SMADA Theory

Introduction

This section covers the basic theory of the methods used in the SMADA program. Also covered are hints and help in applying different methodologies. Included in this theory section are discussions of:

- watershed parameters
- infiltration methods
- hydrograph generation methods, and
- inventory routing.

This manual is not intended to be a textbook in Hydrology. For an in-depth discussion of the theory and methods used by SMADA and for Hydrology in general, the reader is referred to the text: Hydrology: Water Quantity and Quality Control 3rd Edition, Wanielista, Kersten, and Eaglin available from John Wiley and Sons Publishers (www.wiley.com).

Rainfall

SMADA has the ability to generate precipitation from dimensionless rainfall files. These dimensionless rainfalls have been produced and made available by various agencies, most notably the Soil Conservation Service (SCS, now called NRCS). The dimensionless rainfalls recommended by the SCS are the Type I, Type IA, Type II, and the Type III. Each of these dimensionless rainfall curves has a recommended region of the country for which it is applicable.

The actual rainfall used in hydrograph generation is developed from the dimensionless curve. In addition to the use of dimensionless rainfall, you may wish to enter the incremental rainfall directly. SMADA calls this option **User-Defined** on the **Rainfall Properties** dialog window found by selecting **Rainfall, Create/Edit Rainfall**.

Software Note: SMADA stores this dimensionless rainfall information in external files with an STM extension. The user can create these dimensionless rainfall files in the **Edit Dimensionless Rainfall File** dialog window found by selecting **Rainfall, Create/Edit Dimensionless Rainfall**.

Sample of the Dimensionless Rainfall Curves for an SCS Type I and Type IA Storm

Time (hr)	Time dimensionless	Type I	Type IA	Time (hr)	Time dimensionless	Type I	Type IA
0	0.0000	0.000	0.000	12.5	0.5208	0.705	0.683
0.5	0.0208	0.008	0.010	13.0	0.5417	0.727	0.701
1.0	0.0417	0.017	0.022	13.5	0.5625	0.748	0.719
1.5	0.0625	0.026	0.036	14.0	0.5833	0.767	0.736
2.0	0.0833	0.035	0.051	14.5	0.6042	0.784	0.753
2.5	0.1042	0.045	0.067	15.0	0.6250	0.800	0.769
3.0	0.1250	0.055	0.083	15.5	0.6458	0.816	0.785
3.5	0.1458	0.065	0.099	16.0	0.6667	0.830	0.800
4.0	0.1667	0.076	0.116	16.5	0.6875	0.844	0.815
4.5	0.1875	0.087	0.135	17.0	0.7083	0.857	0.830
5.0	0.2083	0.099	0.156	17.5	0.7292	0.870	0.844
5.5	0.2292	0.112	0.179	18.0	0.7500	0.882	0.858
6.0	0.2500	0.126	0.204	18.5	0.7708	0.893	0.871
6.5	0.2708	0.140	0.233	19.0	0.7917	0.905	0.884
7.0	0.2917	0.156	0.268	19.5	0.8125	0.916	0.896
7.5	0.3125	0.174	0.310	20.0	0.8333	0.926	0.908
8.0	0.3333	0.194	0.425	20.5	0.8542	0.936	0.920
8.5	0.3542	0.219	0.480	21.0	0.8750	0.946	0.932
9.0	0.3750	0.254	0.520	21.5	0.8958	0.955	0.944
9.5	0.3958	0.303	0.550	22.0	0.9167	0.965	0.956
10.0	0.4167	0.515	0.577	22.5	0.9375	0.974	0.967
10.5	0.4375	0.583	0.601	23.0	0.9583	0.983	0.978
11.0	0.4583	0.624	0.623	23.5	0.9792	0.992	0.989
11.5	0.4792	0.654	0.644	24.0	1.0000	1.000	1.000
12.0	0.5000	0.682	0.664				

Infiltration and Watershed Characteristics

I. Separate vs. Combined Routing

SMADA will route the impervious and the pervious regions of the watershed separately by default. The directly connected fraction of the watershed excess is calculated for the impervious region as the precipitation times the impervious watershed area.

Precipitation from the non-directly connected impervious region is added to the precipitation volume on the pervious region. Infiltration is calculated from this volume and subtracted from the precipitation to form excess.

If a composite curve number is used then the impervious area should be entered as zero (0), and the directly connected fraction should also be entered as zero. In the case of a composite curve number the effects of the impervious region are included in the estimate of the curve number.

II. Infiltration Methods

SMADA allows for two methods for the calculation of infiltration

- SCS curve number method
- Horton infiltration method.

SCS Curve Number Infiltration Estimation

The SCS Curve Number requires the input of three parameters:

1. Maximum Infiltration
2. Curve Number
3. Initial Abstraction Factor

In the SCS - CN Method of infiltration prediction, a curve number is chosen which represents the cover crop or soil type. This number typically ranges from 25 (for well covered forest with hydrologic Soil Group A) to 98 (for paved impervious areas). An initial abstraction factor (not to be confused with additional abstraction which is a purposefully diverted water volume) can be specified.

The SCS-CN Method typically uses an initial abstraction of 0.2S′ , however the user may specify other values. The 0.2 value is referred to as the abstraction factor. S′ is a maximum soil storage depth and is calculated from the equation:

$$S' = 1000/CN - 10$$

where: CN = Curve Number
S′ = Maximum storage depth

Runoff Curve Numbers for Pervious Areas *

	Hydrologic Soil Class			
Land Use	A	B	C	D
Bare Ground	77	86	91	94
Natural Desert Landscape	63	77	85	88
Garden or Row Crops	72	81	88	91
Good Grass Cover (>75%)	39	61	74	80
Poor Grass Cover (50-75%)	68	79	86	89
Lightly Wooded Area	36	60	73	79
Good Pasture and Range	39	61	74	80

* adopted from USDA-SCS, 1986 and 1975

Using the SCS-CN procedure, rainfall excess calculations are a function of rainfall volume and curve number. Assuming that storage at any time is proportional to maximum storage and rainfall excess is proportional to precipitation volume, the following equations result (USDA-SCS, 1986).

$$R = \frac{(P - .2S')^2}{P + 0.8S'} \quad \text{for P > 0.2S}$$

$$R = 0 \quad \text{for P < 0.2S'}$$

where: R = Rainfall Excess
P = Precipitation

When using the SCS-CN method with composite curve numbers, the user does not have to specify the three land categories. The percentage of impervious area should be specified as 0.0. In place of the **Pervious Curve Number** the user should specify the **Composite Curve Number**.

Horton Infiltration Estimation

The Horton Infiltration Estimation requires the input of four parameters:

1. Maximum Infiltration
2. Horton Limiting Infiltration Rate
3. Horton Initial Infiltration Rate
4. Horton Depletion Coefficient

The use of the double ring infiltrometer provides data which may be applicable to Horton's Equation (Wanielista, 1990):

$$f(t) = f_c + (f_0 - f_c)e^{-Kt}$$

where:
- $f(t)$ = Infiltration rate as a function of time
- f_c = Ultimate(Limiting) infiltration Rate
- f_o = Initial Infiltration Rate
- K = Recession constant (Horton Depletion Coefficient)
- t = time

Units should remain consistent

This equation can be solved to obtain infiltration rate as a function of cumulative infiltration volume in the form:

$$f(t) = f_0 - f_c \ln\left[\frac{f(t) - f_c}{f_0 - f_c}\right] - FK$$

where:
- $f(t)$ = Infiltration rate as a function of time
- f_c = Ultimate(Limiting) infiltration Rate
- f_o = Initial Infiltration Rate
- K = Recession constant (Horton Depletion Coefficient)
- F = Cumulative infiltration

This equation is the solution of infiltration rate as a function of cumulative infiltration. The equation must be solved by trail and error. Use of this equation form allows for more accurate estimation of infiltration because it bases the potential infiltration on the amount of infiltration which has occurred, not on the amount of time elapsed.

Hydrograph Generation Methods

I. SCS Method Hydrograph Generation

The SCS Method of hydrograph produces a triangular shaped unit hydrograph which is then multiplied by each step of the rainfall excess to produce a runoff hydrograph. The shape of the triangular unit hydrograph is determined by the time of concentration, the time step for routing, and the peak attenuation factor (K). The triangular shape is specified by the relationship:

$$t_b = t_p + t_f \qquad t_b = t_p + xt_p$$

where,

t_b = hydrograph base time
t_p = hydrograph time to peak
t_f = hydrograph recession time

X is calculated by:

$x = (2/K) - 1$ for area in acres
$x = (1291/K) - 1$ for area in square miles

where, **K** = attenuation factor (entered by user)

$$25 \leq \mathbf{K} \leq 645$$

Using these relationships and summing of flows for each discrete time step, SMADA creates a normalized unit hydrograph. The normalized unit hydrograph is multiplied by each of the steps of the instantaneous or excess hydrograph. These response hydrographs are then summed to produce an output hydrograph.

All unit hydrographs and routings are performed using the default rainfall time step. It is advisable that this time step be at least 1/3 the time of concentration of the watershed. Some publications advise a time step of less than 1/5 of the time of concentration.

SMADA allows two methods for the calculation of time to peak for each of the unit hydrographs. In the program, each option of SCS hydrograph generation has the notation of Method 1 or 2 by that option. These options are found selecting **Hydrograph**, **Generate Watershed Hydrograph**, then pressing the drop-down button for **Select Method of Hydrograph Generation**.

For Method 1, the time to peak is set equal to the time of concentration:

$$t_p = t_c$$

For Method 2, the time to peak is set equal to the time step divided by 2 plus 0.6 times the time of concentration:

$$t_p = D/2 + 0.6t_c$$

II. Santa Barbara Urban Hydrograph

The Santa Barbara Method uses the routing equation:

$$Q_{n+1} = Q_n + K(R_n + R_{n+1} - 2Q_n)$$

K is the routing coefficient and is determined by the equation:

$$K = \frac{\Delta t}{2t_c + \Delta t}$$

where:

Δt = Time Step
t_c = Time of Concentration
R_n = Instantaneous Hydrograph (excess) flow for time step n
Q_n = Runoff for time step n

All routing involving this equation are done with the default time step used in the rainfall entry. The instantaneous hydrograph is developed using the infiltration and abstraction information.

III. Clark Unit Hydrograph

The Clark Unit Hydrograph procedure is a two step procedure for the development of a unit hydrograph. The first step of the procedure is the development of a time area (TA) curve based on watershed characteristics. This curve is then routed through a linear reservoir to produce the final unit hydrograph.

The TA curve relates time to the fraction of the total watershed area which contributes to runoff. A TA curve can be developed by determining this contribution for time intervals between 0 and the total time of concentration of the watershed. These time intervals are drawn onto a plan drawing of the watershed and the total contributing area of each of these isochrones is determined.

A number of methods for determination of this TA curve have been developed. A common model used by HEC-1 and SMADA assumes a generic shape to the watershed. The total time of concentration of the watershed is broken into a number of intervals and for each of these intervals, the ratio of this time to the total time of concentration is calculated.

$$T_i = t_i/t_c$$

where

T_i = Ratio of time to total time of concentration
t_c = Total watershed time of concentration
t_i = Time step in question

The cumulative TA curve is then developed from the equations (Hydrologic Engineering Center, 1987);

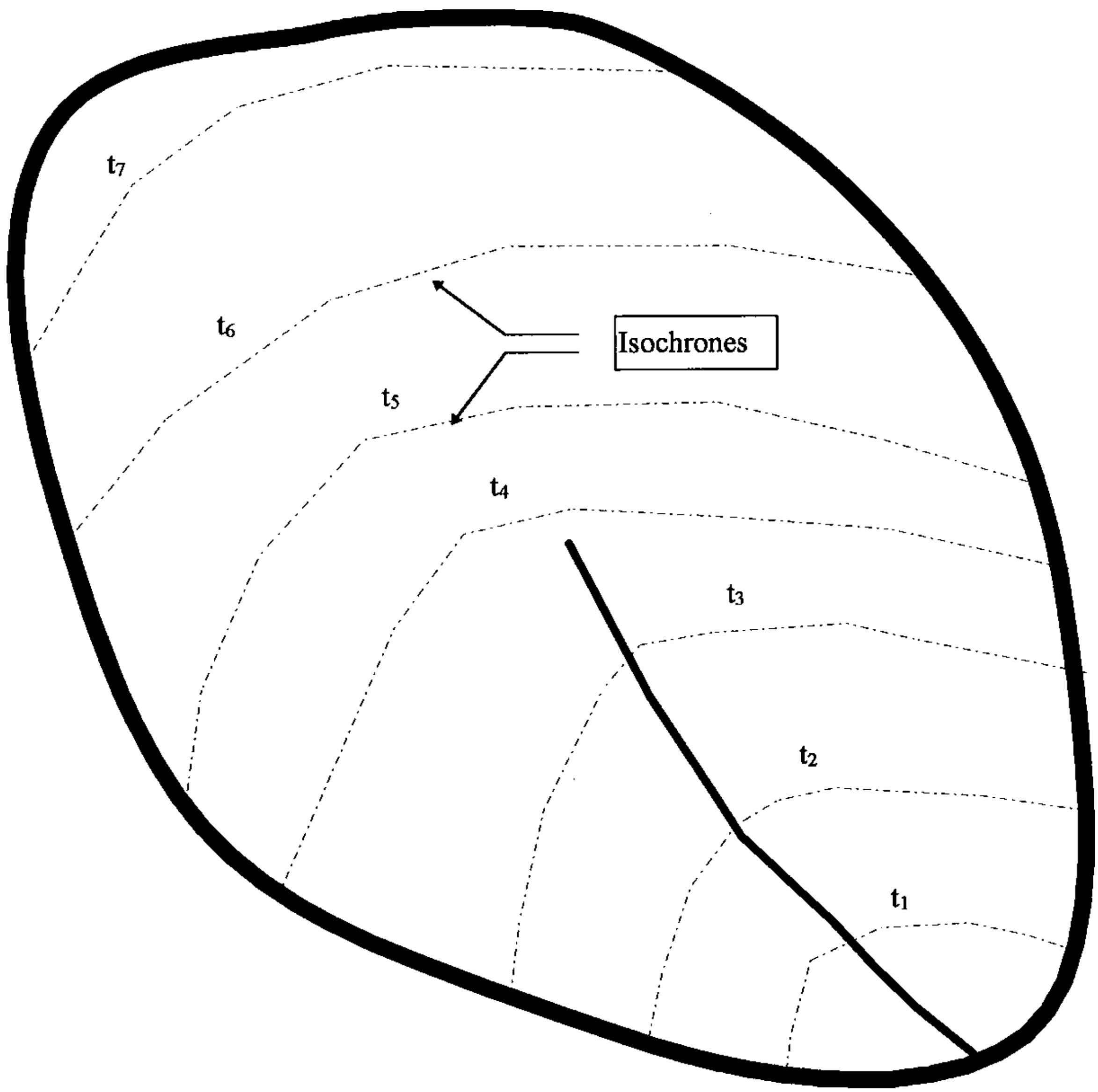
$$TA_i = 1.414T_i^{1.5} \qquad (0 <= T_i < 0.5)$$

$$1\text{-}TA_i = 1.414(1\text{-}T_i)^{1.5} \qquad (0.5 < T_i < 1.0)$$

where

TA_i = Cumulative value of Time Area Curve
T_i = Ratio of time to total time of concentration

Example of a Watershed with Isochrones drawn



Once the TA curve is developed the Clark Unit Hydrograph is generated by routing this TA curve through a linear reservoir with a routing parameter "R". The routing parameter "R" is used to calculate a routing coefficient "c" using the following equation:

$$c = \frac{2\Delta t}{2R + \Delta t}$$

where,

c = Linear routing coefficient (unitless)
R = Clark storage coefficient (time units)
Δt = Time step of analysis (time units)

The routing coefficient and the TA curve are used to find the instantaneous unit hydrograph (IUH) using the linear routing equation:

$$IUH_i = c\overline{TA_i} + (1 - c)IUH_{i-1}$$

where,

IUH_i = Increment of the instantaneous unit hydrograph
c = Linear routing coefficient
TA_i = Average time area ordinate at step i $TA_i = 0.5(TA_i + TA_{i-1})$

The final unit hydrograph can then be generated by averaging two instantaneous unit hydrographs which are the Δt time steps apart.

$$UH_i = 0.5(IUH_i + IUH_{i-1})$$

where,

IUH_i = Increment of the instantaneous unit hydrograph
UH_i = Increment of the unit hydrograph

Inventory Routing

I. Stage-Storage Discharge Relationships

At the heart of all pond routings is the stage-storage-discharge relationship. This relationship relates the pond stage to the storage in the pond. The relationship between these two parameters is dependent upon the pond geometry.

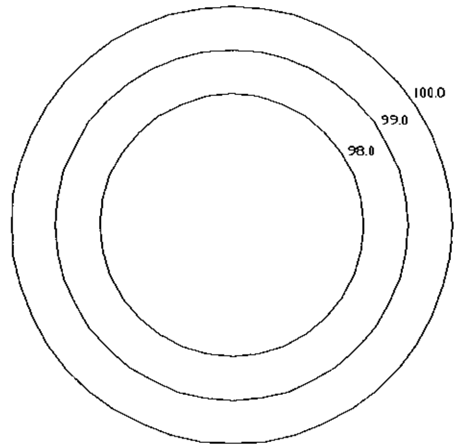
One method for the determination of this stage-storage relationship is using the stage-area relationship. The area referred to is the surface area of the pond at any given stage.

The calculation which uses this relationship is a simple mass balance:

$$\text{Qin} - \text{Qout} = \text{Change in Storage}$$

The **Flow In** (Qin) is received from a hydrograph or a pond. The **Flow Out** (Qout) is calculated knowing the discharge. Discharge is found from the stage which is found from the storage. The discharge relationship can be calculated from weir information or input directly by hand.

Calculation of Stage-Area-Volume



Plan View of a Circular Pond

For example, if a pond has the above plan view at the elevations shown, it is possible to calculate the surface area and the available storage in the pond at each elevation. The storage at 98.0 feet is 0 (pond bottom). The available storage at elevation 99 ft can be calculated by:

$$V_{99} = V_{98} + \frac{A_{98} + A_{99}}{2}(99 - 98)$$

where,

A_{99} = Surface area of pond at elevation of 99 feet
A_{98} = Surface area of pond at elevation of 98 feet
V_{98} = Storage volume of pond at elevation of 98 feet

Calculating Discharges Using Weirs

Weir discharges can be calculated using weir characteristics, invert elevation, and a list of stages. A weir discharge must be calculated for each water elevation above the weir invert.

Each type of weir has an equation and a set of coefficients which are used in the calculation of discharge. The default equations used are as follows:

Q = Flow in cfs
H = Height above weir invert in feet
W = Width of rectangular weirs

60 Degree V-Notch Weir:	$Q = A * H^B$	A = 1.43, B = 2.5
90 Degree V-Notch Weir:	$Q = A * H^B$	A = 2.50, B = 2.5
Broad Crested Rectangular Weir:	$Q = (A * H^B) * (W+0.2*H)$	A = 3.087, B = 1.5
Sharp Crested Rectangular Weir:	$Q = (A * H^B) * (W+0.2*H)$	A = 3.33, B = 1.5
Orifice:	$Q = (A * Area * H^B)$	A = 3.33, B = 1.5

Software Note: The Parameters A and B can be modified in the **Weir Design Information** dialog window found by selecting **Pond, Create/Edit Pond Design**.

To complete the Stage-Storage-Discharge relationship the discharge is calculated at each value of stage in the relationship. This value is crucial to the successful inventory routing.

Once the stage-storage-discharge relationship is entered, it is used in the calculation of outflow in the inventory routing.

Software Note: These discharges may be entered directly by hand on the **Pond Design** dialog widow (**Pond**, **Create/Edit Pond Design**) or calculated by the program by inserting a weir (**Pond**, **Create/Edit Pond Design**, **Pond Design** dialog window, **Weirs**).