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Resolving Inconsistencies between Rational and HEC-1 Methods

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Common practice of determining stormwater runoff has been to apply a distributed model for large watersheds and a lump model for small watersheds. The lack of consistency among the two techniques has caused much concern, however. The authors describe how they calibrated the two approaches for the Las Vegas area. This method can be modified for other areas.

Flood predictions and storm water facility designs apply a risk-based approach to modeling the rainfall and runoff through a watershed. In an urban area, the storm water drainage system consists of micro systems (best management practice controls), minor systems (2-year event), and major systems (100-year event). It is imperative that all levels of drainage systems be designed consistently with a selected risk level. Consequently, the upstream drainage system can be constructed with pipe sizes that increase as the flows move downstream.

Acronyms/ Abbreviations

- HEC: Hydraulic Engineering Center
- IDF: Intensity duration curve
- NOAA: National Oceanic and Atmospheric Administration
- SCS: Soil Conservation Service
- SDN: Storm distribution number

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In practice, a regional master drainage plan is the guidance to warrant a consistent risk among all levels of drainage systems. This does not account, however, for the fact that current practice includes a two-method approach, including the U.S. Army Corps of Engineers' Hydraulic Engineering Center (HEC)-1 model (distributed) for large watersheds and the Rational method (lump model) for small watersheds.

Whether a modeling system is lumped or distributed depends upon the spatial and temporal characteristics of its design variables. A lumped parameter ignores the variability in space. On the other hand, taking the spatial variations into consideration, the system becomes a distributed model. Without a careful calibration, these two methods are method used in the Las Vegas, Nevada, area, where the HEC-1 model is accepted for regional master drainage planning while the Rational method is recommended for local designs. The methodology derived is transferable to other regions.

Hydrologic Loss Functions

Rainfall excess produces storm runoff. It is necessary to understand the relation between the hydrologic loss functions of the HEC-1 prediction method and the Rational method to establish a basis of consistency between the two.

The hydrologic loss function used by the HEC-1 method is associated with the soil curve number, CN. The relationship between a curve number and the initial soil losses, S, is described as:

$$S = 1000 / CN - 10 \tag{1}$$

Where

S = the relationship between a curve number and the initial soil losses.
CN = soil curve number.

According to the SCS (Soil Conservation Service) method, the rainfall excess or direct runoff depth is defined as:

$$P_e = (P - 0.2S)^2 / (P + 0.8S) \tag{2}$$

Where

P_e = rainfall excess in inches
P = design rainfall depth in inches.

By definition, the value of a runoff coefficient, C, is equivalent to:

$$C = P_e / P \tag{3}$$

Substituting Eq. 2 into Eq. 3 yields

$$C = (P - 0.2S)^2 / (P(P + 0.8S)) \tag{4}$$

Eq. 1 and Eq. 4 provide the mathematical relationship between runoff coefficients and curve numbers.

Design Rainfall Intensity Duration Frequency (IDF) Curve

Rational Method. The Rational method is a simplified procedure to predict peak runoff rates by the contributing rainfall only. Kuichling (1889) stated that the peak rate of runoff at a design point is a direct function of the tributary area, and the contributing rainfall amount to the peak runoff is the rainfall depth over the past up to the time of concentration of the catchment. For convenience, the Rational method suggests that the design rainfall distribution be converted into its IDF curve that depicts the highest intensity for the selected duration. For instance, the intensity for duration of 15 minutes represents the most intense rainfall within a period of 15 minutes during the event. An IDF curve decays with respect to the period of duration and can be described as:

$$I = aP / (B + T_d)^c \qquad (5)$$

Where

I = intensity

P = base value to represent the event frequency such as the 100-year 6-hour rainfall depth

a, b, and c = empirical constants

T_d = design rainfall duration that is assumed to be the time of concentration of the watershed.

$$T_d = T_c \qquad (6)$$

Where

T_c = time of concentration.

Eq. 6 warrants the entire watershed to be the tributary area to the design point. There are many empirical formulas developed to estimate the time of concentration. In this study, the regional formula developed for the metropolitan Denver and Las Vegas areas is used (Urban Storm Water Design Criteria Manual 2001). It states:

$$T_c = L / 180 + 10 \qquad (7)$$

Where

T_c = time of concentration in minutes

L = waterway length in feet.

Eq. 7 assumes that the overland flow time is 10 minutes and the flow velocity on a street gutter is 1 m (3 feet) per second. According to the Nation Ocean Atmosphere Administration (NOAA) Rainfall Atlas II, Volume 9 for Nevada, the IDF curve at the McCarran International Airport site in Las Vegas can be mathematically described by:

$$I_n = 12.20P_6 / (10.0 + T_d)^{0.55} \qquad (8)$$

Where

I_n = NOAA rainfall intensity

P_6 = 100-year 6-hour precipitation depth (P = 2.77 inches (70 mm) at the McCarran Airport site.

HEC-1 Method. Similarly, an IDF curve can also be derived from the SCS 6-hour rainfall distribution, or storm distribution number (SDN)-3 curve. Figure 1 on the following page shows the SDN-3 rainfall distribution used in the HEC-1 model to predict storm runoff in the Las Vegas area. For comparison, the SDN-3 curve was further converted to its IDF curve for the most intense 60 minutes, as shown in Table 1.

Aided by Eq. 5, the best fitted equation for the SDN-3 IDF curve was found to be:

$$I_s = 6.10P_6 / (10 + T_d)^{0.55} \tag{9}$$

where

I_s is the intensity for the SDN 3 SCS.

Discrepancy between the Two. As demonstrated in Figure 2, the NOAA IDF formula for the Las Vegas area tends to produce peak rainfall intensities twice as much as the SDN-3 curve. This discrepancy between Eq. 8 and Eq. 9 is the key factor that introduces an inconsistency between the HEC-1 and Rational methods for Las Vegas areas.

Modified Rational Method

Over the past 20 years, many major storm water detention systems and flood channels were constructed in the Las Vegas area using the SDN-3 rainfall curve, while the minor drainage systems were designed using the NOAA's IDF curve. A long-standing concern has been how to establish consistency between these two methods. We first suggest that the Rational method be modified as:

$$Q = K\, C\, I_N\, A \tag{10}$$

Where

K = adjustment factor
I_N = NOAA rainfall intensity
C = the runoff coefficient
A = Area in acres.

Aided by Eq. 4, and considering the 100-year 6-hour precipitation depth, Eq. 10 is rearranged as:

$$K = (Q / AI_N)\, (P_6(P_6 + 0.8S) / (P_6 - 0.2S)^2) \tag{11}$$

The value of K was investigated by conducting a numerical test for a series of hypothetical square watersheds with drainage areas ranging from 0.13 km^2 to 1.3 km^2 (0.05 square mile to 0.50 square mile). The assumed flow path through a square watershed is described in Figure 3. Table 2 provides the summary of the hydrologic parameters for the hypothetical watersheds.

We applied a set of curve numbers ranging from 50 to 90 to each watershed. With an assigned CN, the HEC-1 model was applied to each watershed to produce the 100-year peak flow rate used in Eq. 11. The rainfall depth in Eq. 11 was set to be the 100-year 6-hr rainfall depth of 2.77 inches at the McCarran Airport site.

Eq. 7 was applied to the flow path defined in Figure 3 to calculate the time of concentration. The lag time, Tp, required by the HEC-1 SCS method is estimated as:

$$T_p = 0.60T_c \tag{12}$$

With a known Tc, Eq. 8 was used to calculate the rainfall intensity in Eq. 11. Calculations of the value of K for the hypothetical watersheds are summarized in Table 3. The average value for K is approximately 0.50.

Case Study

A series of small urban watersheds ranging from 8 ha to 80 ha (20 acres to 200 acres) were selected from Pittman Watershed in the City of Henderson, Nevada. The 100-year storm runoff peak rates for the sample watersheds were simulated by HEC-1 using the 100-year SDN-3 SCS curve. Similarly, the modified Rational method was also used to predict the 100-year peak flow rates for the selected sample watersheds. (There was no difference between the summer and winter rainfall conditions.) Table 4 lists the input parameters for both methods and their results for comparison purposes. Figure 4 is the plot of Table 4 with the drainage area up to 225 ha (550 acres).

Using the adjustment factor of 2, the modified Rational method produces 100-year peak flood flows that are compatible with HEC-1 until the watershed area increases to 60 ha (150 acres), or 0.24 square miles. A similar conclusion was reached for the 10-year flood flow predictions.

Another 30 some small urban watersheds in the North Las Vegas and Mesquite areas were also examined for both 10- and 100-year floods. Similar conclusions to those reached for the Pittman watershed were observed.

Conclusion

Various hydrologic methods have been developed for various hydrologic conditions and applicable ranges. Each method has its own limitations and requirements for the design information. After investigating some 50 sample urban watersheds in the Las Vegas area, we have concluded:

- For the Las Vegas area, the NOAA IDF curve used in the Rational method produces rainfall intensities twice as much as the SCS SDN-3 curve used in the HEC-1 method.
- The Rational method is applicable to small urban watersheds. With significant depression and storage effects, the Rational method needs a modification. The

inconsistency between the HEC-1 and Rational methods results mainly from the different design rainfall distributions. The hypothetical watersheds used in this study suggest that the value of the adjustment factor in Eq. 10 be 2.

- More than 50 urban watersheds outlined in the master drainage study published for the Las Vegas area were further investigated to confirm the consistence between the predictions from the HEC-1 and modified Rational methods. The comparison suggests that the modified Rational method is applicable up to 60 ha (150 acres). The HEC-1 model should be used for any watershed larger than 150 acres.

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Related Web Sites:

- http://carbon.cudenver.edu/~jguo/

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