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Abstract

Urban land use and land cover change significantly affect spatial and temporal patterns of runoff, which in turn impacts surface water quality. With the exponential growth in urban areas over the past three decades, changes in land use and land cover to cater for the growth of cities has been a conspicuous spectacle in urban spaces. The main goal of this study was to assess the impacts of land cover change on runoff and surface water quality using a partial area hydrology framework. The study employed ArcHydro GIS extension and a modified version of Long-Term Hydrologic and Nonpoint Source Pollution model (L-THIA-NPS) in estimating runoff and nonpoint source pollutant concentration around Lake Calumet between 1992 and 2001. Data employed include National Land Cover Data set, rainfall data, digital elevation model (DEM), Soil Survey Geographic (SSURGO) data, and The United States Environmental Protection Agency's STORET (storage and retrieval) water quality data. The model was able to predict surface water quality reasonably well over the study period. Sensitivity analysis facilitated a manual calibration of the model. Model validation was executed by comparing simulated results following calibration and observed water quality data for the study area. The study demonstrates that the level of concentration of nonpoint source pollutants in surface water within an urban watershed heavily depends on the spatiotemporal variations in areas that contribute towards runoff compared to the spatial extent of change in major land use/land cover.

Keywords (separated by '-') Surface water quality - Urban land cover change - Partial area hydrology - Lake Calumet - Chicago

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Assessing Surface Water Quality and Its Relation with Urban Land Cover Changes in the Lake Calumet Area, Greater Chicago

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Abstract Urban land use and land cover change significantly affect spatial and temporal patterns of runoff, which in turn impacts surface water quality. With the exponential growth in urban areas over the past three decades, changes in land use and land cover to cater for the growth of cities has been a conspicuous spectacle in urban spaces. The main goal of this study was to assess the impacts of land cover change on runoff and surface water quality using a partial area hydrology framework. The study employed ArcHydro GIS extension and a modified version of Long-Term Hydrologic and Nonpoint Source Pollution model (L-THIA-NPS) in estimating runoff and nonpoint source pollutant concentration around Lake Calumet between 1992 and 2001. Data employed include National Land Cover Data set, rainfall data, digital elevation model (DEM), Soil Survey Geographic (SSURGO) data, and The United States Environmental Protection Agency's STORET (storage and retrieval) water quality data. The model was able to predict surface water quality reasonably well over the study period. Sensitivity analysis facilitated a manual calibration of the model. Model validation was executed by comparing simulated results following calibration and observed water quality data for the study area. The study demonstrates that the level of concentration of nonpoint source pollutants in surface water within an urban watershed heavily depends on the spatio-temporal variations in areas that contribute towards runoff compared to the spatial extent of change in major land use/land cover.

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Keywords Surface water quality · Urban land cover change · Partial area hydrology · Lake Calumet · Chicago

Introduction

Population growth and its associated housing and infrastructural development in cities influence changes in land use and land cover (LULC). This in turn affects the characteristics of runoff, nonpoint source pollution production, transportation and eventually water quality. As cities expand, bare ground, scrub and forest cover within and around urban areas are transformed to impervious surfaces like roads, parking lots, roof tops, sidewalks and other impermeable surfaces (Carter 1961; Leopold 1968). Increase in impervious surfaces in turn results to an increase in runoff and additional avenue for the transportation of nonpoint source pollutants with consequences for water quality (Arnold and others 1982; Bhaduri and others 1997; Klein 1979; Ren and others 2003; Weng 2001a).

Assessing surface water quality resulting from LULC change is a critical challenge to environmental scientists (Engel and others 2007; Van De Griend and Engman 1985). Moreover, capturing the effect of LULC change on surface water quality is extremely important as the latter determines the health and successful existence of plant, animal and human life. LULC change has been extensively studied within the domain of population growth, climate change, runoff and socioeconomic conditions (Beighley and others 2008; Lambin and others 2001; Meyer and Turner 1992; Weng 2001b). In comparison, the relationship between land use and water quality has not been extensively studied. Hydrologists and water quality specialists have made efforts in identifying and estimating point and nonpoint source pollutants entering water bodies from land surfaces (Engel and others 1993; Goonetilleke and others 2005; Mattikalli and Richards 1996).

Most studies exploring the relationship between LULC and water quality examine huge areas spanning urban and rural landscapes. A large fraction of these studies have been concentrated in rural areas (Basnyat and others 2000; Bhaduri and others 1997; Coats and others 2008; Engel and others 1993; Gan and others 2008). These studies mostly concentrate on agricultural, forest and grass land cover in estimating the effects of LULC change on runoff and water quality (McConnel and Keys 2005; Osborne and Wiley 1998). Few studies have examined this phenomenon at the urban–rural fringe (Choi and others 2003; Wear and others 1998). While some researchers have examined the relationship between LULC change and water quality along streams (Tong and Chen 2002); very few studies have attempted an examination of the relationship between LULC change and surface water quality within urban areas (Delleur 2001; Im and others 2003).

Previous studies conducted within urban areas have demonstrated that certain types of human activities on land generate particular types of pollutants (Bolstad and Swank 1997; Carpenter and others 1998; Gan and others 2008). Other researches have singled out one land use and assess its effect on surface water quality (Crabtree and others 2008; Gan and others 2008; Thompson and others 1997). Highways have been found to produce more soluble pollutants than insoluble ones in the short-term and high amounts of insoluble pollutants in the long run (Crabtree and others 2008). Other studies have explored a couple of nonpoint source pollutants and establish their relationship to land use and watershed characteristics (Coats and others 2008).

Some scholars have probed into the pattern of LULC change and its effects on water quality. He (2003) concluded that the extent of land use change and its proximity to water bodies determine the magnitude of water quality impairment that will occur. The more connected impervious surfaces are close to a water body, the greater will be the effect on water quality than impervious surfaces that are fragmented (Wang and others 2001). These studies also concluded that the closer an urban development is to aquatic environment, the greater the extent of water quality impairment that will be exerted on water bodies. Some researchers have revealed that runoff volume, peak rates and sediment load in runoff increases as urban areas expand (Harbor 1994; Osborne and Wiley 1998).

Literature review indicates that previous studies mostly explored the relationship between water quality and one component of land cover change. Land cover change has two broad dimensions; land cover conversion and land cover modification (Jenerette and Wu 2001; Lambin and others 2001; Lambin and Geist 2006). Land cover conversion is the replacement of one land cover type with another, for example, the shift from agricultural to residential or a change from open space to transportation. Land cover modification on the other hand reflect certain changes that affect the character of the land cover without a complete change in the land cover itself (Lambin and Geist 2006). When this occurs, land fragmentation develops which in turn changes the structural complexity of the landscape (Jenerette and Wu 2001; Lopez and others 2001). The latter is mostly evident in urban landscapes where development of land parcel takes place more frequently compared to land cover outside cities. Land cover modification which is the main type of land change process evident in urban areas is either ignored or proved difficult to incorporate into modeling efforts. Furthermore, out of the few studies that attempt incorporating the effects of land cover modification on surface water quality, most are centered on Hortonian uniform overland flow paradigm which assumes that all areas within a watershed contribute towards runoff (Horton 1933). An area that contributes towards runoff in a watershed varies with time, the level of precipitation and other meteorological characteristics (Betson 1964; Van De Griend and Engman 1985). Few studies exploring runoff have integrated contributing and noncontributing areas in modeling surface water flow from land surface (Boughton 1990; Lyon and others 2004; Steenhuis and others 1995). This was actualized with painstaking fieldwork in demarcating active and non-active area's contributions to surface runoff. The use of geospatial technology can facilitate a more accurate delineation of contributing areas to surface runoff which in turn can improve model prediction of surface water quality.

Among studies that have predicted the types of nonpoint source pollutants generated by various land uses, they mostly utilize existing water quality simulation models which are often structured and only allow modest modification to the model. Moreover, land use classes and nonpoint source pollutants predicted rarely exceed five or six. Furthermore, almost all of these studies examine a one time step or a couple of years in predicting water quality resulting from LULC change. As a result, the impacts of LULC change over a more extensive time within a partial area hydrology framework and land modification scenario is partially understood. This study explores the ramifications of LULC change within a partial area hydrology and land cover modification framework over a period of nine years. The main goal of this research is to unearth the extent of water quality effects that will result from LULC change taking into consideration areas that contributes towards runoff in an urban watershed, land cover modification and a relatively long time period.

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Study Area

This study was conducted in the Lake Calumet watershed, Greater Chicago Area. The size of the study area is 54,518 acres (85.2 square miles). Lake Calumet is located 15 miles south of downtown Chicago (Fig. 1). This lake was formed more than 13,500 years ago as a result of retreating glaciers (Ross and others 1989). As early as 1869, the area was promoted as a suitable site for the establishment of manufacturing industries. A number of factors accounted for the area's suitability for industries; these include easy accessibility to Lake Michigan for shipping of raw materials and finished produce, water used by industries within Calumet for manufacturing, and Chicago's railroad hub that facilitates inland transportation of industrial materials and finished product. From this period onwards, a number of industries developed in Calumet reducing the lake's surface area to coastal docks and eventually landfill.

Over this long period of heavy industrial activities around Lake Calumet, a number of industrial contaminants entered the lake. With the establishment of stringent environmental legislation over the past decade, there has been some improvement in the level of pollutants entering the lake from industrial activities. Notwithstanding, a number of anthropogenic metals and polynuclear aromatic hydrocarbons are higher in the waters of lake Calumet than water samples from other water bodies in the area (Illinois Department of Natural Resources 2002). Similarly, the lake has higher concentrations of metals when compared to other lakes in Illinois (Ross and others 1989).

Water pollution in Lake Calumet does not only stem from industrial land use but also from other urban land uses in the region. For instance, metal contamination of sediments have been found in association with municipal waste water operations, coal-fired power plants, landfill leachate, urban runoff, highway runoff, mining and metal-working operations, airborne particulates, and industrial wastewaters (Ross and others 1989).

Data

Two National Land Cover Datasets for the study area was used. These include 1992 and 2001 classified Landsat Thematic Mapper (TM) 30 meter resolution images. Precipitation data was obtained from Illinois State Climatologist Office. Precipitation data originated from Chicago's Midway International Airport which lies approximately three miles west of the study area. Illinois State Climatologist Office converts precipitation data from hourly to daily rain and snowfall. Soil data was solicited from the United States Department of Agriculture Natural Resource Conservation Services (NRCS) in the form of Soil Survey Geographic (SSURGO) shapefile. Ten meter Digital Elevation Model (DEM) was downloaded from the United States Geological Survey DEM data base, while population of study area was obtained from the United States Census Bureau. The United States Environmental Protection Agency's STORET (storage and retrieval) historical and modernized water quality data sets for 1992 and 2001 were used in model calibration and validation of simulated results.

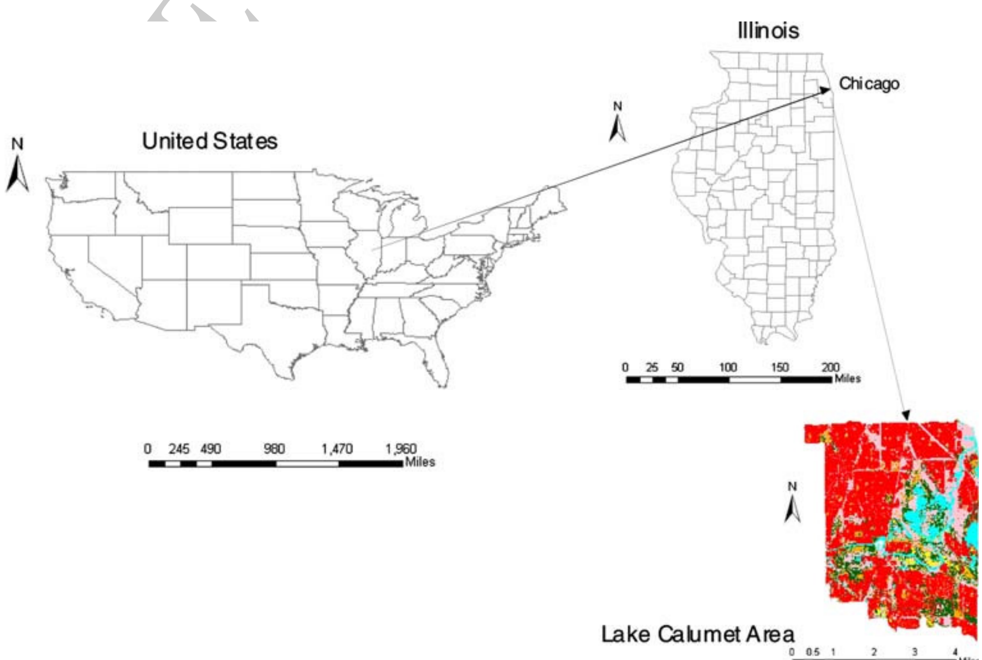

Fig. 1 Lake Calumet Area, South Chicago, Illinois, USA. *Source*: U.S. Census Bureau TIGER/Line Shapefiles and National Land Cover Database

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Methods

National Land Cover Datasets (NLCD) for the two dates of images was adjusted by recoding and combining some classes in each date of image to produce similar classes for both images. This procedure was undertaken because of the different classification scheme used for the 1992 and 2001 images. Recoding was also done to produce LULC classes that can be accommodated by the modified L-THIA-NPS model. The original images for the study area contained 14 and 12 classes respectively for 1992 and 2001 data. These classes were compressed into ten comparable classes (Table 1). For example, low intensity residential and high intensity residential land use in the 1992 NLCD was recoded into a level one classification of residential land cover (Anderson and others 1976). Although a formal accuracy assessment of the 1992 and 2001 National Land Cover Data set is still in progress, preliminary cross validation of classification using regression and decision trees reveals an average classification accuracy of 83.9% with accuracies ranging between 70 and 98% (Homer and others 2004, 2007).

In the 2001 NLCD, developed low and middle intensity were combined into residential, while developed high intensity represented commercial, industrial and transportation. The various land classes were compared with Chicago Metropolitan Area Planning land cover map for verification (Chicago Metropolitan Agency for Planning 2008). The study area was then delineated (subsetted) by Area of Interest method in Erdas Imagine 9.1 using United States Census Bureau's census tracts as guide. Figure 2 illustrate land uses around Lake Calumet in 1992 and 2001. The data sets were reprojected to Universal Traverse Mercator (UTM) coordinates preceding integration into the modified L-THIA-NPS model.

L-THIA-NPS model use the former Soil Conservation Services (SCS) curve number approach in estimating runoff depth and volume (Soil Conservation Services 1972). Runoff depth is predicted by the equation

$$Q_{\mathrm{d}} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (1)$$

where Q_{d} = runoff depth; P = daily rainfall; S = potential infiltration which is determined by the equation

$$S = \frac{1000}{CN} - 10 \quad (2)$$

where CN = curve number.

Runoff volume is calculated by the equation

$$Q_{\mathrm{v}} = Q_{\mathrm{d}} * A \quad (3)$$

where Q_{v} = runoff volume; Q_{d} = runoff depth and; A = land area over which water flows.

In modifying the L-THIA-NPS model, avenue script codes in several files of the program were edited to customize and increase the model's default land use classes from 8 to 10, and also to assign pre-calibration curve numbers for land use and hydrologic soil group combination to reflect those used in the study. Two additional land cover classes (barren land and woody vegetation) were included because they are present in the study area and the default model framework does not account for them. Their inclusion was essential to capture the entire nonpoint source pollutants generated by the land uses within the study area. Figure 3 demonstrate how the model estimates nonpoint source pollution concentration.

Long term rainfall data in the model program file was removed and replaced with those for the study years. Precipitation data was converted from average daily to annual

Table 1 Recoding of national land cover data set

NLCD set 1992 (land use)	NLCD set 2001 (land use)	Recoded land use employed in study
Open water	Open water	Open water
Low intensity residential	Developed, low intensity	Residential
High intensity residential	Developed, medium intensity	
Commercial/industrial/transportation	Developed, high intensity	Commercial/industrial/transportation
Barren land	Barren land	Barren land
Deciduous forest	Deciduous forest	Forest
Evergreen forest		
Grassland herbaceous	Grassland herbaceous	Grassland/scrub
Pasture hay	Scrub/shrub	
Row crops	Cultivated crops	Agriculture
Small grains		
Urban recreational grasses	Developed, open space	Developed, open space
Woody vegetation	Woody vegetation	Woody vegetation
Emergent herbaceous wetlands	Emergent herbaceous wetlands	Emergent herbaceous wetland

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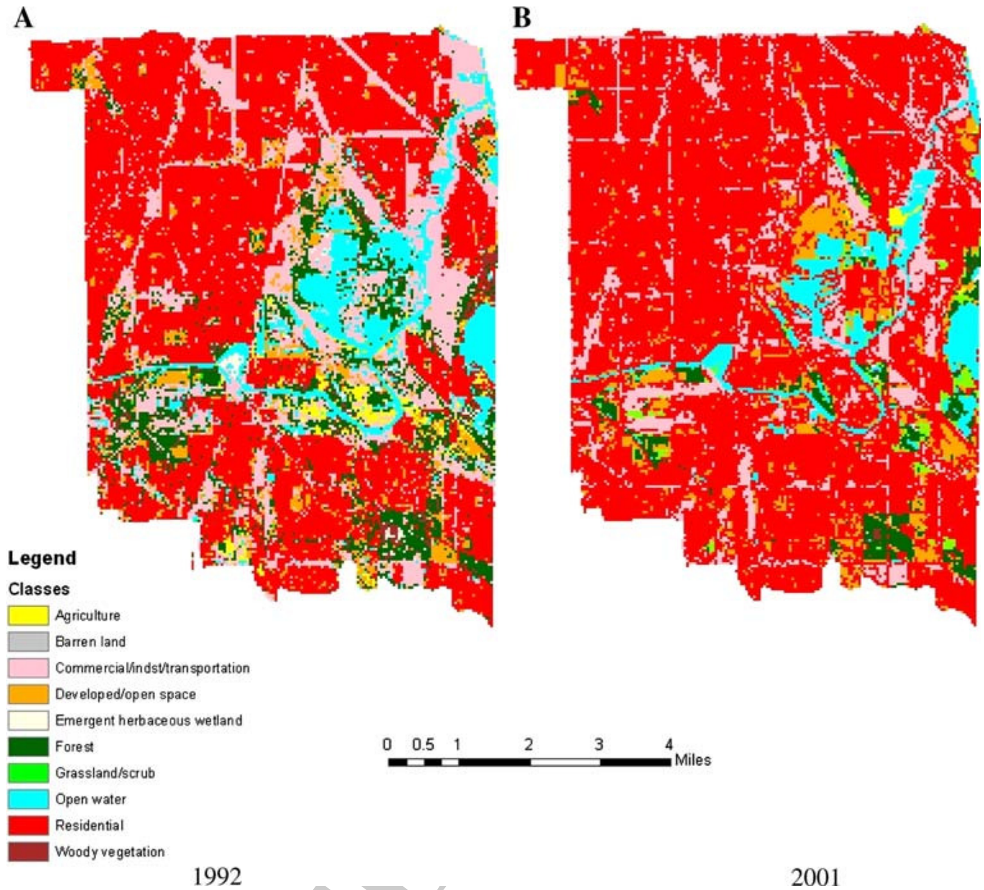

Fig. 2 Land uses around Lake Calumet: **a** 1992; **b** 2001. *Data source*: National Land Cover Database

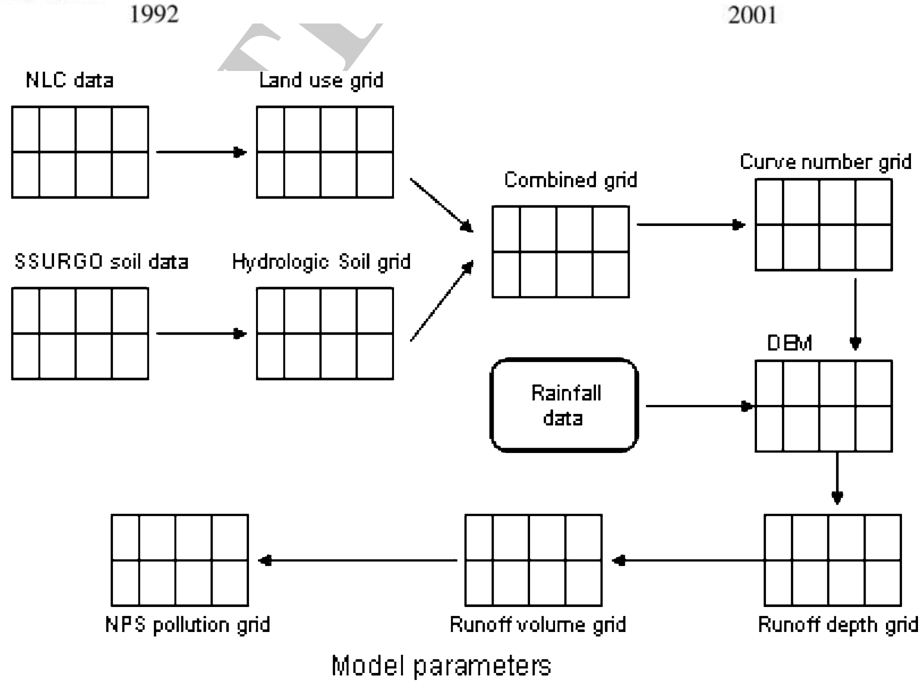

Fig. 3 Modified L-THIA-NPS Model parameters. *NLC data* National Land Cover Landsat image, *SSURGO* Soil Survey Geographic shapefile of the U.S. Department of Agriculture Natural Resource Conservation Services, *L-THIA-NPS* Long Term Hydrologic Impact Assessment and Nonpoint Source Pollution Model, *DEM* Digital Elevation Model

average rainfall. The snowfall component of the precipitation data was excluded as a result of the inability of the model to estimate the contribution of snowmelt to runoff.

Digital elevation models (DEM) covering the study area was mosaicked and delineated (subsetted) according to the study area's perimeter. ArcHydro GIS extension was used to fill sinks on the DEM, calculate flow direction of runoff, storm water routing and delineate the contributing areas (active) of Lake Calumet watershed for 1992 and 2001 respectively.

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Soil data was processed in order to be usable in ArcGIS 9.3. Processing took the form of linking the tabular portion of the data to the spatial component in order to obtain the hydrologic soil groups and other important information contained in the SSURGO data.

The United States Geological Survey Estimated Mean Concentration of nonpoint source pollutants generated by specific land uses were used as a guide in arriving at pre-calibrated estimates for the 12 nonpoint source pollutants predicted in the study. The United States Environmental Protection Agency's STORET water quality data was used in model calibration and validation of simulated results.

In order to enhance model calibration, the L-THIA-NPS model was spatially distributed into two parts within the study area. One part of the study area had the EPA STORET gauge monitoring site while the other part was ungauged. The distribution was created taking into cognizance elevation of landscape, flow direction and flow accumulation of surface water. Calibrated model parameters obtained from the gauged section was then applied to the entire study area during the final model run.

Model Sensitivity Analysis, Calibration and Validation

Sensitivity analysis was performed on the model to ascertain the parameters that experience the largest change in the model with changes in model input. Four sets of rainfall data that varies from low, medium, moderately high and high rainfall values were used to run the model in an uncalibrated framework while the sensitivity of the model parameters to changes in rainfall data was measured. L-THIA-NPS is a simple hydrologic water quality model with the following parameters: Input parameters include rainfall, land use and soil; process parameters encompass runoff depth, runoff volume, potential infiltration, curve number and estimated mean concentration coefficient. Output parameter includes nonpoint source pollutant concentration. Input and process parameters were included in sensitivity analysis using the following equation.

$$O = f(F_1, F_2, F_3, \ldots F_n) \tag{4}$$

where O is the model output; F_1 to F_n are factors that influence O.

Change in model output resulting from changes in model input and process parameters were calculated using the following relative sensitivity function:

$$R_s = \frac{\partial O/O_o}{\partial F_{1\ldots n}/F_{1\ldots n}} = \left[\frac{\partial O}{\partial F_1}\right]\frac{F_1}{O_o} + \left[\frac{\partial O}{\partial F_2}\right]\frac{F_2}{O_o} + \left[\frac{\partial O}{\partial F_n}\right]\frac{F_n}{O_o} \tag{5}$$

where R_s = relative sensitivity of model parameters; ∂O = change in output resulting from a change in model input; O_o = the value of model output (O) at some specified level of each factor (F) that influence model output; $\partial F_{1\ldots n}$ = change in model parameter resulting from change in model input.

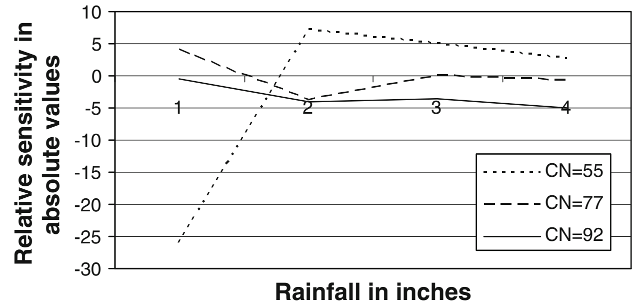

Fig. 4 Sensitivity of curve numbers to changes in rainfall input

Relative sensitivity was performed on the model parameters under different input scenarios. Rainfall was altered in each of the model run and the behavior of curve number, area of land cover, runoff depth, runoff volume, and nonpoint source pollutant concentration coefficient measured. The analysis shows that curve number is the most sensitive model parameter (Fig. 4). Change in rainfall from 1.5 to 2.5 inches resulted to a dramatic shift in the response of curve number 55, while curve numbers 77 and 92 reveal minimal responses. Area of land cover and soil type shows almost no change in behavior under different rainfall scenario. Runoff depth varies directly with rainfall, while runoff volume varies with rainfall and size of land. Size of land cover was constant for each model run within a year. Coefficient for the 12 nonpoint source pollutants predicted in the model shows an almost constant relationship to changes in rainfall. The sensitivity analysis shows that curve number is the most sensitive parameter in the L-THIA-NPS model.

Model calibration was conducted manually by fitting measured data obtained from The United States Environmental Protection Agency STORET dataset to the simulated output of L-THIA-NPS model. This was done using the split-sample technique (McCuen 2003). Split-sample methodology involves dividing the water quality data into two parts. The latter was facilitated by utilizing two sets of water quality data collected within a period of one week by U.S. EPA under the same rainfall regime. One set of the water quality data was used in model calibration. Calibration was conducted iteratively by firstly using the default model coefficient values for curve numbers and estimated mean concentration that match land uses in the original model. For the customized land classes and the two additional land use categories introduced in the study, a modified curve number coefficient prescribed by SCS was used. During model calibration, 25 and 21 iterations were performed for 1992 and 2001 analysis respectively before an acceptable threshold was achieved between simulated results and observed data. Following each model run, the difference between simulated

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Table 2 Calibration and validation test of model simulation efficiency

Test	Relation	1992 Cal.	2001 Cal.	1992 Val.	2001 Val.
r^2	$r^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O}) - (P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2$	0.94	0.99	0.98	0.99
E	$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$	0.72	0.94	0.81	0.96
E_{rel}	$E_{rel} = 1 - \frac{\sum_{i=1}^{n} \left(\frac{O_i - P_i}{O_i} \right)^2}{\sum_{i=1}^{n} \left(\frac{O_i - \bar{O}}{\bar{O}} \right)^2}$	0.67	0.89	0.72	0.45

r^2 = coefficient of determination; O_i = observed data; $\bar{O}$ = average of observed data; P_i = simulated value; $\bar{P}$ = average of simulated value; E = Nash–Sutcliffe coefficient of simulation efficiency; E_{rel} = Relative efficiency of Nash–Sutcliffe coefficient of simulation; Cal = Model calibration; Val = Model validation

and observed data was measured and the direction of curve numbers, runoff volume and coefficient of nonpoint source pollutants compared to the previous time step. Curve numbers were then adjusted in a bid to narrow the difference between simulated and observed data till the acceptable threshold set preceding calibration was achieved. Test of model efficiency was done using coefficient of determination, Nash–Sutcliffe coefficient of simulation efficiency and the Nash–Sutcliffe relative efficiency coefficient (Krause and others 2005). Table 2 demonstrates the above statistics for model calibration.

Coefficient of determination was cut off at 0.8 and above, Nash–Sutcliffe at 0.6 and above, while relative efficiency cutoff point was 0.4 and above. Model iteration was terminated when the threshold set for the above statistics was achieved. In addition, the value of the simulated result was graphically compared to the observed data at the start and end time step of model run (Figs. 5, 6).

The second set of water quality data was used in validating the model. The final simulation result shows comparable estimates with the observed water quality data. The coefficient of determination, Nash–Sutcliffe coefficient of simulation efficiency and the Nash–Sutcliffe relative coefficient were all within the threshold set during model calibration (Fig. 7).

L-THIA-NPS model was employed in the study as a result of its accessibility, simplicity of use, relative ease in customizing major parameters, availability of model inputs and its easy applicability to urban areas compared to complex models.

L-THIA-NPS model combined land use and soil data to assign curve number to the output grid generated using the normal antecedent soil moisture condition 2 (Fig. 8). The curve number grid was then added to the precipitation data producing runoff depth (Fig. 9). Runoff volume was then estimated based on the runoff depth and spatial extent of each LULC. In the final stage of the model operation, nonpoint source pollution concentration loads for 12 pollutants was estimated. The model was run for 1992 and 2001 respectively.

Results

Extent of Land Use/Land Cover Change, 1992–2001

Land use and land cover change detection reveal that four land covers increased over the study period while six experience reduction in their spatial extent. Barren land increased exponentially between 1992 and 2001 (506.7%). The land cover map for 2001 shows that most of this area lies within parts of the former steel mill site around Lake Calumet (Fig. 2). Grassland/scrub increased by 57.1 percent, while residential land use increased by 37.3 percent (Table 3). A closer look at residential land use in the original NLCD image illustrate that most of the increase was low density development. Developed/open space which encompasses parks and parking lots also increased over the study period (Table 3).

Land uses that reduced in spatial extent between 1992 and 2001 include agriculture (89.1%), woody vegetation (87.8%), forest (69.9%), open water (26.2%), and the combined land used for commercial, industrial and transportation (38.3%). Using Chicago Metropolitan Agency for Planning land use map as reference data to unravel the three grouped land covers in the National Land Cover Data classification, most of this decline was observed within land used for industrial activities. Commercial land use demonstrated an increase over the study period while there was minimal changes to land used for transportation.

Changes in Water Quantity

Differences in average annual rainfall between 1992 and 2001 resulted to changes in runoff depth over the study period. Runoff depth for each land use was observed to be

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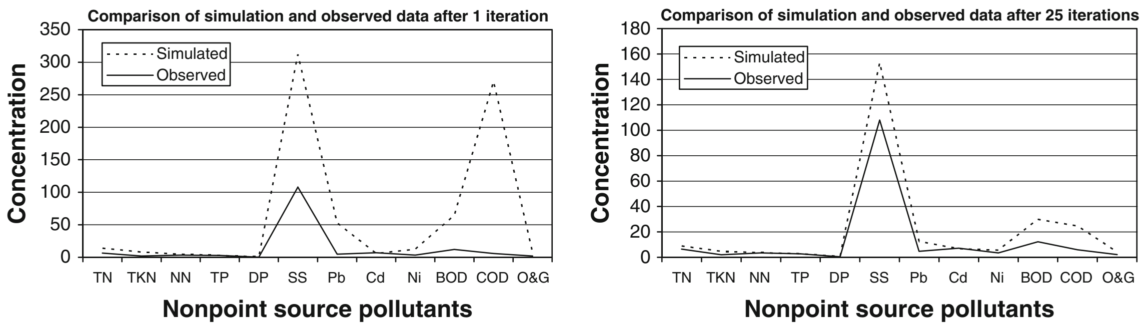

Fig. 5 Observed and predicted nonpoint source pollutants during calibration, 1992

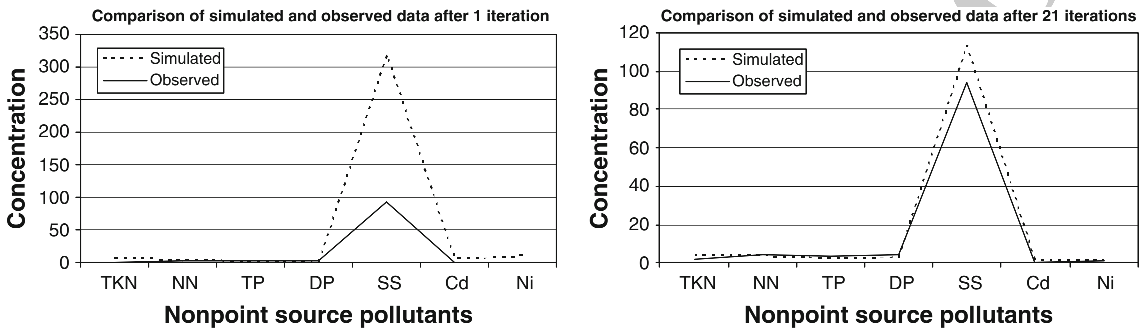

Fig. 6 Observed and predicted nonpoint source pollutants during calibration, 2001

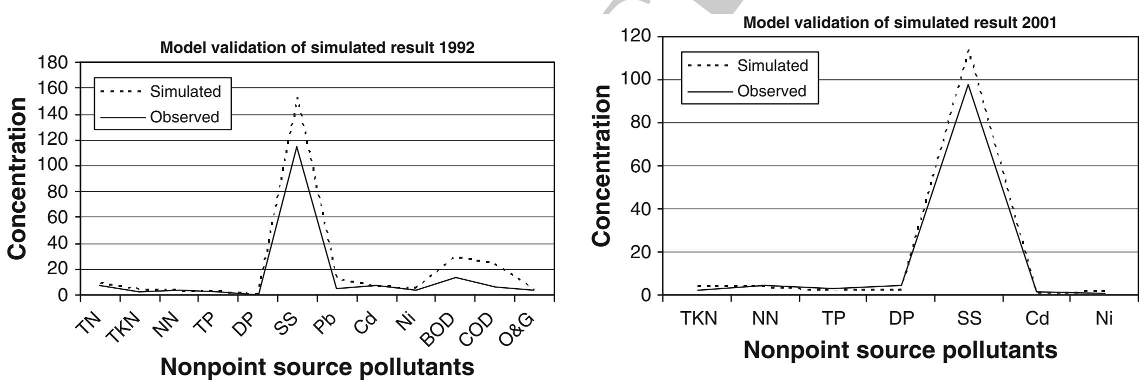

Fig. 7 Observed and predicted nonpoint source pollutants during model validation

higher in 2001 compared to 1992 (Fig. 10). The model predicted that emergent herbaceous wetlands had the highest runoff depth compared to all other land use categories over the study period. Land used for commercial, industrial and transportation activities generated the second highest runoff depth. Average runoff depth for the combined land use increased by 17 percent over the study period. Barren land recorded the third highest runoff depth between 1992 and 2001. These lands are mostly composed of deserted pavements that were initially used for other activities. The model predicted a 20 percent increase in runoff depth for this land use.

Residential land use generated runoff depth of less than 1 inch over the study period; when the two time periods are compared, an increase of 28 percent was observed. Runoff depth recorded within land used for agriculture, grassland/scrub, developed/open space and woody vegetation is less than that of residential land use. Lowest runoff depth predicted over the entire period of study is within woody vegetation (0.08 and 0.1 inch in 1992 and 2001 respectively). Other land use categories of comparatively low runoff depth include forest and grassland.

Runoff volume is a factor of size of the land use and its relationship to hydrologically active areas of a watershed. In 1992, the combined land used for commercial, industrial and transportation activities produced the highest runoff volume (Figs. 11, 12). However, simulation results for 2001 demonstrated a reduction in the average runoff volume

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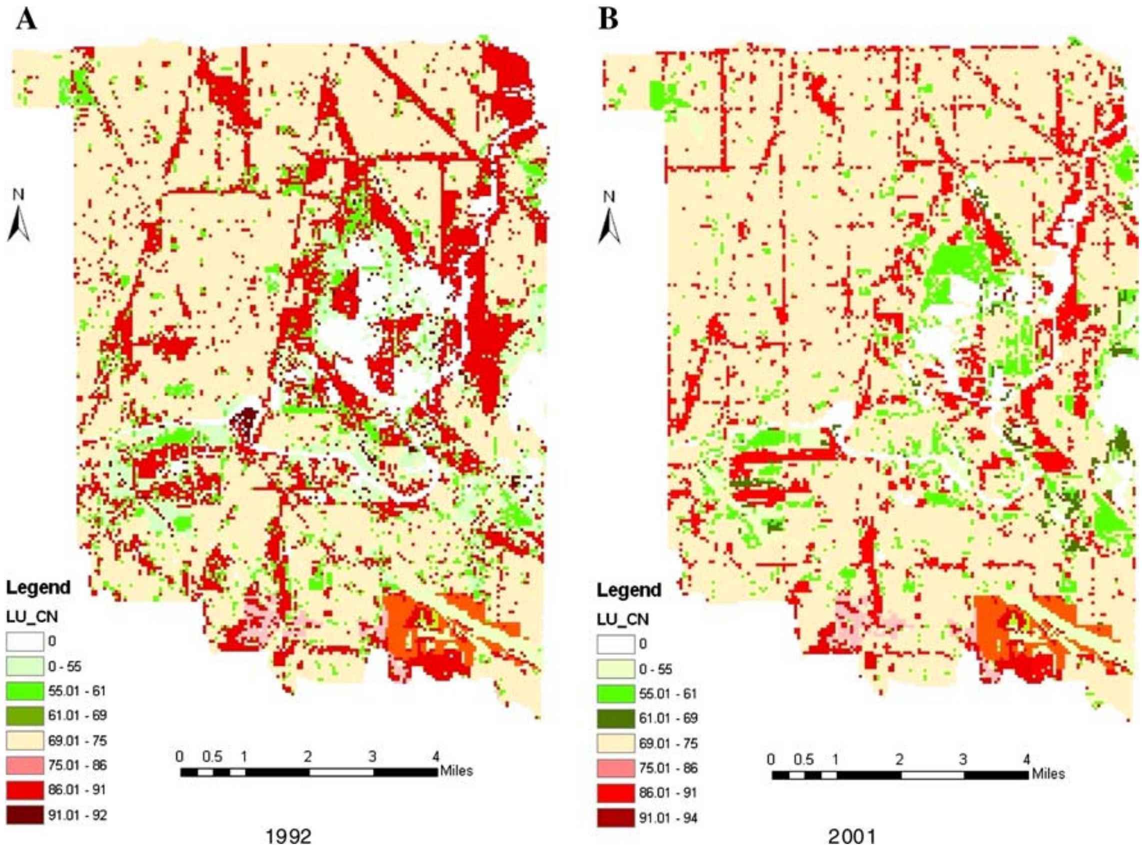

Fig. 8 Curve number grids generated from land and soil data. *Data source*: National Land Cover Database, and U.S. Department of Agriculture Natural Resource Conservation Services

for the aforementioned combined land use (−21%). In 1992, residential land use produced the second highest runoff volume; while in 2001 it generated the highest runoff volume (Fig. 12). This can be attributed to an increase in the spatial extent of residential land use over the study period and also an increase in the amount of residential land cover within areas that contributed towards runoff in 2001. The above scenarios resulted to an increase of 102 percent in runoff volume within residential land cover. Runoff volume recorded for emergent herbaceous wetlands, agriculture, developed/open space and forest are relatively lower than residential and the combined transportation, industrial and commercial land use over the study period. Woody vegetation, grassland/scrub and barren land generated runoff volume of less than 5 acre-feet. Highest change in runoff volume between 1992 and 2001 was produced by grassland/scrub (over tenfold), while the combined land used for commercial, transportation and industrial activities produced the lowest (21%).

Changes in Water Quality

Land use and Land cover produce some type and concentration of nonpoint source pollutants (Baird and Jennings 1996; Loehr 1974). The implication of these pollutants for surface water quality depends on the magnitude of the pollutants produced, spatial extent of the land use, runoff depth, runoff volume and the topography of the landscape. The modified L-THIA-NPS simulation model was used to estimate 12 nonpoint source pollutant concentration loads from the various land uses (Table 4).

In 1992, total nitrogen concentration was highest within agricultural land use (4.51 mg/L). Other land uses of relatively high total nitrogen concentrations include barren land, the combined commercial, industrial and transportation land uses, developed/open space and woody vegetation. Total nitrogen concentration was insignificant within forest, grass/scrub and emergent herbaceous wetlands (<1 mg/L). Total nitrogen concentration for 2001 mirrors that of 1992. In 2001, agriculture had the highest concentration (4.14 mg/L), while forest, grassland/scrub and emergent herbaceous wetland produced lower concentrations (<1 mg/L).

Other nitrogen related pollutants that were estimated include total kjeldahl nitrogen and nitrate nitrite. Highest total kjeldahl nitrogen concentration in 1992 was observed within residential land use (1.9 mg/L) while forest, grassland/scrub and emergent herbaceous wetlands produced relatively small concentrations (0.2 mg/L and lower). The

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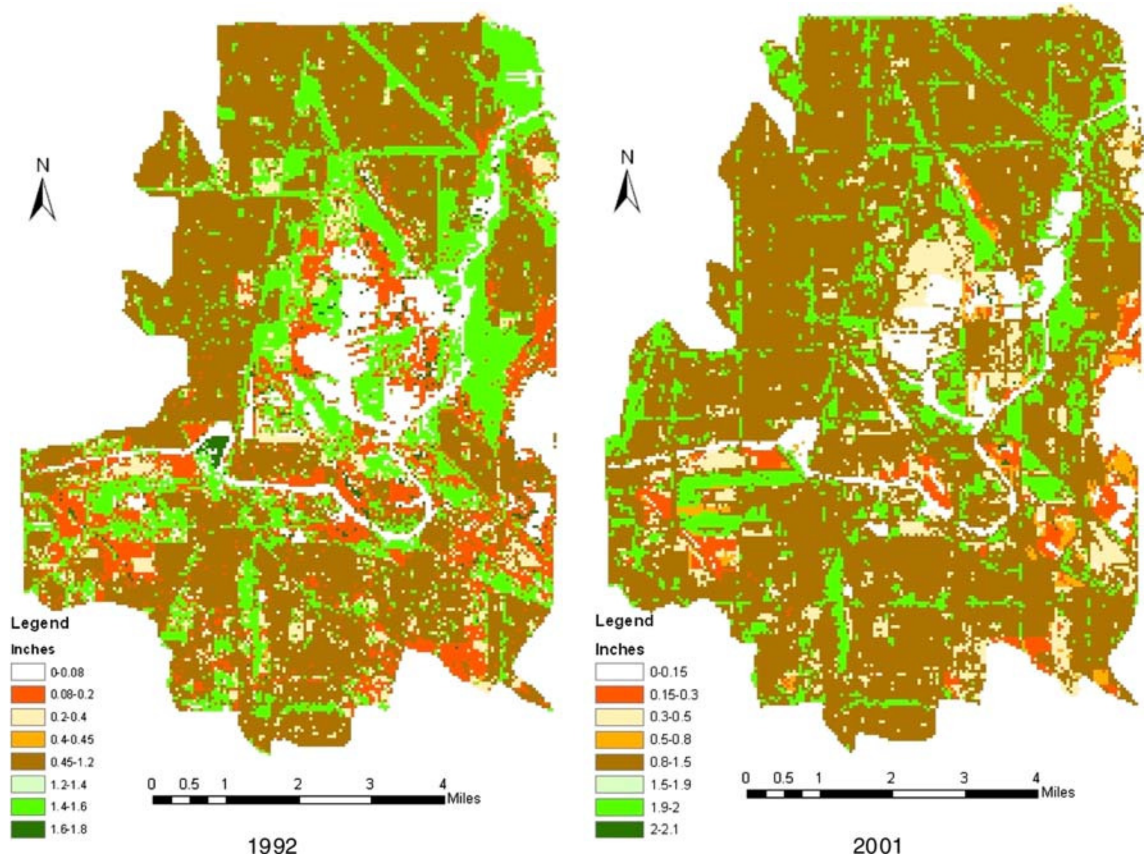

Fig. 9 Runoff depth grid generated from curve number grid

Table 3 Land use/land cover change

Land use	1992	2001	%Change
Open water	4182.57	3085.3	−26.2
Residential	27375.9	37592.5	37.31
Comm/Indst/Trans	11556.1	7133.5	−38.3
Barren land	2.67	16.2	506.7
Forest	5858.8	1762	−69.9
Grassland/scrub	449.15	705.5	57.1
Agriculture	888.7	96.5	−89.1
Developed/open space	3395.5	3977.3	17.1
Woody vegetation	778.6	94.7	−87.8
Emergent herbaceous wetland	429.7	213.1	−50.4

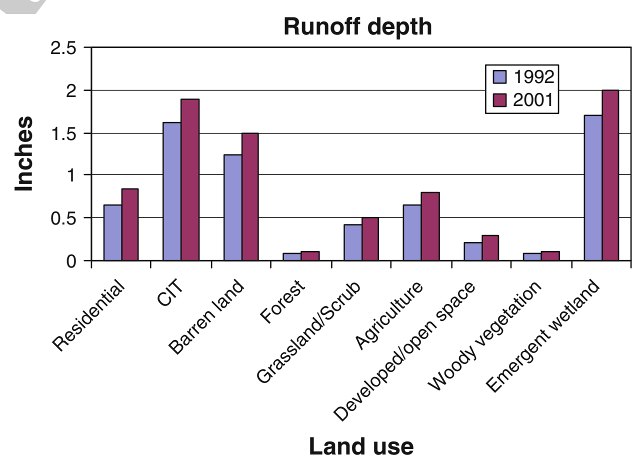

Fig. 10 Runoff depth per land use/land cover type

pattern of total kjeldahl nitrogen generated by the model vis-à-vis land uses in 2001 mirrors that of 1992 (Table 4). Agricultural land use produced the highest nitrate nitrite concentration for both study periods; while all other land uses had concentrations of less than 1 mg/L as N.

Total phosphorus concentration was highest within agricultural land use over the study period while emergent herbaceous wetlands, forest, grassland/scrub and barren land recorded very low concentrations of less than 0.2 mg/L.

Dissolved phosphorus concentration for individual land uses was significantly low (<1 mg/L). Residential land use generated the highest dissolved phosphorus concentration in 1992 (0.48 mg/L) and 2001 (0.57 mg/L). Woody vegetation and barren land produced the lowest dissolved phosphorus concentration while some land use did not generate any of this pollutant (Table 4).

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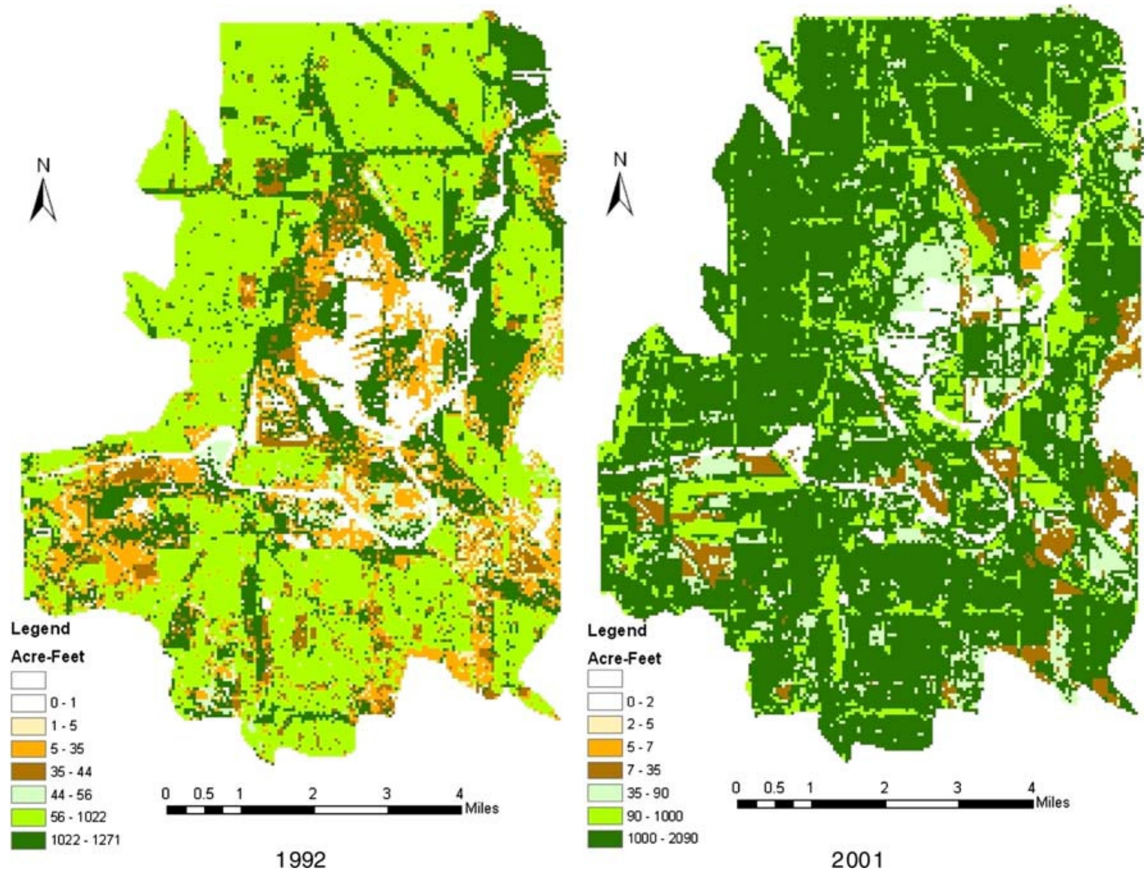

Fig. 11 Runoff volume map calculated from runoff depth grid

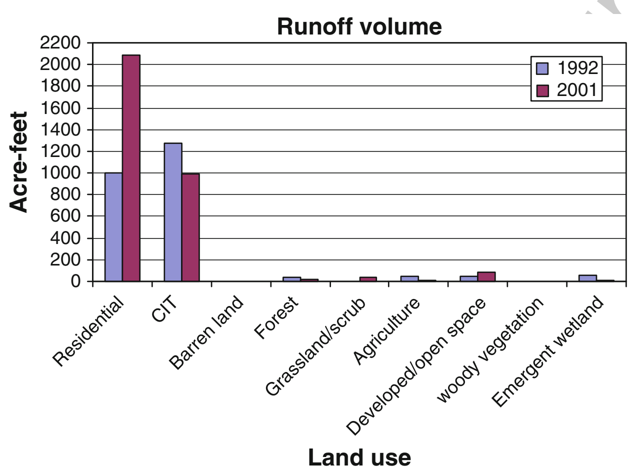

Fig. 12 Runoff volume per land use/land cover type

Suspended solids recorded the highest concentration compared to all other nonpoint source pollutants estimated in the study (Fig. 13). In 1992, highest suspended solids concentration was predicted within agricultural land use (90 mg/L). In 2001, barren land generated the highest concentration of suspended solids (78 mg/L). Other land uses that produced high concentration of suspended solids over the 9 year period include the combined commercial, industrial and transportation, woody vegetation and developed/open space land uses (Table 4).

Lead, cadmium and nickel concentrations were predicted in trace quantities compared to other nonpoint source pollutants estimated in the study. Highest lead concentration was estimated within the combined commercial, industrial and transportation land for both study periods. In 1992, lead concentration within this land was 9 µg/L, and increased to 14.5 µg/L in 2001. Woody vegetation, forest and grassland/scrub generated small quantities of lead (Table 4). Cadmium and nickel concentrations were highest within the combined land used for commercial, industrial and transportation. In 2001, predicted values were lower for the two pollutants compared to 1992 though not proportionally. Over this period, nickel concentration declined by half while cadmium experienced an infinitesimal drop of 0.02 µg/L.

Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) properties of water demonstrate different relationships to runoff depth over the study period. BOD concentration was highest on residential land use over the study period while COD concentration was greatest within the combined commercial, industrial and transportation land use (Fig. 14). Lowest BOD concentration was

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Table 4 Nonpoint source pollution estimation for 1992 (1st row) and 2001 (2nd row)

Land use	TN	TKN	NN	TP	DP	SS	Pb	Cd	Ni	BOD	COD	O&G
Residential	1.82	1.90	0.23	0.72	0.48	41	4	0.75	0.65	18.5	24.6	1.7
	1.96	2.1	0.67	0.83	0.57	52	9	0.73	0.69	25.5	35.5	2.1
Commercial	1.49	1.25	0.37	0.51	0.14	63.17	9	1.25	8.03	11.4	67.5	4.13
	1.41	1.2	0.24	0.27	0.09	56.27	14.5	1.23	4.03	18.47	53.5	4.59
Barren land	1.50	0.96	0.54	0.12	0.03	70	1.52	0	0	0	31	0
	1.9	1.16	0.83	0.26	0.14	78	1.7	0	0	0	40	0
Forest	0.7	0.06	0.40	0.01	0	1	1.5	0.3	0	0.5	0	0
	0.5	0.4	0.32	0.01	0	0.8	2.2	0.18	0	0.46	0	0
Grassland/scrub	0.7	0.10	0.40	0.01	0	1	0.9	0.5	0	0.5	0	0
	0.9	0.2	0.8	0.11	0	1.4	5	0.9	0	0.53	0	0
Agriculture	4.51	1.65	1.60	1.69	0	90	1.1	1	0	4	0	0
	4.14	1.23	1.48	1.3	0	75	0.93	0.8	0	3.2	0	0
Developed/open space	1.23	0.90	0.34	0.35	0.23	41	1.6	1.05	3.8	6.4	59.3	1.2
	1.57	1.12	0.39	0.38	0.29	57.9	2.37	1.15	1.2	17.2	20.5	1.9
Woody vegetation	1.2	0.82	0.44	0.09	0.03	70	0.8	0.3	0	2	30	0
	0.8	0.35	0.29	0.03	0.01	58.2	0.62	0.21	0	1.42	40	0
Emergent wetland	0.7	0.2	0.40	0.01	0	1	0	0.8	0	0.5	0	0
	0.61	0.18	0.35	0.01	0	0.8	0	0.62	0	0.39	0	0

Pb, Cd and Ni are in µg/L (microgram per liter) and all other pollutants are in mg/L (milligram per liter)

TN total nitrogen, *Pb* lead, *TKN* total kjeldahl nitrogen, *Cd* cadmium, *NN* nitrate nitrite, *Ni* nickel, *TP* total phosphorus, *BOD* biochemical oxygen demand, *DP* dissolved phosphorus, *COD* chemical oxygen demand, *SS* suspended solids, *O&G* oil and grease

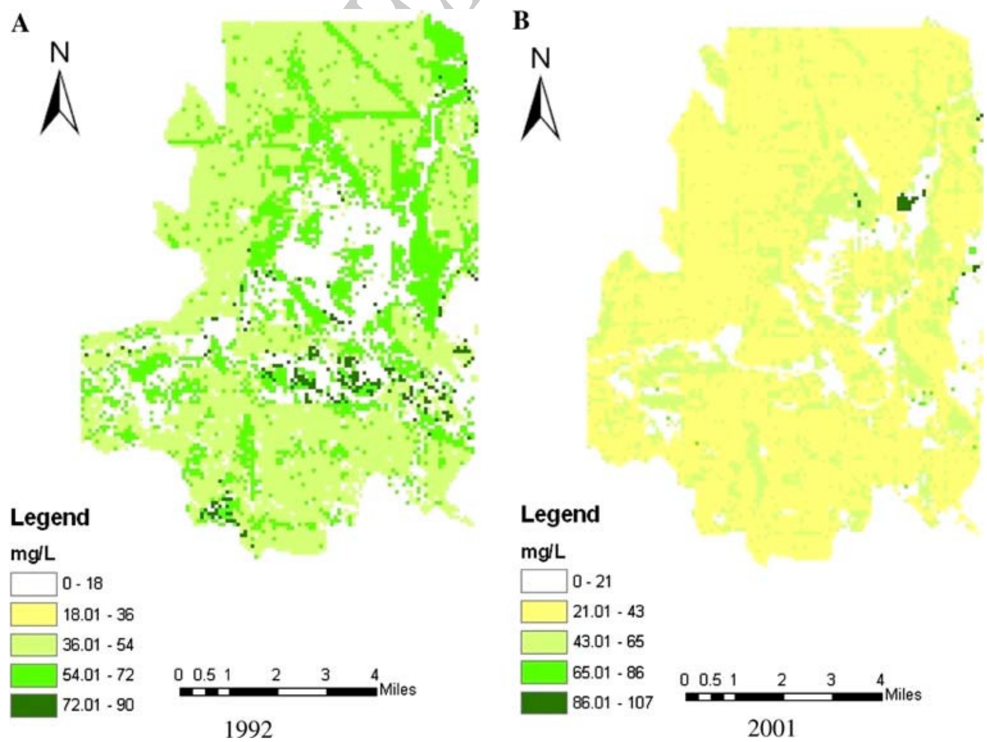

Fig. 13 Nonpoint source pollution estimate for suspended solids

found on forest, grassland/scrub and emergent herbaceous wetlands over the study period. COD concentration was higher than BOD over the 9 year period although COD was nonexistent within six land uses (Table 4).

A very important nonpoint source pollutant mainly emanating from roads and highways in urban areas is oil and grease. Simulation result suggested a slight increase in oil and grease concentration between 1992 and 2001 (Table 4).

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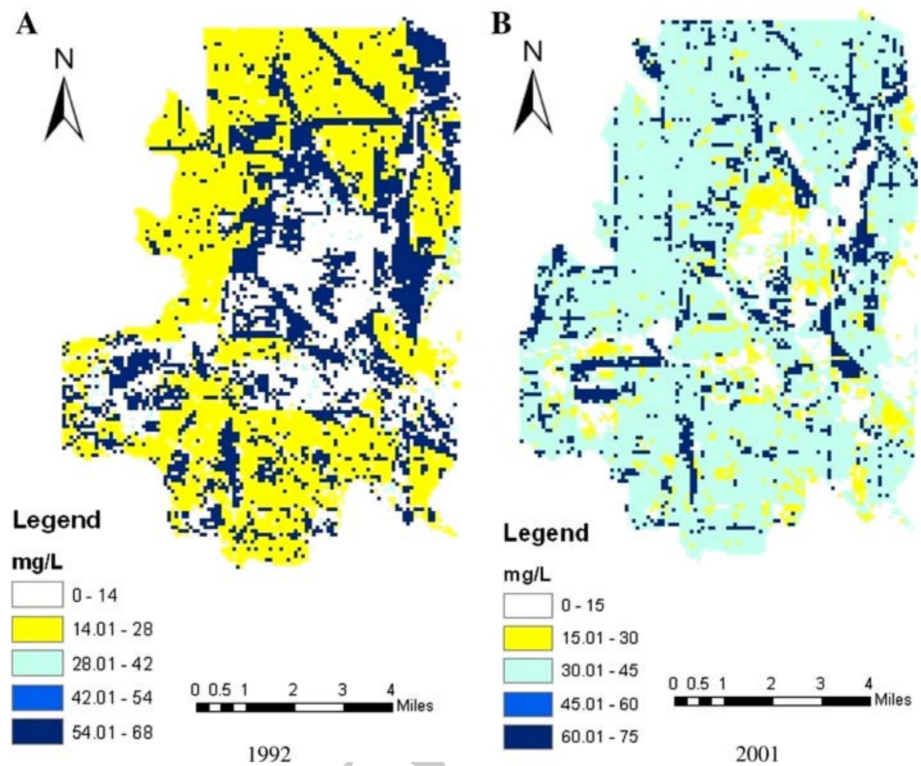

Fig. 14 Chemical oxygen demand property of surface water

The combined land used for commercial, industrial and transportation activities generated the highest concentration of this pollutant over the study period. Less than half of this quantity was found within residential and developed/open space (Fig. 15). There was no trace of oil and grease found in the other land uses.

Discussion

This study attempts to demonstrate the implications of LULC change on surface water quality by taking into consideration hydrologically passive and active areas within an urban watershed. It further models the likely effects this phenomenon will have on urban water resources. Increase in the spatial extent of barren land between 1992 and 2001 reflect some land based policy measures implemented by City of Chicago Department of Environment. A massive land reclamation and brownfield clean up has been ongoing within the vicinity of Lake Calumet following the scale down of industrial activities (City of Chicago Department of Environment 2002). By 2001, a large fraction of the barren land was designated transitional in the process of being reallocated to other land uses.

Runoff depth demonstrated a direct relationship to average annual rainfall over the study period, while runoff volume displays a nonlinear relationship to increase in rainfall over the same period. Runoff volume is mostly related to changes in the spatial extent of each land cover over the study period and more importantly the spatiotemporal variations in hydrologically active area for 1992 and 2001. Runoff volume within residential land use increased far above the increase in spatial extent of this land use type and also the increase in rainfall over the study period. Runoff volume within residential land use increased by 108 percent while the spatial extent only increased by 37.3 percent; whereas increase in rainfall was less than 30 percent. Differences between the increase in runoff volume and spatial extent of land can be attributed to the shifting nature of hydrologically active areas within Lake Calumet's watershed over the study period. In a similar vein, land cover change detection demonstrated a 38.3 percent decline in size for the combined commercial, industrial and transportation land use. Even though runoff depth for this land use increased over the study period, runoff volume declined over the same period (21%). This again suggests that comparatively smaller area of the combined land use fall within active areas of the watershed in 2001.

Nonpoint source pollutant concentration depends on a wide range of anthropogenic and natural factors. However, runoff volume, knowledge of the spatial extent of land uses and a picture of hydrologically active areas within a watershed can shed insight into the level of concentration of these pollutants. Concentration for 11 of the 12 pollutants estimated within residential land use increased over the study period. Some pollutants increased more than others. While nitrate nitrite concentration within residential land use increased close to 200 percent, nickel concentration

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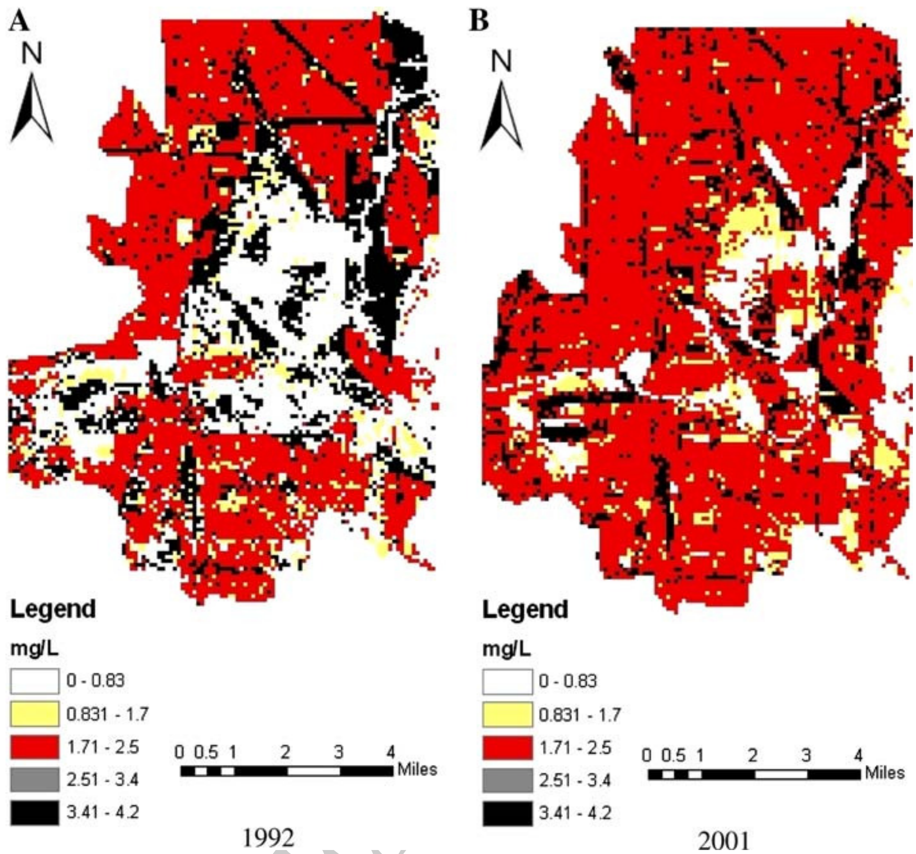
Fig. 15 Oil and grease estimate



only increased by 6 percent. Cadmium concentration declined by 2 percent which might be attributed to lower production of this pollutant from the industrial site within Lake Calumet's vicinity. While the increase in concentration for 11 of the 12 nonpoint source pollutants within residential land use might be attributed to additional anthropogenic production of these pollutants and, or an increase in atmospheric concentration of these pollutants, a causal relationship cannot be directly made without a longitudinal onsite monitoring of these pollutants within the study area. Notwithstanding, the study has demonstrated that the concentration of most nonpoint source pollutants within residential land uses increases with size of land use and runoff volume. Another factor that might be responsible for increase in concentration of nonpoint source pollutants within residential land cover besides the increase in the spatial extent is an increase in population. Census tract population figures covering residential land demonstrated an increase in population between 1992 and 2001. The generation of additional household waste and increased use of automobile might be responsible for the rise of 11 of the 12 nonpoint source pollutants simulated within residential land in the study.

Ten of the 12 nonpoint source pollutant concentration estimated within the combined commercial, industrial and transportation land use reduced while two increased over the study period. The decline of these nonpoint source pollutants ranges between 1.6 percent for cadmium and 47 percent for total phosphorus; while concentration for lead and oil and grease increased by 61 and 11.1 percent respectively. It is likely that the decline in concentration of some of the industrial pollutants arises from downsizing of the industrial plant within Lake Calumet's vicinity. Increase in oil and grease concentration may have partly arisen from increased vehicular traffic resulting from the growth of residential area and commercial establishments.

High concentration of suspended solids within the combined commercial, industrial and transportation land use in 1992 may have resulted from comparatively large industrial activities. While the transition of part of industrial lands to barren land cover in 2001 partly explains the high suspended solid concentration within barren land. Concentration of biochemical oxygen demand and chemical oxygen demand properties of water demonstrate an inverse relationship over the study period. While BOD concentration reduced, COD increased even thought runoff depth increased between 1992 and 2001. A number of factors including increase in the proportion of low density residential vis-à-vis high density, and increase in the size of barren lands which comprised of a large proportion of brownfield as at 2001 might be responsible for the relationship displayed by BOD and COD.

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Conclusions

Modeling the effects of urban LULC change on surface water quality within a partial area hydrology framework is pivotal in monitoring urban water resources. The study demonstrates that surface water quality depends on the extent of LULC change over time and also the spatial extent of hydrologically active areas within the watershed. The model reveals that an increase in runoff volume will contribute to differential increases in concentration among most pollutants. Conversely, biochemical oxygen demand and chemical oxygen demand properties of surface water demonstrated a contrary pattern to the aforementioned one.

This study has demonstrated the importance of urban watershed delineation in estimating the concentration of major nonpoint source pollutants evident in urban environments. Impervious land cover types like residential, commercial, industrial, transportation, and developed/open space that experience higher volume of human activities tend to have greater concentration of BOD, COD, and oil and grease compared to those with lesser human activities. The more land area that exists within active areas of a watershed over time, the greater the concentration levels of most pollutants, while that of biological oxygen demand property of water demonstrates an inverse relationship. The modeling framework employed in this study can be applied to other urban areas with moderate size watershed and a gauged water quality monitoring system. The latter can facilitate calibration of model parameters to fit in with observed data. The study has attempted an investigation into the dynamics of partial area hydrology and its effects on nonpoint source pollution concentration amid LULC change.

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