OPTIMUM SIMULATION OF FLOOD FLOW RATE: COMPARING COMBINATIONS OF PRECIPITATION LOSS AND RAINFALL EXCESS-RUNOFF TRANSFORM MODELS

Issue Date: June 2011

Abstract—*Hydrologists can use many precipitation loss rate functions and rainfall excess-runoff transform techniques to develop watershed runoff hydrographs. For the most part, they can apply the loss and transform approaches in virtually any combination. To evaluate some of the many possible combinations, the author formed a matrix of three commonly used precipitation loss rate models and three rainfall excess-runoff transform models and compared the nine resulting simulated runoff hydrographs for a single large storm. The predicted peak flow rate derived from the US Geological Survey (USGS) regression equation was compared with the predictions obtained from these combination models. The estimates of the parameters of these precipitation loss models and rainfall excess-runoff transform models were also analyzed. The combination of the Natural Resources Conservation Service (NRCS) curve number (CN) loss model and the NRCS unit hydrograph (UH) model was considered the best option, since it requires simple parameters that can sufficiently represent the watershed characteristics. The other combinations also produce reasonable predictions. However, the estimates of some of their parameters result in prediction uncertainty.*

Keywords—*precipitation loss, rainfall excess-runoff transform, watershed runoff hydrograph*

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INTRODUCTION

Predicting the flow discharge at a watershed outlet is one of the most important objectives of a hydrological model. The result provides the basis for the subsequent hydraulic modeling. The Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) is a popular hydrological model developed by the US Army Corps of Engineers. This precipitation-runoff simulation program categorizes the land and water in a watershed into directly connected impervious and pervious surfaces. The precipitation falling on impervious surfaces runs off without loss. Processes are at work on pervious surfaces that result in precipitation excess flowing as runoff to the watershed outlet. In the HEC-HMS model, these precipitation processes fall into two classifications: loss and transform. Precipitation interception by trees, grass, and other land cover; infiltration under land surface; evaporation and transpiration to the air; etc.; are all counted as precipitation losses that do not run off. The precipitation excess flowing to the watershed outlet is defined as transform. [1]

Multiple models have been developed to describe the precipitation losses. The initial and constant-rate (IC) loss model, a simple loss model, uses an initial loss to account for the interception and depression storage of precipitation falling on a land surface. It assumes that the precipitation loss rate is a constant. [2] The Natural Resources Conservation Service (NRCS) curve number (CN) loss model uses the CN to represent the land use/land cover, soil group, and antecedent moisture. [3] The Green-Ampt (GA) loss model is based on a conceptual model of precipitation infiltration. The parameters Moisture Deficit, Suction, and Conductivity are used to represent the infiltration process of precipitation under land surface. [4]

Unit hydrograph (UH) models are system theoretical models that connect the precipitation excess and runoff by ignoring the detailed internal processes. [3] These traditional UH models are widely used in hydrological modeling. The Snyder UH model estimates the UH parameters with watershed characteristics. [4] The NRCS-developed UH model expresses the UH discharge as a function of the UH peak discharge and the time to UH peak. [3] The Clark UH model uses a linear reservoir model to represent the transform of precipitation excess through a watershed. [1]

These models are based on different physical models or empirical data. Their applications require determination of different hydrological

ABBREVIATIONS, ACRONYMS, AND TERMS

BASINS	Better Assessment Science Integrating point and Non-point Sources (software system)
CN	curve number
DEM	digital elevation model
Esri®	Environmental Systems Research Institute
GA	Green-Ampt (loss model)
GIS	geographic information system
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
IC	initial and constant-rate (loss model)
NHD	National Hydrography Dataset
NRCS	Natural Resources Conservation Service
SI	International System of Units
UH	unit hydrograph
USGS	US Geological Survey

parameters. Previous studies were conducted that compared only two of these models. [5–7] In this paper, a matrix of the combination of the three loss rate models and the three excess-runoff transform models was applied for the Linnville Bayou watershed (located in southeast Texas) to explore the advantages and disadvantages of these models.

WATERSHED CHARACTERISTICS

The Linnville Bayou watershed includes the main stream channel of Linnville Bayou (commonly known as Big Linnville Bayou) and a tributary channel known as Little Linnville Bayou. The watershed was divided into eight sub-basins, as shown in **Figure 1**, using the BASINS software developed by the US Environmental Protection Agency. [8] BASINS is composed of a suite of interrelated components for performing various aspects of environmental analysis. Through the use of geographic information system (GIS) techniques, BASINS has the flexibility to display and integrate a wide range of information (e.g., land use, point source discharges, and water supply withdrawals) at a scale chosen by the user. The BASINS data downloading tools were used to obtain the digital elevation model (DEM) dataset, the land use/land cover dataset, and the hydrologic soil dataset from online sources on the Internet. BASINS includes GIS functions that enable highly accurate calculations to be made for the watershed boundary and delineation and drainage area.

Through the use of GIS techniques, BASINS has the flexibility to display and integrate a wide range of information at a scale chosen by the user.

The sub-basins were delineated using a DEM with 30 m by 30 m (98.4 ft by 98.4 ft) data spacing. Streamflow lines were obtained from the National Hydrography Dataset (NHD), a comprehensive set of digital spatial data that encodes information about bodies of water (naturally occurring and constructed), paths through which water flows, and related entities.

PRECIPITATION LOSS AND TRANSFORM METHODS

Based on the delineation results, the HEC-HMS program was applied to build a model of the watershed by employing different combinations of three loss rate models (NRCS CN, GA, and IC) and three excess-runoff transform models (Snyder UH, Clark UH, and NRCS UH). Parameters of these models were determined from the land use/land cover characteristics, soil groups, and watershed delineation.

The loss models describe the precipitation loss as a result of interception, depression, evaporation, etc. A single storm (12.8 in. [32.5 cm] for a 100-year, 24-hour flood) was set up in this hydrologic model to explore the applicability of various loss models. The precipitation excess-runoff transform models describe the change of precipitation excess into runoff from a catchment area. Various transform models were explored by estimating the model parameters from the watershed characteristics using BASINS and ArcGIS® tools. ArcGIS, developed by Environmental Systems Research Institute (Esri®), is an integrated collection of GIS software products that provides a standards-based platform for spatial analysis, data management, and mapping.

USGS REGRESSION EQUATIONS

The US Geological Survey (USGS) has recently developed a set of alternative regression equations for estimating peak streamflow frequency Q_T for watersheds in Texas for various recurrence intervals (T-year recurrence intervals, ft^3/sec). These equations are based on

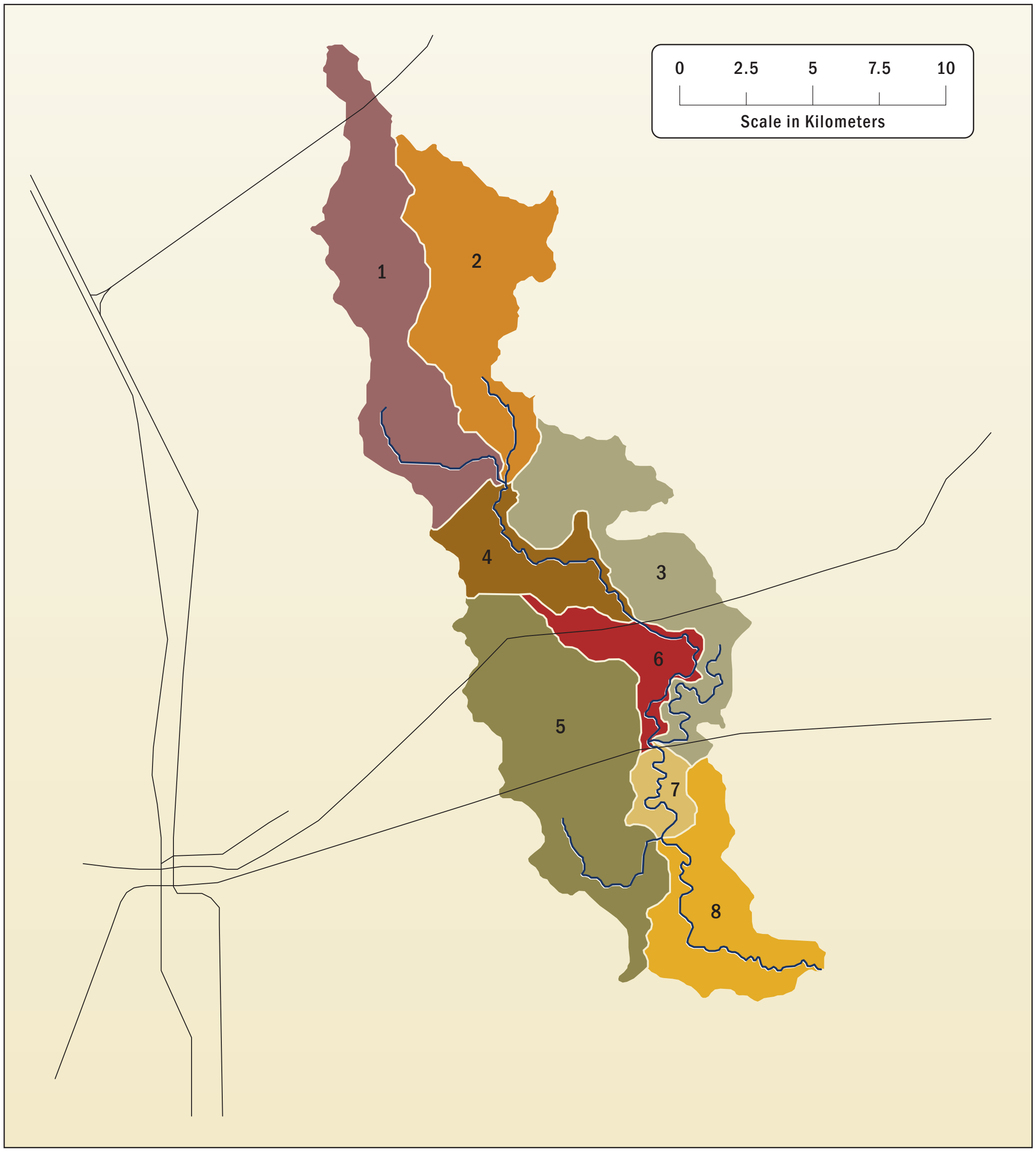

Figure 1. Sub-Basin Delineation for the Linnville Bayou Watershed

Calculated flow discharge from the USGS regression equation was used as the basis for the subsequent HEC-HMS rainfall-runoff modeling results.

a logarithmic transform of drainage area using three predictor variables: A = drainage area, mi²; P = mean annual precipitation, in.; and S = main-channel slope, ft/mi. [9] For the 100-year recurrence interval, the equation is:

$$Q_{100} = 10^{0.3879} A^{0.7133} P^{1.183} S^{0.6660} \qquad (1)$$

The 100-year flood flow for Linnville Bayou watershed calculated with this equation is 9,323 ft³/sec (264 m³/sec). This calculated flow discharge from the USGS regression equation was used as the basis for the subsequent HEC-HMS rainfall-runoff modeling results.

HYDROLOGICAL PARAMETER ESTIMATES

Loss Models

IC Loss Model

One initial condition (initial loss) and one parameter (the constant rate) need to be determined for the IC loss model. The initial loss will approach zero if the watershed is saturated; otherwise, the initial loss will be greater than zero to represent the maximum rainfall depth before runoff occurs in a watershed. The constant rate represents the infiltration speed of the soils

Table 1. IC Loss Model Parameters

Sub-Basin Number	Initial Loss– 10% of Precipitation, in.	Initial Loss– 15% of Precipitation, in.	Initial Loss– 20% of Precipitation, in.	Constant Rate, in./hr
1	1.28	1.92	2.56	0.0350
2	1.28	1.92	2.56	0.0341
3	1.28	1.92	2.56	0.0366
4	1.28	1.92	2.56	0.0350
5	1.28	1.92	2.56	0.0350
6	1.28	1.92	2.56	0.0350
7	1.28	1.92	2.56	0.0350
8	1.28	1.92	2.56	0.0348

Table 2. GA Loss Model Parameters

Sub-Basin Number	Initial Loss, in.	Moisture Deficit, %	Suction Head, in.	Hydraulic Conductivity, in./hr
1	0	38.6	12.0	0.071
2	0	39.0	12.1	0.063
3	0	38.6	11.9	0.079
4	0	38.6	12.0	0.071
5	0	38.6	12.0	0.071
6	0	38.6	12.0	0.071
7	0	38.6	12.0	0.071
8	0	38.6	12.0	0.071

In the NRCS modelology, land use/land cover characteristics are used, in conjunction with hydrologic soil groups, to develop the runoff CN parameter relating rainfall volume to runoff volume.

and is determined by the soil characteristics. The parameters of the IC loss model applied for the Linnville Bayou watershed are shown in **Table 1**.

GA Loss Model

The GA loss model is based on a conceptual model of precipitation infiltration. In this model, a wetting front is assumed to penetrate down once infiltration begins. The soil is divided by the wetting front into two layers, the upper saturated soil with moisture content η and the lower unsaturated soil with moisture content θi. The effective hydraulic conductivity is about half of the saturated hydraulic conductivity, as a rule of thumb. [10] The parameters of the GA loss model applied for the Linnville Bayou watershed are shown in **Table 2**.

NRCS CN Loss Model

The NRCS CN loss model calculates the rainfall runoff based on precipitation, land use/land cover, and antecedent moisture. The initial abstraction represents the precipitation depth before precipitation excess can occur. The CN in each sub-basin represents the combination of the different land use/land cover and soil groups in this sub-basin. The hydrologic characteristics of soils within a watershed are a primary factor influencing the runoff potential. The NRCS classifies soils into four hydrologic groups (A to D), based on runoff-producing potential. The "state soil" dataset was downloaded using the BASINS data downloading tool. Land use/land cover characteristics influence the rainfall-runoff relationship of a watershed due to interception and retardance factors. In the NRCS modelology, the land use/land cover characteristics are used, in conjunction with the hydrologic soil groups, to develop the runoff CN parameter relating rainfall volume to runoff volume.

The NRCS UHs and 24-hour design storms were used to develop runoff hydrographs for each of the eight sub-basins. [11] The US Department of Agriculture NRCS (1986) presented CNs for various hydrologic soil and land use/land cover examples. For this paper, ArcGIS 9.2 was used to map hydrologic soil and land use/land cover in each sub-basin of the Linnville Bayou watershed. The average CN for each sub-basin was calculated based on the types of hydrologic soil and land use/land cover. Stream channel lengths and slopes were also calculated for each sub-basin using the BASINS software. Parameters obtained

Table 3. Linnville Bayou Watershed Hydrologic Parameters

Sub-Basin Number	Drainage Area, mi^2		Runoff, CN	Stream Channel		Lag Time, min.
	Sub-Basin	Cumulative		Length, ft	Average Slope, %	
1	18.81	18.81	85	7,260	0.60	707
2	15.75	34.56	83	4,980	1.01	467
3	15.14	49.70	75	10,130	0.93	855
4	7.26	56.96	81	10,340	0.57	410
5	22.02	78.98	84	7,290	0.95	445
6	4.92	83.90	78	9,120	0.91	322
7	2.50	86.40	86	6,340	1.58	141
8	10.84	97.24	84	12,340	0.65	401

to model storm runoff from the sub-basins are presented in **Table 3**. The calculated CNs for the sub-basins of the Linnville Bayou watershed are shown in **Figure 2**.

The HEC-HMS model uses standard UH techniques to generate runoff hydrographs from excess rainfall. For the Linnville Bayou analyses, the empirical UH relationships developed by NRCS were used. These same NRCS-developed

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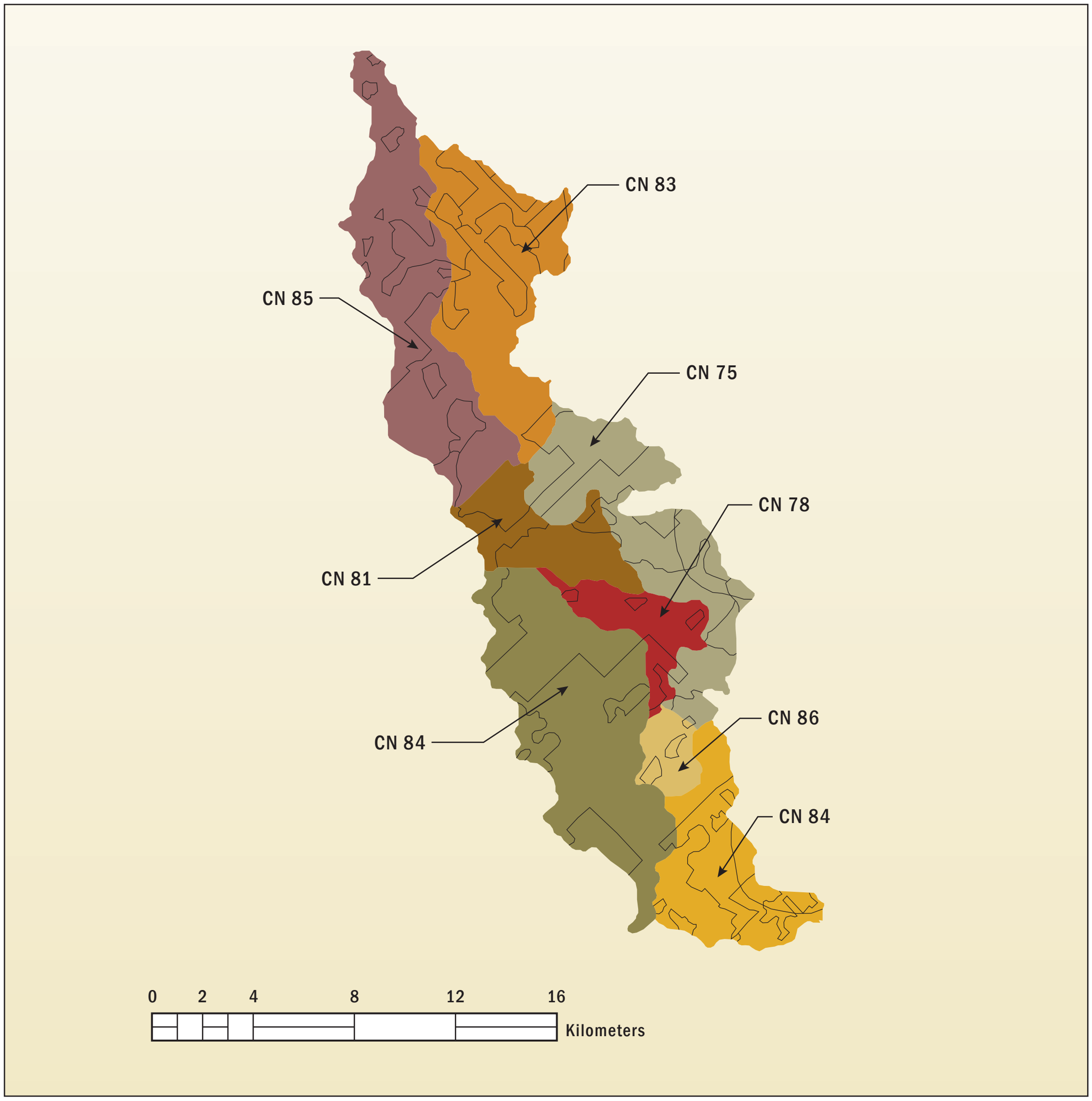

Figure 2. Runoff CNs of the Sub-Basins of the Linnville Bayou Watershed

The primary UH parameter used in conjunction with the NRCS UH is the basin lag time.

Table 4. NRCS CN Loss Model Parameters

Sub-Basin Number	Initial Abstraction, in.	CN	Impervious, %
1	0.41	85	0
2	0.40	83	0
3	0.46	75	0
4	0.47	81	0
5	0.41	84	0
6	0.44	78	0
7	0.41	86	0
8	0.44	84	0

Table 5. Calculated Lag Times for Linnville Bayou Sub-Basins

Sub-Basin Number	Lag Time, min.
1	707
2	467
3	855
4	410
5	445
6	322
7	141
8	401

UH relationships have been used extensively by the US Army Corps of Engineers and other public and private entities in the analysis of watershed runoff characteristics. The parameters of the NRCS CN loss model applied for the Linnville Bayou watershed are shown in **Table 4**.

Transform Models

NRCS UH Transform Model

The primary UH parameter used in conjunction with the NRCS UH is the basin lag time $t_L = 0.6 \times t_c$, where t_c is the time of concentration of the catchment, namely the time for runoff to flow from the most hydraulically remote point of the sub-basin to its outlet. The lag time is a function of CN, watershed slope, and stream length. Lag time in hours is calculated based on watershed parameters as follows:

$$t_L = \frac{L^{0.8}\,(S+1)^{0.7}}{1900\,Y^{0.5}} \qquad (2)$$

where L is the hydraulic length in feet, Y is the watershed slope in percent, and S is the potential maximum rainfall retention in inches [3], where

$$S = \frac{1000}{CN} - 10 \qquad (3)$$

Calculated lag times for the Linnville Bayou sub-basins are given in **Table 5**.

The standard lag time is the time from the centroid of precipitation mass to the hydrograph peak flow [1]:

$$t_p = CC_t\,(LL_c)^{0.3} \qquad (4)$$

where C_t is the basin coefficient, L is the length of the main stream from the outlet to the divide, L_c is the length along the main stream from the outlet to a point nearest the watershed centroid, and C is a conversion constant (0.75 for International System of Units [SI] and 1.00 for foot-pound system). [12] The parameters of the NRCS UH transform (standard lag times) applied for the Linnville Bayou watershed are shown in **Table 6**.

Table 6. NRCS UH Transform Parameters (Standard Lag Times)

Sub-Basin Number	Conversion Constant, C	Basin Coefficient, C_t	Stream Length, L, m	Stream Length, L_c, m	Standard Lag Time, t_p, hr
1	0.75	4	24,915	12,458	12.2
2	0.75	4	18,847	13,193	11.1
3	0.75	4	28,028	19,620	15.4
4	0.75	4	10,343	6,206	11.0
5	0.75	4	17,816	8,908	11.0
6	0.75	4	9,116	7,293	11.1
7	0.75	4	6,340	3,170	7.8
8	0.75	4	12,335	8,635	12.8

Table 7. Snyder UH Transform Parameters

Sub-Basin Number	Calculated Standard Lag, hr	Peaking Coefficient
1	12.2	0.47
2	11.1	0.47
3	15.4	0.47
4	11.0	0.47
5	11.0	0.47
6	11.1	0.47
7	7.8	0.47
8	12.8	0.47

Table 8. Clark UH Transform Parameters

Sub-Basin Number	Concentration Time, hr	Storage Coefficient, hr
1	19.64	28.57
2	12.97	18.87
3	23.75	34.56
4	11.39	16.57
5	12.36	17.99
6	8.94	13.01
7	3.92	5.70
8	11.14	16.21

Snyder UH Transform Model

The standard lag time in the Snyder UH transform model is a function of some measurable watershed characteristics, including *L*, length of the main stream from the outlet to the divide, and L_c, length along the main stream from the outlet to a point nearest the watershed centroid. Both *L* and L_c were obtained based on the watershed delineation results for this paper. The parameters of the Snyder UH transform applied for the Linnville Bayou watershed are shown in **Table 7**.

Clark UH Transform Model

In the Clark UH transform model, the storage effects of the sub-basin are estimated by assuming a linear reservoir at the sub-basin outlet. The time of concentration can be estimated through the lag time in the NRCS UH model. The storage coefficient can be estimated based on the time of concentration. Previous studies have directed that the storage coefficient divided by the time of concentration is constant. [1] The parameters of the Clark UH transform applied for the Linnville Bayou watershed are shown in **Table 8**.

MODELING RESULTS AND DISCUSSION

The hydrographs of these nine combinations of precipitation loss and transform models are shown in **Figure 3**. The predicted flow discharges of various combinations of precipitation loss

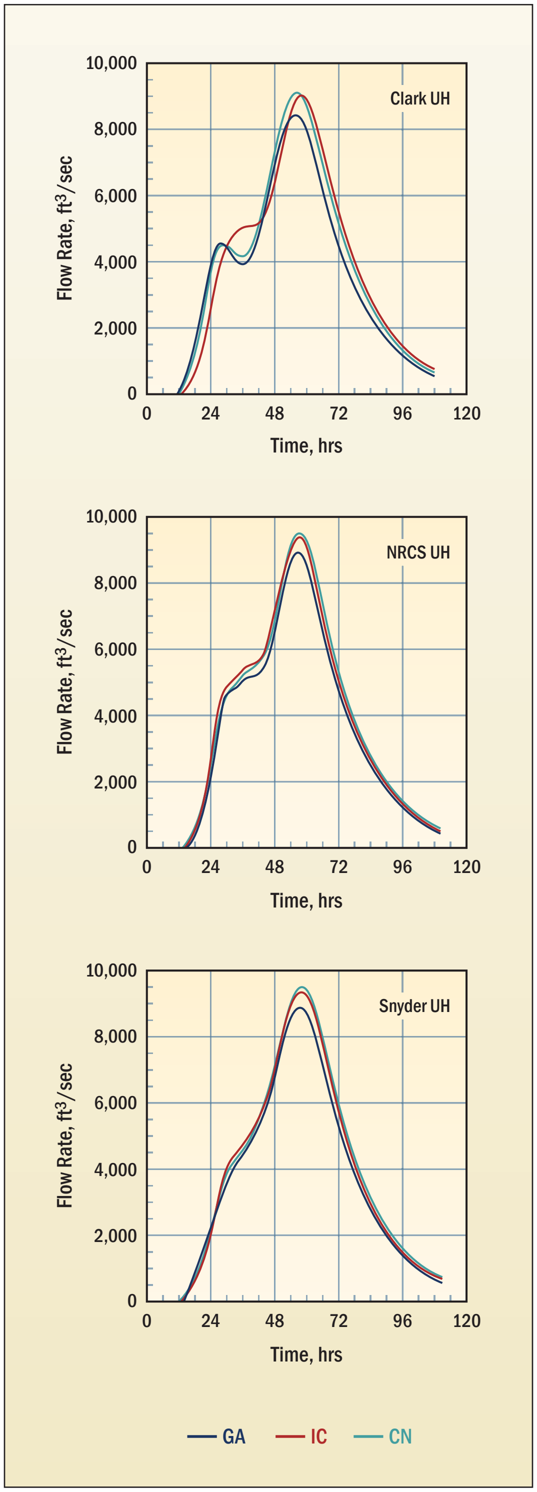

Figure 3. Hydrographs of Nine Combinations of Precipitation Loss Models and Transform Models Applied for Linnville Bayou Watershed

In the Clark UH transform model, the storage effects of the sub-basin are estimated by assuming a linear reservoir at the sub-basin outlet.

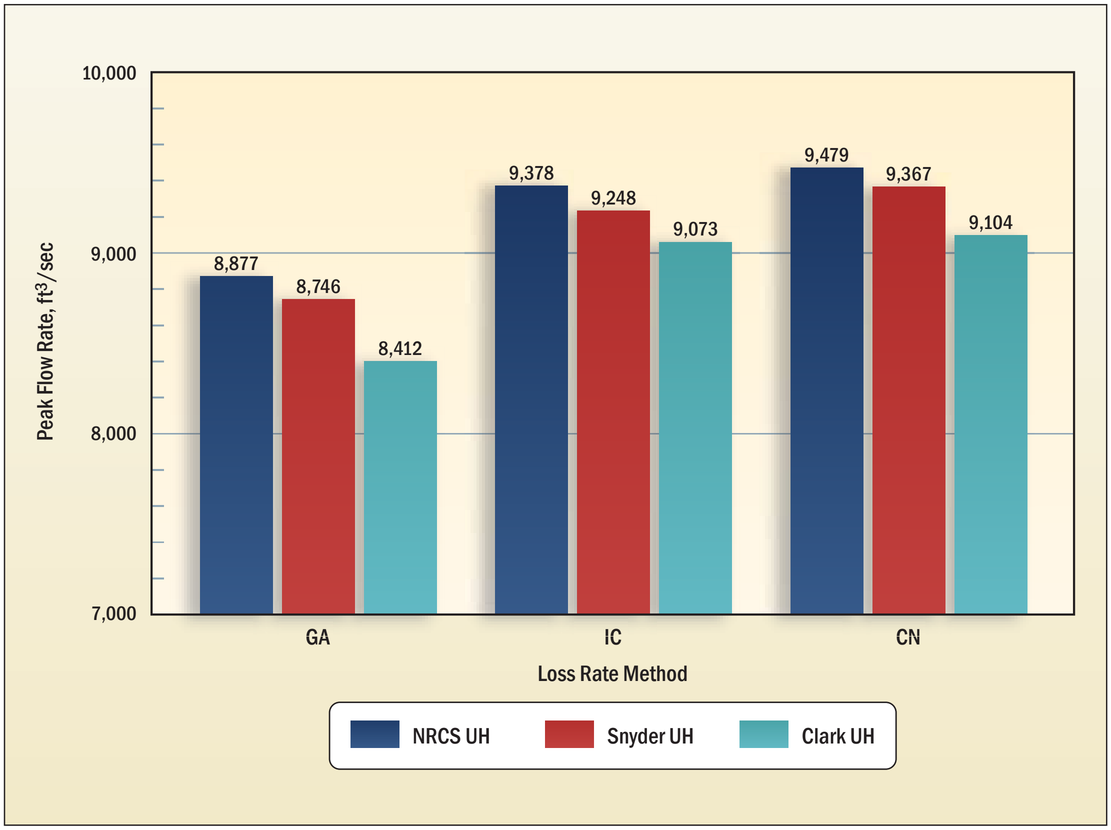

Figure 4. Predicted Peak Flow Rates for Various Transform/Loss Rate Method Combinations

The NRCS CN loss model takes advantage of spatial analysis techniques and the concept of CN, which represents the combined effects of land use and soil groups in a watershed.

and transform models are shown in **Figure 4**. Compared with the USGS regression equation result, the combinations of IC/CN and NRCS UH/Snyder UH provide the best estimates. The other combinations also provide reasonable estimates.

The IC loss model is simple but useful. It assumes that the rate of precipitation loss is constant during a storm and uses the initial loss to account for the interception and depression storage. The precipitation absorbed by surface cover is accounted for by interception. The precipitation falling into the depressions of the watershed topography is accounted for by depression. The constant rate ranges from 10% to 20% of the total precipitation. Accordingly, the flow discharge at the outlet ranges from 8,842 to 9,871 ft^3/sec (250 to 279.5 m^3/sec) when the NRCS UH model is used for rainfall runoff transform.

Conceptually, the GA loss model represents the infiltration process mechanism. However, one of its parameters, the wetting front soil suction head ψ, has a wide value range—from 0.38 in. to 9.98 in. for sand. As a result, the calculated flow discharges with these ψ values range from 5,596 to 9,076 ft^3/sec (158 to 257 m^3/sec). Another parameter, hydraulic conductivity K, varies along with the wetting front soil suction head. It is advisable to specify these parameters during application of this loss model.

The GA loss model accounts for surface ponding by itself; therefore, the initial loss here is additional interception by canopy and, in this application, is simply considered as zero. To be applicable for the GA loss model, daily precipitation data must be disaggregated, which introduces difficulties. [5]

A CN is assigned to a specific combination of land use and soil groups. In this paper, the Linnville Bayou watershed was delineated into eight sub-basins. ArcGIS was used to generate the land use and soil groups distribution for each of these sub-basins. As a consequence, the combined CN for each sub-basin was calculated based on its values for each combination of land use and soil groups and their distribution in that sub-basin. The NRCS CN loss model took advantage of the spatial analysis techniques and the concept of CN, which represents the combined effects of land use and soil groups in a watershed.

The NRCS UH model was developed based on a large number of small agricultural watersheds.

The Linnville Bayou watershed encompasses 97 mi^2 (251 km^2), mostly covered by trees and grass. Thus, the NRCS UH model is applicable for this watershed. This simple, straight-line model has lag time as the only parameter. As a function of CN, watershed slope, and stream length, the lag time incorporates all related watershed characteristics (e.g., land use, soil groups, and antecedent moisture).

The time of concentration in the Clark UH model can be estimated from the lag time in the NRCS UH model. The storage coefficient can be estimated based on the time of concentration. Thus, all parameters in the Clark UH model can be estimated from the only parameter in the NRCS UH model, the lag time. The Clark UH model internally incorporates the advantages of the NRCS UH model. However, the estimate of the linear relationship between the storage coefficient and the time of concentration increases the difficulty of applying this model.

Basin coefficient C_t as a variable of standard time in the Snyder UH transform model ranges from 0.4 to 8.0 in the Gulf of Mexico area. [12] This wide range decreases the accuracy of the flow discharge estimate.

CONCLUSIONS

Various combinations of precipitation loss models and transform models have been formed and explored for predicting peak flow rate for the Linnville Bayou watershed. The following conclusions are drawn from this analysis:

1. Based on the predicted flood discharges, the combination of the NRCS CN loss model and the NRCS UH transform model is considered the best option, since both models have the simplest, least data-intensive parameters that are easy to estimate. The CN and the major parameter of each model, lag time, are widely applied to represent the soil type, land use, antecedent condition, and other measurable watershed parameters.
2. The other combinations of precipitation loss models and transform models can also provide reasonable flood discharge estimates. However, these combinations involve more complex parameters, which present difficulties for the estimates or introduce uncertainties for the results. For instance, the wetting front soil suction head in the GA loss model has a wide value range. For the Snyder UH transform model, it is difficult to estimate the length along the main stream from the outlet to a point nearest the watershed centroid, L_c. Thus, the application of these models is subject to determining these parameters.
3. The GA loss model may perform better than the NRCS CN loss model, since the former considers precipitation intensity and duration. However, this advantage may be diluted by the requirement to disaggregate daily precipitation data for the application of the GA loss model.
4. Development of geological information system techniques improves accuracy and efficiency for estimating the CN and thus eventually for predicting flow discharge by applying the NRCS CN loss model and the NRCS UH transform model.
5. The IC loss model is simple to use, but its initial loss estimate, ranging from 10% to 20% of total precipitation, decreases the accuracy of the flood discharge prediction. ■

The combination of the NRCS CN loss model and the NRCS UH transform model is considered the best option, since both models have the simplest, least data-intensive parameters that are easy to estimate.

TRADEMARKS

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BIOGRAPHY

Zhiyong Duan, PhD, a hydraulics and hydrology engineer in Bechtel's OG&C Global Business Unit, has extensive experience in environmental and water resources engineering. He has an impressive record of delivering key support for projects located in the United States, Nigeria, Thailand, Angola, and Australia. Zhiyong has diverse experience in hydrological and hydraulic modeling, hydraulic transient analysis, water quality analysis and modeling, and water and wastewater treatment.

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