominated by commercial and high density residential uses, which both have very high runoff potential. From 1991 to 1997, most growth was conversion to low density residential uses, which produce a relatively small increase in runoff compared to commercial and high density residential uses.

The impact of urbanization on runoff could have been minimized by appropriate land use planning. Figure 7 illustrates runoff percentage increases for four periods compared to the base years in the scenarios of optimal development, worst case development, and actual development. The actual development increased runoff 44.3 percent, 5.2 percent, and 11.4 percent for the periods 1973 to 1984, 1984 to 1991, and 1991 to 1997, respectively. By locally rearranging land use configurations for development as a function of soil patterns, these increases could have been reduced to 38.2 percent, 3.6 percent, and 9.3 percent, respectively. The overall development from 1973 to 1997 increased runoff by 69 percent, and it could have been reduced to 64.1 percent through careful land use placement. As an example, the land use and soil patterns in the optimal development scenario suggested by the enhanced L-THIA model for the overall development from 1973 to 1997 are presented in Table 2. The development of commercial areas occurred in agricultural land uses with B and C soil, with B as first choice. For high density residential development, the ranking of preferred land use and soil configurations was grass/pasture in B soil, forest in B soil, and agriculture in C soil. For low density residential development, this ranking was agriculture in C soil, water in B soil, grass/pasture in C soil, and forest in C soil. One can see that urban categories have different development preferences on land use configuration in terms of minimum runoff increase.

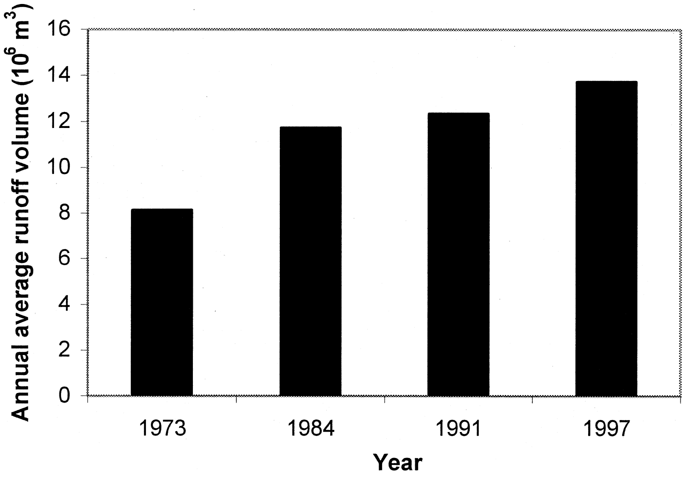


Figure 6. Estimated Annual Average Runoff Volumes in the Little Eagle Creek Watershed.

TABLE 1. The Change in Area of Urban Land Use Categories in the Little Eagle Creek Watershed.

Urban Land Use	Percentage Change in Land Use (percent) 1973 to 1984	1984 to 1991	1991 to 1997
Commercial	6.7	1.1	2.0
High Density Residential	15.7	3.1	6.2
Low Density Residential	-8.5	0.6	18.7

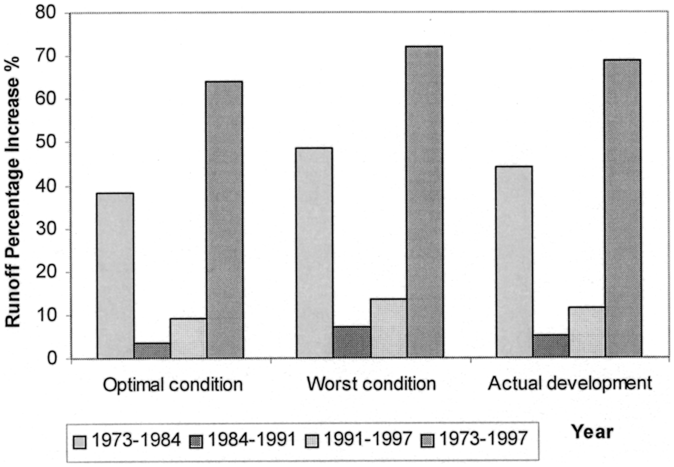


Figure 7. Runoff Percentage Increases for Optimal, Worst Case, and Actual Conditions in the Little Eagle Creek Watershed.

To evaluate the actual development in terms of its impact on long term surface runoff, the increases of runoff resulting from actual development were compared with the potential minimum and maximum runoff increase resulting from optimal and worst case development estimated by the enhanced L-THIA model. The actual runoff percentage increases are 6 percent, 1.6 percent, 2.0 percent, and 5.0 percent higher than the potential minimum runoff increases and 4.4 percent, 1.9 percent, 2.2 percent, and 3.0 percent lower than the potential maximum runoff increase for the periods 1973 to 1984, 1984 to 1991, 1991 to 1997, and 1973 to 1997, respectively. These numbers are the differences between actual runoff percentage increases and minimum or maximum runoff percentage increases as depicted in Figure 7. This indicates that in the context of the long term runoff impact of development, actual development is closer to the potential worst-case development in the time frame 1973 to 1984 and fell almost in the middle of optimal and worst development in the time frames 1984 to 1991 and 1991 to 1997. The entire development from 1973 to 1997 is close to the worst case development that was possible.

The LMR Watershed

Urbanization rarely occurs uniformly across an entire watershed but occurs at different rates in different parts of the watershed. This spatial sensitivity of development, associated with site specific land use and soil patterns of the location where the development occurs, results in the spatial variation of runoff impacts. To explore and minimize runoff impact of urbanization in the LMR watershed, the study was conducted at different spatial scales: the entire LMR watershed and its HUCs.

Analyses of the projected urban change (Table 3) indicate that substantial development will occur at varied paces across the entire watershed. This also holds true for its HUCs. In 1978, the entire watershed was composed of 24.1 percent urban land uses. With nonsprawl development, the entire watershed was estimated at 33 percent and 36.5 percent urban in 2020 and 2040, respectively. With sprawl development, the entire watershed will be composed of 45.2 percent and 52.1 percent urban land uses in 2020 and 2040, respectively. Urban distributions among HUCs are not identical. HUC3, in which Muskegon is partly located, is the most urbanized area compared to HUC1 and HUC2 over the projected time frame. Urbanization occurred more intensively in HUC3 than in the entire watershed. However, HUC2 has the most rapid rates of development in each time period

TABLE 2. Optimized Land Use and Soil Configurations for Urban Development From 1973 to 1997 in the Little Eagle Creek Watershed.

Proposed Urban Land Use	Nonurban Land Use	Hydrologic Soil Group	Area (km^2)
Commercial	Agricultural	B	5.6
	Agricultural	C	1.3
High Density Residential	Grass/Pasture	B	6.9
	Forest	B	8.1
	Agricultural	C	2.6
Low Density Residential	Agricultural	C	1.3
	Water/Wetlands	B	0.1
	Grass/Pasture	C	4.0
	Forest	C	2.2

TABLE 3. The Percentage of Projected Urban Area in the Little Muskegon River Watershed and Its HUCs.

Watershed	1978	1995	2020		2040	
			Nonsprawl	Sprawl	Nonsprawl	Sprawl
HUC1	11.9	15.5	17.8	25.9	20.0	29.5
HUC2	14.3	23.0	26.8	54.2	30.5	63.6
HUC3	35.9	41.8	46.0	57.4	50.4	66.1
LMR	24.1	29.5	33.0	45.2	36.5	52.1

from 1978 to 2040. Its urban proportion increased to about 50 percent of its total area in approximately 60 years. The rapid development in HUC2 can be explained as the result of Muskegon's spread outward beyond the current city boundary.

Estimation of runoff from the entire watershed and each HUC indicates that urbanization will significantly impact runoff generation but with varied patterns. Annual average runoff volume obviously increases in the entire watershed due to an increase in urban areas or imperviousness. The rate of runoff increases for the nonsprawl scenario is relatively even in the modeling time frame, whereas the sprawl scenario shows significant increases in the period of 1995 to 2020 (Figure 8). Annual average runoff volume also increased in each HUC. HUC3 contributed about half the total runoff generated from the entire watershed. HUC2 had the least runoff input, with about 20 percent of the total runoff (Figure 9).

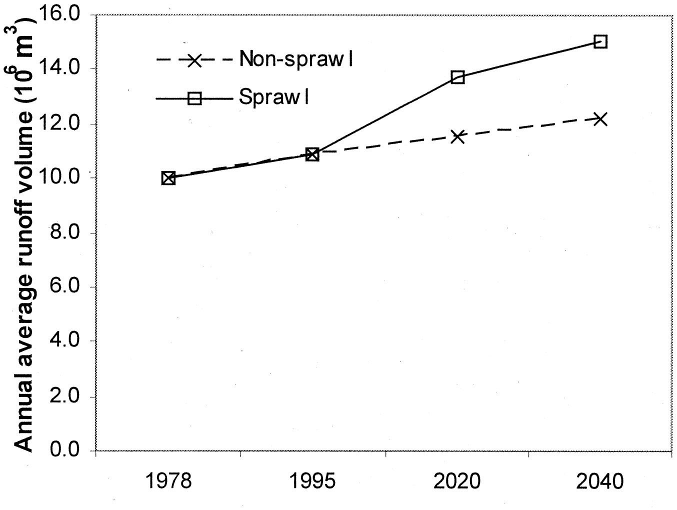


Figure 8. Estimated Annual Average Runoff Volumes in the LMR Watershed.

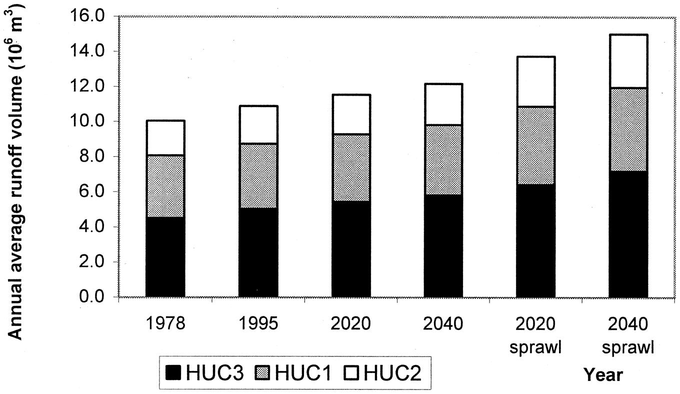
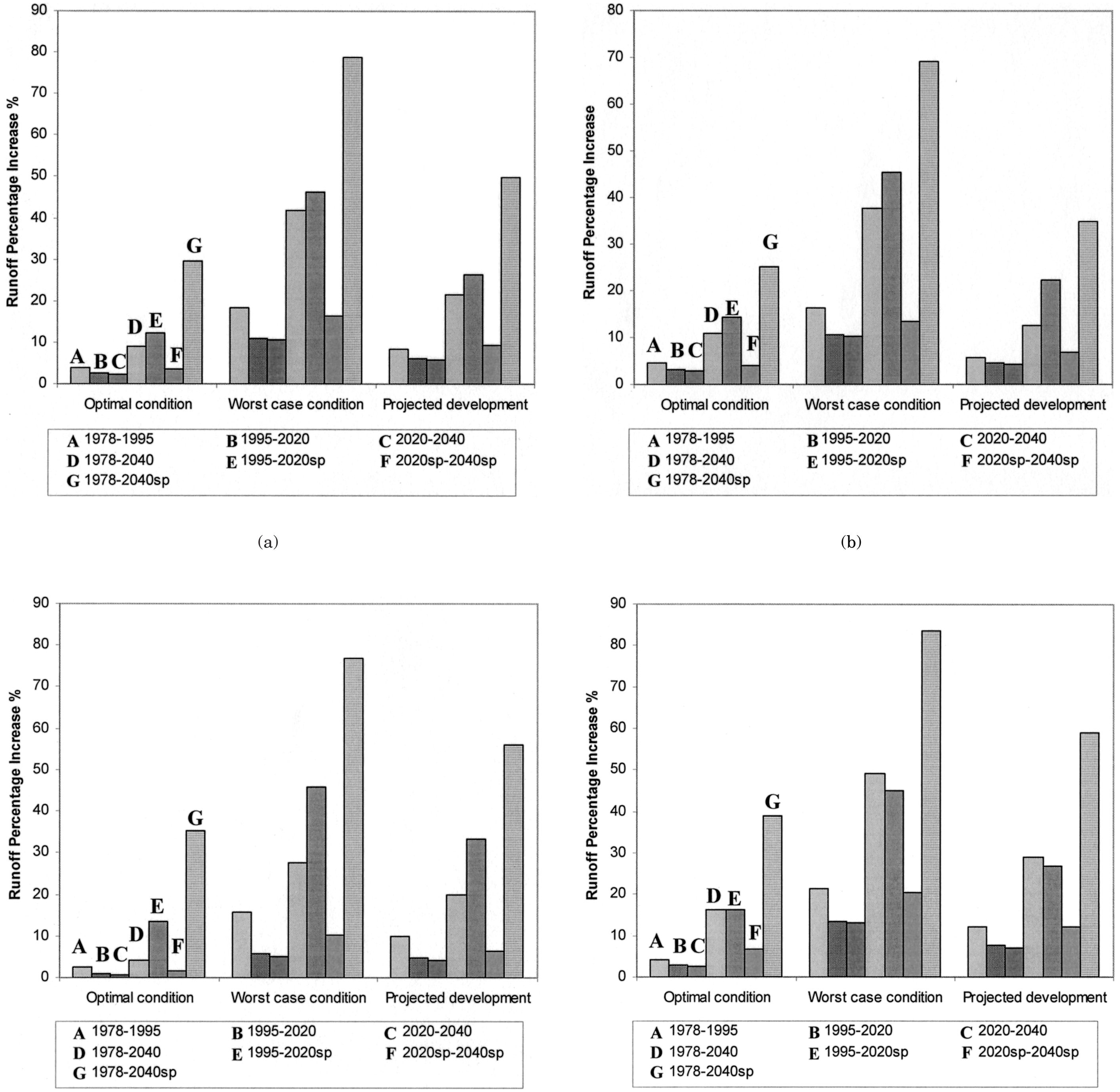


Figure 9. The Distributions of Estimated Annual Average Runoff Volumes Among HUCs in the LMR Watershed.

There is an opportunity to minimize the runoff impacts of the entire watershed and HUCs individually by locally rearranging land use and soil combinations for the projected development in all time periods (Figures 10a through 10d). For the entire watershed, the projected development will increase runoff 21.5 percent and 49.9 percent from 1978 to 2040 for the nonsprawl and sprawl scenarios, respectively. These increases can be reduced to 9.2 percent and 29.4 percent, respectively, if the land use is arranged specifically to minimize runoff. The spatial variability of runoff impact leads to the spatial variation of possible runoff reductions in HUCs. Within the same time period, the projected development increased runoff 12.5 percent in HUC1, 20 percent in HUC2, and 29.1 percent in HUC3 for the nonsprawl scenario, and these increases can be reduced to 10.9 percent in HUC1, 4.2 percent in HUC2, and 16.3 percent in HUC3. For the sprawl scenario, runoff increases in each HUC due to projected development are 34.9 percent in HUC1, 56 percent in HUC2, and 59 percent in HUC3, and these increases can be minimized to 25.0 percent in HUC1, 35.3 percent in HUC2, and 38.9 percent in HUC3. As an example, the land use and soil configurations for the optimal condition recommended by the enhanced L-THIA model from 1978 to



(a)

(b)

(c)

(d)

Figure10. Runoff Percentage Increases for Optimal, Worst Case, and Actual Conditions in (a) the Entire LMR Watershed, (b) HUC1, (c) HUC2, and (d) HUC3.

2040 in the sprawl scenario are presented in Table 4. The development of commercial areas occurred in A soils with agricultural, grass/pasture, and forest land uses. For industrial development, the ranking of preferred land use and soil configurations was forest and water/wetlands in A soils, and agriculture in C soils. For low density residential development, this ranking was agricultural, grass/pasture, and forest all in C soil. One can see A soil is preferred over C soil for optimal development in this case.

TABLE 4. Optimized Land Use and Soil Configurations for Projected Urban Development From 1978 to 2004 for the Sprawl Scenario in the Little Muskegon River Watershed.

Proposed Urban Land Use	Nonurban Land Use	Hydrologic Soil Group	Area (km^2)
Commercial	Agricultural	A	2
	Grass/Pasture	A	42
	Forest	A	540
Industrial	Forest	A	283
	Water/Wetlands	A	22
	Agricultural	C	9
Low Density Residential	Agricultural	C	1,947
	Grass/Pasture	C	2,033
	Forest	C	382

To assess the projected development in each period with respect to its impact on long term runoff, the differences of runoff percentage increase between the projected and optimal or worst case development were analyzed (Table 5). For the entire watershed, the projected development in all time periods is closer to optimal development than worst case development. In HUC1, the projected development is very close to optimal development for the nonsprawl scenario. The runoff increase of the projected development is higher than the runoff increase of optimal development by only 1.6 percent from 1978 to 2040. In HUC2, the projected development is close to the worst case development with respect to runoff. For example, in the periods 1995 to 2000 and 2020 to 2040 for the nonsprawl scenario, the runoff percentage increase of project development is less than the worst development by only 1.1 percent. In HUC3, the projected development falls between the optimal and the worst-case development, slightly closer to the optimal development.

DISCUSSION

Both historical and projected urban development in the LEC and LMR watersheds increase runoff significantly. This impact can be minimized by careful land use planning. The increase in runoff could have been reduced as much as about 4.9 percent from 1973 to 1997 in the LEC watershed, which is almost totally urbanized at 95 percent urban cover in 1997. The reduction of runoff increases from projected development will be as much as 12.3 percent and 20.5 percent for the nonsprawl and sprawl scenarios, respectively, in the entire LMR watershed from 1978 to 2040. The magnitude that runoff can be minimized depends on site specific land use types, soil properties, and the urbanization level of a watershed. The influence of urbanization can be generally expressed in two ways. On the one hand, with the increase of urban proportion within a watershed, its impact will be generally

TABLE 5. Runoff Percentage Increases Between the Projected and Optimal (Actual-Optimal) and Worst Case and Projected (Worst-Actual) Development for the Little Muskegon River Watershed and Its HUCs.

	1978 to 1995	1995 to 2020		2020 to 2040		1978 to 2040	
		Nonsprawl	Sprawl	Nonsprawl	Sprawl	Nonsprawl	Sprawl
HUC1							
Actual-Optimal	1.2	1.4	7.8	1.3	3.0	1.6	9.9
Worst-Actual	10.6	6.1	23.4	5.9	6.6	25.3	34.4
HUC2							
Actual-Optimal	7.6	3.9	19.8	3.4	4.8	15.8	20.8
Worst-Actual	5.5	1.1	12.4	1.1	3.9	7.7	20.9
HUC3							
Actual-Optimal	7.9	4.8	10.5	4.4	5.3	12.8	20.2
Worst-Actual	9.4	5.8	18.2	5.8	8.4	20.0	24.7
LMR							
Actual-Optimal	4.8	3.5	14.3	3.3	5.6	12.3	20.5
Worst-Actual	9.9	5.0	19.7	4.9	7.3	20.4	28.9

expected to increase, and therefore the room to minimize this impact also increases potentially. On the other hand, when urban becomes the predominant land use in the area, the available nonurban areas become limited and the possibility and room to minimize the runoff impact will be very small. This was the case in the LEC watershed. Urban uses made up about 50 percent of the total watershed area in 1973. By 1997, the urban proportion increased to 95 percent of the total area. The available nonurban area for planning in 1997 was thus only 5 percent. Although the runoff increase due to development is as large as 69 percent, it can only be reduced by 4.9 percent. Therefore, land use planning at an early stage of development is much more effective. Few future planning options exist if urbanization trends continue.

The optimization component of the enhanced L-THIA, which is called ROMIN, RunOff MINimization, applies a simple model with only an area constraint and a straightforward solution algorithm to provide general estimates of minimum runoff impacts due to land use change. The use of a simple model satisfied the need for an inexpensive computation approach required by the Web-executable L-THIA model. It also established the basis for the enhanced L-THIA to be an easy-to-use and easy-to-access land use planning tool. However, it has limitations compared to more sophisticated and computationally expensive spatial optimization models (Wright *et al.,* 1983; Minor and Jacobs, 1994; Williams and ReVelle, 1996; Brookes, 1997; Lin and Kao, 1999). In particular, the resultant optimal placement of proposed land uses on available land use and soil group patterns may not be contiguous because the model does not have a constraint for contiguousness to force spatially connected development. Such solutions may not be realistic for development in some cases, but the optimization approach would allow proposed solutions in such instances to be evaluated with respect to the optimal and worst case development scenarios. To overcome this limitation, ongoing research efforts employ a multiobjective spatial optimization model with constraints including contiguousness, compactness, and shape to allocate proposed land uses. The expected spatial optimization model will be capable of estimating not only minimum runoff impacts but also minimum NPS and recharge impacts due to land use change. However, this spatial optimization model is a computationally expensive solution algorithm, which means that the user must accept relatively lengthy computation times before a result is produced.

The enhanced L-THIA model assumes that proposed urban development occurs only in nonurban land use, as it is a major development style in urban sprawl. This assumption can be removed if a more comprehensive analysis of land use change, including urban to urban change, is required.

The estimated runoff impact for the LEC and LMR watersheds in this study are potential minimums and maximums that do not account for regulatory or other social or economic restrictions on the placement of development that would modify the optimization results. For example, a farmland protection regulation may restrict development on agricultural land, which may increase the estimated minimum runoff increase. A wetland protection regulation may restrict development in wetland areas, which may reduce the estimated maximum runoff increase. Since the enhanced L-THIA model provides the option that allows users to specify restricted land uses, the effects of regulation that consider land use protection can certainly be considered when necessary.

The enhanced L-THIA model selects land use change placements that minimize runoff increase, while the economic, social, and other environmental suitability for development was assumed satisfied for urban development. In reality, urban planning involves a complex array of critical factors drawing from economic, social, technical, and environmental disciplines. Because of the complex nature of this problem, hydrologists need to work with other stakeholders and professionals in the disciplines involved to make smart growth decisions.

SUMMARY AND CONCLUSIONS

Increasing concern about the problems caused by urban sprawl has led to proactive measures to guide future development. Smart growth is being promoted as a progressive approach to development. One of the goals of smart growth is water resources protection, in particular minimizing the impact of urban sprawl on runoff and systems affected by runoff processes. To investigate the magnitude of the potential benefits of land use planning that considers impact on runoff, possible runoff reductions of historical and projected urbanization were quantified and evaluated by optimizing placement of land use change in the LEC and LMR watersheds.

A long term hydrological impact analysis model, L-THIA, was enhanced by integrating an optimization component, and the integrated model was employed in this study. This component used a simple continuous optimization model to minimize long term runoff increases. The enhanced L-THIA model provides suggested land use modifications that result in minimum and maximum runoff increase for proposed developments. The same method can be easily modified and applied to optimize nonpoint pollution loadings in surface runoff that can result from urbanization.

The results revealed significant opportunities to minimize runoff impact due to actual development in the LEC watershed and projected development in the LMR watershed. The magnitudes of runoff minimization impacts are different in the two watersheds. Runoff increase can be reduced as much as 4.9 percent from 1973 to 1997 in the LEC watershed. The actual development during this period is closer to potential worst case development compared to optimal development in terms of runoff percentage increases. The reduction of runoff increases from projected development will be as much as 12.3 percent and 20.5 percent for the nonsprawl and sprawl scenarios, respectively, in the entire LMR watershed from 1978 to 2040. The spatial variation of runoff minimization was analyzed for the LMR watershed. For the same period, the runoff increases can be decreased as much as 1.6 percent, 15.8 percent, and 12.8 percent in HUC1, HUC2, and HUC3, respectively, for the nonsprawl scenario, and 9.9 percent, 20.8 percent, 20.2 percent in HUC1, HUC2, and HUC3, respectively, for the sprawl scenario. Among the three HUCs, the projected development in HUC1 is closer to the potential optimal development, while the projected development in HUC2 is closer to the worst case development.

The results of this study have significant implications for urban planning. They suggest that even relatively simple Internet-accessible tools can provide significant guidance regarding the potential reductions in runoff that can be achieved if urbanization locations are selected to minimize runoff changes. The runoff model L-THIA enhanced by the optimization technique provides a decision support capability that can be used by land use planners and other decision makers to identify land use plans that minimize runoff for a desired set of land uses. As a result, planners and developers could modify the location of proposed land use changes to reduce environmental impacts. In other instances planners and developers may wish to compare the impact of proposed development to the optimal situation. Regulations could presumably be developed based on the results of this work that require land use plans to minimize impacts on runoff or incorporate best management practices that would allow the area they wish to develop to achieve runoff levels that are comparable to the optimal location for the planned development.

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