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L-THIA/NPS to Assess the Impacts of Urbanization on Estimated Runoff and NPS Pollution

도시화에 따른 유출과 비점원 오염 영향을 평가하기 위한 L-THIA/NPS

Kyoung-Jae Lim* · Bernard A. Engel · Young-Sug Kim*****
Joong-Dae Choi** · and Ki-Sung Kim*******

임 경 재 · 버나드 엥겔 · 김 영 석 · 최 중 대 · 김 기 성

Abstract

The land use changes from non-urban areas to urban areas lead to the increased impervious areas, consequently increased direct runoff and higher peak runoff. Urban areas have also been recognized as significant sources of Nonpoint Source (NPS) pollution, while agricultural activities have been known as the primary sources of NPS pollution. Many features of the L-THIA/NPS GIS, L-THIA/NPS WWW system have been enhanced to provide easy-to-use system. The L-THIA model was applied to the Little Eagle Creek (LEC) watershed in Indiana to evaluate the accuracy of the model. The L-THIA/NPS GIS estimated yearly direct runoff values match the direct runoff separated from U.S. Geological Survey stream flow data reasonably. The R^2 and Nash-Sutcliffe values are 0.67 and 0.60, respectively. The L-THIA estimated runoff volume and total nitrogen loading for each land use classification in the LEC watershed were computed. The estimated runoff volume and total nitrogen loading in the LEC watershed increased by 180% and 270% for the 20 years. Urbanized areas - "Commercial", "High Density Residential", and "Low Density Residential" - of the LEC watershed made up around 68% of the 1991 total land areas, however contributed more than 92% of average annual runoff and 86% of total nitrogen loading. Therefore, it is essential to consider the impacts of land use change on hydrology and water quality in land use planning of urbanizing watershed.

Keywords : Land use planning, Urbanization, Hydrologic modeling, L-THIA, Geographic information system

* Post Doc. Research Assistant, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907-1146, USA
** Professor, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907-1146, USA
*** Research Fellow, Korea Institute of Construction Technology (KICT), Koyang, Kyounggi-do.
**** Associate Professor, Division of Agricultural Engineering, Kangwon National University
***** Associate Professor, Division of Agricultural Engineering, Kangwon National University
* Corresponding author. Tel.: +82-33-250-6460
fax: +82-33-251-1518
E-mail address: kjlim@ecn.purdue.edu

I. Introduction

For decision makers, such as land use planners and other environmental professionals, it is important to assess the impacts of land use changes on environmental problems – especially on surface runoff and water quality. Hydrology should not be considered separately when assessing environmental effects of urban sprawl, but should be part of the overall analysis of the effects of land use change. Neglecting hydrology associated with land use change may result in flooding, stream degradation, erosion, and loss of groundwater supply (Burke et al., 1988). Land use changes to urban areas usually increase impervious areas and alter spatial and temporal patterns of surface runoff (Bhaduri, 1998). Though it is often believed agricultural areas are the primary source of Nonpoint Source (NPS) pollution, the urban areas have also been identified as critical sources of NPS pollution (Hughes, 1999). It is essential to understand how hydrologic impacts of land use changes affect the surface/subsurface water, since urban/non-urban areas primarily depend on these as a drinking water source (Bhaduri, 1998).

Thus, a model has been needed to estimate the effects of land use changes on hydrology and water quality. The Long-Term Hydrologic Impact Assessment (L-THIA) model was developed for such needs (Harbor, 1994). The L-THIA model estimates the direct runoff based on the Curve Number (CN) method (USDA, 1985) after adjusting the CN values depending on 5-day Antecedent Moisture Condition (AMC). Long-term daily precipitation data is used to determine 5-day AMC during the growing and dormant season within the L-THIA model (Harbor, 1994). A NPS pollution assessment module for urban areas, not for non-urban, was incorporated into L-THIA, and it was integrated with Geographic Information System (GIS) for spatial data analysis, and the vector data format was used in this version of the L-THIA/NPS GIS (Bhaduri, 1998). Many ArcView Avenue scripts were written to use the raster format for all analysis because many of spatial data, such as land cover obtained from the remote sensing classification processing and land use map reclassified based on it, are already in raster format, and computations using the raster format are faster than those using the vector format in the L-THIA/NPS GIS. Thus, the prototype raster based L-THIA/NPS GIS was developed (Lim et al., 1999). Eight land use classifications – Water, Commercial, Agricultural, High Density (HD) Residential, Low Density (LD) Residential, Grass/Pasture, Forest, and Industrial – are considered in the L-THIA/NPS GIS. Since the vector-based L-THIA/NPS GIS didn't predict NPS loadings for the non-urban areas because it calculated the NPS loadings based on dust/dirt builds-up and wash-off in urban areas (Bhaduri, 1998). Thus, the Event Mean Concentration (EMC) data (Baird and Jennings, 1996) were used to predict NPS pollutants for non-urban areas as well as urban areas within the L-THIA/NPS GIS (Lim et al., 1999).

Two prototype versions of L-THIA/NPS WWW system were also developed (Lim et al., 1999). One is a spreadsheet-like version and the other is a Web GIS version. The spreadsheet-like version provides a quick and simple-to-use interface for the L-THIA/NPS model through the Internet. However, this version didn't allow model users to specify the spatial location of interest. Thus, Web GIS version of the L-THIA/NPS was developed using ArcView, Avenue, Java, JavaScript, ArcView Internet Map Server, and Netscape Web Server (Lim et al., 1999). The model users can digitize the area of interest within the web browser to simulate the long-term direct runoff with the Web GIS version (Lim et al., 1999).

The L-THIA/NPS model has been applied to the many watershed to simulate the effects of urbanization without considering the impacts of temporal changes of rainfall and soil infiltration rates (Harbor et al., 2000; Kim et al., 2002). Only land use changes have been considered in these study. These are not good assumptions if there are significant changes in rainfall over the entire simulation period, and also the hydrologic soil group data, one of the input to estimate the direct runoff using Curve Number (CN) method, are obtained based on measurements of native, undisturbed soil samples (Gregory et al., 1999). The use of the original hydrologic soil group data for urbanized areas is often a poor assumption because earthwork operations result in significant compacted soil (Gregory et al., 1999).

Although the prototype versions of the L-THIA/NPS GIS, and the L-THIA/NPS WWW provide easy-to-use interface to the users, there have been needs to improve many features of the system. Also, the L-THIA/NPS model has not been applied considering the temporal changes of rainfall, hydrologic soil group, and land use together.

Thus, the objectives of this study were:

1) To enhance the L-THIA/NPS GIS and L-THIA/NPS WWW system, and
2) To evaluate the accuracy of the L-THIA/NPS model and assess the impacts of land use changes on hydrology and water quality.

Ⅱ. Enhancement of the L-THIA

1. Enhancement of the L-THIA/NPS GIS

The L-THIA/NPS GIS was developed based on the philosophy that the input data should be readily available and it should be an easy-to-operate software. Although the prototype version of the L-THIA/NPS GIS (Lim et al., 1999) automates all procedures to generate runoff and NPS pollutant map using the land use and hydrologic soil group maps with many Avenue programings, there have been many complaints among the L-THIA/NPS GIS users because it did not detect the possible errors in land use and hydrologic soil group maps, resulting in illegal combinations of land uses and hydrologic soil group. To prevent this, new error checking modules were written and were incorporated into the L-THIA/NPS GIS. Thus, the L-THIA/NPS GIS now first checks whether land use and hydrologic soil group maps have the legal classifications (L-THIA/NPS GIS, 2003). The old version of the L-THIA/NPS GIS couldn't simulate the direct runoff from a single storm event. Thus, the ArcView Curve Number method (Engel, 1997) was slightly modified to be fit into the L-THIA/NPS GIS and incorporated into the new version. Thus, the L-THIA/NPS GIS can be used to simulate the direct runoff for a single storm event. The old version of the L-THIA/NPS GIS is provided in ArcView project file, rather than ArcView extension format. Thus, the ArcView extension version of the L-THIA/NPS GIS is built in this study. It is now available in the ArcView GIS extension format, thus the users can download the extension from the Internet (L-THIA/NPS GIS, 2003) and plug it into the ArcView GIS easily without any additional efforts to install/setup the L-THIA/NPS GIS.

Fig. 1 shows the overview of new version of the L-THIA/NPS GIS. The L-THIA/NPS model reads the long-term daily rainfall data and determines AMC to adjust the CN value for every day during the entire simulation periods. The L-THIA/NPS GIS interface generates input parameter file to the L-THIA model. The L-THIA/NPS model then calculates the average annual runoff depth for each unique CN value, provided from the L-THIA/NPS GIS interface. The GIS interface also generates the CN map

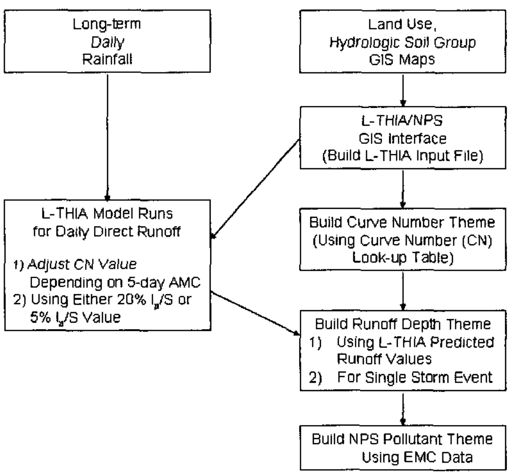

Fig. 1 Overview of the L-THIA/NPS GIS

after running error-checking module to detect the possible illegal land use and hydrologic soil group classification. The runoff depth map and NPS pollutant map are generated automatically within the L-THIA/NPS GIS. This L-THIA/NPS GIS is available in the form of ArcView GIS extension. More details can be found at L-THIA/NPS GIS manual. The L- THIA/NPS GIS ArcView extension and users manuals are available at http://www.ecn.purdue. edu /runoff/lthia/gis/lthia_gis.htm.

2. Enhancement of the L-THIA/NPS WWW SYSTEM

Eight land use classifications were considered in the prototype version of the L-THIA/NPS WWW (Lim et al., 1999). Sometimes, land use planners may have to use detailed land use classification, rather than eight land use classifications. To allow model users to simulate more detailed land use classification, "Land Use Planner" version was developed in this study. Fig. 2 shows the new L-THIA/NPS WWW interface. The users can choose either "Beginner" or "Land Use Planner" version in the main input page depending on the complexity of land use data. (Fig. 2).

The long-term daily rainfall data for the entire U.S are stored in the L-THIA/NPS weather database. However, it was not possible to simulate the direct runoff for a specific period of time. The L-THIA/NPS WWW users may want to use more recent rainfall data rather than the ones in the database. Although the L-THIA/NPS WWW can be accessible outside of the U.S through the Internet, rainfall data for only U.S is available to users. To overcome these limitations,

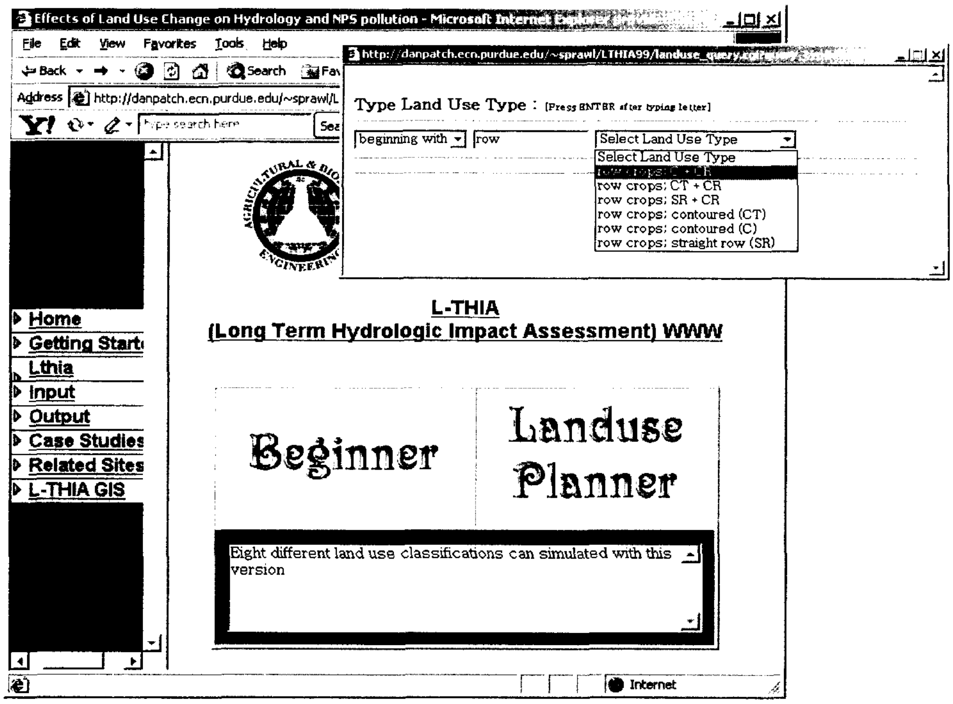

Fig. 2 The L-THIA/NPS WWW system

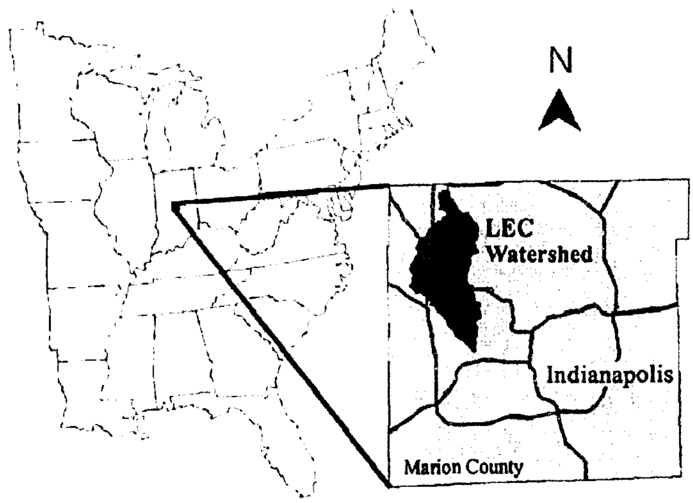

Fig. 3 Location of the Little Eagle Creek (LEC) watershed

"file uploading" function was developed and was incorporated into the L-THIA/NPS WWW interface. With this new approach, the users can easily upload the local rainfall data to the L-THIA/NPS WWW server and run the L-THIA/NPS model to assess the impacts of

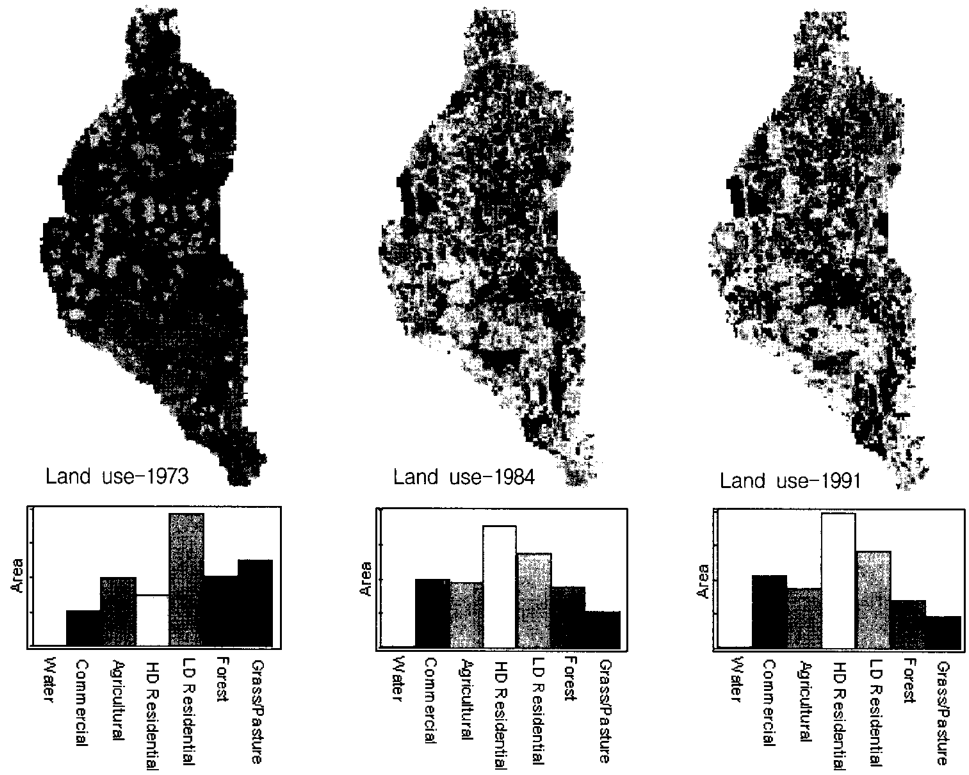

Fig. 4 1973, 1984 and 1991 land use data for the LEC watershed

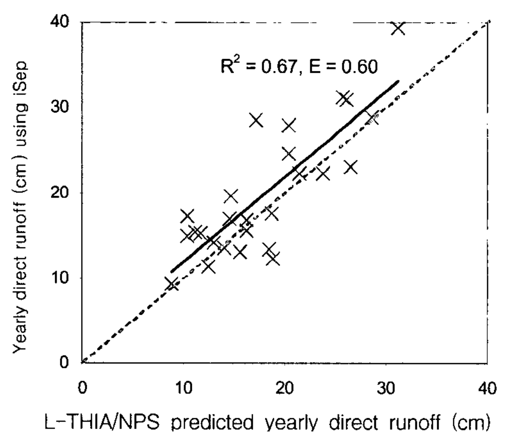

Fig. 5. Relationship between L-THIA/NPS predicted yearly direct runoff and direct runoff separated from USGS stream flow data for the LEC watershed

land use changes on their local areas with the web browser.

Ⅲ. Application of L-THIA/NPS GIS

The Little Eagle Creek (LEC) watershed is located in the central Indiana, 70.5 km^2 in size (Fig. 3). It has experienced significant urbanization (18% increase in urban area) over the last 20 years, with majority changes between 1973 and 1984 (14% increase in urban area) (Bhaduri et al., 2000). Land uses ranging from non-urban natural grass and forested areas and agricultural areas to typical urban residential and commercial categories exist in the LEC watershed. Fig. 4 shows the land use changes for the LEC watershed. There have been land use

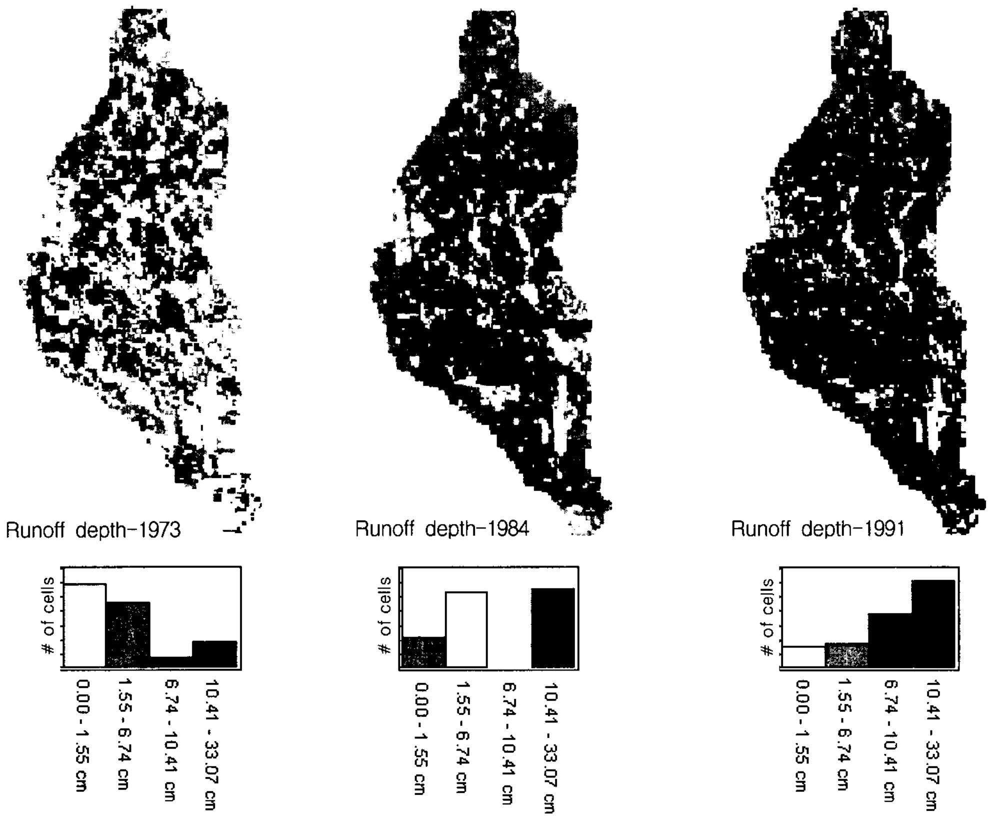

Fig. 6 L-THIA GIS estimated annual average direct runoff depth map for LEC watershed

conversions from non-urban to urban areas, urbanization in this watershed. The areas of "Forest" and "Grass/Pasture" have decreased, while areas of "Commercial", "HD Residential" have increased dramatically (over 200%) in the watershed. The area of "Agricultural" has decreased slightly over years. Urbanized land area in the LEC watershed made up around 50% of the total land area in 1973, while around 68% of urbanized area of the total land area in 1991.

As stated before, the L-THIA/NPS model was applied to the LEC watershed without considering the temporal changes of rainfall and infiltration rate due to earthwork over the entire simulation period (Harbor et al., 2000; Pandey et al., 2000; Kim et al., 2002). The average annual direct runoff value for the entire simulation period was used for each land use data, thus the simulated direct runoff value for the same CN value of historic data is the same in these studies. The estimated direct runoff for a given CN varies depending on the magnitude of the rainfall event. Thus, the long-term daily rainfall data was split into 3 segments based on the LEC land use data. To consider the impacts of urbanization on hydrologic soil group, or infiltration rate, the hydrologic soil group 'D' was used for all urbanized areas as recommended by Ocean County Soil Conservation District (2001). The L-THIA/NPS predicted yearly runoff values

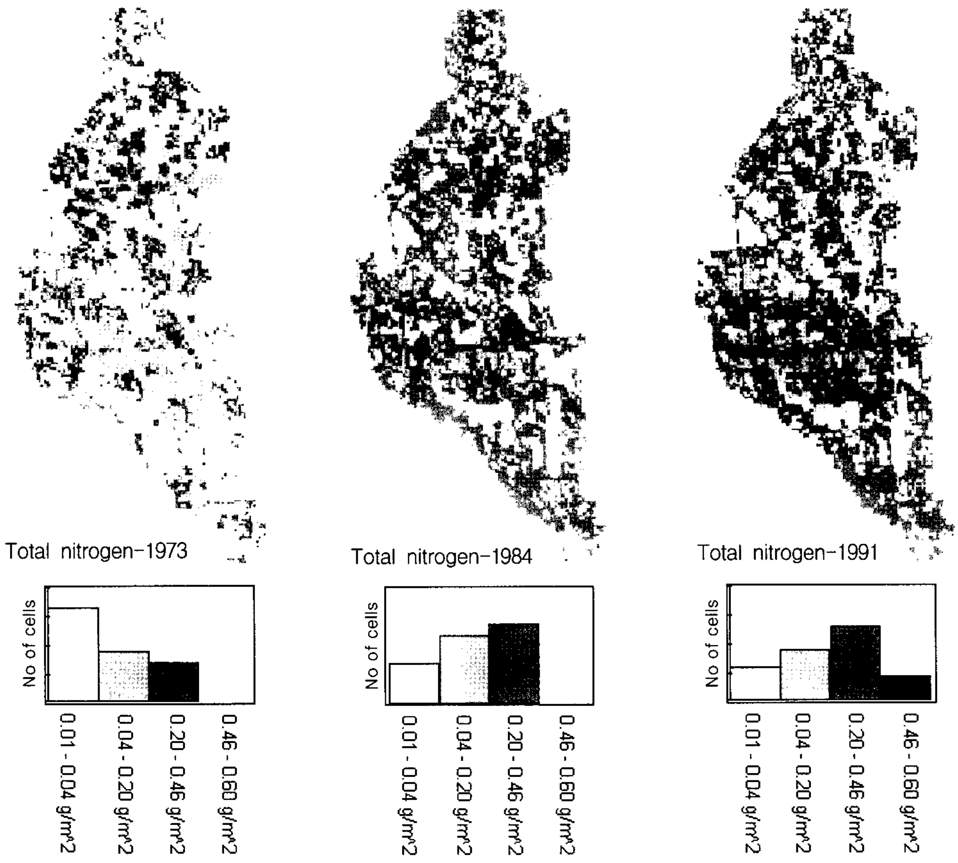

Fig. 7 L-THIA/NPS GIS estimated total nitrogen loading for the LEC watershed

(Lim and Engel, 1999) and average annual runoff values for 11 years, 9 years, and 7 years were used in model evaluation and in urbanization assessment.

To evaluate the accuracy of model, the direct runoff component from the U.S. Geological Survey (USGS) stream flow data was separated using the iSep Web GIS system (iSep Web GIS, http://danpatch.ecn.purdue.edu/~kjlim/iSep) and it was compared with the L-THIA/NPS model predicted yearly direct runoff values. Fig. 5 shows the relationship between the L-THIA/NPS predicted direct runoff and the direct runoff separated from daily stream flow data for the LEC watershed. The coefficient of determinant (R^2) and the coefficient of efficiency (E), called Nash Sutcliffe coefficient (Nash and Sutcliffe, 1970), were calculated to measure the fit between the measured and the L-THIA/NPS predicted direct runoff. The computation of E essentially is the sum of the deviations of the observations from a linear regression line with a slope of 1. If the measured value is the same as all predictions, E is 1. If the E is between 0 and 1, it indicates deviations between measured and predicted values. If E is negative, predictions are very poor, and the average value of output is a better estimate than the model prediction

(Nash and Sutcliffe, 1970). The R^2 and E values are 0.67 and 0.60, respectively, indicating the L−THIA/ NPS predicted values match the direct runoff separated from stream flow data reasonably.

To assess the impacts of land use changes on hydrology and water quality, the L−THIA/NPS estimated direct runoff maps for 1973, 1984, and 1991 LEC land uses are created with 11−year, 9−year, and 7−year average annual runoff depth using the L−THIA/NPS GIS as shown in Fig. 6. These maps show the spatio−temporal variations in estimated direct runoff. The estimated average runoff depth values for 1973, 1984, and 1991 LEC land uses are 6.0 cm, 11.1 cm, and 17.0 cm, respectively. The land use classifications of the dark red areas in Fig. 5 is either "High Density Residential" or "Commercial".

The runoff volume for 1973, 1984, and 1991 LEC land uses are 4.26 10^6 m^3, 7.80 10^6 m^3, and 12.00 10^6 m^3, respectively. The estimated runoff volume increased by 180% for 20 years in the LEC watershed due to urbanization. Urbanized areas − "Commercial", "HD Residential", and "LD Residential" − of the 1991 LEC land use made up around 68% of the total land areas, however contributed more than 92% of estimated average annual runoff in 1991.

The area of "HD Residential" has increased over 260% over 20 years. However the esti− mated runoff volume has increased over 525% for the same period. This is because of increased area and soil compaction occurred during the urbanization. The estimated runoff volume for "LD Residential" area increases slightly, although the area of "LD Residential" has decreased over the years. This is because of the impacts of urbanization on infiltration rate. Hydrologic soil group 'D' is used for all urbanized areas irres− pective of the hydrologic soil group data from soil survey in this study. The estimated runoff volume for "Agricultural" decreases for 1984 land use, and then increases slightly for 1991 data although the area for "Agricultural" has decreased slightly over the years. This is be− cause of increased rainfall amounts for Oct. 1988 to Sept. 1995 period in model runs. The average annual rainfall for Oct. 1998 to Sept. 1995 is 108.8 cm while average annual rainfall for Oct. 1979 to Sept. 1978 is 102.1 cm.

To assess the impacts of urbanization on NPS loadings, the L−THIA/NPS estimated total nitrogen (TN) maps for 1973, 1984, and 1991 LEC land uses were created. As shown in Fig. 7, there have been dramatic increases in estimated TN loadings in the LEC watershed. The TN maps were generated based on the different EMC data for each land use within the L−THIA/NPS GIS. The L−THIA/NPS estimated TN loadings for 1973, 1984, and 1991 LEC watershed are 5,730 kg, 13,525 kg, and 21,225 kg, respectively. There is 270% increase in TN loadings over 20 years in the LEC watershed.

The estimated runoff volume of "Agricultural" and "Commercial" for 1973 land use are 0.59 $10^6 m^3$ and 1.35 $10^6 m^3$. However, the TN loadings of these land uses for the 1973 LEC land use are 1,681 kg and 1,423 kg. These is because of higher TN EMC data for "Agricultural" used in the L−THIA/NPS GIS. Urbanized areas − "Com− mercial", "HD Residential", and "LD Residential" − of the LEC watershed made up around 68% of the total land areas, however contributed more than 86% of TN loadings for 1991.

V. Summary and conclusions

Instead of eight land use classification considered in the old version of the L-THIA/NPS WWW, "Land Use Planner" version was developed to allow users to simulate more detailed land uses, rather than eight representative land uses. The L-THIA/ NPS GIS was applied to the LEC watershed in Indiana and the estimated yearly direct runoff values for the LEC watershed match well the direct runoff separated from the stream flow. The R^2 and Nash-Sutcliffe values are 0.67 and 0.60, respectively.

The L-THIA/NPS GIS estimated runoff volume and total nitrogen loadings for each land use classification were computed for 1973, 1984, and 1991 LEC land use data. The estimated runoff volume and estimated total nitrogen loadings increased by 180% and 270% for 20 years in the LEC watershed due to urbanization Urbanized areas - "Commercial", "HD Residential", and "LD Residential" - of the LEC watershed made up around 68% of the total land areas, however contributed more than 92% of average annual runoff and 86% of total nitrogen loading for 1991. This shows that urban areas are also critical sources of NPS loadings because of higher runoff potential for these areas. It was found that land use conversion from non-urban to urban areas have dramatic impacts on increased NPS loading as well as increased runoff volume. Thus, long-term impacts of land use changes should be considered in sustainable land use planning.

As shown in this study, the L-THIA/NPS GIS is an ideal tool to assess the impacts of land use changes on hydrology and water quality. This easy-to-use system can be used to identify the areas vulnerable to NPS pollution by decision makers without any special training to utilize this system. The L-THIA model can be run many times to find the most environment-friendly land use plans since all functionalities are fully integrated with GIS system.

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