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Evaluation of Hydrological Impacts Caused by Land Use Change

토지이용변화에 따른 수문영향분석

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Abstract

A grid-based hydrological model, CELTHYM, capable of estimating base flow and surface runoff using only readily available data, was used to assess hydrologic impacts caused by land use change on Little Eagle Creek (LEC) in Central Indiana. Using time periods when land use data are available, the model was calibrated with two years of observed stream flow data, 1983-1984, and verified by comparison of model predictions with observed stream flow data for 1972-1974 and 1990-1992. Stream flow data were separated into direct runoff and base flow using HYSEP (USGS) to estimate the impacts of urbanization on each hydrologic component. Analysis of the ratio between direct runoff and total runoff from simulation results, and the change in these ratios with land use change, shows that the ratio of direct runoff increases proportionally with increasing urban area. The ratio of direct runoff also varies with annual rainfall, with dry year ratios larger than those for wet years shows that urbanization might be more harmful during dry years than abundant rainfall years in terms of water yield and water quality management.

Keywords : Hydrological impact analysis, Hydrological model, Land use change, Urbanization

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I. Introduction

The expansion of urban areas is still occurring in most cities, and there is continuing need to implement programs designed to preserve water quality and quantity during development and under new land use conditions (Harbor et al., 2001[10)]). To support such programs it is important to understand the effects land use changes have on hydrologic components, including surface runoff, stream and base flow, and groundwater recharge, because land use change can significantly affect hydrologic characteristics such as storm water peak, total runoff, bank full frequency, evapotranspiration, low flow conditions, and base flow (Doyle et al., 2000[5)]). To adequately manage impacts of ongoing or future

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land use change in a watershed, it is critical to be a to assess the hydrologic impacts of urban expansion, and several types of hydrologic models have been applied to evaluate solutions to urban hydrologic impacts (McClintock et al., 1995[13], Bhaduri et al., 2001[3]). However, to evaluate long-term hydrologic impacts of land use change, two fundamental elements are required: a suitable hydrologic model and available data. In fact, it is often very difficult to find a satisfactory solution because of trade-offs in models and data. For example, a detailed model needs large amounts of data that is sometimes too difficult to obtain, especially for a longitudinal study of urbanization, but a simplified model may be too vague and abstract to provide useful insight into the problem. Finding an optimal combination of model complexity and available data is a challenge faced by most analysts and decision makers.

Most evaluations of the hydrologic impacts of land use change of a watershed are performed with an event modeling approach, for example, direct runoff and peak runoff of a storm event (Linsley, 1981[12]). However, as argued by McClintock et al. (1995[13]), in assessing the long-term impacts of land use change on water quantity and quality, it is important to recognize that these are dominated by the cumulative effects of smaller storm events, rather than by rare high-magnitude storm events. Thus, some important characteristics of long-term impacts cannot be adequately modeled simply by examining impacts associated with single, usually large, storm events. Although some existing hydrologic models are capable of assessing long-term impacts, they are not often suitable for preliminary assessment because of their complexity and the unavailability of the extensive input data required to run them (e.g., Bhaduri et al., 2001[3]). Initial assessment of hydrologic impacts of land-use change requires a simple model that can be run with readily available input data to provide preliminary estimates of the absolute and relative impacts of watershed development and to identify the need for more advanced modeling in some cases or areas.

A Cell-based Long-Term Hydrological Model (CELTHYM) (Choi et al., in press[4]) capable of estimating base flow and surface runoff with readily available data can be used for assessing the hydrologic impacts of land use changes associated with urbanization in a case study performed on a watershed. Given the significance of efforts involved in understanding and minimizing the negative impacts of urbanization, a model such as CELTHYM should prove to be a very useful tool for urban planners, watershed managers, other groups and individuals interested in obtaining access to useable models that allow them to assess relative impacts of urbanization scenarios.

Therefore for this study, a grid based hydrological model capable of estimating base flow and surface runoff using readily available data was presented. The model was used to evaluate long-term hydrologic impacts caused by land use changes associated with urbanization for a mid-western watershed in central Indiana. The model was calibrated and evaluated using observed stream flow data. Qualitative and quantitative analyses of changes in surface runoff and base flow were conducted to evaluate the effects of land use change on hydrologic components.

Ⅱ. CELTHYM Description

1. Main Concept

In general, hydrologic models have been used to comprehend the phenomena of a watershed under conditions of watershed characteristic changes. In the study, CELTHYM (Cell-based Long Term Hydrologic Model) was adapted to simulate the hydrological response of a relatively small watershed. CELTHYM is a simplified, operational and conceptual model that uses grid data and a daily time step and also has pre- and post- processors for inter-operation with GIS (Choi et al., in press$^{4)}$). The conceptual schematic diagram of the model is shown in Fig. 1.

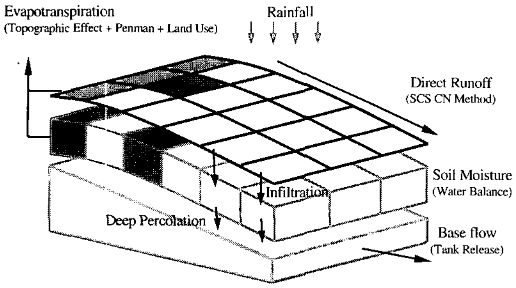

Fig. 1 Conceptual diagram of CELTHYM

The watershed water balance equation used is shown in equation (1).

$$\triangle S = R - Qdr - Qbf - WET \cdots\cdots\cdots\cdots (1)$$

where $\triangle S$ (mm) is watershed storage change, R (mm) is precipitation, Qdr (mm) is direct runoff, Qbf (mm) is base flow and WET (mm) is watershed evapotranspiration.

2. Modeling

가. Direct Runoff

The direct runoff of grids was estimated by the curve number (CN) method of the USDA-NRCS (Natural Resources Conservation Service). The CN method has been used within GIS environments in other research and has been verified to work well for direct runoff simulation.

나. Soil moisture

CELTHYM uses the soil water balance equation from equation (2) in a simplified form by neglecting horizontal flow rate and capillary rise, because these terms are not as important as other terms for long-term simulation, their inclusion would make the model complex beyond the model precision, and obtaining measured field data for these phenomena is difficult.

$$SM_t = SM_{t-1} + SR_t - ET_t - DP_t \cdots\cdots\cdots\cdots (2)$$

$$SR_t = RAIN_t - qdr_t \cdots\cdots\cdots\cdots (3)$$

In equation (3), SR (soil water retention) was adopted in this study to calculate the total infiltrated water from precipitation, and the direct runoff, qdr, was estimated by the CN method.

다. Base flow of a sub-watershed

The base flow of a watershed is the groundwater release from a catchment to a stream. In this study, the base flow of a watershed was calculated from each sub-watershed of a main watershed. The base flow release from a sub-watershed is conceptualized as a tank and release. The base flow detention depth (Z, mm), the same meaning as the depth of a tank, is calculated by adding the average of deep percolation of each grid in a sub-watershed to the depth of the prior date. The base-flow was estimated by multiplying the release rate (K) with the depth. The base flow detention depth on the date of t is calculated by equation (4).

$$DZ = Z_t - Z_{t-1} = DP_t \cdots\cdots (4)$$

In equations (3), DZ is detention depth change, and DP is average deep percolation of a sub-watershed.

Finally, the equation for the base flow calculation is summarized as equation (5).

$$qbf_t = K \cdot Z_t \cdots\cdots (5)$$

where qbf is base flow of a sub-watershed, K is release rate of base flow, and Z is base flow detention depth of a sub-watershed. K is a parameter for base flow estimation, and the value of K affects the quantity of base flow directly. The total base flow at the outlet of a watershed was estimated by area weighted averaging of all base flow of sub-watersheds.

라. Watershed evapotranspiration

The actual evapotranspiration (ETa) of a grid can be obtained by multiplying the cell crop coefficient (Kc) and soil moisture coefficient (Ks) to potential ET (PET). In this study, the actual ET was estimated by land use and soil moisture condition using GIS data. The PET in this study was calculated by Blaney-Criddle (B-C) equation to estimate easy and by limitation of weather data items.

Ⅲ. Land Use Change Impact Analysis

1. Data preparation

가. Site description

To fully demonstrate the hydrological impacts of land use change, a watershed that has experienced dramatic changes of land use is needed. The Little Eagle Creek (LEC) watershed located near Indianapolis was selected because the watershed has experienced extensive land use change over the past three decades by urban expansion of the Indianapolis metropolitan area. Moreover, the watershed also had long-term observed stream flow and weather data for a period of about 20 years. The LEC watershed location map is shown in Fig. 2 and the related information of the watershed is presented in Table. 1.

The watershed area is 27.54 square miles in

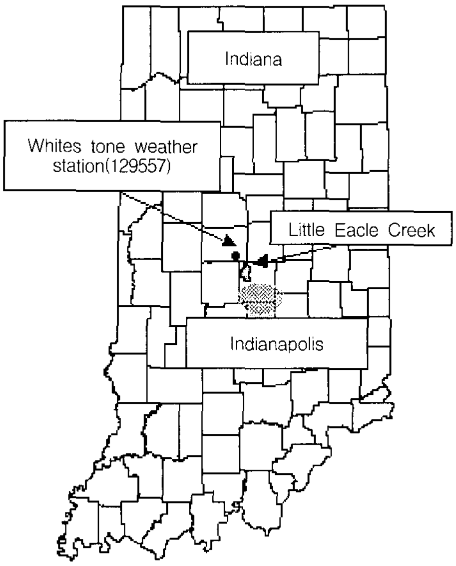

Fig. 2 Location map of Little Eagle Creek watershed

Table 1 Data gathering stations and application period

Watershed name	Weather station	Gauging station	Calibration Period	Validation
Little Eagle Creek (Indiana)	Whitestone (129557)	Little Eagle Creek (03353600)	10/1/1984- 9/30/1986	10/1/1972-9/30/1974 (12 years before) 10/1/1990-9/30/1992 (6 years after)

size, and since the 1990's more than 66% of the area of watershed is dominated by urbanized land use type. Land uses ranging from non-urban natural grass and forested areas and agricultural areas to typical urban residential, commercial, and industrial categories exist in the LEC watershed.

나. Digital data

Grid land use and soil data were prepared to simulate hydrologic impacts evaluation of the watershed. Remotely sensed land use data sets that were used by Grove[6)] (1997) and Bhaduri[2)] (2000) for a long-term hydrologic impact assessment study was used and are shown Fig. 3. The digital land use data were generated from satellite imagery, 80 meter resolution Landsat multi-spectral scanner (MSS) imagery, for 1973, 1984, and 1991. These three images represented land use change in the watershed over time. Digitized soil grid data were generated from Soil Survey Geographic (SSURGO) maps at scales of 1:16,000. Only hydrologic soil groups B and C are present in the watershed as shown in Fig. 4.

Curve Number (CN) values of the LEC watershed were calculated with the land use data and soil data. Table 2 shows the percentile changes for each land use category of LEC watershed, and table 3 describes the assigned CN values for the land use types and hydrologic soil groups. The CN values in the watershed and yearly changes by land use change were presented in Fig. 5.

다. Weather data

The Whitestone weather station that has the

1973 1984 1991

Fig. 3 Land use change of LEC watershed for each application year

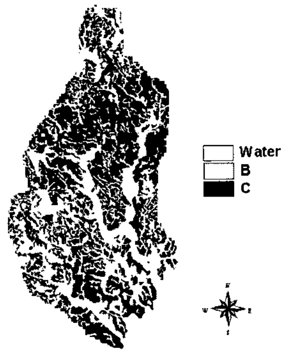

Fig. 4 Hydrologic soil group of LEC watershed from SSURGO

Table 2 Land use change of the LEC watershed for each applied year

Land use		% of total (70.5 km^2) watershed area		
		1973	1984	1991
Non-urban	Agricultural	15.4	14.5	13.1
	Forest	19.5	8.1	7.3
	Grass/Pasture	15.5	13.7	11.0
	Water	0.4	0.3	0.5
Sub total		50.8	36.6	31.9
Urban	Commercial	8.3	15.0	16.0
	HD residential/ Industrial	11.5	27.2	30.4
	LD residential	29.4	21.2	21.7
Sub total		49.2	63.4	68.1

Table 3 Assigned Curve Number by land use and hydrologic soil group

Land use	Hydrologic soil group	
	B	C
Agricultural	76.0	83.0
Commercial	96.0	96.7
Forest	60.5	73.5
Grass/Pasture	67.8	78.5
HD residential/Industrial	86.5	90.5
LD residential	70.0	80.0
Water	98.0	98.0

National Climate Data Center (NCDC) code number 129557 was selected to provide rainfall and temperature data. The station is about 10 miles from the watershed as shown in Fig. 2.

라. Runoff data

To validate the simulation results, observed stream flow data from the Little Eagle Creek gauging station was selected and is described in Table 1. The historic daily stream gauge data for Little Eagle Creek (LEC) were downloaded from the USGS web site in tab delimited text file format. The data spans from 1959 to 1999. This data was fed into the IOWDM program of the USGS to prepare the input file in WDM (Watershed Data Management) format to use with the HYSEP program that separates base flow and surface runoff components from the stream gauge data. The process of separating base flow and surface runoff components from daily stream flow is called base flow separation. The use of the USGS developed computer program for hydrograph separation removes any

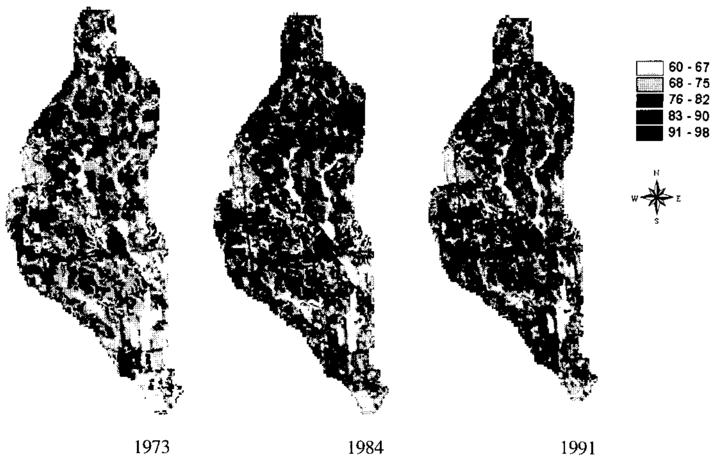

Fig. 5 Curve number change of LEC watershed for each application year

inconsistencies that may arise due to differences in methods of separation and also makes it comparable to similar results.

Any changes or interruptions in the natural flow of streams affect the base flow and surface runoff characteristics. Even though this change is site specific (White and Sloto, 1990[20]), care should be taken to consider this while interpreting the results.

There are three methods of hydrograph separation available in the HYSEP program – fixed interval, sliding interval, and local minimum. For the current study, the local minimum method was selected. More detail on the methods and algorithms used can be found in the HYSEP manual (Sloto and Crouse, 1990[18]).

2. Model verification

Criteria for comparing model output to historical data and analyzing statistical similarity were needed for this study. Three kinds of statistical variables, R^2, E and RMSE (Root Mean Square Error), were selected for the criteria. The determination coefficient (R^2) was selected for analysis of statistical relationship and significance. For the check of precision and correctness of the model, model efficiency (E) proposed by Nash and Sutcliffe[15] (1970) was used. RMSE was used for the quantitative analysis of residuals. If the value of E is equal to 1, it means the calculated and observed values are identical. If the value of E is between 1.0 and 0, the computed values are more useful than use of the mean of the observed values, and if the value of E is negative, the model capability is not proper for the simulation and means the average value of observed data is better than simulation results.

The periods of calibration and verification were determined by following the year of prepared land use data, 1973, 1984, and 1991. For model calibration, land use data for 1984, and weather data and rainfall data for 1984–1986 were prepared. The land use data for the simulation was for 1984 since land use for years shortly before and after were not available. The period 1983–1985 is preferred to the period 1984 – 1986 for simulation, however, the stream flow data for 1983 water year was not supported by USGS. To determine the before and after effects of urbanization, the calibration was conducted for the data set for 1984, and the data sets for 1973 and 1991 were used for verification.

가. Model calibration

CELTHYM calibration was conducted with observed stream flow data from 1984 to 1986. The trial-and-error method was adopted for model calibration because CELTHYM has only two calibration parameters. Initial conditions of soil moisture and release depth were used, and the release rate (K) and soil moisture storage coefficient (STC) were calibrated. The calibration results are shown in Table 4, Table 5 and Fig. 6, and the R, R^2, E and RMSE were 0.721, 0.520, 0.406, and 2.363, respectively. The values of statistical analysis between observed data and simulated results were acceptable under circumstances of simplified conceptual modeling and various sources of error in terms of distance of weather station and time lag of between rainfall and runoff, since CELTHYM simulates the runoff to occur on the same day of rainfall.

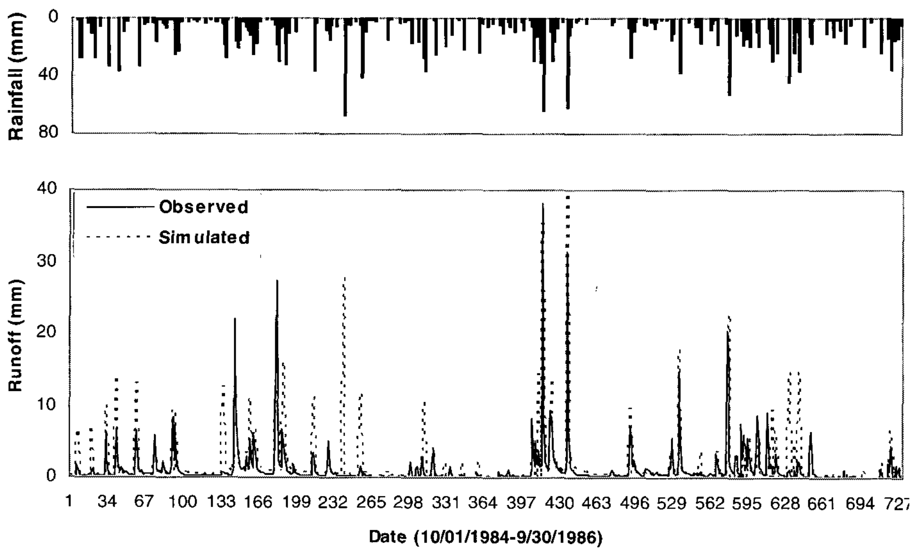

Fig. 6 Simulated and observed hydrograph results for the LEC watershed for 1984-1986

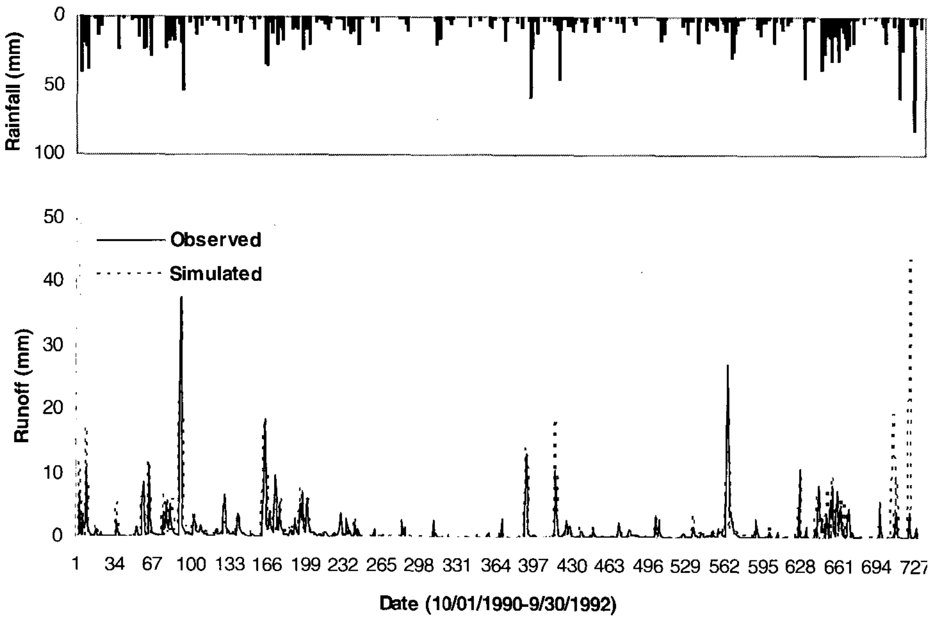

Fig. 7 Simulated and observed hydrograph verification results for the LEC watershed for 1990 - 1992

나. Model verification

CELTHYM was verified to check the model applicability with two kinds of observed data during 1972 through 1974 and from 1990 to 1992. The first set was selected to understand the model application capability and impact assessment under conditions before urbanization and during development, and the later was chosen to get information for more urbanized land uses. The verification results during 1972–1974 are shown in Table 4, Table5, and the R, R^2, E and RMSE were 0.652, 0.425, −0.357, and 1.988, respectively. The verification results during 1990−1992 are shown in Table 4, Table 5 and Fig. 7, and the R, R^2, E and RMSE were 0.727, 0.529, 0.400, and 2.134, respectively. Although the model efficiency was a negative value for the 1972−1974 period, the other statistical values involving correlation coefficient and determination coefficient were acceptable and both results showed similar values to the calibrated results. Although the sources that caused differences between calibration and verification results could come from several reasons, in this study, differences seemed to occur mainly due to mismatching of rainfall and observed runoff (the rain gauge did not seem to always represent rainfall in the watershed) and model limitations by assumptions. Even though the model efficiency was negative in the verification analysis, the other results showed consistency about the correlation coefficients, and by the comparisons as shown in Table 5, amount of runoffs between observed and simulated and ratios between runoffs were quite acceptable in quantitative and qualitative terms. The ratio of runoff, which appears in this study was obtained by direct runoff (base flow) divided by total runoff, not by rainfall amount.

Table 4 Calibration and verification results of CELTHYM model application

Period	R (R^2)	E	RMSE
Calibration 10/1/1984-9/30/1986	0.72 (0.52)	0.41	2.36
Validation (12 years before) 10/1/1972-9/30/1974	0.65 (0.43)	-0.36	1.99
Validation (6 years after) 10/1/1990-9/30/1992	0.73 (0.53)	0.40	2.13

3. Impact evaluation

To determine the hydrological impact of urbanization, two kinds of approaches were introduced. First, the hydrological impacts by land use change, especially urbanization, were analyzed.

This analysis was implemented to obtain information about the effect of land use change on runoff components of the watershed. Secondly, to determine the urbanization effect on direct runoff and base flow by precipitation amount, CELTHYM was run with two sets of rainfall series data and analysis of runoff quantity and the ratio between direct runoff and total runoff were completed.

Table 5 Comparison of observed and simulated runoff

Period	Precipitation (mm)	Total runoff (mm)		Direct runoff				Base flow			
		Obs.	Sim.	Total (mm)		Ratio of Runoff*		Total		Ratio of Runoff*	
				Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Calibration	2393.1	841.7	851.7	552.3	542.0	0.66	0.64	289.4	309.7	0.34	0.36
Validation (12 years before)	2446.5	665.4	842.5	365.1	394.0	0.55	0.47	300.3	448.5	0.45	0.53
Validation (6 years after)	2158.3	753.4	711.8	534.3	467.4	0.71	0.66	219.1	244.4	0.29	0.34

* The value was obtained by direct runoff (base flow) divided by total runoff.

다. Impact by land use change

The impact analysis of land use change of LEC focused on change of the direct runoff and base flow for the three land use data sets for 1973, 1984, and 1991. Urbanization increases direct runoff and decreases base flow. The ratio between direct runoff and total runoff and the change in rate of those ratios for increasing urban land use was examined.

As shown in Table 6, the ratio of direct runoff to total runoff was 46.8 % in 1972-1974. The ratio was increased by urbanization in 1984-1986 as shown in Table 6, and the value was 63.6 %. The analysis of direct runoff increase due to urban area increase was also conducted Badhuri et al.[2] (2000) for the LEC watershed. The results were similar in both studies for direct runoff, although Badhuri et al.[2] (2000) did not present relationships between direct runoff and base flow. The ratio increase of the direct runoff was proportional to the increase in the ratio of urban area. From these results, the ratio change rate of direct runoff had a coincidental tendency with urban area increase.

나. Impact by precipitation quantity

This analysis was conducted to evaluate the impacts of land use change for varying annual rainfall amounts. The runoff response from precipitation depends mainly on the land use and treatment characteristics of a watershed. Therefore, it is necessary to know about land use change effects on runoff amount for the rainfall in terms of rainfall quantity. Since annual total rainfall amount implies the precipitation characteristics of daily rainfall intensity and amount, the biggest and the smallest annual total rainfall were selected among daily rainfall summation series by water year, and daily rainfall series of the selected years were prepared as the rainfall series data sets for simulation. The 1966 rainfall data was selected as the smallest, and the 1993 rainfall data was chosen as the biggest. The average rainfall was 1032.8 mm during 38 years, and the 1993 data was 301.7 mm greater than the average value, and the 1966 data was 388.4 mm smaller than the mean value of annual rainfall.

The ratios of direct runoff by land use year between the wet and dry year were nearly the same as shown in Table 7, Table 8. However, the ratios of direct runoff to total runoff were quite different for the wet and dry years, and during the low rainfall year, the ratios of direct runoff were bigger than those of large rainfall year. Therefore, urbanization might be more harmful during dry years than abundant rainfall years in terms of water yield and water quality management.

Table 6 Comparison between urban area changes and ratio of runoff

Verification (Period)	Land use change				Ratio change of runoff			
	Non-urban area		Urban area		Direct runoff		Base flow	
	%	Increase from 1973	%.	Increase from 1973	%	Increase from 1973	%	Increase from 1973
Validation (10/1/1972-9/30/1974)	50.8	-	49.2	-	46.8	-	53.2	-
Calibration (10/1/1984-9/30/1986)	36.6	-14.2	63.4	14.2	63.6	16.8	37.4	-16.8
Validation (10/1/1990-9/30/1992)	31.9	-18.9	68.1	18.9	65.7	18.9	34.3	-18.9

Table 7 Urban area changes and ratio changes of runoff for 1966 water year

Year of used CN and land use data	Land use change		Runoff change (Rainfall : 644.4 mm: 10/01/1965-9/30/1966)						
	Urban area		Runoff (mm)			Ratio of direct runoff to total runoff		Ratio of base flow to total runoff	
	%.	Increase from 1973	Direct runoff	Base flow	Total	%	Increase from 1973	%	Increase from 1973
1973	49.2	-	37.4	17.8	55.2	**68.8**	-	**31.2**	-
1984	63.4	**+14.2**	63.1	13.3	76.4	**82.6**	**+13.8**	**17.4**	**-13.8**
1991	68.1	**+18.9**	68.0	12.8	80.8	**84.2**	**+15.4**	**15.8**	**-15.4**

Table 8 Urban area changes and ratio changes of runoff for 1993 water year

Year of used CN and land use data	Land use change		Runoff change (Rainfall : 1334.5 mm: 10/01/1992-9/30/1993)						
	Urban area		Runoff (mm)			Ratio of direct runoff to total runoff		Ratio of base flow to total runoff	
	%.	Increase from 1973	Direct runoff	Base flow	Total	%	Increase from 1973	%	Increase from 1973
1973	49.2	-	226.4	196.6	423.0	**53.5**	-	**46.5**	-
1984	63.4	**+14.2**	316.1	158.2	474.3	**66.6**	**+13.1**	**33.4**	**-13.1**
1991	68.1	**+18.9**	334.1	153.8	487.9	**68.5**	**+15.0**	**31.5**	**-15.0**

Ⅳ. Summary and Conclusion

A grid based hydrological model, CELTHYM, capable of estimating base flow and surface runoff with readily available data sets was applied to assess the hydrological impacts caused by land use changes due to urbanization. This study was conducted on a mid-west watershed, and the model was calibrated and evaluated using observed stream flow data. Qualitative and quantitative analysis on changes in surface runoff and base flow components was done to evaluate the effects of land use change on hydrology and the environment, and the summary and conclusions are as follows.

The Little Eagle Creek (LEC) watershed located near Indianapolis was studied, and the watershed area is 27.54 square miles in size and after 1990's more than 66% of area of watershed is dominated by urbanized land use type. To conduct this study, three remote sensed land use data over two decades, SSURGO soil data, weather and observed stream flow data were prepared to simulate hydrologic impacts evaluation of the watershed.

CELTHYM calibration was conducted with observed stream flow data from 1984 to 1986. The R, R^2, E and RMSE were 0.721, 0.520, 0.406, and 2.363, respectively. The values of statistical analysis between observed data and simulated results were acceptable under circumstances of simplified conceptual modeling and various sources of error.

CELTHYM was verified to check the model applicability with two kinds of observed data during 1972 through 1974 and from 1990 to 1992. The R, R2, E and RMSE during 1972–1974 were 0.652, 0.425, −0.357, and 1.988, respectively. The R, R^2, E and RMSE during 1990–1992 were 0.727, 0.529, 0.400, and 2.134, respectively. Although the model efficiency was negative in the verification for 1972–1974, the comparisons between observed and simulated runoff and ratios between runoffs were quite acceptable in quantitative and qualitative terms.

From the analysis of the ratio between direct runoff and total runoff, and change of rate of those ratios for increasing urban land use, the ratio increase of direct runoff showed proportional increases for the increase in the ratio of urban area. The results from the impact assessment of land use change for the rainfall amount showed that the ratio changes of direct runoff by land use changes were nearly the same for the annual rainfall differences, but the dry year ratio of direct runoff to total runoff was bigger than the ratio of the wet year. This result suggests that urbanization might be more harmful during dry years than abundant rainfall years in terms of water yield and water quality management.

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