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Effects of calibration on L-THIA GIS runoff and pollutant estimation

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Abstract

Urbanization can result in alteration of a watershed's hydrologic response and water quality. To simulate hydrologic and water quality impacts of land use changes, the Long-Term Hydrologic Impact Assessment (L-THIA) system has been used. The L-THIA system estimates pollutant loading based on direct runoff quantity and land use based pollutant coefficients. The accurate estimation of direct runoff is important in assessing water quality impacts of land use changes. An automated program was developed to calibrate the L-THIA model using the millions of curve number (CN) combinations associated with land uses and hydrologic soil groups. L-THIA calibration for the Little Eagle Creek (LEC) watershed near Indianapolis, Indiana was performed using land use data for 1991 and daily rainfall data for six months of 1991 (January 1–June 30) to minimize errors associated with use of different temporal land use data and rainfall data. For the calibration period, the Nash–Sutcliffe coefficient was 0.60 for estimated and observed direct runoff. The calibrated CN values were used for validation of the model for the same year (July 1–December 31), and the Nash–Sutcliffe coefficient was 0.60 for estimated and observed direct runoff. The Nash–Sutcliffe coefficient was 0.52 for January 1, 1991 to December 31, 1991 using uncalibrated CN values. As shown in this study, the use of better input parameters for the L-THIA model can improve accuracy. The effects on direct runoff and pollutant estimation of the calibrated CN values in the L-THIA model were investigated for the LEC. Following calibration, the estimated average annual direct runoff for the LEC watershed increased by 34%, total nitrogen by 24%, total phosphorus by 22%, and total lead by 43%. This study demonstrates that the L-THIA model should be calibrated and validated prior to application in a particular watershed to more accurately assess the effects of land use changes on hydrology and water quality.

Keywords: Curve number; Calibration; L-THIA GIS; Runoff; Validation; Watershed

1. Introduction

Urban sprawl is a dominant phenomenon in urbanizing regions worldwide, and it has been increasing in recent decades according to the U.S. EPA (2001). Although land use conversion from non-urban to urban uses provides social and economic benefits to the community, it alters hydrologic response within the watershed. Increased impervious areas in an urbanizing watershed can result in increases of direct runoff and decreases of base flow (Moscrip and Montgomery, 1997), and also increases of nonpoint source (NPS) pollutant loadings within the watershed (Schueler, 1995).

To simulate the land use change impacts on watersheds, many hydrologic and water quality models have been developed and integrated with a Geographic Information System (GIS), such as Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Rewerts and Engel, 1991), Agricultural Nonpoint Source (AGNPS) (Engel, 1996), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1995). These models can be used to assess the impacts of land use management and other changes on hydrology and water quality. However, there has also been a need for a much simpler-to-use model for land use impact assessment.

The Long-Term Hydrologic Impact Assessment (L-THIA) model was developed and integrated with GIS to estimate direct runoff from very basic input data, such as daily rainfall, land uses, and hydrologic soil group (Harbor, 1994; Bhaduri et al., 2001; Lim et al., 2001). There are two components in the L-THIA model; one is the hydrologic

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component and the other is the water quality component. The hydrologic component of the L-THIA model estimates direct runoff based on the curve number (CN) method with daily rainfall data. The water quality component estimates pollutant loadings from the estimated direct runoff and coefficients associated with land use.

The CN method is an empirical method to estimate the direct runoff from the relationship between rainfall, land uses, and hydrologic soil group (NRCS, 1986). The CN values range from 25 to 98, depending on land uses, hydrologic soil group, and antecedent moisture condition (AMC) (NRCS, 1986). The L-THIA model estimates daily direct runoff for a given CN value with daily rainfall data. The yearly and annual average direct runoff values are computed based on estimated daily direct runoff values in the L-THIA model. The L-THIA model has been typically used to assess hydrologic and water quality impacts of land use change using the default CN values provided in the L-THIA GIS (Bhaduri et al., 1997; Minner et al., 1998; Pandey et al., 2000; Grove et al., 2001; Bhaduri et al., 2001; Kim et al., 2002). In these studies, the average annual direct runoff values were computed using the rainfall data for the long-term simulation period with historic land use data.

To most accurately simulate the impacts of land use changes on hydrology and water quality, the hydrologic component of the L-THIA model should be validated first, because the water quality component of the model estimates pollutant loadings from the estimated direct runoff and coefficients associated with land use. Leroy (2004) used the daily direct runoff values from the L-THIA model (Lim and Engel, 1999) to calibrate and validate it for a watershed in northern Indiana. He found that 40% increases in CN values resulted in the best Nash–Sutcliffe coefficient values (Nash and Sutcliffe, 1970), a statistic to quantify the fit between predicted values and measured values—essentially sum of the deviations of the observations from a linear regression line with a slope of 1, during the calibration and validation period. However, there may be a better set of calibrated CN values for each land use and hydrologic soil group combination in that watershed, rather than assuming 40% uniform increases in the CN values for all land use and hydrologic soil group combinations. Thus, a better calibration method, rather than a very time-consuming and tedious manual method, is needed.

The objectives of this study are to: (1) develop an automatic calibration method for the L-THIA model; (2) calibrate and validate the L-THIA model; and (3) estimate the effects of L-THIA calibration on runoff and pollutant estimation.

2. Literature review

The L-THIA model was developed to estimate direct runoff using the CN method from daily rainfall depth, land use, and hydrologic soil group data (Harbor, 1994), and it has been integrated with the ArcView GIS tool (Bhaduri et al., 2001; Lim et al., 2001). In addition to the L-THIA GIS system, a Web-based L-THIA was developed, and it is available from http://www.ecn.purdue.edu/runoff/lthianew.

The hypothesis of the CN method is that the ratio of actual retention in the watershed to the potential maximum retention is the same as the ratio of actual direct runoff to the potential maximum runoff (USDA, 1985; Chow et al., 1988), as indicated by:

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{1}$$

where F_a is the actual retention in the watershed (excluding I_a), P is the precipitation, P_e is the actual direct runoff, S is the potential maximum retention determined by Eq. (1), and I_a is the initial abstraction before ponding. The total precipitation (P) equals the sum of the actual direct runoff (P_e), the initial abstraction before ponding (I_a), and the actual retention in the watershed (F_a). Thus, the runoff equation is:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{for } P > I_a = 0.2S \tag{2a}$$

$$P_e = 0 \quad \text{for } P = I_a = 0.2S \tag{2b}$$

Thus, the L-THIA model estimates direct runoff if the precipitation is greater than 20% of the potential maximum retention. Based on the L-THIA estimated direct runoff, pollutant loadings for non-urban areas, as well as urban areas, are estimated by multiplying the estimated daily direct runoff by pollutant loading coefficients, called Event Mean Concentration (EMC) values, associated with land use (Lim et al., 2001). Yearly and annual average direct runoff and pollutants loadings are estimated based on daily values from the L-THIA model. Fig. 1 shows how the L-THIA system simulates direct runoff and pollutant loadings. As shown in Fig. 1, the pollutant loading is estimated by multiplying direct runoff quantity by the EMC value for each land use.

The L-THIA system has been used in numerous efforts to assess the effects of land use changes on hydrologic and water quality (Pandey et al., 2000; Grove et al., 2001; Bhaduri et al., 2001; Kim et al., 2002). These studies concluded the L-THIA system is a good tool for assessing the hydrology and water quality impacts of land use changes. Lim et al. (2005) applied the daily version of L-THIA (Lim and Engel, 1999) with historic land use in Little Eagle Creek (LEC) watershed in Indiana by grouping the rainfall data for periods around available historic land use data, and computed the yearly direct runoff values for each time period assuming no significant changes in land use occurred for each time period. The L-THIA estimated yearly runoff values were compared with the measured yearly direct runoff, and its comparison gave reasonable results with a Nash–Sutcliffe coefficient of 0.67 (Lim et al.,

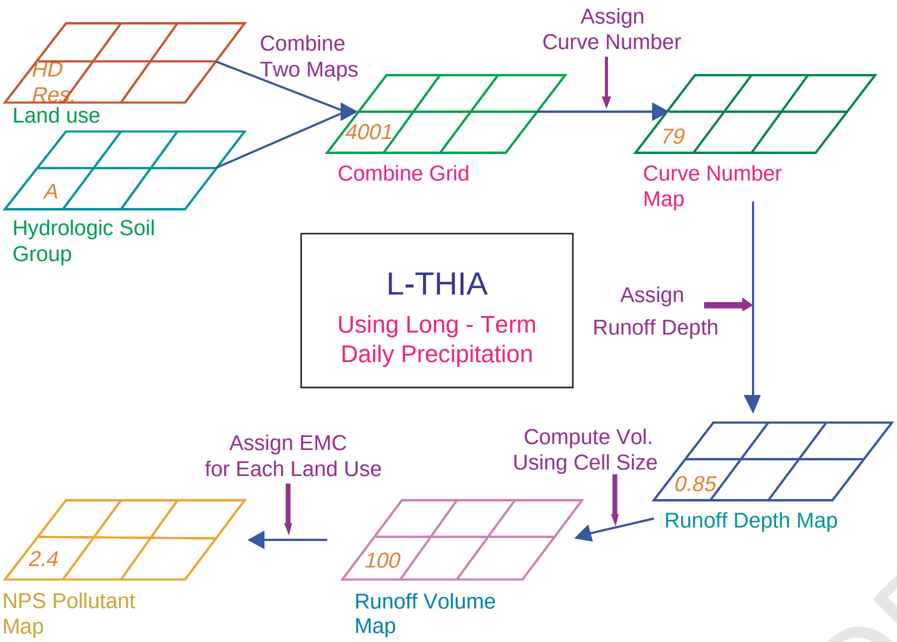

Fig. 1. Overview of the LTHIA GIS system (adapted from Lim et al., 2001).

2005), which can be deemed acceptable in hydrology modeling (Santhi et al., 2001). However, this approach still had limitations, since it assumed no significant changes in land use occurred for several years, which may be inaccurate.

3. Methodology

3.1. Study area

The LEC watershed in Indiana was selected to simulate daily direct runoff for calibration and validation of the L-THIA model daily results. Land use data for 1973, 1984, and 1991 are available and these were used to estimate impacts of long-term land use changes. The LEC watershed, located in central Indiana, is 70.5 km^2 in size (Fig. 2(a)). It experienced significant urbanization (18% increase in urban area) between 1973 and 1991, with the majority of changes in the 1970s (14% increase in urban area) (Bhaduri et al., 2001). Land uses ranging from non-urban natural grass, forested areas and agricultural areas to typical urban residential and commercial categories exist in the LEC watershed. The areas of ‘Forest’ and ‘Grass/Pasture’ have decreased, while areas of ‘Commercial’ and ‘HD Residential’ have increased dramatically (over 200%) in the watershed. The ‘Agricultural’ area has decreased slightly. Fig. 2(b) shows the land uses for the LEC watershed in 1991. Urbanized land area in the LEC watershed was around 68% of the total land area in 1991 (Lim et al., 2005).

Since there have been significant changes in land uses and rainfall data in the LEC watershed over a 20 year period, it would not be a good idea to ignore the temporal changes in land use by running the model for the long-term period with land use data representing one year. Thus, the 1991 LEC land use, soil, and daily rainfall data were used in the daily L-THIA calibration and validation. In this study, the data from January 1, 1991 to June 30, 1991 were used for calibration, and the data from July 1, 1991 to December 31, 1991 were used for validation.

3.2. Separation of baseflow component from stream flow

The L-THIA model simulates direct runoff. For calibration of the direct runoff results from the L-THIA model, the direct runoff component from the stream flow needs to be separated. There are several graphical methods to define baseflow from the stream flow (Chow et al., 1988). However, these methods are not very efficient when separating baseflow for long time periods. Also, these subjective techniques can result in inconsistent results, even with the same flow data. Digital filtering methods have recently become commonplace in hydrograph separation (Lyne and Hollick, 1979; Arnold and Allen, 1999; Eckhardt, 2005). The digital filter method has been used in signal analysis and processing to separate high frequency signal from low frequency signal (Lyne and Hollick, 1979). This method has been used in baseflow separation because high frequency waves can be associated with the direct runoff, and low frequency waves can be associated with the baseflow (Eckhardt, 2005). Thus, filtering direct runoff from baseflow is similar to signal analysis and processing (Eckhardt, 2005). In this study, the digital BFLOW filter (Arnold and Allen, 1999) was used for baseflow separation. Approximately 58% of stream flow is contributed by direct runoff and 42% of stream flow by baseflow in the LEC

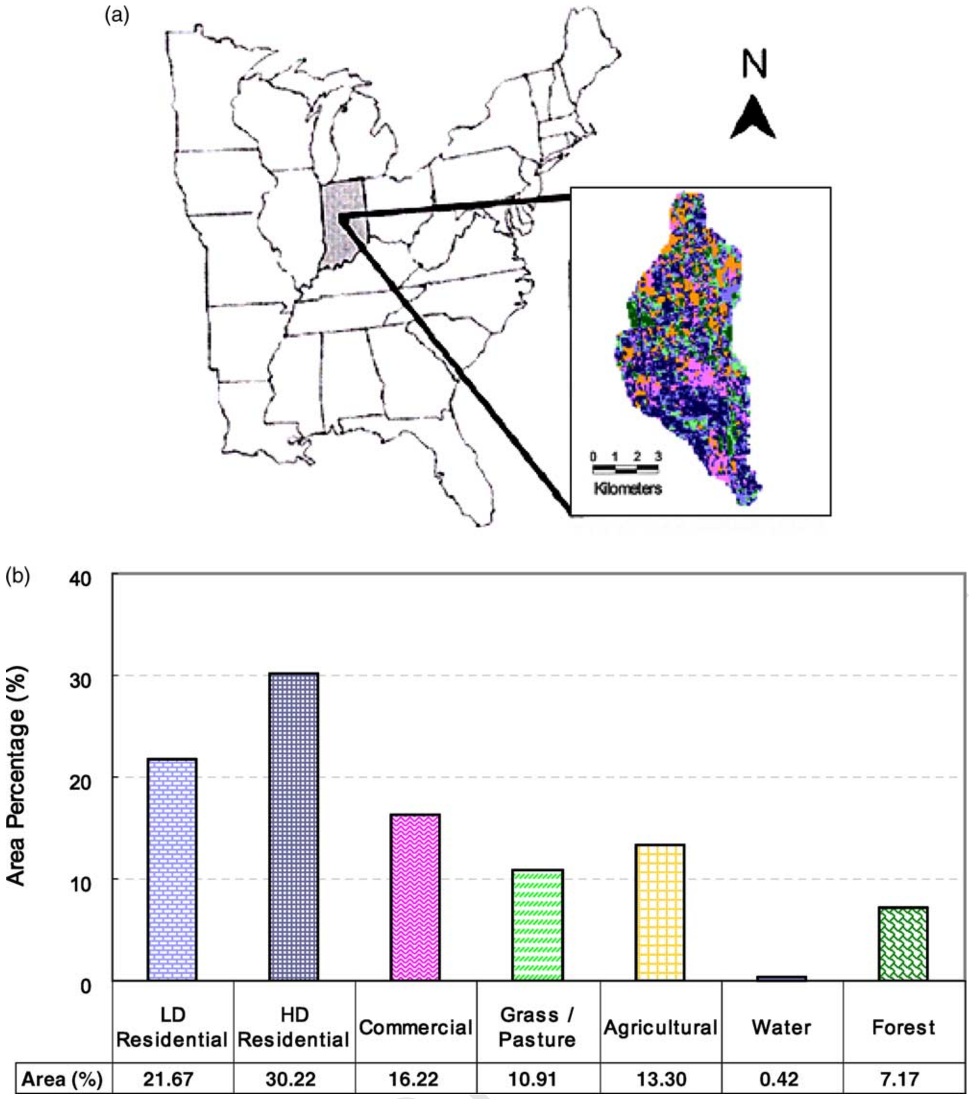

Fig. 2. Location of the little eagle creek (LEC) watershed (a) and its land uses for 1991 (b).

watershed for 1991. The daily direct runoff separated from the stream flow data was used to compute the Nash–Sutcliffe coefficient value for comparison of the L-THIA estimated daily direct runoff with measured daily direct runoff.

3.3. Automatic calibration of L-THIA model

In the L-THIA model runs, the AMC adjustment was not made, although 'AMC adjustment' and 'AMC II condition' options are provided in the L-THIA model. This is because the L-THIA estimated direct runoff after adjusting the AMC condition was generally lower than the measured direct runoff value (62% of measured direct runoff) (Grove et al., 2001). Nearly 70% of days with rain for the long-term simulation period (1967–1995) fell in the AMC I condition, which resulted in lower CN values and lower estimates of direct runoff and as a result under prediction of measured direct runoff (Lim et al., 2005).

In the L-THIA system, default CN values are provided for the land uses and hydrologic soil group combinations. However, there are ranges of CN values for each land use and hydrologic soil group combination depending on hydrologic condition, cover type, and management (NRCS, 1986). For example, the CN value for 'Residential District by Average Lot Size' and hydrologic soil group 'A' varies from 12 to 65 depending on the lot size. The CN values are 12, 20, 25, 30, 38, and 65 for 0.809 ha (2 acres), 0.405 ha (1 acre), 0.202 ha (1/2 acre), 0.135 ha (1/3/ acre), 0.101 ha (1/4 acre), and 0.051 ha (1/8 acre) or less (NRCS, 1986), respectively. These detailed classifications are not readily considered in the L-THIA GIS system for direct runoff estimation. Fig. 3 shows the ranges of CN values for land use and hydrologic soil group combinations in the 1991 LEC watershed (NRCS, 1986). Thus, the use of CN combinations in these ranges can potentially produce a better match with measured direct runoff. There are millions of combinations from these CN value ranges for all land use

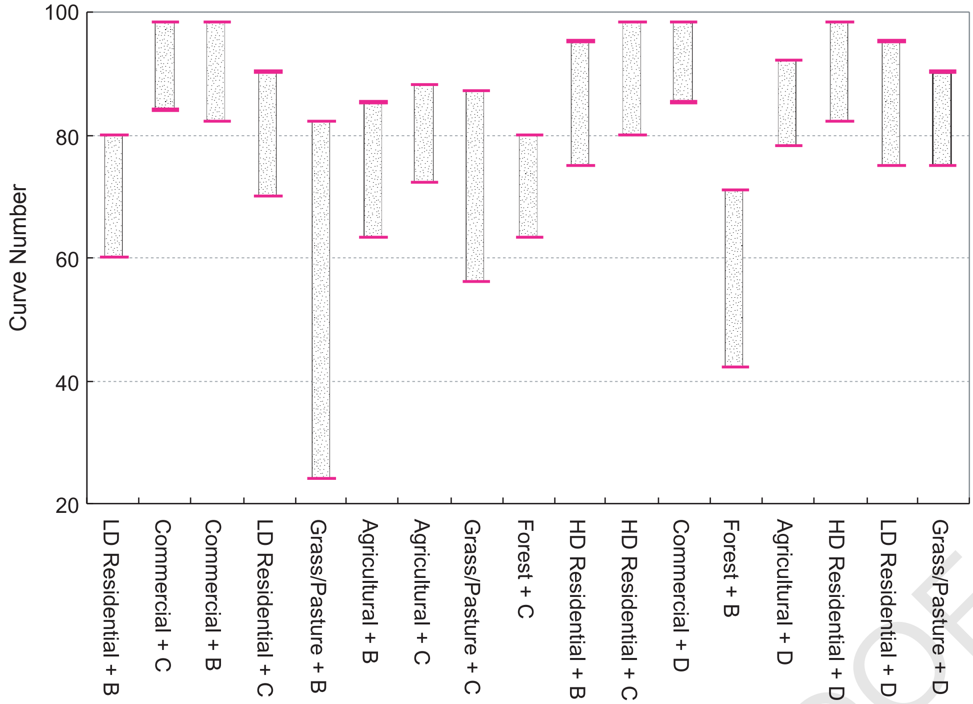

Fig. 3. Minimum and maximum curve number values for land use and soil combinations (NRCS, 1986) in the 1991 LEC watershed.

and hydrologic soil group combinations (NRCS, 1986). Thus, a program was written to automate the calibration processes considering numerous CN combinations in L-THIA runs.

Fig. 4 shows how the automatic calibration system developed in this study works. The automatic calibration system first reads the CN combinations, and then computes daily direct runoff using 1991 LEC land use data and soil data with the first 6 months of daily rainfall data in 1991. The simulated daily direct runoff is compared with the daily direct runoff separated from the stream flow data, and the Nash–Sutcliffe coefficient value is computed. If the Nash–Sutcliffe coefficient is greater than 0.60, the CN values for all land use and hydrologic soil group combinations are stored in the output file. For the calibration method proposed for the SWAT model by Santhi et al. (2001), a Nash–Sutcliffe coefficient greater than 0.50 was deemed acceptable for model calibration. In this study, 0.60 was used, because the Nash–Sutcliffe coefficients for many sets of CN combinations are higher than 0.50. If the Nash–Sutcliffe coefficient was less than 0.60, the next 10 CN combinations were skipped to reduce computational time, since the Nash–Sutcliffe coefficient value would likely be similar. The minimum Nash–Sutcliffe coefficient of 0.60 can be easily modified by the users in the automatic calibration program if needed.

3.4. Effects of calibrated CN values on estimation of runoff and pollutant loading

Many studies have been conducted with the L-THIA model to assess hydrologic and water quality impacts of land use change using the default CN values provided in the L-THIA GIS (Bhaduri et al., 1997; Minner et al., 1998; Pandey et al., 2000; Grove et al., 2001; Bhaduri et al., 2001; Kim et al., 2002). Thus, the use of calibrated CN values in runoff and pollutant estimation was investigated to explore the potential impact of such an assumption. The CN dataset from the automatic calibration process output was used, and the changes in estimated daily direct runoff, total nitrogen, total phosphorus, and total lead for the LEC watershed were assessed to examine the importance of correct estimation of the hydrology component for assessing the hydrologic and water quality impacts of land use changes.

4. Results and discussion

4.1. Calibration and validation of L-THIA model

The automatic calibration system was run with the millions of CN combinations for the 1991 land uses and hydrologic soil group maps in the LEC watershed, and 154 CN combinations producing a Nash–Sutcliffe coefficient value of 0.60 or higher were identified. The use of any CN combination out of these CN combinations will produce a Nash–Sutcliffe coefficient of 0.60 or higher for the calibration period—from January 1, 1991 to June 30, 1991. The land uses, hydrologic soil group, and calibrated CN maps for the LEC watershed are shown in Fig. 5. The L-THIA model was run for July 1, 1991 to December 31, 1991 using 1991 LEC land use, soil data, and rainfall data for validation purposes. The first CN set from the 154 CN

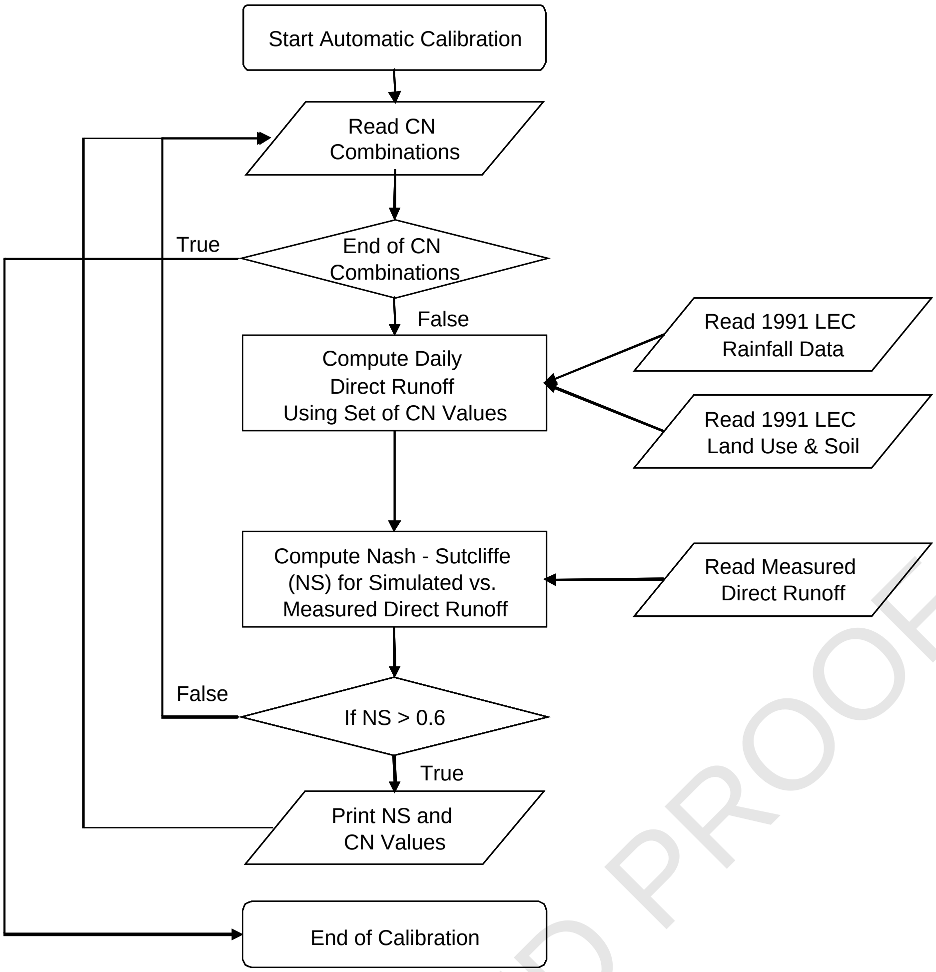

Fig. 4. Schematic diagram of automatic calibration process.

combinations was used for the validation period, since the Nash–Sutcliffe coefficients for these combinations were nearly identical. The coefficient of determinant (R^2) value was 0.88, and the Nash–Sutcliffe coefficient value was 0.60 for the validation period. The daily calibration and validation results using the 1991 rainfall data with the 1991 LEC land use and soil data are shown in Fig. 6. For both calibration and validation periods, the estimated daily direct runoff values match the measured direct runoff reasonably well, with a Nash–Sutcliffe coefficient of 0.60. The Nash–Sutcliffe coefficient was 0.52 for January 1, 1991 to December 31, 1991 using uncalibrated CN values.

4.2. Effects of calibrated CN values on estimation of runoff and pollutant loading

To demonstrate the potential impact of calibration of the L-THIA hydrologic component, changes in direct runoff and the NPS pollutants total nitrogen, total phosphorus, and total lead were assessed with calibrated CN values. The estimated average annual direct runoff in the LEC watershed increased 34%, total nitrogen increased 24%, total phosphorus increased 22%, and total lead increased 43% (Fig. 7) compared with values estimated using the default CN values provided in the L-THIA GIS. In the L-THIA system, the pollutant loading is estimated by multiplying simulated direct runoff by the EMC value. As the simulated runoff increases with the calibrated CN values, the same general trends were found as expected for pollutant loadings. However, the magnitudes of changes were different for each pollutant, because the EMC values for total nitrogen and total phosphorus are higher for agricultural areas, while the EMC value for total lead is higher for residential areas. Since these land uses have different runoff volumes, the changes in NPS pollutants differ somewhat from the overall change in estimated runoff.

4.3. Discussion

The calibration of the L-THIA model was performed using the Nash–Sutcliffe coefficient as the sole indicator to measure the fit between L-THIA estimated direct runoff values and measured direct runoff values. However, other statistics may also need to be considered in calibration of models such as L-THIA because the Nash–Sutcliffe

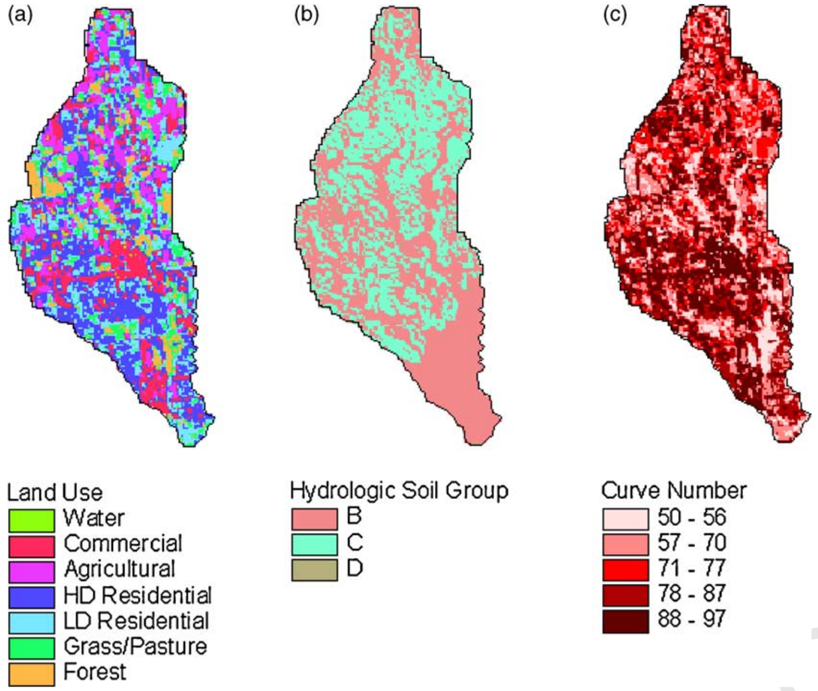

Fig. 5. Land uses (a), hydrologic soil group (b), and calibrated curve number values (c) for the little eagle creek watershed.

coefficient is very sensitive to extreme values (Legates and McCabe Jr., 1999).

The L-THIA model under predicted high values during calibration, but the trend was reversed during validation. As explained before, the AMC adjustment was not made in this study, because the L-THIA model under predicted the measured direct runoff values for this assumption within this watershed (Lim et al., 2005). There were two consecutive rainfall events (34.00 and 34.79 mm) during the calibration period, and the flow rate increased from baseflow to 62.3 and 152.9 m^3/s with the consecutive rainfall events. The estimated direct runoff for the 34.00 mm event was similar to that for the 34.79 mm rainfall that occurred on the very next day. In reality, more direct runoff would be expected with increased soil moisture due to a large rainfall event occurring on the previous day. However, the L-THIA estimated direct runoff did not reflect the effects of these consecutive rainfall events since no AMC adjustment was made. Thus, the L-THIA model under predicted the high runoff value during calibration. During validation, there

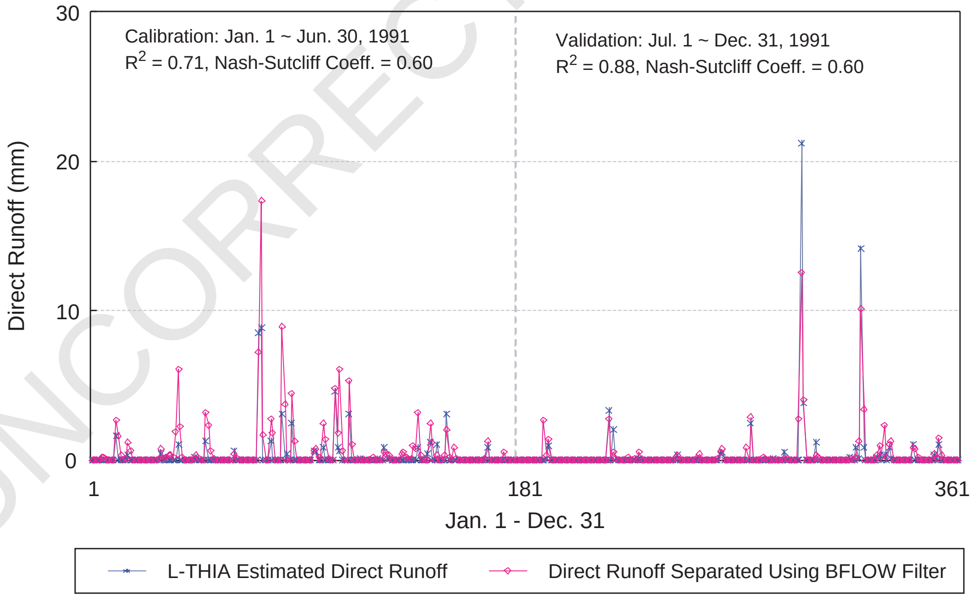

Fig. 6. L-THIA calibration results for January 1, 1991–June 30, 1991 and validation results for July 1, 1991–December 31, 1991 for the little eagle creek watershed.

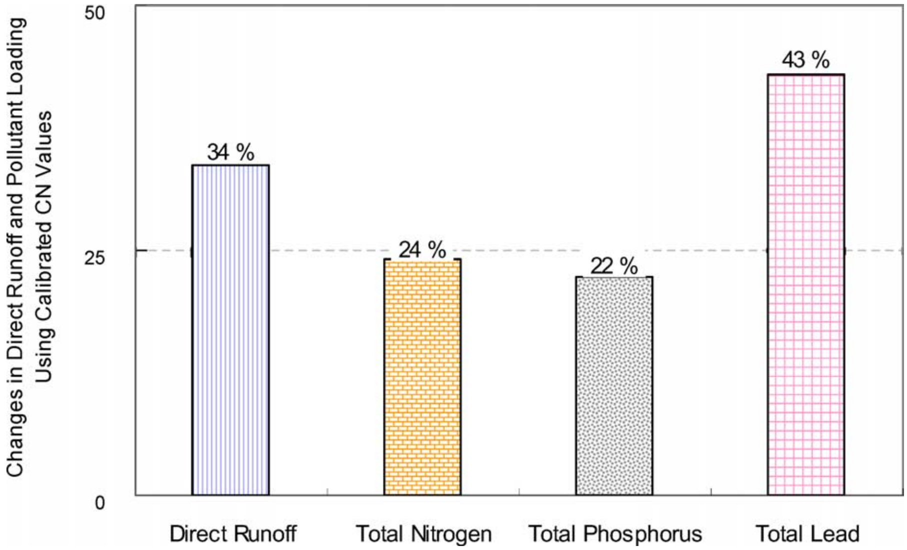

Fig. 7. Changes in average annual direct runoff and pollutant loadings using calibrated CN values for the little eagle creek watershed.

were 2.54 and 58.17 mm rainfall events on consecutive days. L-THIA estimated direct runoff for the 58.17 mm rainfall event was higher than that for the 34.79 mm rainfall event, while the observed stream flow rate was lower than that for the 34.79 mm event at 108.5 m^3/s. Thus, further research is needed to explore possible new criteria for AMC adjustments.

Tens of days were required to run the automatic calibration program for the LEC watershed, because it ran the model and computed the Nash–Sutcliffe coefficient for each set of CN values for the LEC watershed. Thus, better algorithms need to be used in the automatic calibration program to reduce the time needed for calibration.

5. Conclusions

An automatic calibration program for the L-THIA model was developed in this study, because it was not feasible to calibrate the L-THIA model manually for the millions of possible CN combinations that might be used to describe a watershed. It was applied for the calibration/validation processes for the LEC watershed in Indiana. For the calibration period, the comparison of simulated daily direct runoff with the measured daily direct runoff gave an R^2 of 0.71 and a Nash–Sutcliffe coefficient of 0.60. The calibrated CN values were used for the validation of the model using the same land use and soil data for the last six months in 1991. The R^2 value was 0.88 and the Nash–Sutcliffe coefficient was 0.60 for the validation period. The Nash–Sutcliffe coefficient was 0.52 for January 1, 1991 to December 31, 1991 using uncalibrated CN values. The impacts of calibration on estimated direct runoff and NPS pollutant loadings were investigated by comparing the estimated values using calibrated and uncalibrated CN values. The L-THIA estimated average annual direct runoff for the LEC watershed increases by 34% and NPS sources of nitrogen by 24%, phosphorus by 22%, and lead by 43% with the calibrated CN values. This indicates that hydrologic and water quality impacts using the default CN values could be somewhat different than those for calibrated CN values. This study indicated that the L-THIA model should be calibrated and validated prior to application in a particular watershed to more accurately assess the effects of land use changes on hydrology and water quality.

The automatic calibration routine needs to be refined to complement the Nash–Sutcliffe coefficient, which is very sensitive to extreme values. Further investigation is needed for possible new criteria for AMC adjustment by examining rainfall data for numerous locations and conducting validation using a hydrologic model, such as L-THIA. For practical purposes, better algorithms need to be used in the automatic program developed in this study because tens of days were required to run the automatic calibration program for the LEC watershed.

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