# Applied Single Runoff Event Simulation (Hydrology) Computer Models

# MEMORANDUM

## DRAFT #3

TO: DEP Hydrology Research Committee

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RE: Applied Single Runoff Event Simulation (Hydrology) Computer Models

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## A. Introduction

Single event simulation computer models such as the NRCS "TR-20 Hydrology" and U.S. Army Corps of Engineers "HEC-1" are in widespread use to determine peak flow rates in ungauged watersheds.

The models are used for the planning and design of dams, bridges, culverts, channels, and flood storage detention basins, plus are used for regulatory permit applications.

They continue to have broad support among the regulatory agencies and municipal engineers, even though there is a general consensus that peak flow results are often higher than analysis of stream gauge results. A careful review of the literature, instruction manuals, and review of actual models indicates many users are not utilizing the model's flexible input options, resulting in excessively high flow predictions. Consequently, it is important to be aware of specific methods of developing input data to best represent watershed runoff conditions and to minimize overly conservative or unreasonable assumptions.

The comments below are applicable to the TR-20 model and to the HEC-1 model when using the curve number (CN) input data option. They are intended as guidelines on how to develop custom site specific input data to improve watershed parameters and to re-emphasize basic modeling procedures. For example, in many cases, the user manuals allow and encourage development of custom CN parameters, but most users opt for the higher default values.

Note that it is always desirable to check computer model results against nearby gauging stations and their statistical flood frequency analysis prepared by USGS. In large watersheds with little storage, the USGS regression equations may also be used. For small watersheds under 200 acres in size and with little storage, the Rational method remains viable for determining peak flows.

## B. Subwatersheds

1. Computer model results appear to improve when large watersheds are subdivided into numerous small subwatersheds. Special care should be used to emphasize homogeneous watersheds with similar soils, land use, and topography. On watersheds with diverse CN values, it may be desirable to split the watershed into smaller areas rather than use the average CN value.

2. There are hydrologists who believe that the directly connected impervious cover in a basin should be considered separately from pervious areas (Golding, 1997). A single subwatershed with dispersed impervious cover may be represented by using two separate hydrographs, one for pervious areas and one for impervious areas (with separate CN, TC values) and then combining them. By evaluating pervious and impervious areas separately, the errors in averaging their CN and TC values can be minimized.

3. The "reservoir routing" of hydrographs through impoundments, lakes, wetlands and constricted areas is an important part of the models. A review of numerous models indicates users often omit potential storage areas. The modeler should attempt to evaluate all possible storage areas as they have a large influence on the final results. Note that in some cases road culverts with high embankments may delay runoff and should be treated as a reservoir.

4. The use of the channel routing techniques are specially important when using small subwatershed with limited time of concentrations and where overbank flow occurs on floodplains. The SCS TR-20 channel routing procedure (ATKIN) is awkward but technically sound. It reduces peak flows due to both channel storage and travel time through the reach.

   The size of the simplistic prismatic cross section used to determine the X and M coefficients should represent the cross section at the estimated flow rate. The cross section values for a two-year flood contained in a channel are not always suitable for a 100-year event that flows on a broad floodplain. In the latter case, the "channel" width used in the computations approaches the floodplain width. Typical values of "X" range from 0.01 to 10, with the lower values representing lower velocities and increased attenuation. The values of "M" range from 1 to 2. The lower values of M represent lower velocities. The reach lengths should be over 500 feet. Small reach lengths do not provide attenuation and may have a travel time less than $\Delta t$ main time increment.

5. The HEC-1 model provides five alternate methods of routing hydrographs through channel reaches. A careful review of the channel characteristics is necessary to select the most appropriate method. The attached table (USACOE, 1996) provides some guidelines. The "Munsingum-Cunge" method is generally preferred.

6. Some watersheds have very irregular topography that may have areas draining to isolated depressions or vernal pools without any type of discharge to riverine systems and which are not visible on standard USGS topographic maps. The TR-20 and HEC-1 user manuals do not address this condition. This situation can be handled by reducing the watershed area to reflect only the effective runoff producing area.

## C. Runoff Curve Numbers

The SCS runoff curve number (CN) is an empirical system to determine surface runoff volumes from specified rainfall. While there are questions about the fundamental theory for the curve number, this topic is beyond the scope of this paper. However, there is much that can be done to improve their application. SCS publications provide recommended values of CN as a function of soil types, vegetation, and land use. The TR-20 model user manual does not provide data on how to develop CN values, so most engineers use the TR-55 tables. However, earlier SCS publications (NEH4, 1972) provide the raw data. Unfortunately, the original research of the CN values was rather limited and poorly documented (Hjelmfelt, 1991). In urban areas, the published values are using conservative assumptions. Therefore, skilled modelers need to understand how CN values are established and use their judgment in adjusting them for specific watersheds. Use of a fixed CN value is questionable because the percentage of precipitation that becomes runoff should vary with rainfall intensity.

A revised form has been prepared for use in computing the subwatershed runoff curve numbers (CN). The revised form provides space for adjusting the hydrologic soil group for disturbed or urban conditions, and for modifying the CN value for disconnected impervious areas. The following comments on determining the CN value should be considered:

1. The TR-55 manual (June 1986) allows one to deviate from the published natural soil types in urban areas where the soil profiles and infiltration rates have been modified. For example, a natural type D soil may be cut, filled, or regraded, then covered with a pervious type B topsoil. TR-55 appendix A, page A-l, recommends the following adjusted soil types in disturbed areas:

| HSG | Soil Textures | Runoff Potential |
|---|---|---|
| A | Sand, loamy sand, or sandy loam | Low |
| B | Silt loam or loam | Moderate |
| C | Sandy clay loam | High when saturated |
| D | Clay loam, silty clay loam, sandy clay, silty clay or clay | High |

2. The CN value for ponds and lakes is 98.

3. The SCS recommended CN values published in TR-55 for developed areas assume relatively high levels of impervious cover. The percentage of impervious cover assumed for each land use in the TR-55 manual are tabulated below. A literature and site plan review indicates that the TR-55 published CN values for residential areas are consistently higher than local land use practice in suburban Connecticut towns.

   Site specific CN values can be measured or computed for specific watersheds, based on zoning, rather than using default values. MMI has computed impervious cover values for residential areas based on typical Connecticut site plans and zoning as noted below. The values are compared with TR-55 and other published studies. The results below suggest that the impervious cover levels used in TR-55 and other SCS publications to determine CN values are generally on the high side, leading to high CN values.

Total Impervious Cover,
% of Watershed

| Land Use | SCS TR-55 | Debo & Reese (1995) | Alley & Veenhuls (1982) | MMI |
|---|---|---|---|---|
| 1/8 acre. Res. | 65 | | 30-49 | 40 |
| 1/4 acre Res. | 38 | | 30-49 | 31 |
| 1/3 acre Res. | 30 | | 22-31 | 24 |
| 1/2 acre Res. | 25 | 30 | 13-16 | 20 |
| 1 acre Res. | 20 | 12 | 13-16 | 13 |
| 2 acre Res. | 12 | 6 | | 11 |
| Commercial | 85 | 75 | 88 | Varies |
| Industrial | 72 | 90 | 60 | 60 |
| Apartment | | 60 | 60 | Varies |

4. A U.S. Geological Survey study performed in conjunction with the New Jersey Department of Environmental Protection (Stankowski, 1972) also studied the range of watershed total impervious cover levels as a function of land use with the following findings:

| Land Use | Total Impervious Cover, Percent of Watershed for Various Densities Low | Medium | High |
|---|---|---|---|
| Single-family Residential | 12 | 25 | 40 |
| Multiple-family Residential | 60 | 70 | 80 |
| Commercial | 80 | 90 | 100 |
| Industrial | 40 | 70 | 90 |
| Open Space, Recreational | 0 | 0 | 0 |

The highest impervious cover values were found in higher density urban centers, and the lowest values in rural areas. The New Jersey USGS impervious cover range in residential areas is consistent with MMI computations and the data by Alley and Veenhuls. The data indicates that the SCS TR-55 assumed impervious cover values are generally higher than published data.

5. Field observations and published literature indicates that many impervious areas drain onto pervious soils that allow some infiltration to occur, thereby reducing the effect of impervious areas. For developed areas, the SCS curve numbers in TR-55 assume that all impervious areas are connected to and discharge directly into drainage systems, or have concentrated shallow flow to a drainage system preventing subsequent infiltration into pervious soils (See TR-55 Table 2-2a, footnote 2).

   If the runoff from the impervious area passes over a pervious area as sheet flow, it will be subject to infiltration and surface storage and is not considered as an effective impervious area (Prandit and Gopalakrisknon).

   New CN values can be computed with the effective impervious cover, or Figure 2-4 in TR-55 can be used to reduce CN values for watersheds with extensive "Disconnected" impervious areas. This often applies to parking lots without curbs or catch basins, and roof runoff discharging overland. The key issue is to determine what percentage of the total impervious cover is effective in producing runoff.

   a. MMI has recomputed residential CN values for each soil type based upon the assumption that the road and driveway impervious areas are effective and connected directly to drain systems, but the roofs are not connected to a central storm drain system. This is a very common condition, especially for larger lots.

CN Values
Residential Areas

| Land Use | Standard SCS TR-55 Values A | B | C | D | MMI Values, With Disconnected Rooftops A | B | C | D |
|---|---|---|---|---|---|---|---|---|
| 1/8 acre. Res. | 77 | 85 | 90 | 92 | 52 | 68 | 78 | 84 |
| 1/4 acre Res. | 61 | 75 | 83 | 87 | 50 | 68 | 77 | 84 |
| 1/3 acre Res. | 57 | 72 | 81 | 86 | | | | |
| 1/2 acre Res. | 54 | 70 | 80 | 85 | 47 | 66 | 77 | 83 |
| 1 acre Res. | 51 | 68 | 79 | 84 | 43 | 64 | 75 | 81 |
| 2 acre Res. | 46 | 65 | 77 | 82 | 40 | 60 | 74 | 80 |

b. In an article published in the ASCE Journal of Hydraulic Engineering, two USGS researchers (Alley and Veenhuls) tabulated the impervious cover and effective impervious cover for 19 urban watersheds near Denver. Their data suggests that the effective impervious area in residential areas is only about 60% of the total impervious cover.

Their equation for effective impervious area (EIA) is:

$$EIA = 0.15\,(TIA)^{1.41}$$

TIA = Total Impervious Area, % of watershed

The article indicates that the use of TIA instead of EIA in hydrologic models will overestimate runoff volumes and peak flows for ungauged watersheds.

c. Sutherland (Fall 1995) provides a summary of USGS research on effective impervious cover in 40 watersheds in Oregon. In order to get more accurate estimates of runoff, ineffective impervious areas that do not contribute to runoff should be subtracted from the total impervious area to get the effective value. Using USGS data, Sutherland developed a series of equations to estimate the effective impervious cover in four types of basins:

- Highly Connected Basins - Roads with curbs and storm drains, no drywells or infiltration units, roof runoff connected to storm drains or to street. This is typical of many urban areas.

  $EIA = 0.4\,(TIA)^{1.2}$

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- Average Basins – Roads with curbs and storm drains, no dry wells or infiltration units, few roof runoff connections to storm drains. This is typical of many suburban areas with modern curbed roadways with storm drains, but where the driveways and roads do not necessarily drain directly to the road or storm drain.

  $EIA = 0.1\ (TIA)^{1.5}$

- Moderate Connected Basins – 50% of urban areas are without storm drains, some swales and ditches in use, most rooftops not connected to storm drains, few drywells or infiltration units. This condition is typical of many older neighborhoods where many streets lack curbs or storm drains.

  $EIA = 0.04\ (TIA)^{1.7}$

- Low Connected Basins – Few urban areas with storm drains, or 70% of areas drain to drywells or infiltration areas.

  $EIA = 0.01\ (TIA)^{2.0}$

6. The total impervious cover areas determined by MMI for residential areas (paragraph C3) have been combined with the Sutherland (1995) equations to estimate the effective impervious area corresponding to four levels of connectivity, as noted below:

Effective Impervious Cover, % of Watershed

| Residential Land Use | MMI TIA, % | Highly Connected* | Average Basins* | Moderately Connected* | Low Connectivity* | USGS Denver Range** |
|---|---|---|---|---|---|---|
| 1/8 Ac | 40 | 33.4 | 25.3 | 21.2 | 16.0 | 18-32 |
| 1/4 Ac | 31 | 24.6 | 17.3 | 13.7 | 9.6 | 11-19 |
| 1/3 Ac | 24 | 18.1 | 11.8 | 8.9 | 5.8 | 11-19 |
| 1/2 Ac | 20 | 14.6 | 8.9 | 6.5 | 4.0 | 7-10 |
| 1 Ac | 13 | 8.7 | 4.7 | 3.1 | 1.7 | 7-10 |
| 2 Ac | 11 | 7.1 | 3.6 | 2.4 | 1.2 | |
| Formula | | $0.4(T)^{1.2}$ | $0.1\ (5)^{1.5}$ | $0.04(T)^{1.7}$ | $0.01(T)^{2.0}$ | |

* Computed based upon the Sutherland equation using MMI TIA.
** Range of values found in Denver watersheds by Alley & Veenhuls.

The effective impervious cover results for basins with Sutherland's "average connectivity" are very similar to the range of values found in the Denver area USGS study (Alley and Veenhuls, 1983). As expected, the effective impervious cover values for basins with moderate and low levels of connectivity are below the range of values in Denver.

7. MMI has recomputed composite CN values for residential land uses and soil types. They are based upon the MMI estimated impervious cover (paragraph C3) modified by Sutherland's net effective impervious areas, with average connectivity. The CN values for the pervious areas of building lots less than one acre are based on SCS open space CN values, while larger lots assume that the pervious area is 25% wooded.

MMI Composite CN Values*
Effective Impervious Area Plus Pervious Areas, Average Connectivity

| | | CN Values by Soil Types | | | |
|---|---|---|---|---|---|
| Lot Size | MMI EIA % | A | B | C | D |
| 1/8 Ac | 25.3 | 54 | 70 | 80 | 85 |
| 1/4 Ac | 17.3 | 49 | 67 | 78 | 83 |
| 1/3 Ac | 11.8 | 46 | 65 | 77 | 82 |
| 1/2 Ac | 8.9 | 44 | 64 | 76 | 82 |
| 1 Ac | 4.7 | 40 | 61 | 74 | 80 |
| 2 Ac | 3.6 | 39 | 60 | 73 | 80 |

* CN = [(EIA)98] + (100 – EIA) (Pervious CN) ÷ 100.

The above values are quite similar to those determined in paragraph C5A.

Similarly, residential CN values may be computed for watersheds with higher or lower connectivity.

8. The SCS CN values used in TR-55 Table 2-2a for open space (lawns, parks, golf courses, cemeteries) are based upon poor, fair, and good pasture conditions. The three CN classes are listed at <50%, 50% to 75%, and >75% ground cover.

The TR-55 CN values for open space have been found to correspond exactly with Figure 22-23 from Chow's Handbook of Applied Hydrology, using assumed ground cover densities of 30%, 65%, and 90% cover. In Connecticut, where grass lawns are seldom in the form of pastures and are usually providing full ground cover with few, if any, areas of bare soil, it will often be appropriate to use the Chow Figure 22-23 CN values for 100% ground cover rather than the higher SCS CN values for >75% ground cover as shown below.

| | Ground Cover Actual % | CN Values by Soil Type | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Open Space (lawns, parks, golf courses, cemeteries, etc.) | | | | | |
| TR-55 Poor Condition (grass cover < 50%) | (30%) | 68 | 79 | 86 | 89 |
| TR-55 Fair Condition (grass cover 50% to 75%) | (65%) | 49 | 69 | 79 | 84 |
| TR-55 Good Condition (grass cover > 75%) | (90%) | 39 | 61 | 74 | 80 |
| MMI Excellent Condition | 100% | 36 | 55 | 70 | 80 |

The above table indicates that the reasonable assumption of 100% ground cover in most open space areas will reduce the CN values for open grass areas on A, B, and C soils.

9. Connecticut has extensive woodlands with both tree canopies and shrub layers with ground cover. Common practice in use of hydrology models is to assign CN values to these areas based upon the published TR-55 values for "woods." A review indicates these values may overestimate runoff in Connecticut forest lands.

The published CN values for "woods" in the TR-55 Table 2-2c are based upon small farm wood lots, occasionally grazed or cut for firewood. This represents a disturbed woodland, similar to small wooded areas in residential neighborhoods. The values do not correspond to a mature forest land cover as found in rural areas of Connecticut and will overestimate CN values. Other references are available.

The SCS Hydrology Manual (NEH4) and Chow's Handbook of Applied Hydrology (1964) both provide guidance on selecting CN values for humid forested areas. The key factors are soil types and the thickness and condition of the humus organic material on the forest floor. The humus consists of porous partially decomposed organic material, mixed with mineral soils, in the O1 and A1 horizons. A review of the county soils surveys indicates Connecticut woodland soils typically have three to eight inches of humus. Based upon an assumed four inches of a loose humus, the hydrologic condition is IV, with the following CN values (NEH#4, Fig. 9.2):

| | CN Values by Soil Type | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Forest, 4" Humus | 30 | 50 | 60 | 67 |
| TR-55 Woods, Good Condition | 30 | 55 | 70 | 77 |

The above CN values for forest with four inches of humus are much lower than the commonly used TR-55 values. CN values for forests with other humus conditions can be obtained from the attached figure.

## D. Time of Concentration

The time of concentration (TC) input data for the TR-20 and HEC-1 models is an important input variable and has a significant impact on the final computed peak flow rates. In small watersheds, the overland flow component of the TC is critical. In larger watersheds, the channel travel times and routings tend to dominate overall lag periods.

The preferred procedure is to utilize a modified version of the three step "velocity method" as described in TR-55. The recommended procedure is:

1. The "sheet flow" (also called overland flow) component is used as per TR-55. The flow length varies, from as little as 100 feet in irregular topography that channelizes the water, to several hundred feet on smooth permeable soils that delay concentrated flow. SCS suggests a 300-foot limit, while Haan (1982) recommends up to 450 feet, depending on site conditions.

2. The "shallow concentrated flow" component of the time of concentration can be determined with or without using TR-55 figure 3.1. The figure is based on the Manning equation with fixed predetermined values of Manning Equation Roughness factor "N" and hydraulic radius "R". Instead of using these fixed values, one may use the Manning equation with appropriate values of "N" and "R". The attached page from the King County (Washington) Surface Water Design Manual provides suggested values.

3. The "channel flow" velocities should normally be computed with the Manning equation as in TR-55, with special attention to selecting appropriate "N" values and depths for each channel segment.

   In computing the channel slope, it is important to omit the vertical grade differences that occur over short lengths, such as waterfalls, rapids, and sudden drops, because their inclusion would alter the mean channel slope (Chow, 1964).

4. It is important to use multiple stream reaches for determining flow velocities with the Manning equation, each with a uniform slope, rather than averaging overall slopes. The sum of travel times for a steep segment and a flat segment is much greater than the composite travel time of an equivalent average slope segment due to the non-linear terms in the Mannings equation.

5. For large floods, much of the water flow is on the vegetated overbank floodplains rather than in the comparatively smooth channel. Use the appropriate composite friction coefficient for computing the time of travel.

6. The flow velocities of a two-year flood in a channel are different than for a 100-year overbank flood. It is not always appropriate to use a single TC value for a wide range of flood depths.

7. The computed flow velocities should be checked by comparing them to the threshold velocity of the observed bed material. For example, computed velocities of five feet per second are not reasonable on a fine sandy bed which would have been eroded.

8. Do not use the SCS Lag method of TC.

9. The time of travel through small ponds and lakes is zero. For large lakes, use the wave equation to determine the lake's wave velocity and travel time. The following velocities result:

| Water Depth, FT | Velocity, FPS |
|---|---|
| 2 | 8.0 |
| 4 | 11.3 |
| 8 | 16.0 |

10. Many natural channels in the upland portions of Connecticut have relatively steep gradients. The computation of mean velocities for use in the time of concentration, using standard steady state uniform flow techniques (Mannings equation) can lead to supercritical flow conditions and velocities, with a rapid time of concentration leading to high peak flow predictions.

    Research shows that supercritical flow in natural channels seldom occurs over long reaches (Trieste, 1992). This is due to high friction roughness, formation of riffles or chutes with mild gradient pools, and energy dissipating hydraulic jumps.

    Channels with Froude numbers over 1.0 (supercritical) are very erosive and tend to readjust into cascades/riffles with flat pools (Anderson et al, 1996). This reduces mean velocities and increases TC. Reasonable mean channel velocities can be assumed to have an upper limit at critical depth. For steep sheds, this is approximated by:

$$V = 3.81\ R^{0.83}\ S^{0.12}$$

## E. Precipitation

1. Rainfall totals used in the TR-20 model are not automatically adjusted for annual or partial duration data sets. The conversion from annual data series to partial-duration series is:

| Frequency | Conversion Multiplier |
|---|---|
| 2 | 1.13 |
| 5 | 1.04 |
| 10 | 1.01 |
| 25 | 1.00 |

2. The point rainfall data from publications such as TP-40 and HMR-35 should have a watershed area adjustment for basins greater than 10 square miles. The HEC-1 model has an optional step to do this. In the TR-20 model, it can be done manually using the adjustment factors in the HEC-1 manual. This adjustment reduces the net rainfall depths because intense storm cells have a discrete size and seldom cover large watersheds uniformly.

3. The TR-20 model has seven pre-coded rainfall distributions. The Type III storm pattern is used as the standard in Connecticut, and reviewers generally object to use of alternatives. The precipitation data in TP-40 and HMR-35 can be used to create site specific rain distributions in lieu of the standard SCS Type III.

## F. Time Increment

1. The main time increment affects the number of points used to define hydrographs. The TR-20 and HEC-1 models both have a limit of 300 points which may not allow use of small ΔT values for long duration storms. Ideally, the Δt value should be 0.1 to 0.3 TC so that the rising limb of the hydrograph has several computed points. It is difficult to select an ideal Δt value when the subwatersheds vary in size. For very small subareas, Δt maximum is 0.5 TC of smallest subarea. Typical values are 0.1 to 1.0 hours.

2. Avoid use of subwatersheds with a larger TC range, particularly with the TR-20 model, as the computer may not evaluate the peak points on small hydrographs.

3. The Δt value may be changed (increased) part way through a run by using a new increment card in the TR-50 model.

## G. Lag Time

The SCS hydrology methods use the watershed's time of concentration as a key input data relating to unit hydrograph development. Internally, the TR-20 program computes unit hydrographs based on watershed lag. The watershed lag is generally defined as the time interval between the centroid of rainfall to the center of mass of runoff, or peak of unit hydrograph. It may be thought of as a weighted time of travel.

It can be expressed as:

Lag = K TC (SCS, NEH4)

K = Coefficient less than 1.0

In the TR-20 program, a value K = 0.6 is used (Han, 1982) based upon empirical data. It may vary depending on watershed characteristics. In a "frying pan" shaped watershed, with an outlet at the end of handle, K may approach 1.0. In small basins with simple drainage patterns, the time of concentration may be very close to the lag time of peak flow (Chow, 1964). This adjustment would tend to decrease predicted peak flows.

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