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EFFECTS OF INITIAL ABSTRACTION AND URBANIZATION ON ESTIMATED RUNOFF USING CN TECHNOLOGY[1]

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ABSTRACT: Few studies have been conducted to explore the effects of initial abstraction on estimated direct runoff despite the widespread use of the curve number (CN) method in many hydrologic models to estimate direct runoff. In this study, use of a 5 percent ratio of initial abstraction (I_a) to storage (S) to estimate daily direct runoff with modified CN values for a 5 percent I_a/S value was investigated using the Long-Term Hydrologic Impact Assessment (L-THIA) geographic information system (GIS). In addition, the effects on estimated runoff of altering the hydrologic soil group due to urbanization were investigated. The L-THIA model was applied to the Indiana Little Eagle Creek watershed with 5 percent and 20 percent I_a/S values, considering hydrologic soil group alteration due to urbanization. The results indicate that uses of a 5 percent I_a/S and modified CN values and Hydrologic Soil Group D for urbanized areas in model runs can improve long term direct runoff prediction.
(KEY TERMS: hydrology; curve number; initial abstraction; runoff; urbanization; infiltration; hydrologic soil group; antecedent moisture condition.)

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INTRODUCTION

A hydrograph is a graph showing the flow rate versus time at a specific point on a stream. The spikes in the hydrograph, caused by and directly following storm events and snow melting events, are called "direct runoff" (Chow *et al.,* 1988). The CN method is an empirical approach to estimate the direct runoff from the relationships between rainfall, land uses, and hydrologic soil group. The CN values range from 25 to 98, depending on land uses, hydrologic soil group, and antecedent moisture condition (USDA-SCS, 1986). Many hydrologic models use the CN method to estimate direct runoff from fields or watersheds. The CN runoff method was initially developed from many experimental watersheds, and an empirical relation between the initial abstraction and the storage was developed; 20 percent of storage is initial abstraction (Equation [1]) based on the guidance from the National Engineering Handbook, Section 4, Hydrology (USDA-SCS, 1985).

$$Ia = 0.2S$$

where I_a is the initial abstraction (cm) and S is storage (cm).

The relationship between the CN values and storage (S) is expressed by

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

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However, Hawkins *et al.* (2002) used event analysis and model fitting methods and found that 5 percent may be a better representative ratio of initial abstraction to storage (I_a/S) than 20 percent. Also, the CN values with 5 percent I_a/S value are not the same as the CN values with a 20 percent I_a/S value because the value of S with a 5 percent I_a/S value is not the same as the one used in estimating direct runoff with a 20 percent I_a/S value. Thus, the CN values need to be modified when a 5 percent I_a/S value is used in estimating direct runoff (Hawkins *et al.,* 2002).

Many hydrologic models have been developed and used; however, most models are limited because of their intensive input data requirements. A significant amount of time is typically required for model users in preparing input data for models. Calibration/validation of the model requires even more efforts for accurate model application. Thus, there is a need for easy-to-use hydrology models with reasonable accuracies. To address this need the L-THIA model was developed and integrated with the ArcView GIS system (ESRI, 2002). The L-THIA GIS system estimates direct runoff from very basic input data, such as long term daily rainfall data, land uses, and hydrologic soil group (Harbor, 1994; Bhaduri, 1998; Lim *et al.,* 2001). Grove *et al.* (2001) applied the L-THIA GIS system to the Little Eagle Creek (LEC) watershed in Indiana without considering temporal changes of land use and alteration of the hydrologic soil group due to possible soil compaction and disturbance that often occurs during urbanization (Ocean County Soil Conservation District, 2001). The L-THIA model underpredicted direct runoff compared with observed U.S. Geological Survey (USGS) direct runoff values from hydrograph separation. The predictions amounted to around 62 percent of observed direct runoff values. Grove *et al.* (2001) used the common CN method that assumes initial abstraction is 20 percent of storage. The results indicated that a 20 percent I_a/S value might not be an appropriate value. Improvements in L-THIA's predictive ability may be expected with a 5 percent I_a/S value. Further improvements may be expected when land use changes are considered as well as the impacts of these changes on hydrologic soil group.

The first objective of this study was to verify whether a 5 percent I_a/S value with corresponding CN values improves direct runoff estimation. The second objective was to assess the effects of altering the hydrologic soil group due to soil compaction associated with urbanization and the use of a 5 percent I_a/S value and corresponding CN values on the L-THIA model's prediction of direct runoff.

LITERATURE REVIEW

Curve Number (CN) Method

The CN method, developed by the U.S. Department of Agriculture Soil Conservation Service (USDA-SCS), now Natural Resources Conservation Service (USDA-NRCS), has been widely used to estimate direct runoff. The hypothesis of the USDA-SCS 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-SCS, 1985; Chow *et al.,* 1988), as indicated by

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{3}$$

where F_a is the actual retention in the watershed, excluding I_a (cm); P is the precipitation (cm); P_e is the actual direct runoff (cm), S is the storage determined by Equation (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

$$P_e = \frac{\left(P - I_a\right)^2}{P - I_a + S} \qquad \text{for } P > I_a = 0.2S \tag{4a}$$

$$P_e = 0 \qquad \text{for } P < I_a = 0.2S \tag{4b}$$

Curve Number Initial Abstraction Ratio

The relationship I_a = 0.2S (Equation [1]) was derived from the study of many small, experimental watersheds, and details on this relationship can be found in the National Engineering Handbook, Section 4, Hydrology (USDA-SCS, 1985, 1986). Since the history and documentation of this relationship are obscure, Hawkins *et al.* (2002) used event analysis and model fitting methods to determine the ratio of I_a to S with hundreds of rainfall-runoff data from numerous U.S. watersheds.

For event analysis, Hawkins *et al.* (2002) analyzed rainfall and runoff data for 134 USDA Agricultural Research Service (USDA-ARS) watersheds. The storm rainfall depth when direct runoff started was considered the initial abstraction value. With the known values of event rainfall, direct runoff, and initial abstraction value, S was obtained from Equation (4a).

The ratio of I_a to S was obtained for each storm event. The median value of these ratios for all storm events was used as a representative value for each watershed.

For model fitting, the ratio of I_a to S was determined by iterative least squares fitting. Rainfall and runoff data for 307 watersheds and plots were used in these model fittings (Hawkins *et al.,* 2002). In the model fitting, the natural pairs of rainfall and direct runoff, which naturally occur in time, and ordered pairs of rainfall and direct runoff were used. Hawkins *et al.* (2002) found that the ratio of I_a to S varies from storm to storm and watershed to watershed and that the assumption of $I_a/S = 0.20$ is usually high. According to the event analysis, the median I_a/S ratio for each watershed varied from 0.0005 to 0.4910, and the median value was 0.0476. More than 90 percent of I_a/S ratios were less than 0.2. Results from model fitting were more varied than those from event analysis. I_a/S ratios for natural data ranged from 0 to 0.996, with a median of 0, and I_a/S ratios for ordered data ranged from 0 to 0.9793 with a median of 0.0618 (Hawkins *et al.,* 2002).

Based on the study by Hawkins *et al*. (2002), use of an I_a/S ratio of 0.05 rather than the commonly used value of 0.20 would seem appropriate. Thus, the CN runoff equation becomes

$$P_e = \frac{\left(P - 0.05S_{0.05}\right)^2}{P + 0.95S_{0.05}} \qquad \text{for P > 0.5S} \qquad (5a)$$

$$P_e = 0 \qquad \text{for P < 0.5S} \qquad (5b)$$

In Equation (5a), the value of $S_{0.05}$ is not the same as the one used in estimating direct runoff with an I_a/S ratio of 0.20, because 5 percent of the storage is assumed to be the initial abstraction in Equation (5a). The relationship between $S_{0.05}$ and $S_{0.20}$ was obtained from model fitting results using rainfall-runoff data from 307 watersheds, and the new CN values with $S_{0.05}$ can be obtained with (Hawkins *et al.,* 2002),

$$S_{0.05} = 1.33{S_{0.20}}^{1.15} \qquad (6a)$$

$$CN_{0.05} = \frac{100}{1.879\left[\frac{100}{CN_{0.20}} - 1\right]^{1,15} + 1} \qquad (6b)$$

where $S_{0.05}$ and $CN_{0.05}$ are the storage (cm) and CN values with a 5 percent I_a/S ratio, and $S_{0.20}$ and $CN_{0.20}$ are the values with a 20 percent I_a/S ratio. The conjugate CN values ($CN_{0.20}$ and $CN_{0.05}$) were computed with corresponding storage values ($S_{0.20}$ and $S_{0.05}$) using Equation (6b).

Alteration of Hydrologic Soil Group Due to Urbanization

The hydrologic soil group is used to estimate the CN value in the L-THIA model. Hydrologic soil group values, commonly associated with the soil infiltration rate, are obtained based on measurements of native, undisturbed soil samples (Gregory *et al.,* 1999). However, land surfaces are becoming less pervious due to disturbance of established soil structure in urbanizing watersheds, which results in increased flow (Holman-Dodds *et al.,* 2003). Thus, the use of the original hydrologic soil group value for urbanized areas is often a poor assumption because earthwork operations result in significantly compacted and disturbed soil (Gregory *et al.,* 1999).

The Ocean County Soil Conservation District (2001), in New Jersey, investigated the effects of soil modification and compaction during construction operations in urban areas on soil infiltration rates to determine whether the effects are sufficient to alter the hydrologic soil group classification. The results show that the runoff from many recently constructed housing developments exceeds the simulated runoff based on the CN method using undisturbed hydrologic soil group values. The Ocean County Soil Conservation District found that the hydrologic soil group at recently urbanized sites were Group A or B, based on soil survey data and texture. However, the observed infiltration rates were less than 0.38 cm/hr, suggesting Hydrologic Soil Group C or D. The Ocean County Soil Conservation District study indicated that construction operations significantly compacted the soil, resulting in the alteration of the hydrologic soil group classification, likely to a Group C or D condition. Thus, the study recommended that planners and designers should account for the effects of soil compaction when estimating runoff. However, the impacts of increased direct runoff due to greater areas covered by pavement and buildings were not assessed in the study.

Overview of the L-THIA GIS System

The L-THIA model was developed to estimate the direct runoff from daily rainfall depth, land use, and hydrologic soil group data (Harbor, 1994), and it has been integrated with the ArcView GIS system. The L-THIA model computes the daily direct runoff value from land use and hydrologic soil group data with daily rainfall data. Then, it computes long term average annual runoff depths. For nonpoint source pollutant estimation for non-urban areas as well as urban areas with L-THIA, event mean concentration (EMC) coefficients for each land use were incorporated into L-THIA (Lim *et al.,* 2001). Figure 1 shows how the L-THIA system simulates direct runoff and pollutant loadings based on the estimated direct runoff. As shown in Figure 1, the pollutant loading is estimated by multiplying direct runoff quantity by the EMC value for each land use. In the L-THIA GIS system, eight representative land use classifications are used: Water, Commercial, Agricultural, High-density (HD) Residential, Low-density (LD) Residential, Grass/Pasture, Forest, and Industrial. Hydrologic Soil Groups A, B, C, and D are used to compute the CN values for corresponding combinations of eight land uses and four hydrologic soil groups using a CN look-up table. Based on the CN values for an area of interest, the L-THIA model estimates daily direct runoff using daily rainfall data. More details about the L-THIA GIS system can be found in the L-THIA GIS Users Manual (Engel, 2005).

METHODS

Precipitation Producing More Runoff With 5 Percent I_a/S Ratio

Hawkins et al. (2002) computed a critical precipitation value, at which the direct runoff using a 0.20 I_a/S value is the same as the direct runoff using a 0.05 I_a/S value for the conjugate CN. In this study, the precipitation ranges producing more runoff were computed numerically for all CN values to identify precipitation values that fall between these precipitation criteria. The direct runoff with 20 percent I_a/S and 5 percent I_a/S values were calculated for a series of CN values.

Study Area

In this study, the L-THIA GIS system was applied to the LEC watershed in Indiana to simulate average annual runoff. The LEC watershed, located in central Indiana, is 70.5 km^2 in size (Figure 2). It has experienced significant urbanization (18 percent increase in urban area) over the past 20 years, with most changes

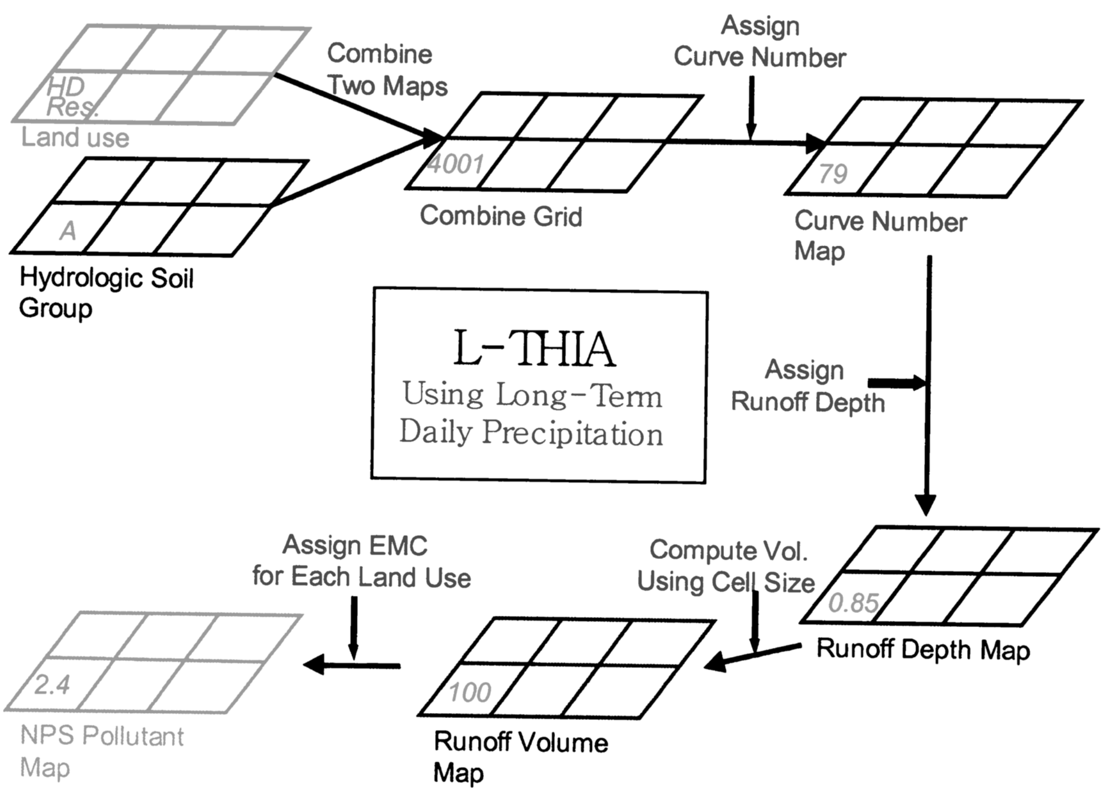

Figure 1. Overview of the LTHIA GIS System (modified from Lim *et al.,* 2001).

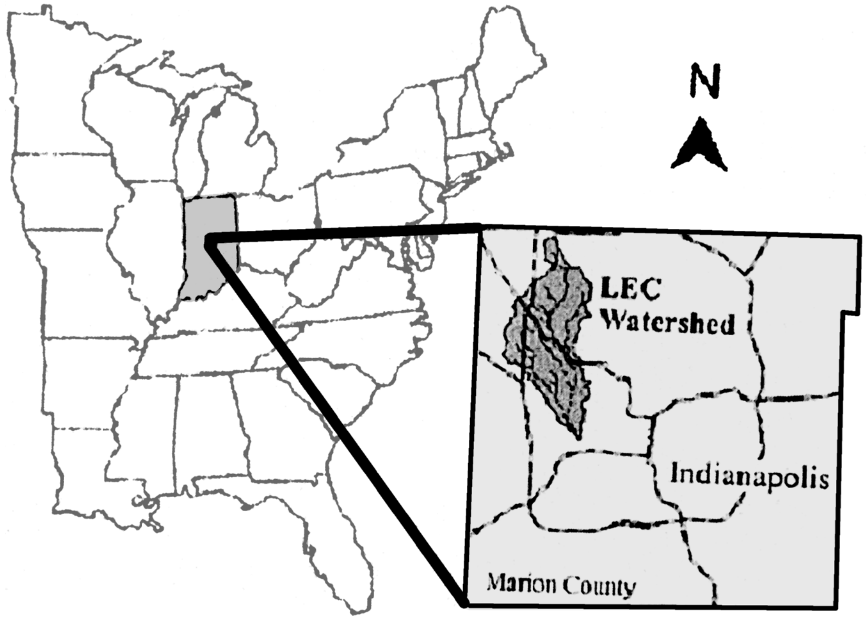

Figure 2. Location of the Little Eagle Creek (LEC) Watershed.

between 1973 and 1984 (14 percent increase in urban area) (Bhaduri *et al.,* 2000). Land uses ranging from nonurban natural grass and 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 (more than 200 percent) in the watershed. The Agricultural area has decreased slightly over the years. Urbanized land area in the LEC watershed made up about 50 percent of the total land area in 1973 and about 68 percent of the total land area in 1991.

Application of L-THIA GIS System

The L-THIA GIS system was run for the LEC watershed to simulate direct runoff using 20 percent and 5 percent I_a/S ratio values, with corresponding conjugate CN ($CN_{0.20}$ and $CN_{0.05}$) tables. When L-THIA estimates daily direct runoff, it assumes that direct runoff is not produced when the precipitation is less than the initial abstraction. Thus, the simulated direct runoff values will be different for 5 percent and 20 percent I_a/S values. The 1973, 1984, and 1991 land use data for the LEC watershed were used (Bhaduri, 1998). In the L-THIA GIS system, long term daily precipitation data are used to compute annual average direct runoff for a series of land use maps. Many past L-THIA applications to estimate the direct runoff used the long term average runoff depth for the entire simulation period without considering the temporal changes in precipitation over the simulation period (Pandey *et al.,* 2000; Kim *et al.,* 2002). However, this is not a reasonable assumption if significant differences exist in the precipitation quantity for the simulation period. To facilitate comparison of observed and L-THIA estimated runoff, the rainfall data were grouped for periods around available land use data, that is, for 1973, 1984, and 1991. Thus, the long term daily precipitation data, built into L-THIA (Engel, 2004), were split into three segments: October 1, 1967, to September 30, 1979 (11 years), for 1973 land use data; October 1, 1979, to September 30, 1988 (nine years) for 1984 land use data; and October 1, 1988, to September 30, 1995 (seven years) for 1991 land use data. It is assumed that within each of the three periods, the effects of land use changes are minor. As stated before, the hydrologic soil group can change due to possible soil compaction and disturbance that often occurs during urbanization (Ocean County Soil Conservation District, 2001). Thus, the L-THIA GIS system was run for three soil scenarios: original hydrologic soil data; Hydrologic Soil Group C data for urbanized areas; and Hydrologic Soil Group D data for urbanized areas.

To run the L-THIA GIS system with a 5 percent I_a/S ratio value for the three hydrologic soil group scenarios, the original CN table had to be modified based on Equation (6b) (Hawkins *et al.,* 2002). Thus, a new CN table for the 5 percent I_a/S ratio was prepared (Table 1) and used in the L-THIA GIS system. The input parameter file to the LTHIA GIS system was

TABLE 1. Conjugate Curve Numbers in the Little Eagle Creek Watershed.

Land Use	HSG	$CN_{0.20}$	$CN_{0.05}$	Land Use	HSG	$CN_{0.20}$	$CN_{0.05}$
Commercial	A	89	85	Grass/Pasture	A	39	24
	B	92	90		B	61	47
	C	94	93		C	74	64
	D	95	94		D	80	72
Agricultural	A	64	51	Forest	A	30	17
	B	75	65		B	55	40
	C	82	75		C	70	59
	D	85	80		D	77	68
HD Residential	A	77	68	Industrial	A	81	74
	B	85	80		B	88	84
	C	90	87		C	91	88
	D	92	90		D	93	91
LD Residential	A	54	39				
	B	70	59				
	C	80	72				
	D	85	80				

Notes: HD is high density. LD is low density. HSG is hydrologic soil group.

modified to use the 5 percent I_a/S ratio value in L-THIA model runs. Figure 3 shows how the yearly L-THIA GIS was used to compute yearly direct runoff depth for each year with each set of historical land use data.

Comparison of L-THIA-Simulated Direct Runoff With Direct Runoff Separated From USGS Streamflow Data

To evaluate the predictive ability of the L-THIA GIS system with 20 percent and 5 percent I_a/S ratio values, the L-THIA-predicted direct runoff values

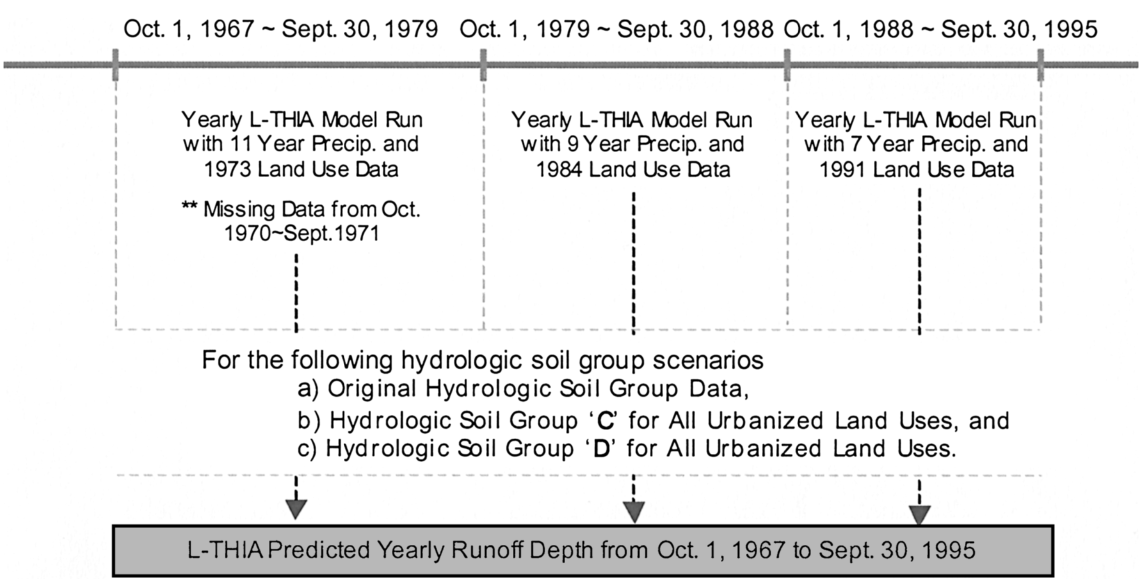

Figure 3. Yearly L-THIA Model Runs With 1973, 1984, and 1991 Land Use Data for the Little Eagle Creek Watershed.

were compared with the direct runoff separated from USGS daily streamflow data for the LEC watershed (USGS, 2003). The automatic hydrograph separation method in the iSep Web GIS (S. Muthukrishnan, K.J. Lim, J. Harbor, and B.A. Engel, unpublished manuscript) was used to separate direct runoff from the streamflow data (Muthukrishnan *et al,* 2005).

RESULTS

Precipitation Producing More Runoff With 5 Percent I_a / S Ratio

For all CN numbers with the 5 percent I_a/S value, the direct runoff was higher than that with the 20 percent I_a/S value for a range of precipitation. Based on the CN method definition, any precipitation less than initial abstraction will not contribute direct runoff ($P_{e0.05} = 0$, for $P < = 0.05S$), and if the precipitation is greater than the initial abstraction value, which is 0.05 multiplied by the storage, it contributes to direct runoff. Therefore, the L-THIA model with a 5 percent I_a/S value will produce more direct runoff if daily precipitation falls within a range of precipitation criteria for the corresponding CN. These precipitation ranges will be called the critical precipitation ranges in this paper. However, if the precipitation exceeds the upper bound of the critical precipitation ranges, more direct runoff is produced with a 20 percent ratio than with a 5 percent ratio because the storage $S_{0.05}$ is not the same as $S_{0.20}$ (Equations 4a, 5a, and 6a). Thus, the estimated direct runoff with a 5 percent ratio is not always greater than that with a 20 percent ratio.

The critical precipitation ranges that contribute more direct runoff with the 5 percent I_a/S value for each CN value are shown in Table 2. For instance, the results indicate that more direct runoff will be produced with the 5 percent ratio for Agricultural land with highly permeable soil ($CN_{0.20}$ = 50) when precipitation is greater than 2.3 cm (0.9 inches) and less than 13.5 cm (5.3 inches).

Effects of 5 Percent I_a / S Ratio on Estimated Long Term Runoff in the LEC Watershed

The L-THIA GIS system was applied to the LEC watershed to compute long term direct runoff with 20 percent I_a/S and 5 percent I_a/S values. The long term annual average direct runoff values with the 5 percent I_a/S ratio are higher than those with the 20 percent I_a/S ratio. This can be explained in that direct runoff with the 20 percent I_a/S ratio value begins only after precipitation exceeds the initial abstraction, which is 20 percent of storage. However, for a 5 percent I_a/S, even small amounts of precipitation, which did not contribute any runoff with the 20 percent ratio, now contribute direct runoff due to the smaller initial abstraction values, 5 percent of storage.

TABLE 2. Conjugate Curve Numbers and Critical Precipitation Ranges Producing More Direct Runoff With a 5 Percent I_a/S Ratio Than a 20 Percent I_a/S Ratio Value.

$CN_{0.20}$	$S_{0.20}$ (cm)	$CN_{0.05}$	$S_{0.05}$ (cm)	Min. P_{crit}. (cm)	Max. P_{crit} (cm)
25	76.2	13.1	168.9	8.4	30.5
30	59.2	16.7	126.5	6.4	25.1
35	47.2	20.7	97.3	4.8	21.1
40	38.1	25.0	76.2	3.8	18.0
45	31.0	29.7	60.2	3.0	15.5
50	25.4	34.7	47.8	2.3	13.5
55	20.8	40.1	37.8	1.8	11.7
60	17.0	45.9	30.0	1.5	10.2
65	13.7	52.0	23.4	1.3	8.9
70	10.9	58.5	18.0	1.0	7.9
75	8.4	65.3	13.5	0.8	6.6
80	6.4	72.4	9.7	0.5	5.8
85	4.6	79.6	6.6	0.3	4.8
90	2.8	86.9	3.8	0.3	4.3
95	1.3	94.0	1.5	0.0	6.1

However, this is only valid when the precipitation falls within the critical precipitation ranges. Thus, the number of precipitation events falling within the critical precipitation ranges for all CN values in the LEC watershed, 40, 47, 59, 64, 65, 72, 75, 80, 87, 90, 93, and 94, were computed. There are 4,626 days with rainfall in the 38-year LEC watershed dataset. For CN values of 40, 47, 59, 64, 65, 72, 75, 80, 87, 90, 93, and 94 in the LEC watershed for the 38-year precipitation record, there are 123, 282, 769, 1028, 1072, 1567, 1777, 2126, 2819, 3150, 3602, and 3832 days, respectively, when daily precipitation falls within these ranges of critical precipitation.

Figure 4 shows the predicted yearly direct runoff with 20 percent and 5 percent I_a/S ratio values for CN values of 25, 45, 65, and 85 during the entire simulation period (from October 1, 1960, to September 30, 1999) for the LEC watershed. The predicted yearly direct runoff values with a 5 percent I_a/S ratio value are higher than those with a 20 percent I_a/S ratio value (74 percent increase in annual average runoff depth for the CN of 85). Also, there are fluctuations in differences between predicted direct runoff values with 20 percent and 5 percent I_a/S ratio values. These are due to the occurrence and magnitude of precipitation that falls between critical precipitation ranges producing more direct runoff with the 5 percent I_a/S ratio value.

Figure 5 shows the percentage runoff increases for a series of conjugate CN values when 20 percent and 5 percent I_a/S ratio values were used. The percentage runoff increases are higher for lower CN values, which are comparable with the results of Hawkins *et al.* (2002). It is worth noting that the total amounts of runoff contribution by the lower CN values may be lower than those by the higher CN values with a 5 percent I_a/S ratio value. This is because more direct runoff is produced with higher CN values in terms of absolute quantity.

The L-THIA GIS predicted runoff value for each land use classification and the percentage runoff increases with a 5 percent I_a/S value were computed for 1973, 1984, and 1991 historic land uses in the LEC watershed to examine the effects of using a 5 percent I_a/S value on percentage runoff increase for each land use classification (Figure 6). The percentage increase in runoff using long-term precipitation was inversely proportional to the average CN value for each land use classification for 1973, 1984, and 1991 historic land uses. This trend is comparable with the results obtained by Hawkins *et al*. (2002). Although average $CN_{0.05}$ values for all land use classifications in 1973, 1984, and 1991 were lower than $CN_{0.20}$ values, there were 2 mm to 57 mm runoff increases annually from 20 percent to 5 percent I_a/S values for each land use. This is because small precipitation amounts contribute more direct runoff with the smaller initial abstraction values (5 percent I_a/S) and less direct runoff with the 20 percent I_a/S value.

The L-THIA predicted annual average direct runoff for the LEC watershed is shown in Figure 7. The predicted runoff with 20 percent and 5 percent I_a/S ratio values were classified into five classes, and the number of cells (area) for each class is shown in the histogram. As shown in runoff depth maps and histograms, there are increases in runoff when the 5 percent I_a/S ratio was used in L-THIA model runs compared to results for a 20 percent I_a/S ratio. For some areas, runoff increases were greater than other areas in the LEC watershed. The Commercial and HD Residential land uses were the primary areas having the largest runoff increases in terms of absolute quantity (not percentage increase in runoff). This indicates that the use of a 5 percent I_a/S ratio value in the L-THIA model with precipitation similar to that of the LEC watershed increases the predicted runoff depth in urbanized watersheds as well as Forest dominated, Grass/Pasture dominated, and Agricultural dominated watersheds because the percentage runoff increases were higher for lower CNs (nonurban area).

Comparison of the L-THIA GIS Predicted Direct Runoff With Direct Runoff Separated From USGS Daily Streamflow

The coefficient of determinant (R^2) for the comparison of the L-THIA predicted direct runoff values using 20 percent and 5 percent I_a/S ratio values with the direct runoff values are similar as shown in Figure 8 (0.681 with 20 percent I_a/S ratio value, and 0.675 with 5 percent I_a/S ratio value), and these data deviate from the 1:1 slope as shown in Figure 8. Thus, the coefficient of efficiency (E), also called the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970), was calculated to quantify the fit between the L-THIA model predicted direct runoff and the measured data. The computation of E essentially is the sum of the deviations of the observations from a linear regression line with a slope of 1 (Equation [7]). 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.

$$E = \frac{\sum_{i=1}^{n}\left(Q_m - Q_{mea\_avg}\right)^2 - \sum_{i=1}^{n}\left(Q_m - Q_p\right)^2}{\sum_{i=1}^{n}\left(Q_m - Q_{mea\_avg}\right)^2} \quad i = 1,2,\ldots n \qquad (7)$$

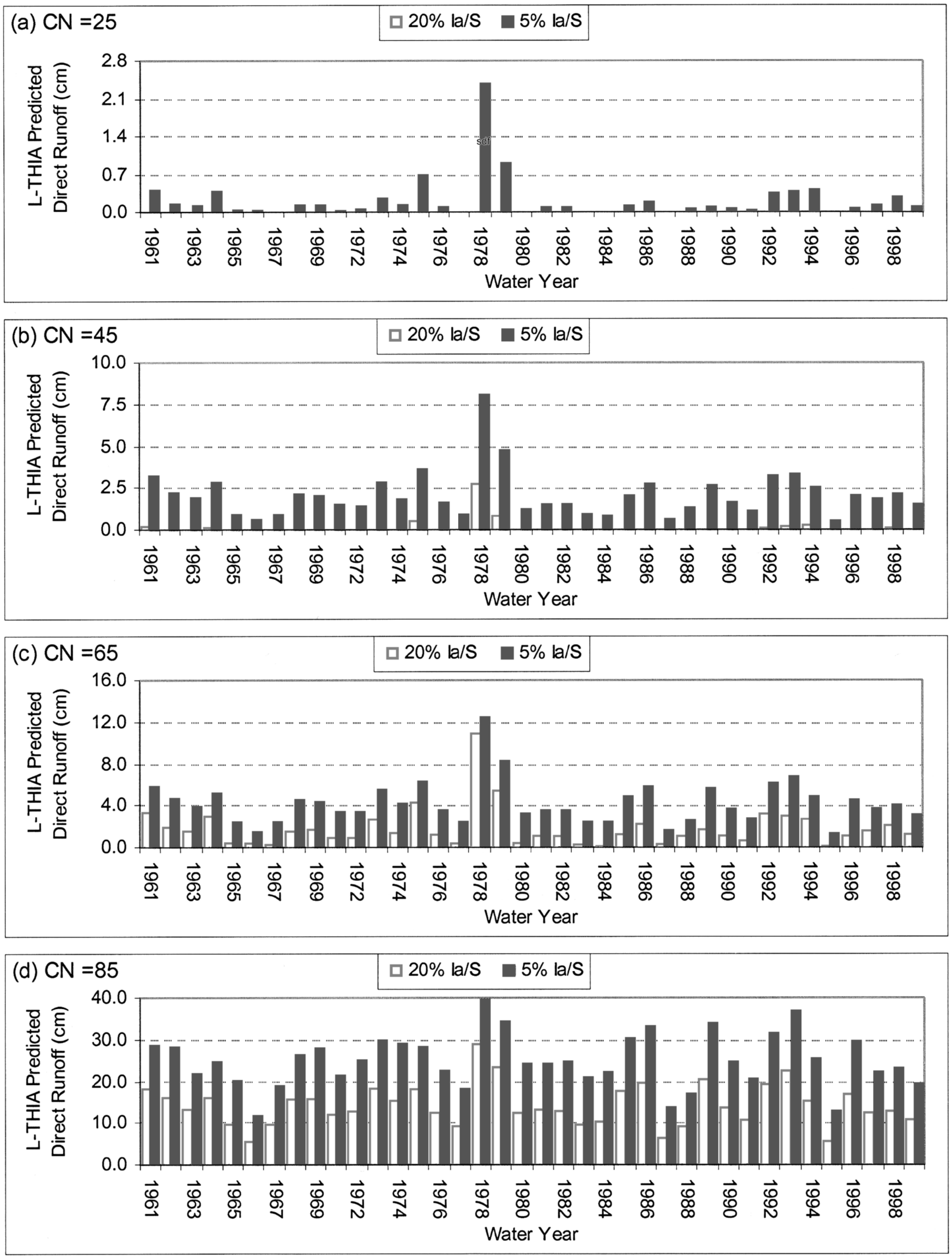

Figure 4. L-THIA Predicted Direct Runoff With 20 Percent and 5 Percent I_a/S Ratio Values for the Little Eagle Creek Watershed.

where E is the coefficient of efficiency (Nash-Sutcliffe coefficient), Q_m is the measured value, Q_p is the predicted value, and Q_{mea_avg} is the arithmetic average measured value.

For the calibration method proposed for the Soil and Water Assessment Tool (SWAT) model by Santhi *et al.* (2001), an E value greater than 0.50 was deemed acceptable for model calibration. The E values for the comparison of measured and predicted

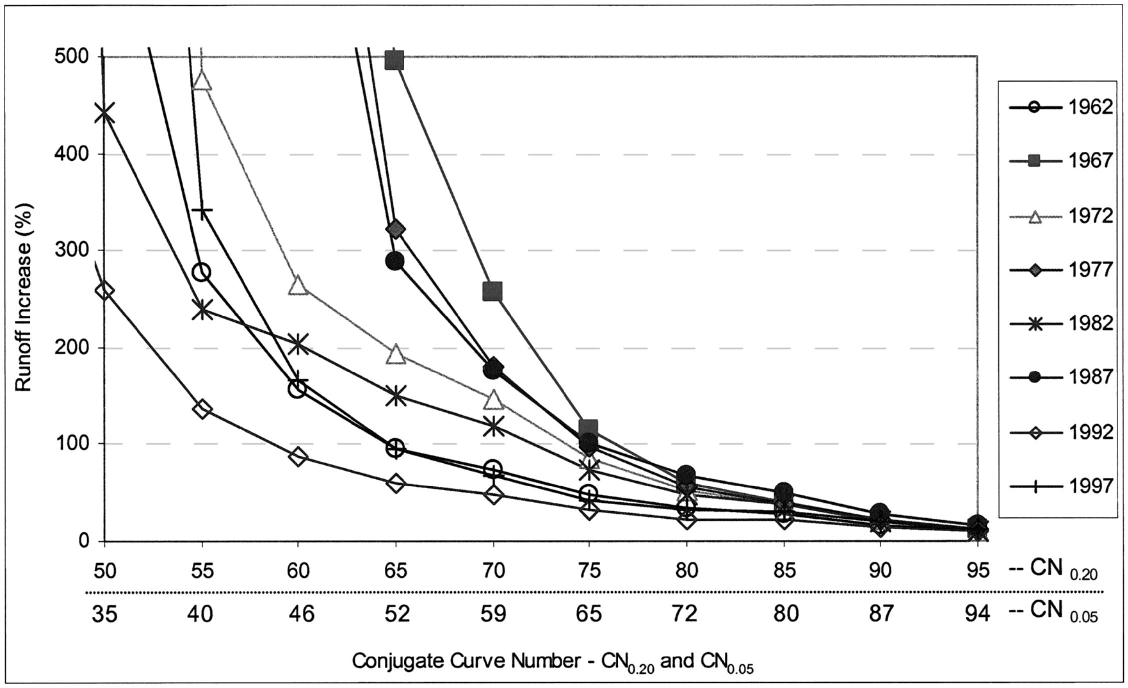

Figure 5. Percentage of Increase in Predicted Direct Runoff From 20 Percent to 5 Percent I_a/S Ratio Values for the Little Eagle Creek Watershed. (Percentage of runoff increase was computed for conjugate CNs for every five years from 1962 to 1997.)

direct runoff was -2.27 with a 20 percent I_a/S ratio value, and -1.19 with a 5 percent I_a/S ratio value, indicating very poor model performance. The predicted direct runoff with 20 percent and 5 percent I_a/S values was always lower than the measured direct runoff for the entire simulation period. These lower predicted direct runoff values, compared with the measured values, are responsible for these poor E values. These results indicate that predictions were very poor, and the average observed value of runoff was a better estimate than the model prediction.

Underprediction of the Direct Runoff Due to Antecedent Moisture Condition Adjustment for the LEC Watershed

The model predicted values were generally lower than the measured direct runoff for all simulation periods, and thus the E values are poor. Thus, the effects of adjusting the antecedent moisture condition (AMC) in the L-THIA model runs were investigated to explain why the L-THIA model underpredicts direct runoff. In the L-THIA model, the direct runoff is estimated based on the CN after adjusting CN values depending on preceding five-day rainfall values. Nearly 70 percent of days with rain for the long term simulation period fall in the AMC I. If the five-day precipitation is less than 3.56 cm (1.4 inches) during the growing season and less than 1.27 cm (0.5 inches) during the dormant season, it is considered AMC I (Chow *et al.,* 1988) and eventually results in lower CN values and lower estimation of direct runoff. This may be one of the reasons the L-THIA model always underpredicts the direct runoff, as shown in Figure 8.

L-THIA GIS System Estimated Direct Runoff Considering Soil Compaction

The L-THIA model was run without adjusting AMCs with the three hydrologic soil group scenarios as described before to assess the effects of soil compaction and disturbance on the predicted direct runoff. The L-THIA-predicted yearly direct runoff values were compared with the measured direct runoff for all simulation periods to evaluate the predictive ability of the L-THIA GIS system with 20 percent and 5 percent I_a/S ratio values and different hydrologic soil group scenarios. Figure 9 shows the comparisons of the L-THIA-predicted yearly direct runoff with the measured direct runoff with three soil scenarios, assuming AMC II for all simulation periods. As shown in this figure, the L-THIA-predicted direct runoff values increased compared to those with adjusted AMCs (57 percent and 48 percent increases by assuming AMC II with 20 percent and 5 percent I_a/S values, respectively). This was because nearly 70 percent of days with rain for the 38-year simulation period have AMC I resulting in decreased CN values and therefore decreased direct runoff estimation.

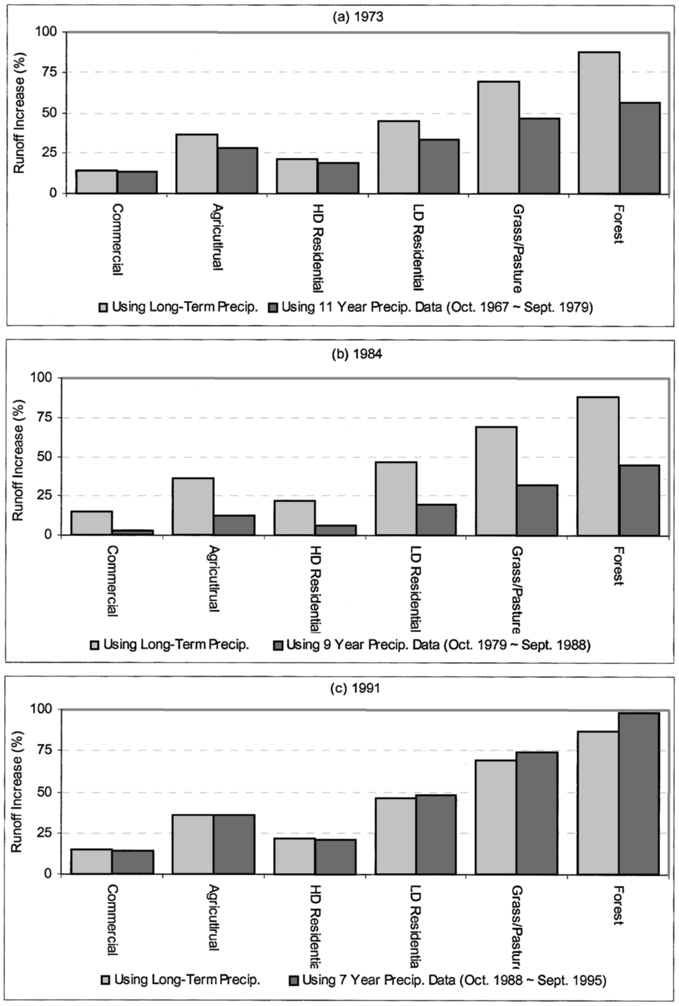

Figure 6. Percentage Runoff Increase With 5 Percent I_a/S Ratio Values for Land Uses in the Little Eagle Creek Watershed during: (a) 1973, (b) 1984, and (c) 1991.

Figure 10 shows the relationships between L-THIA predicted yearly direct runoff with three hydrologic soil group scenarios and measured direct runoff. The coefficient of determinant (R^2) values for the comparison of the L-THIA predicted direct runoff with different soil scenarios and the USGS direct runoff were similar for all cases. However, the Nash-Sutcliffe coefficients (E) were very low (-0.57 and 0.19) when the original hydrologic soil group data were used (Figures 10a and 10b). This indicates that the prediction was very poor, with high deviations from the measured data. As shown in Figures 10c and 10d, the coefficient of efficiency (E) with a 5 percent I_a/S value and the Hydrologic Soil Group C for all urbanized areas was much higher than that with a 20 percent I_a/S value, and the predicted direct runoff with a 5 percent I_a/S value was closer to the measured direct runoff. The coefficient of efficiency (E) with the Hydrologic Soil Group D for all urbanized land uses was higher compared to other scenarios considered in this study. The R^2 and E values with 20 percent and 5 percent I_a/S ratio values were similar when Hydrologic Soil Group D was used. Therefore, the L-THIA simulation with Hydrologic Soil Group D and a 5 percent I_a/S ratio value for all urbanized areas would be reasonable. This conclusion is consistent with that of the Ocean County Soil Conservation District (2001) study. Therefore, the use of the 5 percent I_a/S ratio value in the L-THIA model runs considering temporal changes of land use and hydrologic soil group alterations due to soil compaction and disturbance in urbanized areas could improve the model predictive ability as shown in this study.

CONCLUSIONS

In estimating direct runoff with a 5 percent I_a/S value using the CN method, the CN values need to be modified because the storage value with a 5 percent I_a/S value is not the same as the one used in estimating direct runoff with a 20 percent I_a/S value. Hydrologic soil group data for urbanized areas also need to be modified due to possible soil compaction during the urbanizing processes, which results in alteration of CN values. The L-THIA GIS system was applied to the Little Eagle Creek watershed in Indiana to investigate effects on estimated direct runoff of the uses of a 5 percent I_a/S value, modified CN values for I_a/S value, and Hydrologic Soil Group D for urbanized areas in this study. The comparison of the L-THIA model predicted direct runoff values with observed direct runoff separated from USGS daily streamflow data indicates that the use of a 5 percent I_a/S value with modified CN values for a 5 percent I_a/S value and Hydrologic Soil Group D for urbanized areas can improve long term direct runoff estimation.

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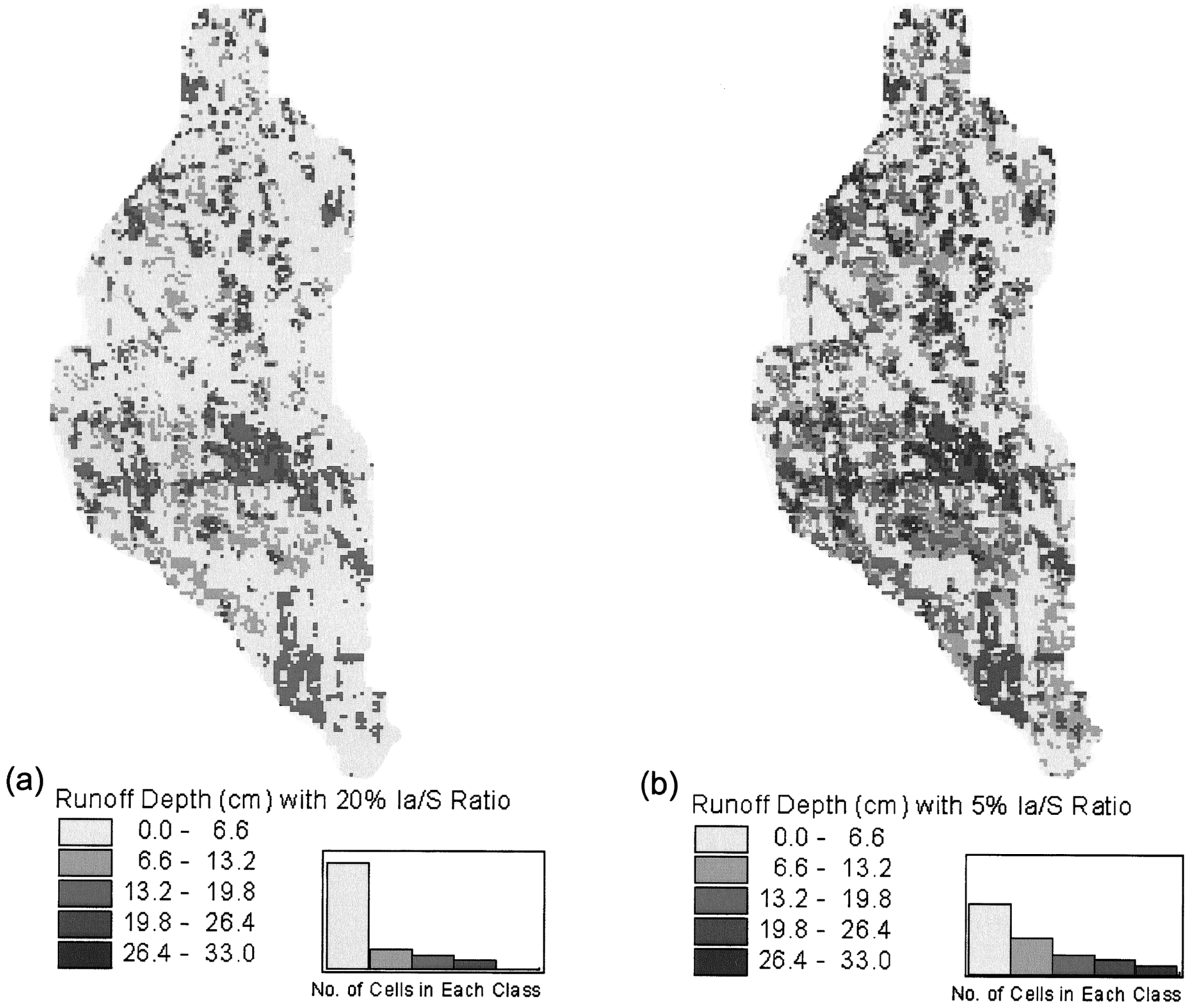

Figure 7. L-THIA Predicted Runoff Depth Using 1991 Little Eagle Creek Land Use Data With Seven-Year Precipitation Data (1989 through 1995).

LITERATURE CITED

Bhaduri, B., 1998. A Geographic Information System Based Model for Assessing Long-Term Impact of Land Use Change on Non-Point Source Pollution at a Watershed Scale. Ph.D Dissertation. Purdue University, West Lafayette, Indiana.

Bhaduri B., J. Harbor, B.A. Engel, and M. Grove, 2000. Assessing Watershed-Scale, Long-Term Hydrologic Impacts of Land-Use Change Using a GIS-NPS Model, Environmental Management 26(6): 643-658.

Chow, V.T., D.R. Maidment, and L.W. Mays, 1988. Applied Hydrology. McGraw-Hill. Singapore.

Engel, B.A., 2004. L-THIA: Land Use Impacts on Water Quality. *Available at* http://www.ecn.purdue.edu/runoff/lthianew/. *Accessed in* March 2006.

Engel, B.A., 2005. L-THIA NPS: Long-Term Hydrologic Impact Assessment Non Point Source Model, Version 2.3. *Available at* http://www.ecn.purdue.edu/runoff/lthia/gis/lthia_gis_users_manual_ver23.pdf. *Accessed in* March 2006.

ESRI (Environmental Systems Research Institute), 2002. ArcView 3.3. Environmental Systems Research Institute, Inc., Redlands, California.

Gregory, M.A., B.A. Cunningham, M.F. Schmidt, and B.W. Mack, 1999. Estimating Soil Storage Capacity for Stormwater Modeling Application. *In:* Proceedings of 6th Biennial Stormwater Research and Watershed Management Conference. Southwest Florida Watershed Management District, Tampa, Florida. CD-ROM.

Grove, M., J. Harbor, B.A. Engel, and S. Muthukrishnan, 2001. Impacts of Urbanization on Surface Hydrology, Little Eagle Creek, Indiana, and Analysis of L-THIA Model Sensitivity to Data Resolution. Physical Geography 22:135-153.

Harbor, J., 1994. A Practical Method for Estimating the Impact of Land Use Change on Surface Runoff, Groundwater Recharge and Wetland Hydrology. Journal of American Planning Association 60:91-104.

Hawkins, R.H., R. Jiang, D.E. Woodward, A.T. Hjelmfelt, and J.A. Van Mullem, 2002. Runoff Curve Number Method: Examination of the Initial Abstraction Ratio. *In:* Proceedings of the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada. U.S. Geological Survey, Lakewood, Colorado. CD-ROM.

Holman-Dodds, J.K., A.A. Bradley, and K.W. Potter, 2003. Evaluation of Hydrologic Benefits of Infiltration Based Urban Storm Water Management. Journal of the American Water Resources Association (JAWRA) 39(1):205-215.

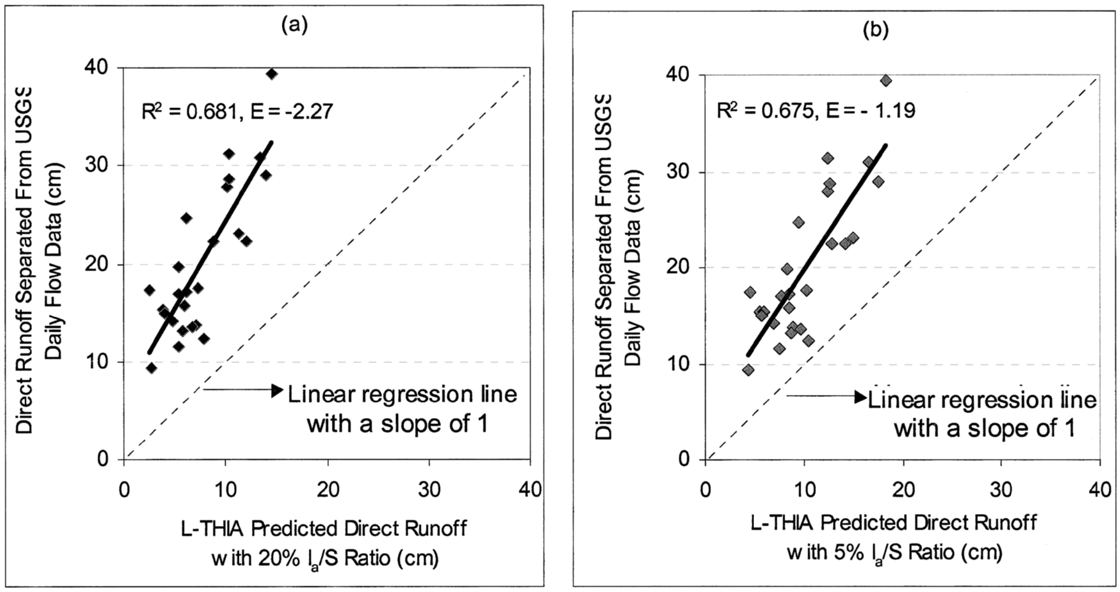

Figure 8. The Relationship Between Direct Runoff Separated From USGS Daily Streamflow and L-THIA Predicted Direct Runoff (AMC adjusted) With (a) 20 percent and (b) 5 percent I_a/S Ratio Values (where R^2 is coefficient of determinant and E is coefficient of efficiency, also called Nash Sutcliffe coefficient).

Kim, Y., B.A. Engel, K.J. Lim, V. Larson, and B. Duncan, 2002. Runoff Impacts of Land-Use Change in Indian River Lagoon Watershed. Journal of Hydrologic Engineering, 7(3):245-251.

Lim, K.J., B.A. Engel, Y. Kim, and J. Harbor, 2001. Development of the Long-Term Hydrologic Impact Assessment (L-THIA) WWW Systems. *In:* Sustaining the Global Farm – Selected Papers From the 10th International Soil Conservation Organization Meeting, D.E. Stott, R.H. Mohtar, and G.C. Steinhardt (Editors). International Soil Conservation Organization in cooperation with the USDA and Purdue University, West Lafayette, Indiana, pp. 1018-1023.

Muthukrishnan, S., K.J. Lim, J. Harbor, and B.A. Engel, 2005. iSep: Hydrograph Separation Model. *Available at* http://www.ecn.purdue.edu/runoff/iSep. *Accessed in* March, 2006.

Nash, J.E. and J.V. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models Part I – A Discussion of Principles. Journal of Hydrology 10:282-290.

Ocean County Soil Conservation District, 2001. Impact of Soil Disturbance During Construction on Bulk Density and Infiltration in Ocean County, New Jersey. *Available at* http://www.ocscd.org/soil.pdf. *Accessed in* March 2006.

Pandey, S., R. Gunn, K.J. Lim, B.A. Engel, and J. Harbor, 2000. Developing a Web-Enabled Tool to Assess Long-Term Hydrologic Impact of Land Use Change: Information Technologies Issues and a Case Study. Urban and Regional Information Systems Journal 12(4):5-17.

Santhi, C., J.G., Arnold, J.R., Williams, W.A. Drugs, R. Srinivasan, and L.M., Hauck, 2001. Validation of the SWAT Model on a Large River Basin With Point and Nonpoint Sources. Journal of the American Water Resources Association (JAWRA) 37(5): 1169-1188.

USDA-SCS (U.S. Department of Agriculture-Soil Conservation Service), 1985. National Engineering Handbook, Section 4, Hydrology. U.S. Department of Agriculture Soil Conservation Service, Washington, D.C.

USDA-SCS (U.S. Department of Agriculture-Soil Conservation Service), 1986. Urban Hydrology for Small Watersheds. Technical Release 55, U.S. Department of Agriculture Soil Conservation Service, Washington, D.C.

USGS, 2003. Daily Streamflow for the Nation. USGS 03353600, Little Eagle Creek at Speedway, Indiana. *Available at* http://nwis.waterdata.usgs.gov/nwis/discharge/?site_no=03353600. *Accessed in* July 2003.

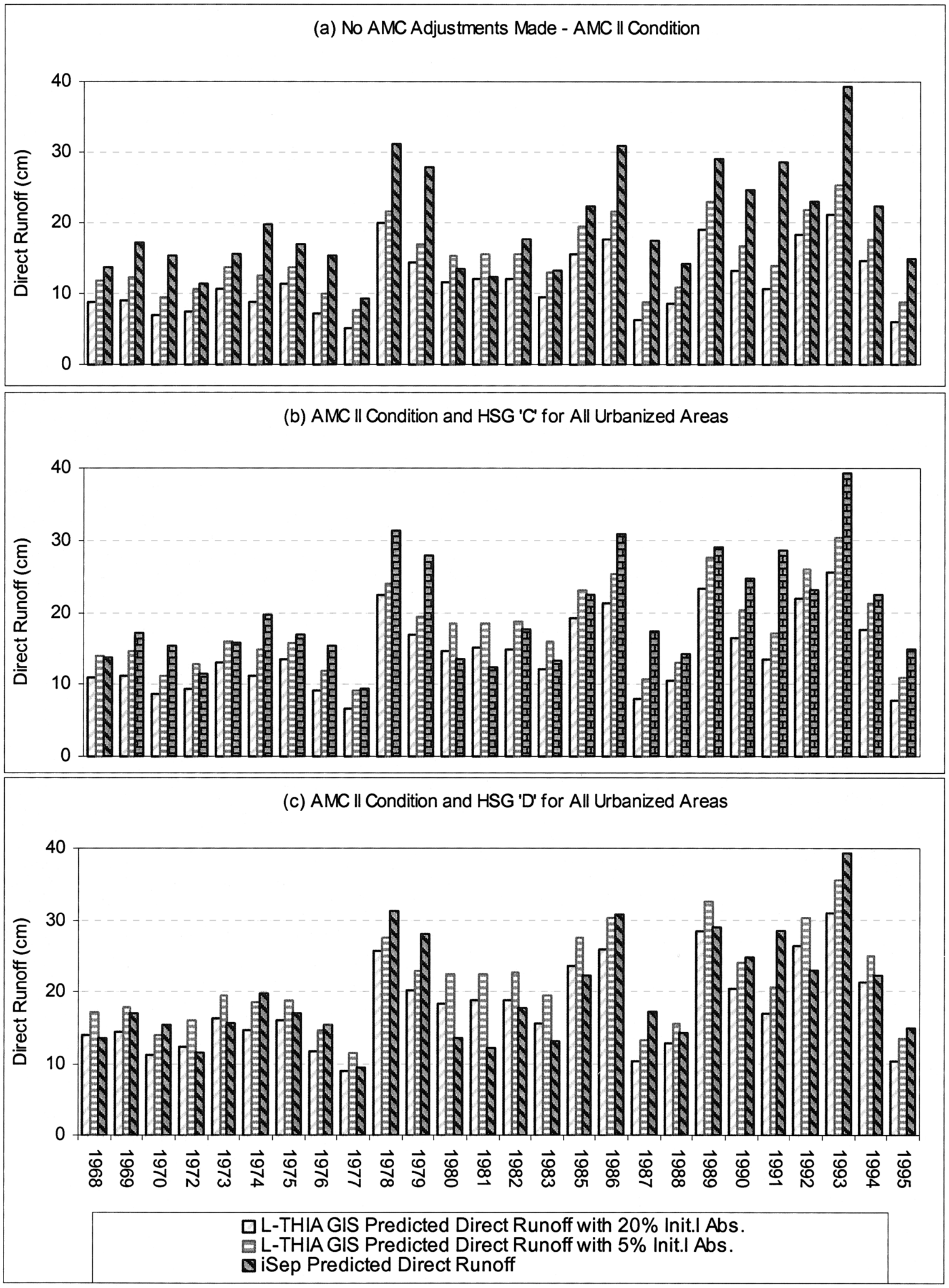

Figure 9. Yearly Runoff Depth for 1968 to 1995 for the Little Eagle Creek Watershed.

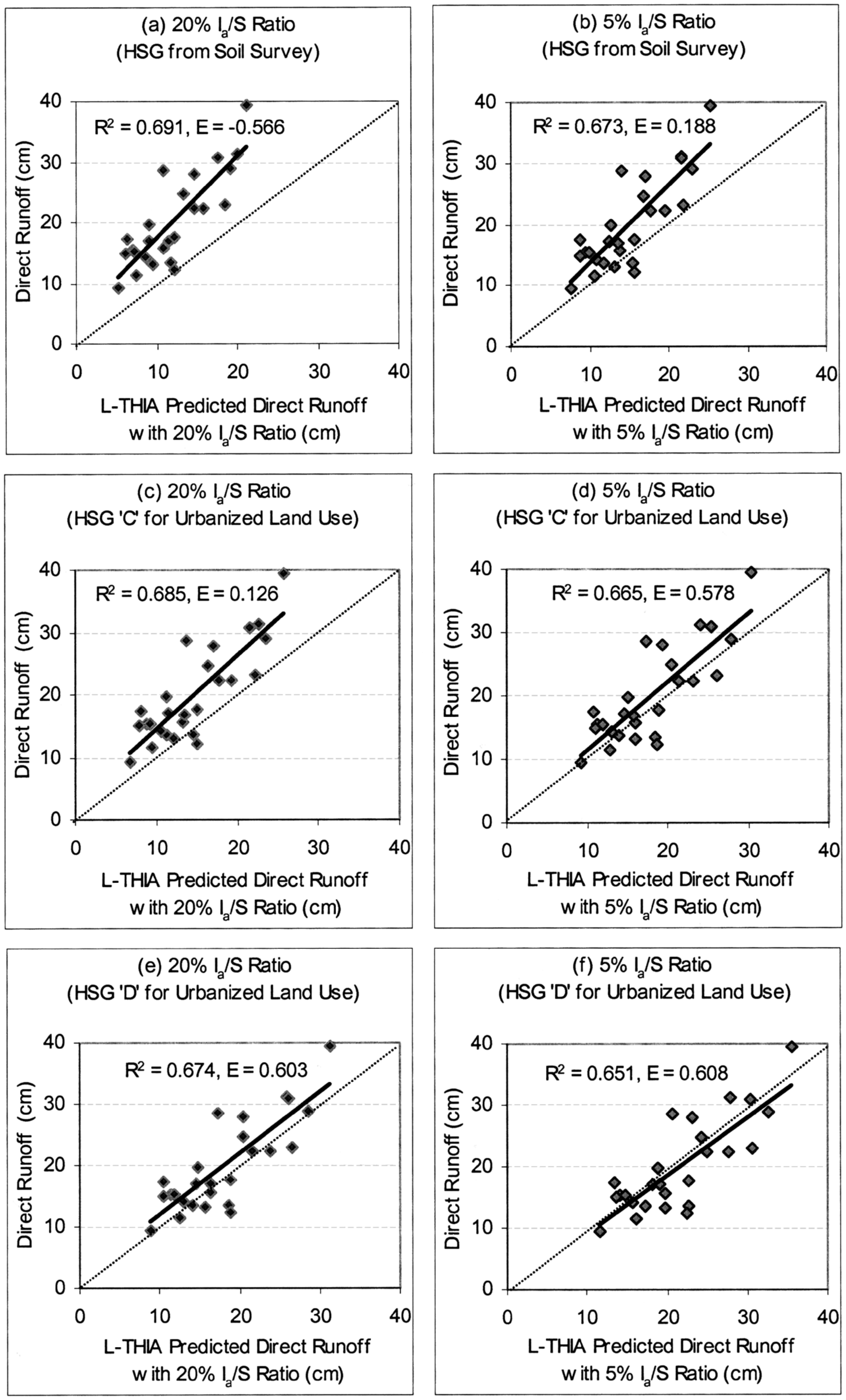

Figure 10. The Relationship Between USGS Direct Runoff and L-THIA-Predicted Yearly Direct Runoff With 20 Percent and 5 Percent I_a/S for Three Hydrologic Soil Group Scenarios.