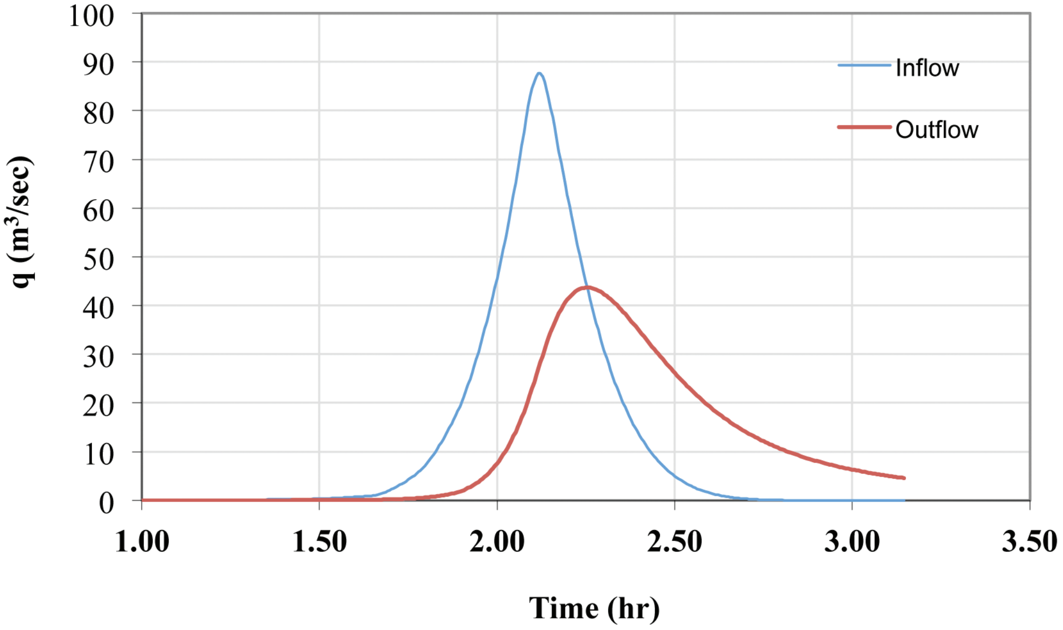
United States Department of Agriculture

Wildcat5 for Windows, A Rainfall-Runoff Hydrograph Model: User Manual and Documentation

Richard H. Hawkins and Armando Barreto-Munoz



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Abstract

Wildcat5 for Windows (Wildcat5) is an interactive Windows Excel®-based software package designed to assist watershed specialists in analyzing rainfall runoff events to predict peak flow and runoff volumes generated by single-event rainstorms for a variety of watershed soil and vegetation conditions. Model inputs are: (1) rainstorm characteristics, (2) parameters related to watershed soil and cover, (3) runoff timing parameters, and (4) unit hydrograph shape and scale selections. Many choices are available for each of the input categories and guidance is provided for their appropriate selection. The model is intended for small catchments responsive to conditions of upland soils and cover. Its peak flow estimation techniques are appropriate for projects such as gully control, culvert sizing and forest roads, environmental impact analyses, and post-wildfire hydrologic response.

Keywords: hydrology, model, Curve Number, hydrograph, fire, grazing

Authors

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Contents

Background

The original version of this software was written in 1974 for class use at Utah State University on an early Wang desktop computer (Wang Laboratories, Inc., Lowell, MA), and programmed in Wang BASIC. Patterned directly after examples in the in-service hydrology guide of the U.S. Department of Agriculture (USDA) Soil Conservation Service (now the Natural Resources Conservation Service), it used runoff Curve Numbers as the rainfall excess mechanism and fixed triangular unit hydrographs. It had limited capabilities. It was later rewritten, successively improved, and circulated in GW-BASIC® and QuickBASIC® (Microsoft Corp., Redmond, WA)[1]. The source code for these early programs could be contained on two single-spaced pages and was nameless.

In 1978, the Utah Division of Oil, Gas, and Mines contracted with Utah State University to reprogram the model in Fortran. It was also made available to the U.S. Department of the Interior, Bureau of Land Management (BLM) and the USDA Forest Service, for use on mainframes. Co-existing with the desktop versions, it was widely applied, and incrementally improved. An enhanced version, including graphical outputs, was developed about 1985 by Richard S. Moore, under a contract with the BLM Denver Federal Service Center.

In 1989 and 1990, a much-enhanced Microsoft Disk Operating System (DOS) desktop version with additional options was constructed at the University of Arizona by Richard H. Hawkins and R.J. Greenberg under a contract with the BLM Denver Federal Service Center. This version was called Wildcat4 and used the QuickBASIC source code. It is still used in compiled form in DOS environments. Its performance checks well against the current model.

However, advances in computer technology gradually left DOS software stranded, and Wildcat4 is increasingly awkward to use in Microsoft Windows®-based systems. In 2005, as a student exercise at the University of Arizona, a version of Wildcat4 in Visual Basic® for Windows was contributed by Armando Barreto-Munoz. Called Wildcat4W, it is the point of departure for Wildcat5, the current offering.

Disclaimer

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Download Information

The Wildcat5 program and manual can be downloaded from http://www.stream.fs.fed.us/publications/software.html.

This software and publication may be updated as features and modeling capabilities are added to the program. Users may wish to periodically check the download site for the latest updates. Errors of omission, logic, or miscalculation should be brought to the attention of the authors or the National Stream and Aquatic Ecology Center.

Wildcat5 is supported by, and limited technical support is available from, the U.S. Forest Service, National Stream and Aquatic Ecology Center, Watershed, Fish, Wildlife, Air, and Rare Plants Staff, Fort Collins, CO. The preferred method of contact for obtaining support is to send an email to rmrs_stream@fs.fed.us requesting "Wildcat5 Support" in the subject line. You may also write to the U.S. Forest Service, Rocky Mountain Research Station, National Stream and Aquatic Ecology Center, 2150A Centre Avenue, Suite 368, Fort Collins, CO 80526-1891, or call 970-295-5986.

Chapter 1: Introduction

1.1 Purpose of Wildcat5

Wildcat5 for Windows is a rainstorm-runoff hydrograph model designed to run interactively within Microsoft Excel. The user-friendly software program is designed to assist watershed specialists in analyzing rainfall-runoff events to predict peak flow and runoff volumes generated by single-event rainstorms for a variety of watershed soil, vegetation, and land-use conditions, including post-wildfire conditions.

The general model strategy of Wildcat5 is that of a traditional rainfall-runoff model. Necessary model inputs are: (1) rainstorm characteristics of depth, duration, and distribution; (2) parameters related to watershed soil and cover to calculate runoff depths; (3) runoff timing parameters to define the travel times to the watershed outlet; and (4) unit hydrograph shape and scale. Multiple choices are available for each of the input categories and guidance is provided for their appropriate selection. The model is intended for small catchments responsive to upland soil and vegetation conditions. Regardless of the application, considerable user judgment or experience is required to select appropriate input parameters and obtain reasonable results.

The model is based largely on the U.S. Department of Agriculture (USDA) Curve Number method for generating rainfall-runoff, with several other options. It also follows USDA's use of unit hydrographs. Primary technical sources for these approaches are two National Engineering Handbooks by the USDA Natural Resources Conservation Service (NRCS; formerly the Soil Conservation Service, or SCS) and its widely distributed Technical Release 55, hereafter abbreviated as NEH4, NEH630, and TR55, respectively. Full citations are given in the Chapter References.

1.2 Applications of Wildcat5

A common problem in applied hydrology is that of estimating rates of runoff volume and peak flows of various return periods from ungauged wildland watersheds. The peak flow estimation techniques in Wildcat5 are applicable to the many kinds and complexity of projects on which U.S. Forest Service hydrologists and others typically work. Examples of projects requiring peak flows are the design of gully stabilization structures, culvert and bridge sizing for low-volume forest roads, flood plain mapping in rural areas, environmental impact analysis, and the estimation of peak flows after wildfires. In cases involving water storage, such as stock ponds and small reservoirs, runoff volume is also required and the entire hydrograph must be developed. More sophisticated methods including unit hydrograph, flood routing, and stochastic frequency analysis are available and may be appropriate for projects where failure would cause catastrophic property damage or loss of life.

Because Wildcat5 is based on general rainfall-runoff hydrology, it can be applied to almost any kind of land use and watershed where model inputs are available and where peak flows are due to large rainfall events. Most rainfall-runoff models like Wildcat5 have conceptual origins on rain-fed agricultural watersheds, urban areas, and rangelands. Thus, most general models, including Wildcat5, do not work as well in forested watersheds with deep soils and heavy cover. An attempt to bridge this gap—with some supporting data—is offered here as the Complacent–Violent option for rainfall excess in chapter 4. Transfer of this tool to western wild lands was made more in response to a need for a calculation method (despite some loss of validity and usefulness) rather than because the methods fit well with western wildland conditions.

Wildcat5 and similar rainfall-runoff models were intended for watersheds where flow originates as direct runoff from rainfall. This condition is sometimes satisfied after severe wildfires that create extensive hydrophobic conditions. Rainfall-runoff models are not well suited to handle situations where maximum runoff includes snowmelt or watersheds where runoff may be delayed by heavy forest litter, porous topsoil, or lakes and wetlands. Some of these limitations can be overcome by carefully adjusting input parameters. In all instances, however, sound judgment is required and the user should be aware of the uncertainty associated with model outputs and inputs.

1.3 Overview of User Manual

This manual provides a Quick Start Guide for using the software, including an example for ready use of the program. It also describes the fundamental concepts, capabilities, limitations, features, input requirements, and output of Wildcat5. The manual is organized in the same logical fashion in which the data are entered when using the program, as follows:

Chapter 1: Introduction—this chapter.

Chapter 2: Quick Start Guide and Example—provides a short explanation of how to use the program, along with an example for those with experience using rainfall-runoff models.

Chapter 3: Storm Rainfall—provides guidance on selecting storm distributions. Available options are the (1) SCS Type B (the most widely used), (2) Farmer–Fletcher, (3) uniform, (4) custom, and (5) generic design storm distribution.

Chapter 4: Rainfall Excess—provides guidance on selecting a conceptual model for determining direct runoff (in other words, rainfall excess) from rainstorms. Available options are (1) distributed Curve Number (the default with initial abstraction of 0.2), (2) distributed Curve Number with initial abstraction set at 0.05, (3) exponentially distributed infiltration capacities, (4) distributed loss depth (F), (5) lumped constant loss rate (ϕ- index), (6) lumped constant loss fraction, and (7) Complacent–Violent.

Chapter 5: Timing Parameters—provides guidance on timing parameters for how quickly rainfall excess becomes runoff in terms of time of concentration or lag. Available options are (1) user choice override, (2) Kirpich's equation, (3) Kent's equation, and (4) Simas' equation.

Chapter 6: Unit Hydrographs—provides guidance on selecting the form of the unit hydrograph for runoff. Available options are (1) the simple triangular unit hydrograph (most used), (2) the variable triangular unit hydrograph, (3) the broken triangular unit hydrograph, and (4) the SCS dimensionless curvilinear unit hydrograph.

Chapter 7: Output Information—explains the graphical and tabular outputs generated by Wildcat5. Output displays are (1) Summary Output Table; (2) Runoff hydrograph Table; (3) Outflow Graphs; (4) Cum. Rainfall(P) and Runoff(Q) with Time and rainfall excess, or Rainfall(P) - Runoff(Q); and (5) Comparative Rainfall(P) - Runoff(Q) graph.

Chapter 8: Reservoir Routing—provides guidance for estimating inflow and outflow hydrographs due to routing runoff through a storage reservoir.

1.4 Features of Wildcat5

Wildcat5 is a user-friendly, touch-and-feel, follow-your-nose program usable by anyone who has experience in Excel and some background in the fundamentals of rainfall-runoff models. To these users, most of it should be self-explanatory and intuitively obvious. The program offers extensive help options that provide guidance for the large number of input options. The most commonly used options are generally highlighted as defaults.

Wildcat5 and this user manual are organized in the same sequence in which you would input data into a traditional rainfall-runoff model. The sequence of natural processes represented in rainfall-runoff models, the computational steps, and user options are shown in figure 1-01. A simple reservoir (pond) routing model based on the calculated hydrograph is also included. This manual follows the same sequence. Internally, Wildcat5 calculations are in English units. If you work with metric units, Wildcat5 converts all input and output values internally.

Necessary inputs to the model are:

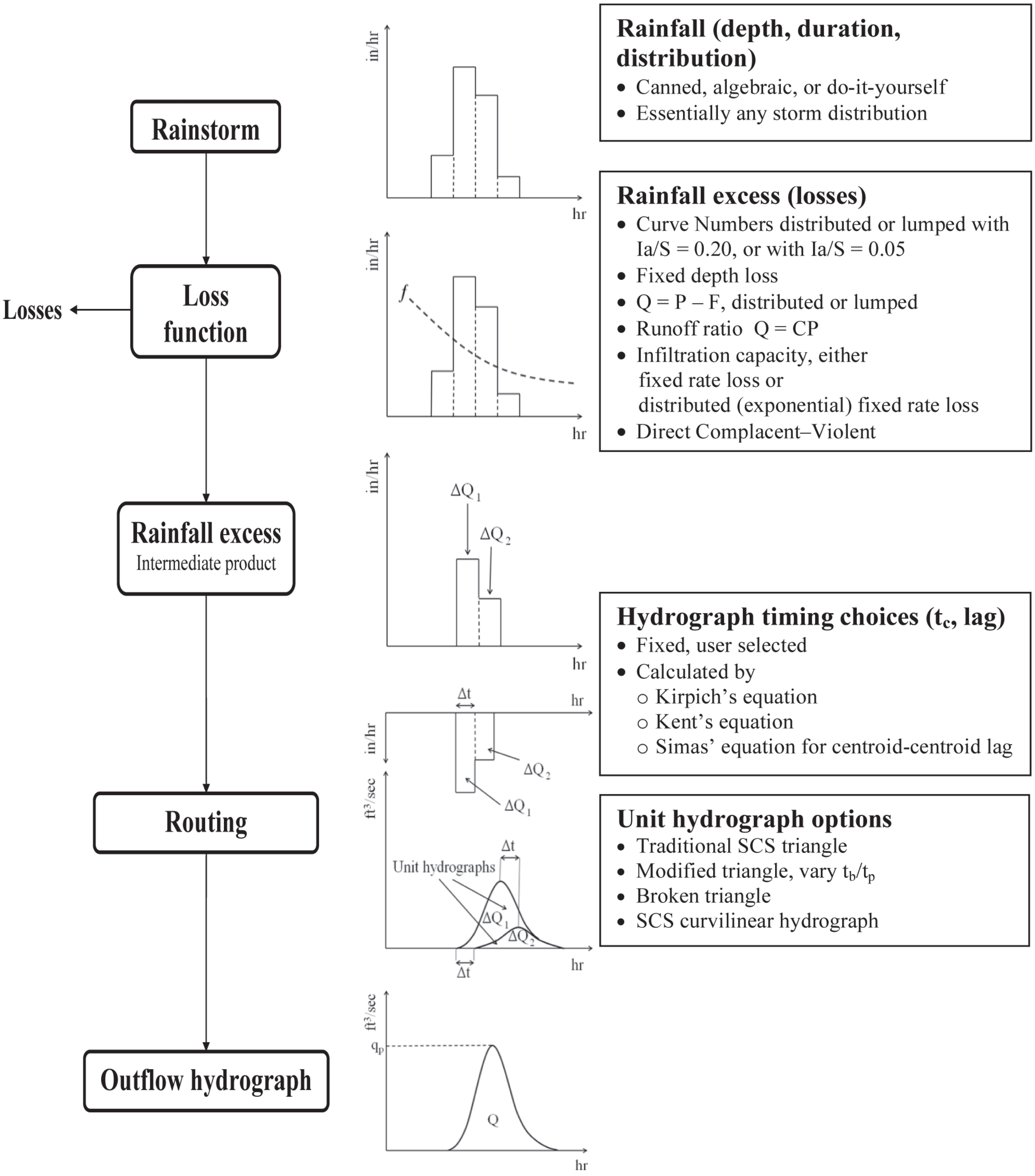
1. Rainfall characteristics of depth, duration, and distribution. Almost any storm distribution can be entered.
2. Parameters related to watershed soil and cover to calculate rainfall excess (runoff depths). Usually Curve Numbers are used for this calculation, but other options are available.
3. Timing parameters to define the travel times to the watershed outlet. Several ways to compute time of concentration are provided.
4. Unit hydrograph shape and scale selections to produce the runoff hydrograph. Four commonly used choices are included.

Outputs are the calculated hydrograph and a detailed report on all the relevant information derived and produced. Similar to all Windows applications, charts and tables can be copied and applied to reports and other external files.

1.5 Limitations and Omissions

Although Wildcat5 has many options, it omits several items found in some similar models. Some of these options may be available in subsequent versions of Wildcat5.

1. It does not contain the Green-Ampt infiltration loss function (either lumped or distributed), a popular choice in some models.



Rainfall (depth, duration, distribution)
- Canned, algebraic, or do-it-yourself
- Essentially any storm distribution

Rainfall excess (losses)
- Curve Numbers distributed or lumped with Ia/S = 0.20, or with Ia/S = 0.05
- Fixed depth loss
- Q = P – F, distributed or lumped
- Runoff ratio Q = CP
- Infiltration capacity, either
  fixed rate loss or
  distributed (exponential) fixed rate loss
- Direct Complacent–Violent

Hydrograph timing choices (t_c, lag)
- Fixed, user selected
- Calculated by
  - ○ Kirpich's equation
  - ○ Kent's equation
  - ○ Simas' equation for centroid-centroid lag

Unit hydrograph options
- Traditional SCS triangle
- Modified triangle, vary t_b/t_p
- Broken triangle
- SCS curvilinear hydrograph

Figure 1-01—The sequence of natural processes represented in rainfall-runoff models, computational steps, and options available to users of the Wildcat5 model.

2. It uses unit hydrographs as the watershed routing devices—a choice appropriate to the small watersheds targeted. Thus it contains neither overland flow routing (for example, kinematic wave) nor channel routing, for which there are many options. It does not contain software to alter the shape and peak flow factor of the curvilinear unit hydrograph. However, it does contain reservoir routing for the outflow hydrographs; with this feature, advanced users can represent channel routing or additional watershed routing, or a combination thereof.
3. Other than the single reservoir case described, it does not account for the influence of any additional structures in the watershed.
4. It does not distribute rainfall in space. All rainfall is assumed uniform across the watershed.
5. With Curve Number modeling, it does not consider any values of initial abstraction ($Ia/S = \lambda$) other than 0.20 and 0.05.
6. Only a single process-group can be represented. For example, the rainfall excess cannot be modeled by watershed fractions of Curve Numbers and linear runoff ratios at the same time.
7. There is no designated accounting for transmission losses.
8. The time of concentration must be greater than 1/360 of the storm duration. This is 4 min in a 24-hr storm.

1.6 Computer Requirements

Wildcat5 is a Windows-based program and requires Microsoft Office Excel 2003 or later. The program is written within Excel in Visual Basic for Applications. Macros must be enabled for the program to work properly. Procedures for enabling macros are different for every version of Excel. This manual does not provide a listing of how to enable macros for each Excel version. Search “How to enable macros for Excel” for your installed version of Excel by using any of the common search engines.

1.7 Chapter References

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U.S. Soil Conservation Service. 1986. Urban hydrology for small watersheds. Technical Release 55. Washington, DC: U.S. Department of Agriculture. 164 p. www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf. (March 18, 2015).

Chapter 2: Quick Start Guide and Example

2.1 Overview

Wildcat5 for Windows was written for use under the Windows operating system using Microsoft Excel spreadsheets and Visual Basic code to carry out the details. Wildcat5 will operate in Excel 2003 or later. You as the user are assumed to have a basic knowledge of the Windows operating system and to be familiar with the concepts of pull-down menus, buttons, scroll bars, opening/closing/moving/resizing windows, and so forth. You are also assumed to be acquainted with Excel spreadsheets and their use. This application is programmed in Visual Basic but inherits all the characteristics and limitations of Excel. Macros must be enabled for all versions of Excel. Another reminder is to use the “Enter” key every time you put data into a cell (this step is a requirement of Excel). Finally, this program can be used only with a mouse or similar pointing device.

The quick start guide in this chapter will allow you to begin to use the program within a matter of minutes. The program is intended to be a user-friendly, touch-and-feel, follow-your-nose operation. Users who are familiar with Excel and rainfall-runoff models can expect to find most of it self-explanatory and intuitively obvious. It is possible to work through the model without reading the instructions, but be alert to the cell-cursor phenomenon, and observe the repeated warning about enabling macros.

Numerous information (help) buttons are provided to give background, clarification, and suggested parameter values. Ultimate choices and responsibility for those choices are left to the user. In addition, generous navigation buttons are included to get you from screen to screen.

Additional details about specific computation features of Wildcat5 are provided in the rest of this manual.

2.2 Program Installation and Execution

Place all of the Wildcat5 files into a single folder that you have created. Alternatively, download the program and its associated files from the Internet and save them in this folder.

The current (April 2015) Wildcat5 program is a file called **Wildcat5_Dec07_2015_64bits.xlsm**. Accessory files include storm files ***.STM** (for the included drop-down menu **STORM AND STORM DISTRIBUTIONS**), ***.CST** (custom storms), and ***.GST** (generic storms). Default depth and duration information is included in the storm files, but you can alter this information. There are also ***.PDF** files containing the information for the help screens that are found under the “**?**” buttons. All of these files are intended for use by the program.

To run Wildcat5, double click on or load the current **Wildcat5_Dec07_2015_64bits.xlsm** file. A security warning at the top of the screen will require you to enable macros. You must do this every time. Procedures for enabling macros are different for every version of Excel, so if difficulties arise at this step, we suggest applying any of the common search engines for “How to enable macros for Excel xxxx” for your installed version of Excel. After macros are enabled, Wildcat5 should run properly.

After you double click the file **Wildcat5_Dec07_2015_64bits.xlsm**, the main screen should appear (fig. 2-01). You can select English or metric units for input and output, but this example will be all in English. Note that the current version date (the Build) is shown in the lower left-hand corner of the main screen.

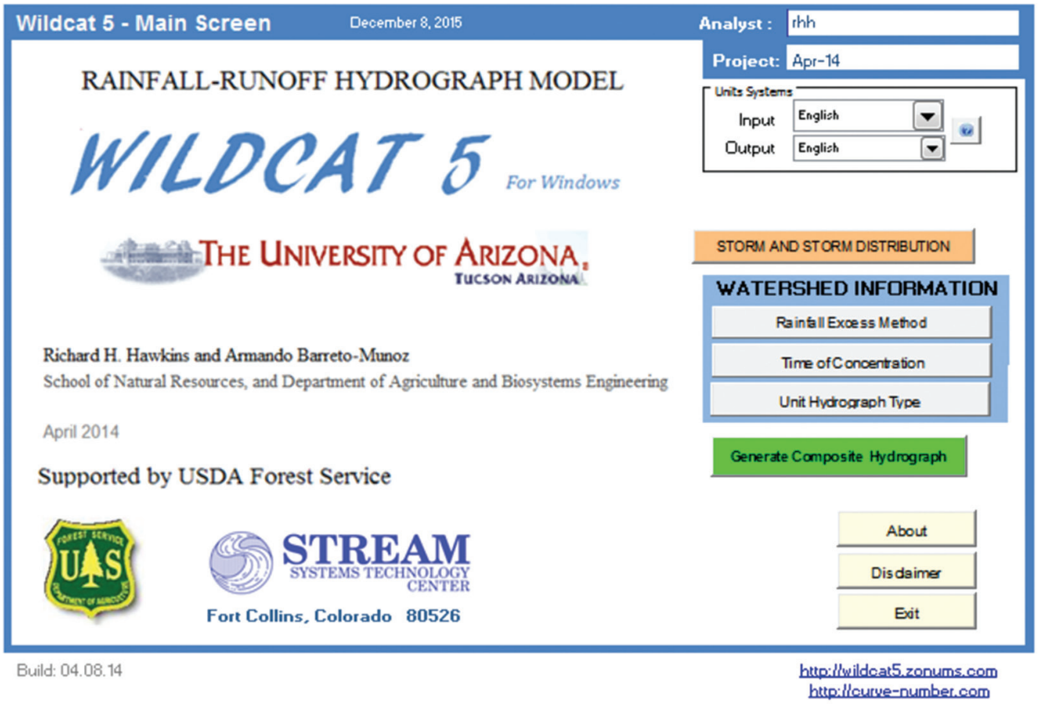

Analyst : rhh
Project: Apr-14
Input English
Output English

Figure 2-01—Screen capture of Wildcat5 main screen.

The main menu offers two major input groups, **STORM AND STORM DISTRIBUTION** and **WATERSHED INFORMATION**, with subgroups within the watershed category: (1) rainfall excess, in other words, how we determine runoff from rainfall, such as with Curve Numbers (CNs); (2) watershed timing, and (3) unit hydrograph choices. These are roughly in the order that they happen on the watershed, and as shown on the process chart (fig. 1-01).

The model operates by having you select inputs from each group. Click on each one, fill out the choices and information, hit the **Accept & Continue** button, and go on to the next input button.

The **STORM AND STORM DISTRIBUTION** screen lets you specify the duration, storm depth, and distribution. If the distribution is not listed there, then the **CUSTOM** and **GENERIC** options allow building it and saving it for later use.

Under **WATERSHED INFORMATION**, the **Rainfall Excess Method** screen gives options for both **DISTRIBUTED** and **LUMPED** systems. Again, note the information buttons on the right of each option. These buttons provide details and assumptions, and suggested typical values. If you want runoff based on CNs with initial abstraction (Ia) = 0.05S, where S = transient storage, then enter the traditional 0.20S-based CN values. The equivalent 0.05S CNs and S values are computed internally and then displayed.

The **Time of Concentration** screen collects specifications on timing for the unit hydrograph, and thus the model time step.

The **Unit Hydrograph** screen has four options, including the common SCS triangle and the curvilinear hydrographs from which it was derived. Two other options are also available. There are no do-it-yourself options for building custom unit hydrographs beyond altering the shape variable of the triangular hydrograph option.

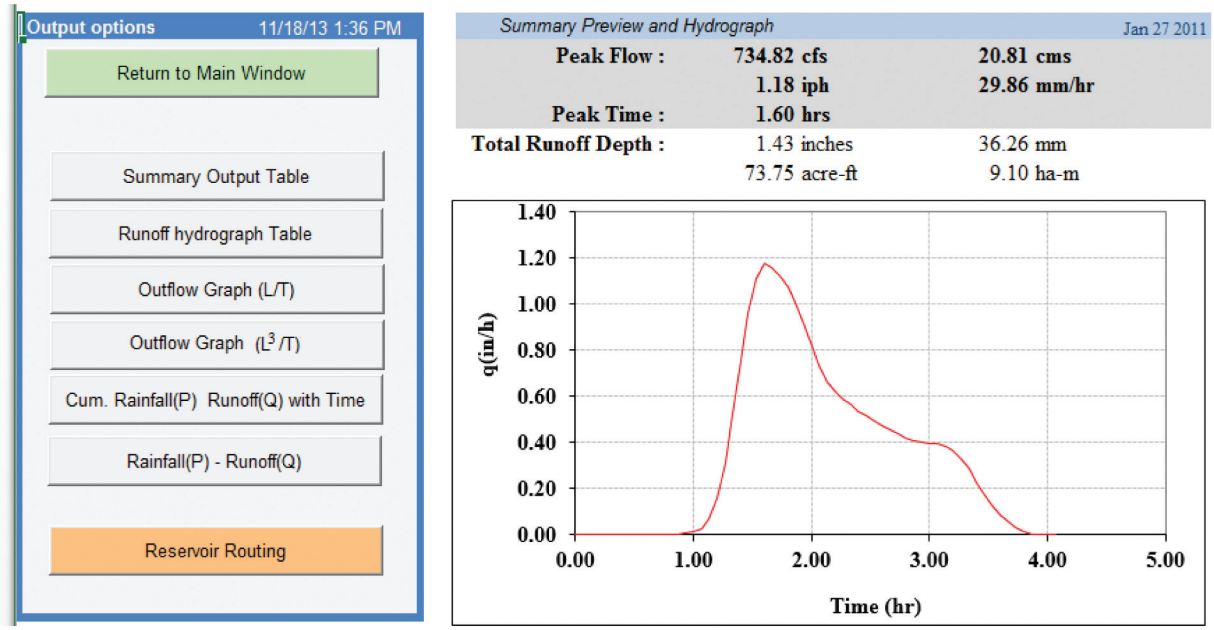
Each of the four input screens has an **Accept & Continue** option. The **Storm Data** screen also has **Load File** and **Save File** options. From each of the four input screens there is an option to return to the main screen.

- **Load File** allows you to select a previous input dataset, such as a previously used rainstorm. These files are stored with distinctive extensions (*.stm).
- **Save File** saves the specified storm on the current screen. You can then load it (see above) later if needed. This option saves the contents of the current storm.
- **Accept & Continue** does just that. The interface keeps the storm values and characteristics for the hydrographs it will create.

When all four selection groups have been completed, return to the main screen. Click on the Generate Composite Hydrograph button.

Wildcat5 will then give you an interim panel of **Summary Input Data** and a last check to confirm your inputs. Note the option to cancel and return to the main screen. If these values are acceptable, then click on the **Calculate Hydrograph** button.

Things will happen: The input data will be used to generate a composite hydrograph along with summary tables of input and output details. This step may take a few seconds. Be patient, and do not hit the keys during the computations. There may be several screens that flash by, and the output screen (fig. 2-02) will be displayed. This **Summary Preview and Hydrograph** screen may provide all the information that you require. From this screen additional details of the runoff can be selected with the buttons on the left side.



Summary Preview and Hydrograph Jan 27 2011

Peak Flow :	**734.82 cfs**	**20.81 cms**
	1.18 iph	**29.86 mm/hr**
Peak Time :	**1.60 hrs**	
Total Runoff Depth :	1.43 inches	36.26 mm
	73.75 acre-ft	9.10 ha-m

Figure 2-02—Screen capture of Wildcat5 output screen, showing summary results.

For more details, click on the **Summary Output Table** button on the top left. This summary screen gives most of the inputs as well. This is all of the output that most users require.

The **Hydrograph Table** shows the runoff values for each time step.

The **Reservoir Routing** is designed to route the hydrograph that was just generated through a reservoir of given surface area and spillway length, with a specified broad-crested weir coefficient.

There are more output features, but this should be enough to get started. You are encouraged to explore and discover on your own. For example, there are other graphics screens that can also be captured and used outside of the program for presentations and reports.

Here is a summary of the entire process:

- First enable the macros. Then go to the main screen.
- **Units Systems** gives you options for metric and English units with an information button on the main screen. Input can be in either metric or English units, with the same choices for outputs, including mixed, such as metric in, English out. However, the internal program calculations are carried out in English units.
- From the main screen click on the buttons and fill in the choices for the **Storm**, **Rainfall Excess**, **Watershed Information**, **Time of Concentration**, and **Unit Hydrograph**. Input follows the order of the flow chart in figure 1-01. You can navigate back and forth by the buttons offered, and easily return to the main screen. Help buttons containing advice, background, and suggestions are given at many locations and in each window. On every screen there is an **Accept & Continue** button.

- When you have made your selections for these inputs, hit the **Generate Composite Hydrograph** button, which leads to an intermediate screen with a summary check of the inputs.
- If OK, then hit the **Calculate Hydrograph** button, and the calculations begin. The ensuing calculations may take several seconds.
- The output screen that first appears gives the **Summary Preview and Hydrograph**. Often these results are sufficient for the project.
- For additional outputs, there are buttons on the left side that return to the main screen, to the reservoir routing procedure, or to six other output screens. You may also return to the main screen and begin anew. The same input values are still there.
- The six other output screens are self-explanatory, and are detailed under the buttons. Briefly, they show alternative views of both the inputs and outputs.
    - o The **Summary Output Table** gives technical details on the inputs, the calculations, and some nontraditional interpretations of the outputs.
    - o Four different plots give alternative presentations of the rainfall-runoff event.
    - o The **Runoff Hydrograph Table** gives calculated values line-by-line, including **TRANSIENT STORAGE**.

From any of these output screens you may also return to the main screen and begin again.

- The **Reservoir Routing** button (in orange) leads to the reservoir routing option. This option pertains to the hydrograph just computed, and will require the following information: reservoir surface area, spillway length, and weir coefficient. An information button elaborates on the routing process.
- The tables and figures produced can be copied directly for use in other publications and reports.

2.3 Example

This is a simple example to get started.

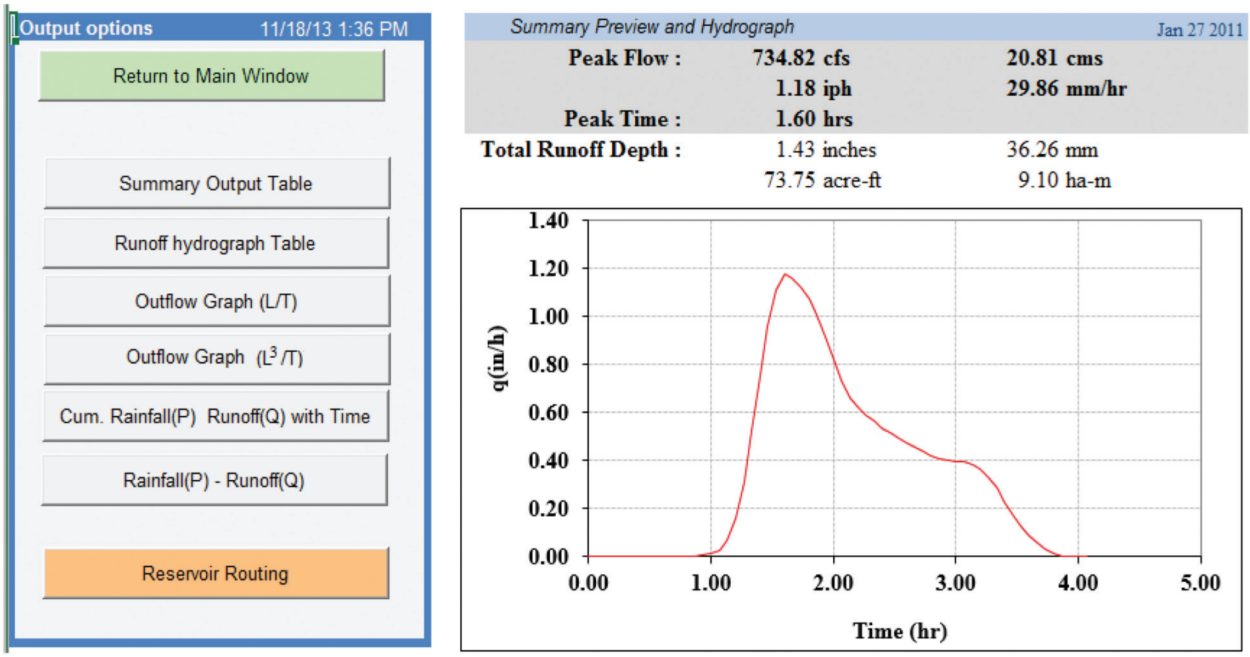
Storm: NEH4 Type B storm of 4 inches in 3 hr
Rainfall excess: 20 ac CN = 90; 200 ac CN = 80; 200 ac CN = 70; 200 ac CN = 60
Timing: $t_c = 0.5$ hr specified
Unit hydrograph: simple triangular unit hydrograph (standard SCS triangle)

- Go to **Storm Data** and input **Storm Duration** = 3 hr, **Storm Rainfall** = 4 in, **Storm Distribution** = NEH4B. Be sure to use the Enter key. Clicking on **Accept & Continue** will get you back to the main screen, or you may want to hit the **Save File** tab, and save the selection for later use.
- Go to the **Rainfall Excess Method** screen, and click on **Curve Number (default) λ = 0.2**. Click on the **CN Values** tab to bring up the **Hydrologic Response Units** screen. In the table enter:

20 acres grassland	CN = 90
200 acres brush/open	CN = 80
200 acres forest	CN = 70
200 acres deep forest	CN = 60

Note that it calculates the CN based on λ = 0.05 simultaneously. Clicking on **Accept & Continue** gets you back to the main screen.

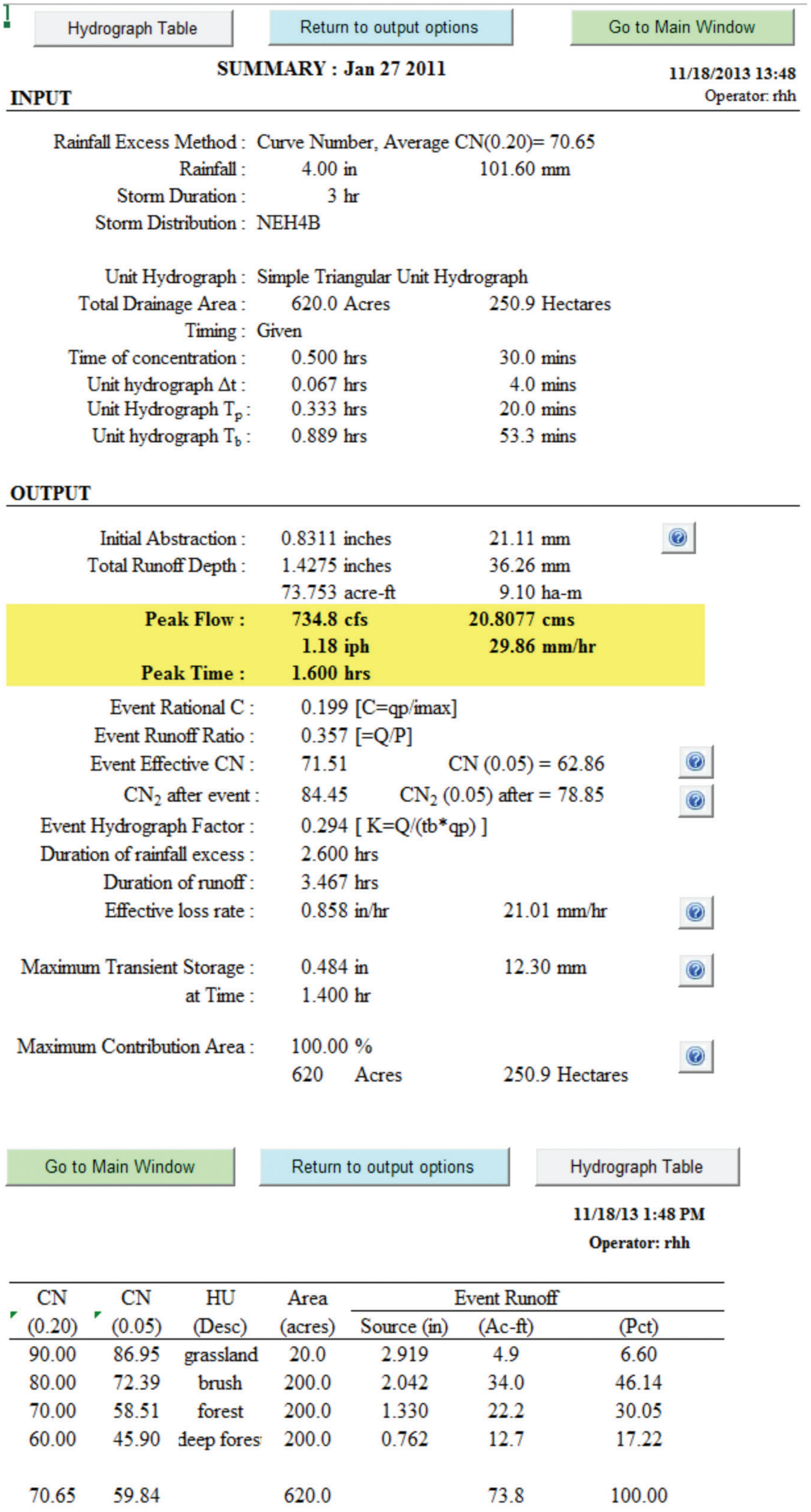
- Go to the **Time of Concentration** screen. Enter **Given value T_C = 0.5 hours**. Click on **Accept & Continue** to return to the main screen.
- Go to the **Unit Hydrograph** screen. Click on the **Simple Triangular Unit Hydrograph** button, HF=484. Click on **Accept & Continue** to return to the main screen.
- Click on **Generate Composite Hydrograph**. A summary input screen will come up, and if everything is OK, then hit the **Calculate Hydrograph** button. Screens will flash by. Hands off now: wait until you see the output results. It is the same **Summary Preview and Hydrograph** screen (fig. 2-02) as shown previously and inserted here (fig. 2-03).



Peak Flow :	734.82 cfs	20.81 cms
	1.18 iph	29.86 mm/hr
Peak Time :	1.60 hrs	
Total Runoff Depth :	1.43 inches	36.26 mm
	73.75 acre-ft	9.10 ha-m

Figure 2-03—Screen capture of Wildcat5 output screen, showing summary results for the step-by-step example.

- Click on the **Summary Output Table** tab near the top of the **Output Options** screen on the left. It will give you the table in figure 2-04.
- For a line-by-line output, click on **Hydrograph Table**. It will give you the table in figure 2-05. Clicking on the **Save to File** button will export the page to a **TXT** file.
- After the **Summary Output Table** and the main table output are generated, you are on your own to explore the other output options. All screens have a button to return to the main screen to start a new analysis.



SUMMARY : Jan 27 2011

11/18/2013 13:48
Operator: rhh

INPUT

Rainfall Excess Method : Curve Number, Average CN(0.20)= 70.65
Rainfall : 4.00 in 101.60 mm
Storm Duration : 3 hr
Storm Distribution : NEH4B

Unit Hydrograph : Simple Triangular Unit Hydrograph
Total Drainage Area : 620.0 Acres 250.9 Hectares
Timing : Given
Time of concentration : 0.500 hrs 30.0 mins
Unit hydrograph Δt : 0.067 hrs 4.0 mins
Unit Hydrograph T_p : 0.333 hrs 20.0 mins
Unit hydrograph T_b : 0.889 hrs 53.3 mins

OUTPUT

Initial Abstraction : 0.8311 inches 21.11 mm
Total Runoff Depth : 1.4275 inches 36.26 mm
73.753 acre-ft 9.10 ha-m
Peak Flow : 734.8 cfs 20.8077 cms
1.18 iph 29.86 mm/hr
Peak Time : 1.600 hrs
Event Rational C : 0.199 [C=qp/imax]
Event Runoff Ratio : 0.357 [=Q/P]
Event Effective CN : 71.51 CN (0.05) = 62.86
CN_2 after event : 84.45 CN_2 (0.05) after = 78.85
Event Hydrograph Factor : 0.294 [K=Q/(tb*qp)]
Duration of rainfall excess : 2.600 hrs
Duration of runoff : 3.467 hrs
Effective loss rate : 0.858 in/hr 21.01 mm/hr

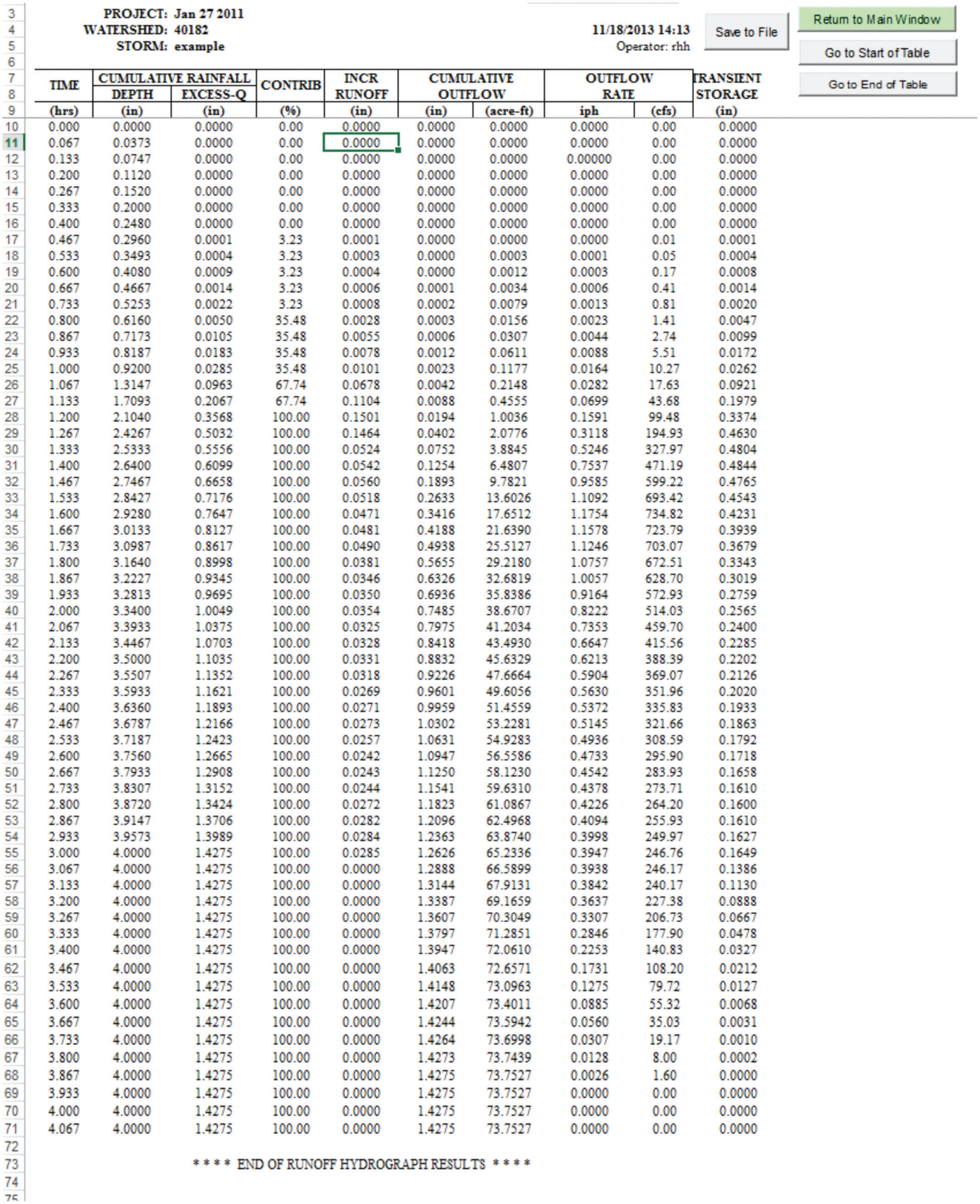
Maximum Transient Storage : 0.484 in 12.30 mm
at Time : 1.400 hr

Maximum Contribution Area : 100.00 %
620 Acres 250.9 Hectares

11/18/13 1:48 PM
Operator: rhh

CN	CN	HU	Area	Event Runoff		
(0.20)	(0.05)	(Desc)	(acres)	Source (in)	(Ac-ft)	(Pct)
90.00	86.95	grassland	20.0	2.919	4.9	6.60
80.00	72.39	brush	200.0	2.042	34.0	46.14
70.00	58.51	forest	200.0	1.330	22.2	30.05
60.00	45.90	deep fores	200.0	0.762	12.7	17.22
70.65	59.84		620.0		73.8	100.00

Figure 2-04—Screen capture of Wildcat5 summary output table, which also shows input data.



PROJECT: Jan 27 2011
WATERSHED: 40182
STORM: example

11/18/2013 14:13
Operator: rhh

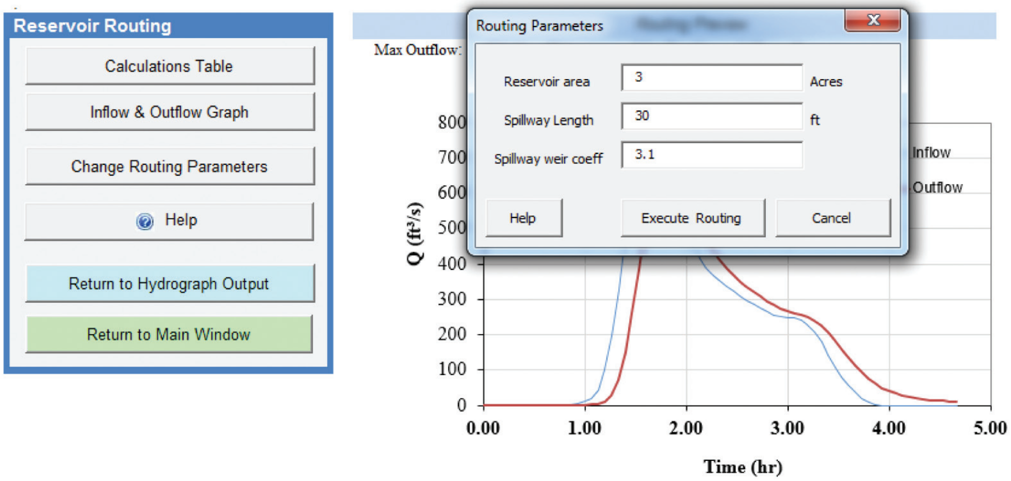
TIME	CUMULATIVE RAINFALL		CONTRIB	INCR RUNOFF	CUMULATIVE OUTFLOW		OUTFLOW RATE		TRANSIENT STORAGE
	DEPTH	EXCESS-Q							
(hrs)	(in)	(in)	(%)	(in)	(in)	(acre-ft)	iph	(cfs)	(in)
0.000	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.067	0.0373	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.133	0.0747	0.0000	0.00	0.0000	0.0000	0.0000	0.00000	0.00	0.0000
0.200	0.1120	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.267	0.1520	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.333	0.2000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.400	0.2480	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.00	0.0000
0.467	0.2960	0.0001	3.23	0.0001	0.0000	0.0000	0.0000	0.01	0.0001
0.533	0.3493	0.0004	3.23	0.0003	0.0000	0.0003	0.0001	0.05	0.0004
0.600	0.4080	0.0009	3.23	0.0004	0.0000	0.0012	0.0003	0.17	0.0008
0.667	0.4667	0.0014	3.23	0.0006	0.0001	0.0034	0.0006	0.41	0.0014
0.733	0.5253	0.0022	3.23	0.0008	0.0002	0.0079	0.0013	0.81	0.0020
0.800	0.6160	0.0050	35.48	0.0028	0.0003	0.0156	0.0023	1.41	0.0047
0.867	0.7173	0.0105	35.48	0.0055	0.0006	0.0307	0.0044	2.74	0.0099
0.933	0.8187	0.0183	35.48	0.0078	0.0012	0.0611	0.0088	5.51	0.0172
1.000	0.9200	0.0285	35.48	0.0101	0.0023	0.1177	0.0164	10.27	0.0262
1.067	1.3147	0.0963	67.74	0.0678	0.0042	0.2148	0.0282	17.63	0.0921
1.133	1.7093	0.2067	67.74	0.1104	0.0088	0.4555	0.0699	43.68	0.1979
1.200	2.1040	0.3568	100.00	0.1501	0.0194	1.0036	0.1591	99.48	0.3374
1.267	2.4267	0.5032	100.00	0.1464	0.0402	2.0776	0.3118	194.93	0.4630
1.333	2.5333	0.5556	100.00	0.0524	0.0752	3.8845	0.5246	327.97	0.4804
1.400	2.6400	0.6099	100.00	0.0542	0.1254	6.4807	0.7537	471.19	0.4844
1.467	2.7467	0.6658	100.00	0.0560	0.1893	9.7821	0.9585	599.22	0.4765
1.533	2.8427	0.7176	100.00	0.0518	0.2633	13.6026	1.1092	693.42	0.4543
1.600	2.9280	0.7647	100.00	0.0471	0.3416	17.6512	1.1754	734.82	0.4231
1.667	3.0133	0.8127	100.00	0.0481	0.4188	21.6390	1.1578	723.79	0.3939
1.733	3.0987	0.8617	100.00	0.0490	0.4938	25.5127	1.1246	703.07	0.3679
1.800	3.1640	0.8998	100.00	0.0381	0.5655	29.2180	1.0757	672.51	0.3343
1.867	3.2227	0.9345	100.00	0.0346	0.6326	32.6819	1.0057	628.70	0.3019
1.933	3.2813	0.9695	100.00	0.0350	0.6936	35.8386	0.9164	572.93	0.2759
2.000	3.3400	1.0049	100.00	0.0354	0.7485	38.6707	0.8222	514.03	0.2565
2.067	3.3933	1.0375	100.00	0.0325	0.7975	41.2034	0.7353	459.70	0.2400
2.133	3.4467	1.0703	100.00	0.0328	0.8418	43.4930	0.6647	415.56	0.2285
2.200	3.5000	1.1035	100.00	0.0331	0.8832	45.6329	0.6213	388.39	0.2202
2.267	3.5507	1.1352	100.00	0.0318	0.9226	47.6664	0.5904	369.07	0.2126
2.333	3.5933	1.1621	100.00	0.0269	0.9601	49.6056	0.5630	351.96	0.2020
2.400	3.6360	1.1893	100.00	0.0271	0.9959	51.4559	0.5372	335.83	0.1933
2.467	3.6787	1.2166	100.00	0.0273	1.0302	53.2281	0.5145	321.66	0.1863
2.533	3.7187	1.2423	100.00	0.0257	1.0631	54.9283	0.4936	308.59	0.1792
2.600	3.7560	1.2665	100.00	0.0242	1.0947	56.5586	0.4733	295.90	0.1718
2.667	3.7933	1.2908	100.00	0.0243	1.1250	58.1230	0.4542	283.93	0.1658
2.733	3.8307	1.3152	100.00	0.0244	1.1541	59.6310	0.4378	273.71	0.1610
2.800	3.8720	1.3424	100.00	0.0272	1.1823	61.0867	0.4226	264.20	0.1600
2.867	3.9147	1.3706	100.00	0.0282	1.2096	62.4968	0.4094	255.93	0.1610
2.933	3.9573	1.3989	100.00	0.0284	1.2363	63.8740	0.3998	249.97	0.1627
3.000	4.0000	1.4275	100.00	0.0285	1.2626	65.2336	0.3947	246.76	0.1649
3.067	4.0000	1.4275	100.00	0.0000	1.2888	66.5899	0.3938	246.17	0.1386
3.133	4.0000	1.4275	100.00	0.0000	1.3144	67.9131	0.3842	240.17	0.1130
3.200	4.0000	1.4275	100.00	0.0000	1.3387	69.1659	0.3637	227.38	0.0888
3.267	4.0000	1.4275	100.00	0.0000	1.3607	70.3049	0.3307	206.73	0.0667
3.333	4.0000	1.4275	100.00	0.0000	1.3797	71.2851	0.2846	177.90	0.0478
3.400	4.0000	1.4275	100.00	0.0000	1.3947	72.0610	0.2253	140.83	0.0327
3.467	4.0000	1.4275	100.00	0.0000	1.4063	72.6571	0.1731	108.20	0.0212
3.533	4.0000	1.4275	100.00	0.0000	1.4148	73.0963	0.1275	79.72	0.0127
3.600	4.0000	1.4275	100.00	0.0000	1.4207	73.4011	0.0885	55.32	0.0068
3.667	4.0000	1.4275	100.00	0.0000	1.4244	73.5942	0.0560	35.03	0.0031
3.733	4.0000	1.4275	100.00	0.0000	1.4264	73.6998	0.0307	19.17	0.0010
3.800	4.0000	1.4275	100.00	0.0000	1.4273	73.7439	0.0128	8.00	0.0002
3.867	4.0000	1.4275	100.00	0.0000	1.4275	73.7527	0.0026	1.60	0.0000
3.933	4.0000	1.4275	100.00	0.0000	1.4275	73.7527	0.0000	0.00	0.0000
4.000	4.0000	1.4275	100.00	0.0000	1.4275	73.7527	0.0000	0.00	0.0000
4.067	4.0000	1.4275	100.00	0.0000	1.4275	73.7527	0.0000	0.00	0.0000

* * * * END OF RUNOFF HYDROGRAPH RESULTS * * * *

Figure 2-05—Screen capture of Wildcat5 table of output data from step-by-step example.

- If there is a reservoir at the watershed outlet, Wildcat5 can route a hydrograph through it. Click on the **Reservoir Routing** button on the **Output options** window, and arrive at a new screen. It will ask for the full reservoir surface area (**Reservoir area**, ac or ha) and the **Spillway Length** (ft or m). A broad-crested weir coefficient (**Spillway weir coeff**) is also required. A typical value in English units for the coefficient is 3.0 to 3.1. If you use metric units, Wildcat5 will make conversions internally. Click on **Execute Routing**. For the example here, the assumed surface area is 3 ac and the spillway width is 30 ft (fig. 2-06).

The values for each time step are given in the **Calculations Table**. A button for exporting the tabular results to a **TXT** file is included on that screen.



Reservoir area: 3 Acres
Spillway Length: 30 ft
Spillway weir coeff: 3.1

Figure 2-06—Screen capture of Wildcat5 input screen for routing a hydrograph through a reservoir.

Chapter 3: Storm Rainfall

3.1 Concepts

Rainstorms come in a variety of depths, durations, and distributions. Although Wildcat5 allows specifying all three of these variables, only the distribution itself is discussed here. The depth (P) and duration (T) together define the frequency, or return period of the storm. Rainfall intensities within a storm tend to vary with time. The sequence and magnitude of interval intensities within a storm is called its distribution.

While the notion refers to the spread of intensities in a rainstorm, it is common to describe the time progress of a storm as a series of break points of cumulate rainfall depth $P(t)$ with cumulative time t. The internal interval slope $\Delta P/\Delta t$ is the interval intensity.

The storm distribution inputs are standardized to a basis of 0 to 100 percent, in both the storm time and cumulative storm depth. Wildcat5 then uses the user-specified storm depth (in or mm) and duration (hr) to create the dimensioned storm times and depths used in the model simulations. This is done internally.

Dimensionless rainfall distributions have much in common with probability distributions or histograms used in statistics. Though not shown here, they can be described in terms such as means, medians, modes, and variances, when the interval intensities play the role of the histogram columns. The area under the dimensionless intensity curve is unity, as is cumulative total.

Graphs of cumulative rainfall depth and storm duration have characteristic shapes, and two important attributes stand out: (1) the maximum intensity in terms of the average intensity, and (2) the timing of the peak intensity. These characteristics are summarized for some of the distributions in Wildcat5 in table 3-01. Sometimes these are described by the time-quarter of the storm in which the maximum intensity happens, for example, first-quarter storms or third-quarter storms. Design storms are usually unimodal: they have only a single peak intensity.

3.2. Distributions in Wildcat5

3.21 User Choices

In practice, design hydrology applies specific distributions keyed to the local climate and general storm characteristics. These may or may not be events that actually occur and cause floods. However, when distributions are used with specific models, it is assumed that they will produce return period flood peaks that are consistent with regional observations. Often, the distribution is specified by an approving jurisdiction, but it may also be chosen by the analyst based on sound judgment, common practice, or experience.

Table 3-01—Some general characteristics of selected design storms.

Distribution	Peak intensity (% of avg. intensity)	Timing of peak within storm: % of duration	Timing of peak within storm: Comments
Farmer–Fletcher[a]			
Great Basin, UT	365	0–10	1st 10 percent of the storm
Wasatch Front, UT	270	20–30	3rd 10 percent of the storm
NEH4B[b]	444	33–41.6	5th 0.5 hr in a 6-hr storm
Uniform	100	No peak intensity	Default for interval bursts
Iowa 3-hr[c]	526	40–53.3	hr 1.2 to 1.6 in 3-hr storm
Type I (SCS)[d]	626	42	hr 10 to 11 in a 24-hr storm
Type II (SCS)[d]	700	44–47	17th 5-min interval in a 3-hr storm
TSMS[e]	750	2.8–5.6	2nd 5-min interval in a 3-hr storm
CNphi00	454.7	0–5	1st 9 min of a 3-hr storm
CNphi25	421.1	25–30	45 to 54 min in a 3-hr storm
CNphi50	378.8	45–55	81 to 99 min in a 3-hr storm
CNphi75	424.1	70–75	119 to 135 min in a 3-hr storm
CNphi100	454.7	95–100	last 9 min of a 3-hr storm

[a] Source: Farmer and Fletcher (1972).
[b] Source: U.S. Soil Conservation Service (1954).
[c] Source: Elhakeem and Papanicolaou (2009).
[d] Source: U.S. Natural Resources Conservation Service (2003).
[e] Tucson Stormwater Management System. Source: Simons, Li Associates (1995).

3.22 Standard Distributions

Three of the storm options in table 3-01 are offered in the drop-down menu: (1) the **Farmer–Fletcher** (a first-quarter storm), (2) the **NEH4B** (a second-quarter storm, and also called the SCS Type B or simply the Type B), and (3) the **uniform** storm. Simply click on the choice, and the time and intensity calculations are performed internally.

3.221 Farmer–Fletcher (Great Basin, UT)

This distribution is claimed to be characteristic of first-quadrant storms in the Great Basin area of Utah, and is notable for having the major intensities at the very start of the storm. In models, it tends to produce lower flood peaks than storms with heavy bursts at the end of the storm. See Farmer and Fletcher (1972). Note that there are two separate distributions with the **Farmer–Fletcher** designation.

3.222 NEH4B

This distribution can be traced to the early version of the NEH4 (U.S. Soil Conservation Service 1954) and has been widely used. It was originally specified for a storm lasting 6 hr. It has the maximum intensity burst (37 percent of the total storm rainfall) in the 5th twelfth of the storm duration (fifth half-hour of a 6-hr storm). It can be found in TR-60 (U.S. Natural Resources Conservation Service 1990). It is also called the NEH4 Type B, or simply the Type B.

3.223 Uniform

This is a constant steady rainfall, the simplest and reference distribution, but it is uncommon in recorded flood rainfall. It is also the assumed short-term distribution of discrete bursts within a complete storm. From a hydrograph standpoint, it leads to minimal flood peaks. There is no change of intensity as the storm proceeds.

3.23 Custom Distributions

The **Custom** option allows you to specify the breakpoint coordinates for any feasible rainfall distribution. The points must begin at (0, 0), and end at (100,100), with all interval point sequences non-diminishing. That is, the distribution cannot have any intervals of negative slopes. Thus, any distribution desired or required by local practice can be used if the dimensionless coordinates are known. The program can accept up to 50 breakpoints. These are saved as ***.CST** files and can be selected again for later use. Some sample-example CST-formatted storms are supplied as files with Wildcat5. These are:

- **SCS Type I and II**. These distributions have a large following in the urban hydrology and flood control design community. Coordinates are drawn from http://hydrocad.net/rainfall/tables.
- **Farmer–Fletcher (Wasatch Front).** This is appropriate for the Wasatch Front area of Utah, and was issued jointly with the Great Basin distribution. See Farmer and Fletcher (1972).
- **Iowa 3-hour.** This was used in simulator studies by Elhakeem and Papanicolaou (2009), and was extracted as the major rainfall burst from a 24-hr "Type II" storm. It is notable that plot-simulator rainfall-runoff data generated with this distribution are consistent with the runoff values created following Curve Number [CN] methods in Natural Resources Conservation Service handbooks.
- **TSMS.** This distribution was constructed for application to the Tucson [AZ] Stormwater Management System (TSMS) hydrology (Simons, Li Associates 1995). It is very similar to distributions developed from and applied to events at Walnut Gulch, AZ.
- **CN–ϕ distributions**. These have the unique property of generating consistent relationships between the CN and the time-constant loss rate (ϕ) for a given storm duration (T). Five time-of-peak options are included. These distributions assume the timing of the peak intensity within the storm does not destroy the CN-ϕ relationship: $CN = 1200 / (12 + \phi T)$, where T is the storm duration in hr, ϕ is in in/hr, and only a single lumped CN is used.

3.3 Generic Design Rainstorm Distribution

3.31 General

Generic rainstorms represent event rainfall distributions (that is, intensity distribution and sequence in time) in functional (algebraic) form. The major descriptors are the event depth (P), the event duration (T), the maximum intensity (i_x), the minimum intensity during the storm (i_o), and the location of the peak intensity within the storm (t_p). Note that this t_p is not the same as the t_p used in hydrograph descriptors. Only unimodal storms are covered with this option. It was used in several earlier versions of Wildcat.

3.32 Application in Wildcat5

The **General** choice is offered in the **STORM AND STORM DISTRIBUTION** selection as the **Generic** option. The input screen asks for the minimum and maximum rainfall intensities, as a percentage of the average intensity. The average intensity is defined as the total storm rainfall depth divided by the storm time, or P/T. It also asks for the placement within the storm duration of the maximum intensity as a percentage of the duration. For example, if the maximum intensities are to be in the latter part of the storm, you may input 80, for 80 percent. If the storm specified was 6 hr long, then the maximum intensity would occur at hour 4.8.

For computational reasons, the minimum specified intensity cannot be zero. But it can be approached with a very small number, such as 0.001 percent. A true 0 will cause an error message. The exponent "n" is defined by the storm specifications (i_o and i_x) and the calculation made internally. The basic algebraic form used is:

$$i(t) = i_o + (i_p - i_o)(t/t_p)^n \qquad \text{for } 0 < t < t_p$$
$$i(t) = i_o + (i_p - i_o)[(T - t) / (T - t_p)]^n \qquad \text{for } t_p < t < T$$

where

i = intensity (length/time)
i_o = minimum intensity at time = 0 (length/time)
i_p = peak intensity at time = t_p (length/time)
t = time from beginning of storm (time)
t_p = time of peak intensity during the storm (time)
T = total storm duration (time)
n = a dimensionless exponent.

The exponent "n" is fixed (back-defined) by the other storm specifications, and calculated internally as $n = (i_p - P/T) / (P/T - i_o)$. P/T is the mean storm intensity (length/time).

The cumulative depths at time t can be determined by integration, or by knowledge of geometry directly. The equations are:

$$P(t) = t\{i_o + [(i_p - i_o) / (n + 1)](t/t_p)^n\} \qquad 0 < t < t_p$$
$$P(t) = P - (T - t)\{[i_o + [(i_{p-} - i_o)/(n + 1)][(T - t)/(T - t_p)]^n\} \qquad t_p < t < T$$

P is the total storm depth, and P(t) is the depth at time = t. An illustration is given in figure 3-01.

3.4 Effects of Distribution Selection

The choice of a distribution can influence the hydrograph generated. The maximum intensity described by the distribution affects the flood peak, as will the timing of the most intense rainfall burst in some cases. This is especially true when using the CN method to generate interval rainfall excess. Peak-intensity rainfall bursts early in a storm will usually lead to smaller peak flows than will late-storm peak intensities.

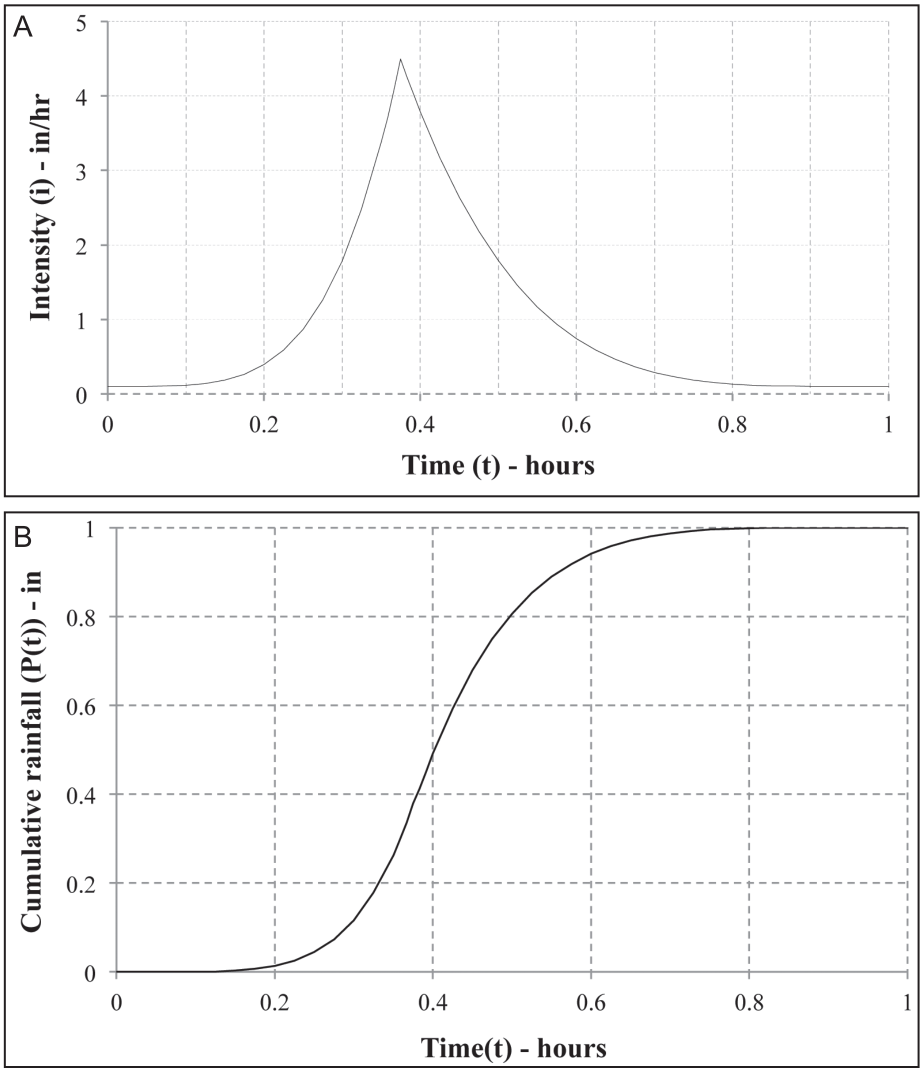


Figure 3-01—Definition figures, for the case of P = 1 in, T = 1 hr, t_p = 0.375 hr, i_o = 0.20 in/hr, and i_p = 4.5 in/hr. For these conditions, n = 4.3. Note that the intensity (A) shows on the cumulative rainfall (B) as the slope of the curve. The maximum slope occurs under the peak at 0.375 hr. This rainfall distribution is similar to the NEH4B distribution.

3.5 Chapter References

There is a rich literature on storm distributions. The following list is a small sample. A useful Web site is http://hydrocad.net/rainfall/tables.

Elhakeem, M.; Papanicalaou, A.N. 2008. Estimation of runoff curve number via direct rainfall simulator measurement in the State of Iowa, USA. Water Resources Management. DOI: 10.1007/s11269-008-9390-1.

Farmer, E.E.; Fletcher, J.E. 1972. Some intra-storm characteristics of high-intensity rainfall bursts. In: Davies, D.A., ed. Geilo Symposium, Distribution of precipitation in mountainous areas. Proceedings and key-papers presented during the session. Publ. 326. Geneva, Switzerland: World Meteorological Organization: 525-531.

Simons, Li Associates. 1995. Rev. Existing-conditions hydrologic modeling for Tucson Stormwater Management Study, Phase ii, Stormwater Master Plan (Task 7, Subtask 7A-3). Prepared in association with Camp Dresser & McKee, Lewis & Roca, Rillito Consulting Group, SWCA, Inc. 47 p.

U.S. Natural Resources Conservation Service. 1990. Earth dams and reservoirs. Technical Release 60. U.S. Department of Agriculture. 66 p.

U.S. Natural Resources Conservation Service. 2003. Updated 2012. National engineering handbook. Part 630, Hydrology. Washington, DC: Department of Agriculture. directives.sc.egov.usda.gov/viewerFS.aspx?hid=21422. (March 17, 2015).

U.S. Soil Conservation Service. 1954 [and following]. National engineering handbook. Section 4, Hydrology. Washington, DC: U.S. Department of Agriculture. 115 p. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=18393.wba. (March 19, 2015).

U.S. Soil Conservation Service. 1986. Urban hydrology for small watersheds. Technical Release 55. Washington, DC: U.S. Department of Agriculture. 164 p. www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf. (March 18, 2015).

Chapter 4: Rainfall Excess

4.1 Concepts

Quantifying rainfall excess is a key step in the modeling process. During a rainstorm, rain reacts with the watershed, so it is divided into "losses" that remain on the land, and rainfall excess, which becomes runoff. The response of rainfall excess is a measure of the hydrologic properties of the uplands, which in turn reflect the land use and condition of these lands. Estimating rainfall excess is often the most important step in modeling runoff volume or peak flow rates. However, several different mechanisms for generating rainfall excess may be found on a single watershed. The spatial and temporal variations of processes—and of the rainfall—are masked by the lumping, or assumed uniformity, necessary to apply Wildcat5.

Professional consensus has not identified a single best technique for estimating rainfall excess. One widely applied technique is the Curve Number (CN) method. Because of its simplicity, popularity, and wide use, it has been highly scrutinized and often criticized.

Many factors affect rainfall excess. Several options defining these factors are offered in Wildcat5. These options are soil and vegetation properties that either are intrinsically based on rate (driven by infiltration) or on depth (driven by rainfall depth), or are spatially lumped or distributed.

4.2 Runoff Curve Numbers

4.21 General

The CN method is widely used to determine direct runoff (rainfall excess) from rainstorms, and is applied throughout the world. Pioneered by the U.S. Soil Conservation Service (now the U.S. Natural Resources Conservation Service, or NRCS), the technique has been widely used since the late 1950s.

The current reference handbook is NEH630 (U.S. NRCS 2003). Further development and discussion are presented in several sources, such as Hawkins and others (2009). Some guidance is given here for wild lands affected by fire and grazing.

This section addresses runoff generation only by the CN method. Several other options offered in Wildcat5 and covered in this manual have been long associated with the CN method, but are more generally simply "NRCS methods."

4.22 Concepts

Direct rainfall-runoff is modeled in a lumped form as:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \qquad \text{for } P \geq 0.2S,\ Q = 0 \text{ otherwise} \qquad (4\text{-}01)$$

where S is a measure of maximum possible difference between P (the rainfall) and Q (the runoff, or more appropriately, the rainfall excess). In practice, S is 5/6 of that maximum possible difference, between P and Q when the initial abstraction (Ia) of 0.2S is included. The initial abstraction is the rainfall depth at the onset of the event required for runoff to be initiated. For convenience and ease in understanding, S is transformed to the coefficient CN by

$$CN = 1000 / (10 + S) \qquad (4\text{-}02)$$

when S, P, and Q are in inches. For most applications, values of CN are found in handbook tables (see below) and other agency sources, and vary from 0 (no runoff for any storm) to 100 (all rainfall becomes runoff). In Wildcat5 this technique models rainfall excess depths Q from rainfall P for a series of time steps within a storm. The incremental runoff pulses from each time step are transformed to distributed rates via unit hydrographs.

4.23 Use

The original CN technique targeted rain-fed agricultural lands and was based on studies on small watersheds throughout the United States. The CN technology was subsequently extended to application on urban land, wild land, and disturbed lands. Success on humid traditional forested watersheds has been limited. Note that in the NRCS table (table 4-01) the only forested land use entry is simply "Woods," a rather limited choice given the wide variety of forest types and uses. There are no table entries for "forests" directly; and no adjustments for silvicultural treatments, land use, or fire condition are offered.

4.24 Parameters

In this technique, the most important parameter of interest is the CN, which may vary from 0 to 100, though most are in the range of 55 to 95. Several studies have shown that the choice of CN is critical. Runoff peaks and volumes are usually more sensitive to CN than to rainfall depths or duration.

Handbook tables of CNs for a variety of conditions are given in tables 4-01 through 4-03. Note that they are defined on the basis of Hydrologic Soil Groups (HSGs), cover, land use, and, in some cases, hydrologic condition. The hydrologic condition is a description of the surface condition, for example, compacted (poor) or well-vegetated (good). Exercise sound judgment when determining the condition; alternatively you may run Wildcat5 for both conditions and report the range of potential outcomes. Once you select the CN, Wildcat5 calculates S from equation (4-02), and runoff depth from equation (4-01).

An additional approach to CNs for selected wildland settings is given in chart form in NEH630 (U.S. NRCS 2003: figs. 9.1 and 9.2). As shown in table 4-01, however, CNs can be represented by functions based on soil, cover density, and vegetation type. The general equation is CN = a – (b × percent cover).

Table 4-01—Coefficients for Runoff Curve Numbers (Antecedent Runoff Conditions-II) for selected western forest-range complexes. Application is CN = a – (b × percent cover).

Type	Hydrologic Soil Group	a	b
Sage-grass	B	74	0.46
	C	87	0.47
Juniper-grass	B	82	0.49
	C	90	0.32
Oak-aspen	B	73	0.51
	C	83	0.48
Herbaceous	B	83	0.25
	C	90	0.18
	D	95	0.08

Table 4-02—Curve Numbers for wildland management conditions for Hydrologic Soil-Cover Complexes, Antecedent Runoff Conditions-II, and Ia/S = 0.20.

Land use	Treatment or practice	Hydrologic condition[a]	Hydrologic Soil Group A	B	C	D
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads			59	74	82	86
Roads (dirt)			72	82	87	89
Roads (hard surface)			74	84	90	92
Herbaceous: mixture of grass, weed, and low-growing brush, with brush the minor element						
		Poor		80	87	93
	`	Fair		71	81	89
		Good		62	74	85
Oak-aspen: mountain brush mixture of oak brush, aspen, mountain mahogany, butter brush, maple, and other brush						
		Poor		66	74	79
		Fair		48	57	63
		Good		30	41	48
Pinyon-juniper: pinyon, juniper, or both; grass understory						
		Poor		75	85	89
		Fair		58	73	80
		Good		41	61	71
Sage-grass: sage with an understory of grass						
		Poor		67	80	85
		Fair		51	63	70
		Good		35	47	55
Desert shrub: major plants include saltbrush, greasewood, creosotebush, blackbrush, bursage, paloverde, mesquite, and cactus						
		Poor	63	77	85	86
		Fair	55	72	81	86
		Good	49	68	79	84

[a] Poor is <30 percent ground cover (litter, grass, and brush overstory), Fair is 30 to 70 percent ground cover, and Good is >70 percent ground cover. Source: excerpted from U.S. NRCS (2003: tables 9.1 and 9.2).

The Antecedent Runoff Condition (ARC; formerly Antecedent Moisture Condition, or AMC) used in tables 4-01 and 4-02 adjusts CN—and calculated runoff—based on lower (ARC-I), median (ARC-II), and upper (ARC-III) bounds. These conditions were originally attributed solely to the site's soil moisture content at the onset of the storm. Condition II is the reference-status CN, which is usually assumed for design runoff calculations. Although adjusting for ARC is not recommended here or in general practice, you can see how the reference-status CN compares to the CN at different ARCs in table 4-03.

Table 4-03—Runoff Curve Number (CN) for each Antecedent Runoff Condition (ARC).

CN (ARC-II)	CN (ARC-I)	CN (ARC-III)
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	55
0	0	0

Source: condensed from U.S. NRCS (2003: table 10.1).

If the ARC is not specified, it is assumed to be ARC-II. As an alternative to soil moisture effects, the variety of CNs—and runoff—has also been described simply as “error bands,” and cumulative conditional probabilities of 10, 50, and 90 percent estimated for conditions I, II, and III, respectively, for runoff for a given P (Hjelmfelt and others 1982).

4.241 Hydrologic Soil Groups

As implied in the above, selection of CN hangs heavily on the HSG. These identities are assigned to soil series in the United States by the NRCS based on soil survey criteria and are sometimes adjusted locally by state NRCS offices. Up-to-date HSG assignments are available from the NRCS Web Soil Survey at http://websoilsurvey.nrcs.usad.gov/app/WebSoilSurvey.aspx.

Simpler criteria for assigning HSGs based solely on soil texture are offered in the U.S. Soil Conservation Service’s Technical Release 55 (TR55; 1986). These categories are taken from an earlier paper by Brakensiek and Rawls (1983). However, assignments have been found to be inconsistent when considered internally against soil physical properties (Nielsen and Hjelmfelt 1997), and often in error by as much as ±1 HSG when checked against field data in hydrologic modeling (Sartori and others 2011; Stewart and others 2010, 2012).

Table 4-04—Hydrologic Soil Group (HSG) based on texture.

Texture	HSG
Sand, loamy sand, sandy loam	A
Silt loam or loam[a]	B
Sandy clay loam	C
Clay loam, silty clay loam, sandy clay, silty clay, or clay	D

[a] The silt textural classification is missing, but when the above information is plotted on a textural triangle, silt is an extension of the B category.
Source: U.S. Soil Conservation Service (1986).

4.25 Effects of Fire on Curve Numbers

4.251 General

Loss of vegetation to wildland fire can dramatically change the hydrologic regime and hence the runoff CN. But unlike research on the effects of cropping patterns, urbanization, or grazing, there are no comprehensive studies of the effects of wildland fire on CNs. Severe wildfires are unplanned events, and hydrologic instrumentation is seldom installed onsite. Furthermore, applying a “hot fire” treatment on a research watershed is difficult for administrative and practical reasons. In addition, recovery times are surprisingly short, in the range of 3 to 10 yr, and less than the length of record required for hydrologic definition of CNs. Therefore the CNs themselves may change quickly. Nonetheless, professional needs have led to pragmatic local practices.

Adjustments to CNs to reflect fire response have been compiled from several sources. Tables 4-05 through 4-14 represent values in current practice for a variety of conditions. Consider these CNs as suggestions, and draw upon judgment and local expertise about local practices and conditions.

4.252 U.S. Forest Service Tables

Table 4-05—Post-fire Curve Numbers (CNs) based on fire severity, derived from research at Salt Creek Burned Area Emergency Response, Uinta National Forest (now Uinta-Wasatch-Cache National Forest), UT.

Fire severity	Post-fire CN[a]
High	Pre-fire + 15
Moderate	Pre-fire + 10
Low	Pre-fire + 5
None	Pre-fire

[a] Maximum CN = 100. Sources: Foltz and others (2009: 57), Higginson and Jarnecke (2007).

Table 4-06—Post-fire Curve Numbers (CNs) based on fire severity or conditions during fire on Santa Fe National Forest, NM.

Fire/condition	Post-fire CN
High burn severity with water repellency	95
High burn severity without water repellency	90–91
Moderate burn severity with water repellency	90
Moderate burn severity without water repellency	85
Low burn severity	Pre-fire + 5
Straw mulch with good cover	60
Seeding with LEBs[a] – 1 yr after fire	75
LEBs[a] without water repellency	85

[a] Log erosion barriers installed on the contour at the recommended spacing.

Sources: Foltz and others (2007: 57); Greg Kuyumjian, U.S. Forest Service, Okanogan-Wenatchee National Forest, Wenatchee, WA, pers. comm.

Table 4-07—Post-fire Curve Numbers (CNs) by fire severity or conditions based on research on Fishlake National Forest, UT (Foltz and others 2009: 58; Solt and Muir 2006).

Fire/condition	Post-fire CN
High burn severity	90
Moderate burn severity	85
Low burn severity	80
Unburned and pre-fire	80

Table 4-08—Post-fire Curve Numbers (CNs) by soil group and fire severity based on research on the Coronado National Forest, AZ and NM (Foltz and others 2009: 58).

Post-fire CN Hydrologic Soil Group	Pre-fire CN	Low burn severity	Moderate severity	High burn severity
B	56	65	—	—
C	67	70 to 75	80	90
D	77	80 to 85	90	95

4.253 Santa Barbara, CA, Tables

Table 4-09—Pre-fire and post-fire Curve Numbers (CNs) by pre-fire conditions[a] and Hydrologic Soil Group in the Santa Barbara Flood Control District, CA (Constantine and others 2010; C.R. Constantine, Atkins Global Inc., California, pers. comm.)[b].

Land cover type and burn severity	Hydrologic Soil Group A	B	C	D
Forested pre-burn	25	55	70	77
Low	45	66	77	83
Moderate	70	80	88	92
High	70	80	88	92
Scrub/chaparral pre-burn	55	65	77	83
Low	70	77	83	87
Medium	70	80	88	92
High	70	80	88	92
Range/agriculture pre-burn	39	61	74	80
Low	68	79	86	89
Medium	70	80	88	92
High	70	80	88	92
Water–rock pre-burn	100	100	100	100
Low	100	100	100	100
Moderate	100	100	100	100
High	100	100	100	100
Developed pre-burn	72	82	87	89
Low	72	82	87	89
Moderate	72	82	87	89
High	72	82	87	89

[a] Average antecedent conditions assumed to be ARC-II.

[b] Fire effects and HSGs are not shown for developed areas or for water-rock conditions.

4.254 Easterbrook Estimates

The following estimates for CN by cover, fire conditions, and Hydrologic Soil Group have been provided for use in geographic information systems (GIS)-based models; see Easterbrook (2006). They are presented in tables 4-10 through 4-13 with only minor editing.

Table 4-10—Curve Numbers by vegetation type and conditions or fire severity for Hydrologic Soil Group A (Easterbrook 2006).

	Conditions or fire severity							
							With hydrophobicity	
Vegetation type	**Good**	**Prescribed fire**	**Fair**	**Poor**	**Mod burn**	**High burn**	**Mod burn**	**High burn**
Oak-aspen-mountain brush	20	33			77	77	82	98
Herbaceous-grass-brush	51	65			77	77	82	82
Conifer	27	38	36	45	77	77	82	98
Sagebrush-grass	30	55			77	77	82	82
Oak-woodland	32	47	44	55	77	77	82	98
Pinyon-juniper	30	59			77	77	82	98
Broadleaf chaparral	31	41	40	53	77	77	82	98
Narrowleaf chaparral	55	67	55	70	77	77	82	98
Barren	77	77		77	77	77	82	82
Annual grass	38	51	49	65	77	77	82	82

Table 4-11—Curve Numbers by vegetation type and conditions or fire severity for Hydrologic Soil Group B (Easterbrook 2006).

	Conditions or fire severity							
							With hydrophobicity	
Vegetation type	**Good**	**Prescribed fire**	**Fair**	**Poor**	**Mod burn**	**High burn**	**Mod burn**	**High burn**
Oak-aspen-mountain brush	30	53	48	66	63	86	72	98
Herbaceous-grass-brush	62	76	74	85	81	86	85	85
Conifer	55	63	60	66	73	86	79	98
Sagebrush-grass	35	60	51	67	65	86	73	73
Oak-woodland	58	69	65	73	80	86	85	98
Pinyon-juniper	41	68	58	75	77	86	82	98
Broadleaf chaparral	57	67	63	70	75	86	81	98
Narrowleaf chaparral	65	77	72	82	77	86	89	98
Barren	86	86	86	86	86	86	89	98
Annual grass	61	74	69	78	83	86	87	87

Table 4-12—Curve Numbers by vegetation type and conditions or fire severity for Hydrologic Soil Group C (Easterbrook 2006).

	Conditions or fire severity							
							With hydrophobicity	
Vegetation type	**Good**	**Prescribed fire**	**Fair**	**Poor**	**Mod burn**	**High burn**	**Mod burn**	**High burn**
Oak-aspen-mountain brush	41	63	57	74	72	91	79	98
Herbaceous-grass-brush	74	86	81	87	89	91	91	91
Conifer	70	75	73	77	84	91	88	98
Sagebrush-grass	47	73	63	80	78	91	83	83
Oak-woodland	72	79	76	82	89	91	91	98
Pinyon-juniper	61	83	73	85	87	91	91	98
Broadleaf chaparral	57	67	63	70	75	86	81	98
Narrowleaf chaparral	71	77	75	80	81	91	82	98
Barren	91	91	91	91	91	91	93	93
Annual grass	75	83	79	86	90	91	92	92

Table 4-13—Curve Numbers by vegetation type and conditions or fire severity for Hydrologic Soil Group D (Easterbrook 2006).

	Conditions or fire severity							
							With hydrophobicity	
Vegetation type	**Good**	**Prescribed fire**	**Fair**	**Poor**	**Mod burn**	**High burn**	**Mod burn**	**High burn**
Oak-aspen-mountain brush	48	69	63	79	93	93	94	98
Herbaceous-grass-brush	85	91	89	93	93	93	94	94
Conifer	77	81	79	83	93	93	94	98
Sagebrush-grass	55	78	70	85	93	93	94	94
Oak-woodland	79	84	82	86	93	93	94	98
Pinyon-juniper	71	85	80	90	93	93	94	98
Broadleaf chaparral	78	82	81	85	93	93	94	98
Narrowleaf chaparral	83	87	86	90	93	93	94	98
Barren	93	93	93	93	93	93	94	94
Annual grass	81	87	84	89	93	93	94	94

4.255 Goodrich–Automated Geospatial Watershed Assessment (AGWA) Simulations

The CNs in table 4-14 were developed from existing CN cover tables and GIS-based CN determinations (Goodrich and others 2005). Fire impacts were represented by reductions in cover. You might estimate CNs similarly by using table 4-02.

Table 4-14—Curve Numbers for Hydrologic Soil Groups, by land cover and burn severity[a].

		Hydrologic Soil Group			
Cover	**Burn severity**	**A**	**B**	**C**	**D**
Shrubland	Pre-burn	63	77	85	88
	Low	65	79	86	89
	Medium	68	82	88	90
	High	73	88	91	91
Deciduous forest	Pre-burn	55	55	75	80
	Low	59	60	78	82
	Medium	65	65	80	85
	High	70	71	83	87
Coniferous forest	Pre-burn	45	66	77	83
	Low	49	71	80	85
	Medium	55	76	82	88
	High	60	82	85	90
Mixed forest	Pre-burn	55	55	75	80
	Low	59	60	78	82
	Medium	65	65	80	85
	High	70	71	83	87

[a] Recommended for Automated Geospatial Watershed Assessment simulations.

4.26 Effects of Grazing on Curve Numbers

4.261 General

Grazing activities reduce land cover and cause soil compaction, thereby affecting runoff and the CNs that describe it, and are of interest to wildland hydrologists. Values of CN for pasture, range, and meadow conditions from the NRCS (2012) handbook are given in table 4-02. Values of CN as a function of vegetative type and ground cover, as recommended in NRCS (2012), are given in table 4-15. Results of several studies on grazing and grazing-related impacts are also given as guides (tables 4-15 through 4-17).

4.262 Jornada Experimental Range, NM, Cover Studies

Rainfall and runoff data were collected on plots at the Jornada Range (NM) Long Term Ecological Research Site in a joint study by the National Science Foundation and New Mexico State University. The effects of ground cover on CN were found to converge to CN ~90 at no cover, and the largest variations with cover were found on the sites with the highest percentage of cover. Table 4-15 gives coefficients that approximate the results for the five plot groups using the same equation as in table 4-01; see Hawkins and Ward (1998).

Table 4-15—Coefficients for estimating Curve Numbers (CNs), where CN = a – (b × percent cover), for sites on Jornada Experimental Range, NM (Hawkins and Ward 1998).

Site	Cover	Hydrologic Soil Group	a	b
Creosote Control	Brush	B	88.7	0.0790
Creosote Termite	Brush	B	88.4	0.1367
Creosote Caliche	Brush	B	92.7	0.0636
Grass Summerford	Grass	B	83.8	0.3159
Grass IBP	Grass	A	87.2	0.4815

4.263 Badger Wash, CO, Paired Watershed Studies

Data were collected in a U.S. Geological Survey (USGS) study of runoff from paired watersheds on shale-derived soils (HSG D) in Badger Wash, CO, during 449 storms. Curve Numbers were found to be lower on all four ungrazed watersheds than on their grazed counterparts (Lusby 1976, Lusby and others 1971):

• Grazed	92–94	Average CN = 93
• Ungrazed	91–93	Average CN = 92

4.264 Effects of Vegetation Conversion

University of Arizona studies (Rietz 1999, Rietz and Hawkins 2000) analyzing data from the U.S. Department of Agriculture (USDA) and USGS found the following effects of land cover change on CN:

• Brush to grass conversion at Boco Mountain, CO	Decrease in CN ~18 units
• Mesquite removal at Riesel, TX	Increase in CN ~13 units

4.265 Pasture–Meadows Studies

The effects of cover and land use on CNs were examined by comparing USDA data from pasture land and meadows in the same watershed (Ohio and Nebraska) and in separate watersheds in Texas (Rietz 1999, Rietz and Hawkins 2000). Curve Numbers for ungrazed (meadow) and grazed (pasture) lands are shown in table 4-16.

Table 4-16—Curve Numbers derived from pasture–meadows comparisons.

Location	Meadows (ungrazed)	Pasture (grazed)	Number of watersheds
Coshocton, OH	70.2–82.6	77.8–88.4	6
Hastings, NE	71	86	1
Riesel, TX	88.3	73.8–96.0	1 meadow, 11 pasture

4.266 Australian CNs by Grazing Intensity

The effects of grazing intensity were studied in New South Wales, Australia. Data were collected from plots of about 1/40 ac after rainstorm events over sample periods varying from 6 to 33 yr and CNs were determined (table 4-17). Average annual rainfall was about 23 to 31 in/yr (Cao and others 2011).

Table 4-17—Curve Numbers for two Hydrologic Soil Groups, by grazing intensity, New South Wales, Australia (Cao and others 2011: fig. 7).

	Grazing intensity		
Soils and location	**Light**	**Medium**	**Heavy**
C soils			
Cowra	70.0		77.8
Inverell	75.7		72.4
Wagga-Wagga	83.4		87.0
D soils			
Gunnedah	72.6		84.5
Scone	76.8		79.4
Burned		80.8	
Wellington	72.6		72.6

4.27 Curve Number with Ia/S = 0.05

4.271 Concepts

This is the Curve Number method, but here Ia/S is set at 0.05 instead of 0.20. Historically the common practice was to set Ia/S, or λ (lambda) at 0.20, but in some cases λ has been found to have other values. Several recent studies (see Chapter References, *Curve Number with Ia/S = 0.05*) have found much smaller values for some conditions. Wildcat5 offers the alternative **λ = 0.05**, which is the consensus value from these studies.

Thus, instead of the runoff equation of

$$Q = (P - 0.2S)^2 / (P + 0.8S) \qquad \text{for } P > 0.2S \qquad (4\text{-}03)$$

the use of Ia/S = 0.05 gives

$$Q = (P - 0.05S)^2 / (P + 0.95S) \qquad \text{for } P > 0.05S \qquad (4\text{-}04)$$

Because the traditional land use and soils tables of CNs are based on Ia/S = 0.20, equation (4-03) should more properly have the subscript $S_{0.20}$, and equation (4-04), $S_{0.05}$. When applying Ia/S = 0.05, you need a different CN. Accordingly, the following conversion equation is based on analysis of data from 307 watersheds by Jiang (2001):

$$S_{0.05} = 1.33 S_{0.20}{}^{1.15} \qquad (4\text{-}05)$$

This fitting had an r^2 of 0.993, and a standard error of 0.36 in for ordered data. When the original rainfall-runoff data (P >1 in) were backfitted, a higher r^2 was achieved by using 0.05 in 252 of the 307 cases. With substitution and simplification the transfer function becomes:

$$CN_{0.05} = 100 / \{1.879[(100/CN_{0.20}) - 1]^{1.15} + 1\} \qquad (4\text{-}06)$$

4.272 Application

In Wildcat5, conversions using equations (4-05) and (4-06) are made internally. You do not need to input $CN_{0.05}$ (nor is it possible). Equations (4-05) and (4-06) are valid only up to $CN_{0.20} = 98.5$. Above that value, $CN_{0.05} = CN_{0.20}$.

4.3 Constant Infiltration Capacity: ϕ-Index

4.31 Concepts

The ϕ-index (phi-index) method assumes a constant infiltration capacity or loss rate (ϕ) in both time and spatial distribution across the watershed. Assuming a watershed time-constant loss rate ϕ, and a storm described with intensity i, then the momentary rainfall excess rate q is:

$$q = i - \phi \qquad \text{for } i > \phi \qquad q = 0 \text{ otherwise}$$

and for each interval of time (Δt) within a given storm:

$$\Delta Q = q\Delta t = (i - \phi)\Delta t \qquad \text{for } i > \phi \qquad \Delta Q = 0 \text{ otherwise}$$

For the entire storm:

$$Q = \Sigma q\Delta t = \Sigma(i - \phi)\Delta t \qquad \text{for all } i > \phi$$

$$P = \Sigma i\Delta t$$

The value of ϕ has also been treated as the overall loss rate in a storm, or (P – Q) / duration (Linsley and others 1982).

4.32 Parameter Values

Tables of ϕ values based on land characteristics have been widely described and suggested for hydrologic analysis in design projects, but no authoritative tables of ϕ values are available. For guidance, values are offered in table 4-18.

Table 4-18—Suggested values for loss rate (ϕ) on soil with and without vegetation, by soil texture (Lee 1980).

	Bare soil		**Vegetated**	
Texture	**mm/hr**	**in/hr**	**mm/hr**	**in/hr**
Clay	0–5	0–0.20	5–10	0–0.40
Clay loam	5–10	0.20–0.40	10–20	0.40–0.80
Loam	10–15	0.40–0.60	20–30	0.80–1.20
Sandy loam	15–20	0.60–0.80	30–40	1.20–1.60
Sand	20–25	0.80–1.00	40–50	1.60–2.00

Some references, such as Linsley and others (1982), suggest estimating ϕ from observed local events, and extending the values to design situations.

Some land use (grazing) adjustments for observed steady-state infiltration rates (approximating ϕ), are given by Gifford and Hawkins (1978). A summary of 25 plot studies on several soil types on infiltration for various grazing intensities can be grouped into three statistically significant clusters (table 4-19).

Table 4-19—Observed effects of grazing intensity on loss rate.

Grazing intensity	Infiltration capacity (average)	
Ungrazed	1.60 in/hr	(41 mm/hr)
Light to moderate	~1.25 in/hr	(32 mm/hr)
Heavy	0.80 in/hr	(20 mm/hr)

4.33 Discussion

This is an infiltration-based technique that ignores the observed variation of infiltration capacity with time or its surrogate, site wetness. However, the variable capacity found in many infiltration equations, such as Horton's, falls to near-stable values in a relatively short time (Overton and Meadows 1976: 33).

Some references suggest determining the loss rate for current storms for a one-time application. Alternatively, an areally distributed ϕ-index option is also available for an analysis with "Distributed infiltration capacities."

4.4 Distributed Infiltration Capacity

4.41 General

This method of rainfall excess generates overland flow, assuming that point infiltration capacities (f) of a watershed are constant with time but vary by location within a watershed. At any point in the watershed the runoff rate q (for example, in/hr) is:

$$q = (i - f) \qquad \text{for } i > f, \qquad q = 0 \text{ otherwise}$$

where both i, the intensity, and f are in units of rate, such as in/hr.

The spatial variation of f is assumed to follow the exponential distribution, with its descriptive parameter being the mean point fixed-rate infiltration capacity, μ_f. Within Wildcat5, the interval intensities and loss rates are calculated, and applied for discrete rainfall intervals.

4.42 Concepts

It is assumed that these time-constant point loss rates f are exponentially distributed with a mean of μ_f. The exponential density distribution g(f) and cumulative G(f) are given by:

$$g(f) = (1/\mu_f)\mathbf{exp}(-f/\mu_f) \tag{4-07}$$

$$G(f) = 1 - \mathbf{exp}(-f/\mu_f)$$

With these equations, the areal weighted average rainfall excess rate q for an intensity i for a plot or watershed is:

$$q = i - \mu_f + \mu_f\,\mathbf{exp}(-i/\mu_f) \quad \text{or} \quad q = i - \mu_f\,[1 - \mathbf{exp}(-i/\mu_f)] \tag{4-08}$$

The characterizing watershed variable μ_f is the spatial mean f, or expected value of the time-constant infiltration capacities over the watershed area under rainfall conditions. The variables f, q, and i are in units of rate.

4.43 Parameter Selection

The only parameter needed is μ_f, the mean point infiltration capacity. Its selection for model use is ultimately left to your judgment and experience based on knowledge of local conditions. However, selection of a value is approached by the use of the "effective" hydraulic conductivity K_e, which depends on soil texture and cover. Some background follows.

4.431 Soil Hydraulic Conductivity

Water infiltration rate into the soil depends largely on the soil texture and cover The literature offers some insights into soil intake rates with soil texture, mainly through interpretation and manipulation of the soil hydraulic conductivity, K_s. Refer to Clapp and Hornberger (1978) or Rawls and others (1983). Their work is based on ideal conditions, which are not usually seen in field situations. Accordingly, an adjusted or "effective" value (K_e) is used to account for such real-world conditions as air trapping and variable rainfall intensity; sometimes it has been approximated by $K_s/2$ (Bouwer 1966). Suggested values for K_s and K_e (not μ_f) for different textures of bare soils are given in table 4-20.

Table 4-20—Rangeland soil (K_s) and effective (K_e) hydraulic conductivity values by soil texture.

Soil texture	K_s(mm/hr)[a]	K_s(in/hr)[a]	K_e (in/hr)[b]
Sand	90.0	3.543	1.772
Loamy sand	30.0	1.181	0.591
Sandy loam	11.0	0.433	0.217
Loam	6.5	0.256	0.128
Silt loam	3.4	0.134	0.067
Silt	2.5	0.098	0.049
Sandy clay loam	1.5	0.059	0.030
Clay loam	1.0	0.039	0.020
Silty clay loam	0.9	0.035	0.018
Sandy clay	0.6	0.024	0.012
Silty clay	0.5	0.020	0.010
Clay	0.4	0.016	0.008

[a] Sources: Stone and others (1992) and Rawls and others (1983). Other values from literature or agency sources might be used as alternatives, for example Clapp and Hornberger (1978).

[b] The K_e shown is $K_s/2$.

Furthermore, the state-of-the-technology does not yet accommodate the transfer from (1) a soil physics-based K_s to (2) an effective loss rate K_e based on results from a controlled rainfall simulator, to (3) K_e determined from natural rainfall events, to (4) a spatially varied loss rate for natural rainfall events described by μ_f. Recent research, such as Nearing and others (2011), suggests that the transition from (2) to (3) above is a factor between 1/3 and ½. In the following discussion of parameters, the factor is assumed to be 1/3.

4.432 Cover Effects

The above estimation of parameters assumes a bare soil, with no accounting for the effects of land use, condition, or cover. The following approach, which considers soil and land cover (Nearing and others 2011), has been developed from the Rangeland Hydrology and Erosion Model (RHEM; U.S. Agricultural Research Service 2013), using rainfall simulator data from 49 rangeland locations in the western United States. See Wei and others (2009) for the list of locations.

First, a baseline loss rate, K_{eb}, is calculated for primary soil and cover effects:

$$K_{eb} = (1/3)\mathbf{e}^{(0.174 - 1.45clay + 2.975GC + 0.923CC)} \qquad (4\text{-}09)$$

where

K_{eb} is the effective baseline conductivity in mm/hr

clay is the fraction in clay in the top 4 cm of the soil profile, ranging from 0 to 1

GC is the fraction in ground cover (0–1). Ground cover is defined as the sum of litter on the ground surface, gravel and rock >5 mm in size, vegetation in contact with the ground, and cryptogamic crusts both inside and outside the vegetative canopy.

CC is the fraction in canopy cover (0–1). Canopy cover is defined as any standing live or dead vegetative matter not in contact with the ground surface.

In equation (4-09) GC should equal 1 minus the fraction of bare soil. Note that it is possible to have both CC = 1.0 and GC = 1.0. As described in Nearing and others (2011), the factor of 1/3 adjusts K_{eb} computed from rainfall simulator data to K_{eb} computed for natural rainfall-runoff events.

Second, the above is adjusted to the effective conductivity in mm/hr, K_e, for vegetative types with

$$K_e = K_{eb} \times \text{vegetative type factor} \qquad (4\text{-}10)$$

Vegetative type factors are given in table 4-21, and are the only vegetation types for which this information is currently available.

Table 4-21—Vegetative type factors for calculating effective conductivity in mm/hr (Nearing and others 2011).

Vegetative type	Factor
Sod grass	0.80
Bunch grass	1.00
Shrubs	1.20

K_e is the practical loss rate estimated from less-than-extreme natural events, or with rainfall simulation. K_e values have also been developed for forest conditions including undisturbed forests and low- and high-severity fires on the U.S. Forest Service Water Erosion Prediction Project (WEPP) interface (http://forest.moscow.fsl.wsu.edu). If you select the **Disturbed WEPP** interface from this site, specify the soil texture and the cover, and then click on the **soil texture** button above the soil selection box, the soil properties for that texture are presented (Elliot 2004).

Third, an estimate of μ_f is taken from approximate relationships based on rainfall simulator data found by Stone and others (2008; J.J. Stone, U.S. Agricultural Research Service, Tucson, AZ, 2012, pers. comm.):

$$\mu_f = 8\mathbf{e}^{0.0912K_e} \tag{4-11}$$

with μ_f and K_e in mm/hr. Note that μ_f is always equal to or greater than K_e.

4.44 Example

Given a site with 20 percent clay in the upper 4 cm, 50 percent ground cover, and 20 percent canopy cover, then equation (4-09) becomes:

$$K_{eb} = (1/3)e^{0.174 - 1.45(0.20)+2.975(0.50) + 0.923(0.20)} = 1.596 \text{ mm/hr} = 0.065 \text{ in/hr}$$

Calculating K_{eb} for different vegetative types produces K_e via equation (4-10) and the values in table 4-22.

Table 4-22—Adjustment factors and effective conductivity (K_e) by vegetative cover.

Type	Factor	K_e(mm/hr)	K_e(in/hr)
Sod grass	0.80	1.28	0.050
Bunch grass	1.00	1.60	0.065
Shrubs	1.20	1.92	0.078

If we use shrubs as an example, then calculating μ_f, from equation (4-11) yields:

$$\mu_f = 8e^{0.0912K_e} = 8e^{0.0912(1.92)} = 9.53 \text{ mm/hr} = 0.375 \text{ in/hr}$$

This μ_f value is suitable for Wildcat5 input. You may also use other values of K_e, such as those found in the WEPP interface.

The outcome from the above example is shown in table 4-23 below. It uses equation (4-08) directly with $\mu_f = 0.375$ in/hr, for a 100-ac watershed.

Table 4-23—Example of distributed loss-rate calculation where $\mu_f = 0.375$ in/hr.

Intensity i (in/hr)	Runoff rate q (in/hr)	Acres with $i \geq f,\ q \geq 0$
0	0.000	0.0
0.1	0.012	23.4
0.2	0.045	41.3
0.3	0.093	55.1
0.4	0.154	65.6
0.5	0.224	73.6
0.6	0.301	79.8
0.7	0.383	84.5
0.8	0.469	88.2
0.9	0.559	90.9
1.0	0.651	93.1
1.2	0.840	95.9
1.4	1.034	97.6
1.6	1.230	98.6
1.8	1.428	99.2
2.0	1.627	99.5
2.5	2.125	99.9
3.0	2.625	99.97

4.45 Discussion

Use of this method—and μ_f as its defining parameter—acknowledges that not all points in the watershed will be contributing to rainfall excess. That is, μ_f is the average potential infiltration rate for all the points. For a rainfall intensity $i = \mu_f$, only 63.2 percent of the watershed will be contributing. In other words, 36.8 percent of the points will have an infiltration capacity greater than the intensity i. This general distributed loss rate approach to runoff has been reported in several studies (Hawkins 1981, Hawkins and Cundy 1989, Stone and others 2008).

It bears repeating that with this approach, the point infiltration capacity does not vary with time. It is best to think of μ_f as the mean point infiltration rate after the initial wetting. In most field situations, a nearly time-constant capacity is achieved after reasonable durations (0.2 to 0.8 hr). This method does assume that the time-constant capacity varies over space. It is not the same at all points in the watershed. Variation is assumed to be described by the exponential distribution as stated above.

4.46 Other Influences on Loss Rates

Some land use (grazing) adjustments for observed steady-state infiltration rates are given by Gifford and Hawkins (1978). A summary of about 25 plot studies on infiltration for various grazing intensities aligns into three statistically significant clusters (table 4-24).

Table 4-24—Average infiltration capacity associated with different grazing intensities (Gifford and Hawkins 1978).

Grazing intensity	Infiltration capacity (average)
Ungrazed	~1.60 in/hr (41 mm/hr)
Light/moderate	~1.25 in/hr (32 mm/hr)
Heavy	~0.80 in/hr (20 mm/hr)

4.5 Runoff Fraction (Runoff Ratio)

4.51 Concepts

The runoff fraction is the most simplistic expression of rainfall-runoff. The rainfall excess is a simple linear fraction of the rainfall:

$$Q = CP$$

where C is the “runoff ratio,” $0 \leq C \leq 1$, and Q and P have units of depth. Despite its simplicity, it may be the most appropriate model for some situations. The parameter C does have a specialized physical interpretation as the fraction of the watershed impervious area (including water surface).

4.52 Parameters

The parameter C must be between 0 and 1. There are very few studies using field data to quantify the runoff ratios or the rational coefficients. Therefore, rely on your judgment and experience, and institutional acceptance, when selecting runoff ratios. Tables 4-25 and 4-26 present rational coefficients, which are often assumed to be equivalent.

Other rational coefficients (table 4-26) are offered for application to wild lands as pre-fire runoff coefficients (Easterbrook 2006).

Table 4-25—Coefficients for runoff fraction and rational equation (Chow 1964: chapters 14 and 21).

Type of drainage area	Coefficient "C"	Type of drainage area	Coefficient "C"
Lawns: sandy soil, flat (2% grade)	0.05–0.10	Apartment dwelling areas	0.50–0.70
Lawns: sandy soil, flat (2–7% grade)	0.10–0.15	Industrial: light industry	0.50–0.60
Lawns: sandy soil, steep (7% grade)	0.15–0.20	Heavy industry areas	0.60–0.90
Lawns: heavy soil, flat (2% grade)	0.13–0.17	Parks, cemeteries	0.10–0.25
Lawns: heavy soil, moderate (2–7%)	0.18–0.22	Playgrounds	0.20–0.35
Lawns: heavy soil, steep (7%)	0.25–0.35	Railroad yard areas	0.20–0.35
Business: downtown areas	0.70–0.95	Unimproved area	0.10–0.30
Neighborhood areas	0.50–0.70	Streets: asphaltic	0.70–0.95
Residential: single family	0.30–0.50	Streets: concrete	0.80–0.95
Multifamily units, detached	0.40–0.60	Streets: brick	0.70–0.85
Multifamily units, attached	0.60–0.75	Drives and walks	0.75–0.85
Suburban	0.25–0.40	Roofs	0.75–0.95

Soil type	Cultivated	Pasture	Woodlands
Above-average infiltration: sandy soil or gravel	0.20	0.15	0.10
Average infiltration: no claypans; loams/similar soils	0.40	0.35	0.30
Below-average infiltration: heavy clay soils, soils with a claypan near the surface, shallow soils above impervious rocks	0.50	0.45	0.40

Table 4-26—Additional rational coefficients by vegetation type.

Vegetation type	Runoff coefficient
Riparian	0.02
Sagebrush/other shrubs	0.18
Rocks–soils	0.50
Grass–forb	0.20
Conifer	0.10
Aspen	0.08
Pinyon–juniper	0.20
Gambel oak	0.12

4.53 Discussion

As the most basic "model" for rainfall-runoff response, the runoff fraction, C, is intuitively obvious to the point of being seldom mentioned by name in hydrology literature. However, it has a specific interpretation as a direct source area for watersheds with conspicuous impervious areas. For small values of C, from about 0.002 to 0.05, it represents the Complacent response, which is later offered in Wildcat5 as an option under **Rainfall Excess Options**.

The Wildcat5 **Summary Output Table and Hydrograph** gives the de facto values of the found C (= Q/P) for the modeled storm from the rainfall excess used.

The similarity is apparent between this form and the widely used rational equation:

$$q_p = Ci_{max} \tag{4-12}$$

with q_p as the peak flow and i_{max} as the maximum storm intensity for a duration equal to the time of concentration, both in units of intensity (such as in/hr, or mm/hr). When the input is in in/hr and the output is calculated in ft^3/sec for a drainage area of A ac, it takes the familiar form of

$$q_p = Ci_{max}A \tag{4-13}$$

The units conversion between equations (4-12) and (4-13) for the English system is 121/120, and is usually ignored and treated as 1.00.

4.6 Distributed Loss Depth

4.61 General

This method assumes that losses are not limited by rate, such as with infiltration capacities (for example, in/hr), but instead are limited by depth (for example, inches). That is, after that depth has been filled by rain, all additional rainfall becomes runoff (rainfall excess). However, Wildcat5 allows this process to be distributed in space on the watershed.

4.62 Concepts

This is not an infiltration rate method, but a loss depth method. It imagines the watershed to be composed of distributed points of F, where F is the ultimate retention storage at a point potentially satisfied in the rainstorm. It might be seen as a collection of open tin cans of variable depth F with each can (point) performing as:

$$Q = 0 \qquad P < F$$

$$Q = P - F \qquad P \geq F$$

After a "can" has been filled by rain, all additional rain spills and becomes rainfall excess draining directly to the outlet. For example, if a point F is 1 inch, then no runoff occurs from that point as long as $P \leq 1$ in. Above that, all additional rain becomes rainfall excess. This is equivalent to saying $Q = 0$ for $P < 1$ inch and $Q = P - 1$ for $P > 1$ in. This is a straight line with an intercept of -1 and a slope of 1.00.

4.63 Distributed Performance

More realistic representations of observed rainfall and runoff behavior can be estimated by weighting values of F to different areas (acres) of the watershed. F_i is the loss depth F for an individual fractional part in the watershed. The fraction is α_i, where all the fractions add up to 1.00. The representation of this is:

$$Q = \Sigma\alpha_i Q_i = \Sigma\alpha_i(P - F_i) \qquad \text{for all i, and for all } P > F_i$$

The robustness and practical possibility of this approach rest in the distributed form. The single-point linear all-or-nothing "tin can" runoff process is a greatly simplified representation. But by amassing a number of fractional areas of varying properties, a more realistic overall performance can be simulated. For example, there is a distribution of F that results in the CN equation of Q with P. Note that no specific statistical distribution is suggested here.

4.64 Parameter Values

No authoritative or handbook values of F are available, and parameter choices are ultimately the responsibility of the user. However, insofar as F is the maximum possible retention of rainfall, it is the approximate cross product of the soil depth and the effective porosity (field capacity – ambient soil moisture). Thus, it might be imagined as a simplified representation of Ia + S (= 1.2S) from the CN method. With this in mind the values in table 4-27 are given as a guide for those experienced in CN usage.

Keep in mind that 1.2S is the limit, attained as $P \rightarrow \infty$, and this distributed loss depth tactic is not the CN method. Thus lower values—at perhaps 20 to 60 percent of the table entries—should be drawn from the above for realistic use as "F" values. The relevance of the range of suggested F values (table 4-27) has not been verified in the field.

Table 4-27—Suggested potential losses for distributed loss depth model.

CN	1.2S (in)	Range of suggested F (in)
100	0	0
95	0.632	0.12–0.36
90	1.333	0.27–0.80
85	2.118	0.42–1.28
80	3.000	0.60–1.80
75	4.000	0.80–2.40
70	5.143	1.03–3.09
65	6.462	1.29–3.88
60	8.000	1.60–4.80

4.65 Example

A 500-ac watershed with 100 ac each of F at 0.5, 1.0, 1.5, 2.0, and 2.5 in would have no runoff until P = 0.5 in, and the following array of rainfall and runoff depths as successive F elements became active by exceeding successive thresholds (table 4-28).

In the above simplified example, the areal fraction α is 0.20 for all cases (not to be confused with the 0.2 initial abstraction coefficient used in the CN method). A cumulative total can be kept for as many stated points (or continuous distribution) as needed. In this example the descriptor F is specified for a user-chosen array of different areas.

4.66 Simulating Complacent and Violent Responses

Complacent and Violent response options are described in the next section, but can be modeled by using the distributed loss method.

You can represent the Complacent response by setting F = 0 for the appropriate small fraction, and an absurdly high F value, like 10 in for the remainder of the areas.

Table 4-28—Example of distributed loss calculation.

P (in)	Q (in)	Calculation	Percent contributing
0	0	none	0
0.25	0	none	0
0.50	0	none	0
0.75	0.050	0.2(0.75 – 0.50)	20
1.00	0.100	0.2(1.00 – 0.50)	20
1.25	0.200	0.2(1.25 – 0.50) + 0.2(1.25 – 1.00)	40
1.50	0.300	0.2(1.50 – 0.50) + 0.2(1.50 – 1.00)	40
1.75	0.450	0.2(1.75 – 0.50) + 0.2(1.75 – 1.00) + 0.2(1.75 – 1.50)	60
2.00	0.600	0.2(2.00 – 0.50) + 0.2(2.00 – 1.00) + 0.2(2.00 – 1.50)	60
2.25	0.800	0.2(2.25 – 0.50) + 0.2(2.25 – 1.00) + 0.2(2.25 – 1.50) + 0.2(2.25 – 2.00)	80
2.50	1.000	0.2(2.50 – 0.50) + 0.2(2.50 – 1.00) + 0.2(2.50 – 1.50) + 0.2(2.50 – 2.00)	80
2.75	1.250	0.2(2.75 – 0.50) + 0.2(2.75 – 1.00) + 0.2(2.75 – 1.50) + 0.2(2.75 – 2.00) + 0.2(2.75 – 2.50)	100
3.00	1.500	0.2(3.00 – 0.50) + 0.2(3.00 – 1.00) + 0.2(3.00 – 1.50) + 0.2(3.00 – 2.00) + 0.2(3.00 – 2.50)	100

Thus the following array would simulate the Complacent response Q = 0.02P for rainfalls up to 10 in:

$$\alpha_1 = 0.02 \qquad F_1 = 0 \text{ in}$$
$$\alpha_2 = 0.98 \qquad F_2 = 10 \text{ in}$$

Violent response (see next section) can be represented similarly, by selecting F_2 at the threshold P and an appropriate value of a. For example, assuming

$$\alpha_1 = 0.02 \qquad F_1 = 0 \text{ in}$$
$$\alpha_2 = 0.98 \qquad F_2 = 2 \text{ in}$$

leads to

$$Q = 0.02P \qquad \text{for } P \le 2 \text{ in}$$
$$Q = 0.02P + 0.98(P - 2) \qquad \text{for } P \ge 2 \text{ in}$$
$$= P - 1.96$$

4.7 Complacent–Violent Response

4.71 Concepts

This option is a response pattern found on many forested watersheds. Though not unknown in nature, it is generally unappreciated and does not have a long history of application or authoritative coefficients. It differs significantly in form and concept from the CN approach.

Here the rainfall-runoff process hangs on three identifying elements: (1) a low linear response early in the storm (the Complacent phase), (2) a characteristic threshold rainfall, and (3) an abrupt change to a high incremental response (Violent phase) above the threshold rainfall depth. The two phases may be more than an order of magnitude different in converting rainfall to runoff. Wildcat5 represents the Complacent–Violent option by the following:

Complacent behavior $$Q = CP \qquad \text{for } P \le P_t \qquad (4\text{-}14)$$

Violent behavior $$Q = CP + (b_2 - C)(P - P_t) \qquad \text{for } P \ge P_t \qquad (4\text{-}15)$$

$$= CP_t + b_2(P - P_t) \qquad \text{for } P \ge P_t$$

where P_t is the threshold rainfall above which the violent condition applies and b_2 is the runoff rate fraction at rainfalls greater than P_t.

4.72 Parameter Selection

The three parameters in the Complacent–Violent model have some physical interpretation, at least in the simplest cases. C is the Complacent coefficient, or Q/P, and may be taken as the fraction of the watershed with direct impervious runoff. This fraction has been linked to the channel source area (Panky and Hawkins 1983). C is also the **Constant fraction** option offered elsewhere in Wildcat5.

If P is less than P_t, the entire storm runoff will be in the Complacent mode. Values for C found in data analysis vary from 0 to about 0.06. Values taken from field data in the range of 0.005 to 0.02 are common (see table 4-29).

P_t is the threshold or "tip-over" rainfall. In settings with soils with limited storage and high entry rates, this is the depth of rain needed to fill the canopy and litter, and the soil column to the point of soil water movement by gravity. Threshold rainfall begins at field capacity (FC), and reaches a maximum condition at saturation, at which point surface (overland) flow may occur. Values for P_t found by data analysis are typically from 1.5 to 3.0 in, with a cluster near 2 in. It can be less if the soil has a higher water content at the start of the storm for pre-wetted conditions.

With the model described by equation (4-13), most runoff does not occur until well into the storm, when P_t has been exceeded. Values for the runoff rate fraction found by data analysis are in the range of 0.60 to 1.00. Examples with $b_2 = 1.00$ have been calculated in such datasets. By the above reasoning, $0 \leq C \leq (C + b_2) \leq 1$.

Insofar as the Violent phase operates at the rarer, larger storms and creates unexpected out-of-channel peak flow rates, clean datasets displaying it are not as common as for pure Complacent response. Some suggested typical coefficient values are presented in table 4-29.

Table 4-29—Typical values for coefficients used in equations (4-14) and (4-15) for predicting Complacent–Violent runoff.

C	0.001–0.07	Complacent, live channel, some forested watersheds.
	0.07–0.30	High linear, for varied sources. "Dry" complacent.
P_t	1.5–3.0 in	In stable watersheds. Much smaller if freshly burned or wetted. Values are suggested by the maximum rainfall values in table 4-30. P_t for these cases should equal or exceed the values shown.
b_2	0.70–1.00	Violent limb, $(C + b_2) \leq 1.00$ in extreme rainstorms or shallow soils, or both.

As with all such efforts, including the CN method, coefficient selection is subject to your judgment. Note that either Complacent or Violent behavior can be modeled depending on the coefficient values selected. The difference between b_2 and C is a measure of the behavior change at threshold rainfall P_t. You can represent the entire process by manipulating the **Distributed F** option also offered in Wildcat5. More recent documentation on the Complacent–Violent response, with found values of C, P_t, and b_2, is given in Hawkins and others (2015).

4.73 Discussion

The Complacent–Violent option may be more useful in explaining otherwise puzzling on-the-ground or in-channel observations than in direct design or environmental appraisals. A difficulty in using this option is identifying the nature of the runoff and the coefficients from field information. Curve Number tables and Hydrologic Soil Groups cannot explain Complacent–Violent behavior when it occurs.

An infrequently applied example of a Complacent response is given in Dunne and Leopold (1987: 289), a commonly used text that shows rainfall-runoff response from a 147-ac U.S. Agricultural Research Service watershed at Danville, VT. For 10 events up to $P = 3$ in, the observed runoff conforms closely to $Q = 0.06P$. Here it can be inferred that $C = 0.06$, and $P_t > 3$ in. For perspective, a rainstorm of 3 in is at about a 100-yr return period for a 3-hr duration for this part of Vermont.

Though suggested here as a channel interception process, the general low-linear rainfall-runoff (Complacent) response is also found in some "dry" conditions in wildland and other settings. For example, forest land at Beaver Creek, AZ, which has ponderosa pine cover but little or no baseflow, performs as Complacent–Violent with the following approximate values: $C = 0.07$, $P_t = 1.80$ in, and $b_2 = 0.94$ (Hawkins 1989). Fully covered sugar cane fields on lateritic (clay) soils in Brazil show a C of about 0.008 for storms up to about 3 in (Sartori and others 2011).

Data-based examples of the Violent phase are rarer than for the Complacent phase because they occur at higher (rarer) rainfalls, and the extremes sometimes exceed flow measurement capabilities. The split Complacent–Violent phenomenon is more apparent when data are treated as rank ordered (frequency matched).

Table 4.30 shows Complacent response for many western U.S. wildland watersheds (Springer and others 2005). The P_{max} return periods for selected entries in the tables are as follows: Arizona: 1-hr duration, 120-yr return interval; 3-hr duration, 30-yr return interval; Colorado: 1-hr duration, ~20-yr return interval; and Utah: 1-hr duration, 30-yr return interval; 3-hr duration, 10-yr return interval.

Table 4-30—Selected wildland watershed Complacent rainfall-runoff characteristics[a].

Name	State	Area (ac)	From	To	P_{max} (in)	N	C	r^2 (%)	Standard error (in)	Reference
North Thomas	AZ	467	1965	1970	2.35	9	0.0008	79	0.0006	Anderson (1975)
South Thomas	AZ	562	1963	1970	2.19	12	0.0010	48	0.0011	Anderson (1975)
Missouri Gulch	CO	4,600	1940	1959	1.58	14	0.0030	79	0.0011	Hawkins (1961)
Eggers	ID	318	1969	1978	2.31	38	0.0048	87	0.0015	McGurk (1982)
Control	ID	401	1969	1976	2.58	32	0.0054	53	0.0030	McGurk (1982)
Cabin	ID	271	1970	1978	2.62	43	0.0046	43	0.0032	McGurk (1982)
Ditch	ID	252	1969	1975	2.43	27	0.0043	76	0.0024	McGurk (1982)
C Creek	ID	460	1970	1978	2.31	29	0.0206	64	0.0126	McGurk (1982)
D Creek	ID	292	1969	1978	2.31	30	0.0159	64	0.0105	McGurk (1982)
Murphy	ID	306	1967	1977	1.66	27	0.0074	24	0.0105	McGurk (1982)
West Chicken	UT	217	1962	1971	1.96	16	0.0096	67	0.0070	Johnson and Doty (1972)
East Chicken	UT	137	1962	1971	1.31	12	0.0048	91	0.0013	Johnson and Doty (1972)
Halfway	UT	484	1940	1966	1.50	14	0.0113	90	0.0038	Walker (1970)

[a] C is the least squares fit to $Q = CP$ with natural data; r^2 is the variance reduction (percent) achieved by the fitting. Source: Springer and Hawkins (2005); some entries have been corrected from the original publication with later data.

4.8 Chapter References

Curve Numbers

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Chapter 5. Timing Parameters

5.1 Concepts

The timing characteristics of a small watershed control how rapidly generated rainfall excess runs off, and thus how “flashy” or delayed the resulting hydrograph might be. In Wildcat5 the timing descriptors—time of concentration (t_c) or lag (t_L)—are used in scaling the unit hydrographs. From them the unit hydrograph time base (t_b), time to peak (t_p), and the time increment (Δt) used to step through the design storm are calculated. Here, as in most professional applications of this kind, Δt is taken to be $t_p/5$.

Timing characteristics also give you an intuitive glimpse of actual watershed conditions, allowing inference of an average flow velocity as flow distance/t_c. Several options—all empirical formulas—are available in Wildcat5, as is a user override.

The most popular notion of watershed timing is t_c, defined as the time required for water to travel the length of the longest runoff path in the watershed to the outlet. It arose from applying the rational equation, equation (4-11), and asserts that during that time interval all parts of the watershed contribute runoff simultaneously to the outlet, the ideal condition for maximum flood peak generation.

A centroid-peak lag is also used. It is taken to be the time from the centroid of the rainfall excess to the flood peak. This is the usual interpretation when the expression “lag time” is used.

A third alternative, the centroid-centroid lag, is defined as the time from the centroid of the rainfall excess to the centroid of the resulting hydrograph.

Any one of the three measures above may be used to arrive at the unit hydrograph dimensions t_b and t_p Results will differ among methods and equations. Note that shorter times of concentration or lag can be expected to lead to higher peak flows.

5.2 Choices and Parameter Selection

Four alternatives are offered: (1) a user’s choice override, (2) a direct t_c equation, (3) a lag time equation, and (4) an option for the centroid-centroid lag. In alternatives 2, 3, and 4 you supply the watershed parameters required, and Wildcat5 calculates the unit hydrograph (t_p) and time step (Δt) parameters.

1. **User choice**. This option allows you to specify from judgment or experience t_c in hours. It also allows you to calculate t_c separately from equations not offered here.
2. **Kirpich’s equation** for t_c. Although several different forms exist, the original equation (Kirpich 1940) is:

$$t_c = (11.9L^3 / H)^{0.385}$$

where

t_c is in hr
L is the length of the longest runoff path (mi)
H is the difference in elevation along the above flowpath (ft)

Wildcat5 asks for the information in slightly different form:

Channel slope (percent), and
Channel length (ft)

The changes are made internally for the calculations.

3. **Kent's equation** for lag time. This equation was developed from U.S. Natural Resources Conservation Service (NRCS) applications and the definition of flood-peak lag:

$$t_{L(ctp)} = L^{0.8}(S+1)^{0.7} /(1900Y^{0.5})$$

where

t_L is the lag time (hr)
L is the hydraulic length of the watershed (ft)
S is 1000/CN – 10 (in). Average Curve Number (CN) is taken from previous steps.
Y is the average watershed land slope (percent)

The time of concentration is then determined from the equation $t_L = 0.6t_c$.

4. **Simas' equation**. This work deals with the centroid-centroid lag time, and arises from work done at the University of Arizona on 31,030 events on 168 small watersheds (Simas 1996). It uses CN, watershed length (ft), and watershed width (ft). The equation is:

$$t_{L(cc)} = 0.0051W^{0.594}\mathrm{Slope}^{-0.150}\ S^{0.313}$$

where

$t_{L(cc)}$ is in hr
W is the width in feet = area (ft^2) / length (ft). Length is the longest flowpath (ft) to the highest elevation.
Slope is a channel slope (ft/ft) = the elevation difference along the flowpath length
S = (1000/CN) – 10 (in).

With this method, Δt and t_p are calculated internally without using t_c, but by exploiting the unique geometric characteristics of the unit hydrograph, and proceeding on the assumption of $\Delta t = t_p/5$.

5.3 Discussion

Numerous other t_c and t_L equations exist and continue to be developed, as reported in the literature. Thus you are given the option of entering your preferred t_c on the input page.

One common method recommended in the U.S. Soil Conservation Service and NRCS publications is to estimate overland and channel velocities of water as it makes its way from the top of the catchment to the outlet, and then to sum up the times for each segment of the flowpath. The various methods do not necessarily give the same results, just as the above three equations will give different estimates. As most methods predicting peak flow are quite sensitive to time of concentration, take care when selecting the methods to predict t_c and t_L.

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Chapter 6: Unit Hydrographs

6.1 Concepts

Unit hydrograph (UH) methods are widely used for routing periodic pulses of rainfall excess from the upland source areas to the watershed outlet. The UH is used as a template to generate contributing hydrographs starting from different periods within a storm. These hydrographs are lagged in time, superimposed, and summed to create a composite storm hydrograph at the outlet. The routing is necessary to model the short-duration surface runoff from the upland watershed sources to the outlet. This process of lagging and summing is sometimes called a convolution.

The UH is defined as the characteristic hydrograph for a unit of rainfall excess for a subject watershed. It accounts for the watershed properties by its time to peak, the total duration, and the shape. These characteristics describe the drainage network and slopes, distribution of source areas, and total drainage area. A UH may be visualized as the distribution of travel times from the source points to the watershed outlet. By definition and custom, the UH has a volume of 1 unit. The units are linear (ordinates are proportional to the volume), time consistent (described by fixed time descriptors such as time to peak and duration), and superimposable (they can be lagged and summed). A number of unit hydrograph options are offered in Wildcat5.

More advanced alternative techniques that achieve similar results are overland flow routing by kinematic wave technology, or linear reservoirs or channel routing for the drainage network. Neither of these alternatives is offered in Wildcat5 because of the unit hydrograph's comparative simplicity and long-time precedent.

6.2 Triangular Unit Hydrographs with General Geometry

6.21 General

Triangular unit hydrographs are a long-used simplification of the curvilinear unit hydrograph that accompanied the emergence in the 1950s of the U.S. Soil Conservation Service (SCS) methods, which included the Curve Number (CN) method. However, they are not really a part of the CN method, but are a separate technology.

6.22 Background and Description

The SCS triangular unit hydrograph has a time to peak of t_p, and time of recession of $1.67t_p$, and thus a base of $2.67t_p$. Its peak flow is q_p (1/T). Note that 2.67 is a rounded-off value for 8/3, as 1.67 is for 5/3.

The area of the triangular UH is:

$$2.67t_p\, q_p/2$$

which contains the ΔQ from an impulse of rainfall excess. Thus $2.67t_p\, q_p/2 = \Delta Q$.

Solving for q_p, we find:

$$q_p = \Delta Q/(1.333t_p)$$

where

q_p is in in/hr
ΔQ is in inches.

To apply this to produce q_p in ft^3/sec from a watershed with a drainage area of A (mi^2) requires conversion of inches to feet, square miles to square feet, and hours to seconds, leading to:

$$q_p = 484A\,\Delta Q/t_p$$

where

A is in mi^2
ΔQ is incremental impulse of rainfall excess (in)
t_p is in hr
q_p is in ft^3/sec.

In most models ΔQ is the runoff amount for time period of Δt, and Δt is often equal to $t_p/5$, as mentioned in section 5.1 and following.

6.23 General Case

The value 484 is often called the hydrograph factor (HF), or the peak flow factor. The term "factor" suggests that the value may be changed. However, doing so requires preserving the mass (do not change ΔQ), which can happen only if the relationship between t_b and t_p changes.

For a general case, consider that the recession (falling) limb is not fixed at $1.67t_p$, but rather is generalized as bt_p. Then the time base of the entire hydrograph is $(1 + b)t_p$. Following the example above leads to the general expression:

$$q_p = 1290.67A\Delta Q / [(1+b)t_p] \quad (6\text{-}01)$$

with b = 1.67.

Accounting for rounding error, equation (6-01) becomes the familiar $q_p = 484A\Delta Q/t_p$.

6.24 Results

The following results (table 6-01) are for the general case of $t_r = bt_p$. The value "#Δt" is the number of calculations needed for the component hydrographs. Section 4 of the National Engineering Handbook (NEH4; U.S. SCS 1954)

Table 6-01—Characteristics of variable triangular hydrographs[a] for the general case of t_r.

$b = t_r/t_p$	**(1+b)**	**HF = 1290.67 / (1 + b)**	**#Δt = 5(1 + b)**
1	2 = 2.00	645.33	10
3/2	5/2 = 2.5	516.27	12.5→13
5/3 = 1.67	8/3 = 2.67	484	13.3→14 = the traditional case
2	3	430.22	15
7/3 = 2.33	10/3 = 3.33	387.20	16.7→17
8/3 = 2.67	11/3 = 3.67	352	18.4→19
3	4	322.67	20
4	5	258.13	25
5	6	215.11	30

[a] t_p is time to peak; HF is hydrograph factor.

recommends $\Delta t \leq t_p/5$. The value must be a whole number, so decimal answers are rounded up to the next integer.

6.241 Equations for Rising and Falling Limbs

For calculating the q at intervals of t (called τ here) for the component hydrographs:

1. For the rising "limb" when $\tau \leq t_p$:

   $q(\tau) = (\tau/t_p)q_p$ calculated every Δt from 0 to t_p (5 of them)

2. For the declining limb, following t_p, or $t_p \leq \tau \leq [(1+b)t_p = t_b]$ works out to:

   $q(\tau) = (q_p/b)[1 + b - \tau/t_p]$ calculated every Δt from t_p to t_b (5b of them)

6.242 Direct Solutions for HF and "b"

Recall from equation (6-01) that $q_p = 1290.667A\,\Delta Q / [(1 + b)t_p]$, which is:

$q_p = 484A \times \Delta Q/t_p$ when b = 1.6667 or

$q_p = HF \times A \times \Delta Q/t_p$

where HF is the hydrograph factor, customarily 484. Thus

$HF = 1290.667 / (1+ b)$

$b = 1290.667 / HF - 1$

6.25 Discussion

A persistent claim in applied hydrology—much-repeated but from an unknown source—is that lag = $0.6t_c$. Note the dimension of 3/3 for t_p and 5/3 for the falling limb for the traditional triangular hydrograph. If t_p is taken to be the lag, and the falling limb time is taken to be the time of concentration (the time it takes to drain from the farthest point) and for the instantaneous case $\Delta t \rightarrow 0$, then the time to peak is the traditional "lag time." Then lag = $t_p = 0.6t_c$.

6.3 Broken Triangular Unit Hydrograph

6.31 Concepts

The broken triangular unit hydrograph is conceptually similar to the simple triangle with two exceptions: it has a change of slope in the recession limb, and the time dimensions are fixed. It gives a longer hydrograph ($t_b = 5t_p$), a break in slope in the recession limb, and a more depressed peak. The breakpoints and dimensions of the broken triangular unit hydrograph are as follows (table 6-02):

Table 6-02—Properties of the broken triangular unit hydrograph[a].

t/t_p	q/q_p	Unit hydrograph ordinate	Cumulative area fraction
0	0	0	
1	1	5/9 = 0.5555	0.2778 = 5/18
2	0.4	2/9 = 0.2222	0.6667 = 2/3
5	0	0	1.0000

[a] t_p is time to peak; q_p is peak flow.

The area under this broken triangle is $1.8q_pt_b$, or $0.36t_pq_p$. Thus the UH peak factor is $1/1.8 = 5/9 = 0.555$. The UH equation for this comes from $5t_pq_p\ (1.8/5) = \Delta Q$, or $q_p = 0.555\Delta Q/t_p$.

6.32 Technical Details

The general equation is $q_p = 358.52A\Delta Q / t_p$, where q_p is in ft^3/sec (cfs), A is in mi^2, ΔQ is in inches, and t_p is in hr. Thus the “Hydrograph Factor” for this case is fixed at 358.52. The following equations describing the three straight line portions in figure 6-01 apply for UH at time τ:

$0 \le \tau \le t_p$	$q = (\tau/t_p)q_p$	rising limb
$t_p \le \tau \le 2t_p$	$q = (1.6 - 0.6\tau/t_p)q_p$	first falling limb
$2t_p \le \tau \le 5t_p$	$q = (0.6667 - 0.1333\tau/t_p)q_p$	second falling limb

If $\Delta t \le t_p/5$, then this configuration requires at least 25 (= 5 × 5) Δt units for modeling. The centroid (lag time) comes out to be $47/27t_p = 1.7407t_p$. Thus $t_p = 27/47\ t_L = 0.5744t_L$.

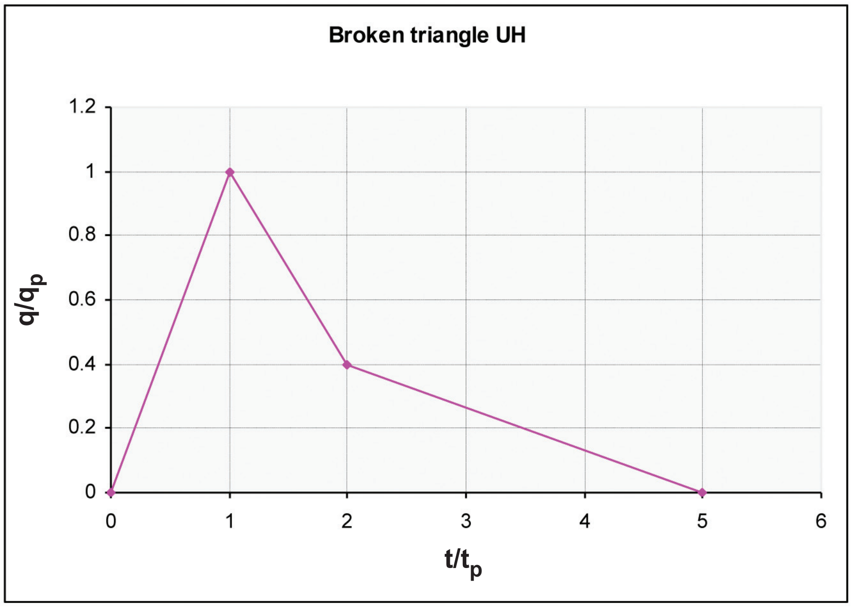

Figure 6-01—Plot of the broken triangular unit hydrograph (UH).

6.4 Curvilinear (SCS–NRCS) Unit Hydrograph

6.41 General

The curvilinear unit hydrograph is the hydrograph from which the triangular approximations are derived. It is represented in Wildcat5 as a table of 33 points, with coordinates found in NEH4 (U.S. SCS 1954) and NEH630, chapter 16 (U.S. Natural Resources Conservation Service [NCRS] 2003). Important features of the curvilinear (SCS-NRCS) unit hydrograph are given in table 6-03.

Table 6-03—Properties of the curvilinear unit hydrograph (UH)[a].

t/t_p	$q(t)/q_p$	$Q(t)/Q_{total}$	Comments
0	0	0	UH begins
~0.5	47.0	6.5	inflection point
1	100.0	37.5	peak (mode)
~1.17		50.0	median
~1.3	86.0	58.9	centroid (mean)
~1.5	68.0	70.5	inflection point
2	28.0	87.1	
3	5.5	97.7	
4	1.1	99.7	
5	0	100.0	UH ends

[a] t_p is the time to peak and q is the runoff rate (in units of length/time); q_p is the peak flow and Q is the runoff depth, both as a percentage of the maximum value.

6.42 Use

Use of the curvilinear hydrograph in lieu of the triangular option may give higher flood peaks because the component hydrographs have broader peaks than with the pointed triangular shape. It is also a more realistic representation of natural hydrographs. It has an HF of 484.

6.43 Discussion

Inspection of table 6-03 shows that most of the flow contributions—about 98 percent—have occurred by about $t/t_p = 3$. This may have been the rationale for the shortcut time base of 8/3 t_p in the triangular unit hydrograph option. Alternative UH choices (not given here) ending at $t/t_p = 3$ and suitably adjusted for the small changes in volume, should give very similar results in hydrograph models.

A close approximation to the above hydrograph can be taken from the function

$$q(t) = (t/t_p)^m \mathbf{e}^{m(1-t/t_p)}$$

with m = 3.697. This shape is based on the gamma distribution. However, calculation must be limited to $t/t_p = 5$. At that point the function should be truncated and forced to $q(t) = 0$, and the area adjusted to a unit value by proportioning the ordinates. It also has an HF of about 484.

6.5 Chapter References

Triangular Unit Hydrographs

U.S. Natural Resources Conservation Service [NRCS]. 2003. National engineering handbook. Part 630, Hydrology. Chapter 16, Hydrographs. Chapter 16, Hydrographs. www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html. (November 2007). Also see http://directives.sc.egov.usda.gov/viewDirective.aspx?hid=21422. (March 17, 2015).

U.S. Soil Conservation Service [SCS]. 1954 [and following]. National engineering handbook. Section 4, Hydrology. Chapter 6. Washington, DC: U.S. Department of Agriculture. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=18393.wba. (March 19, 2015).

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Curvilinear Unit Hydrographs

U.S. Natural Resources Conservation Service [NCRS]. 1997 [and following]. National engineering handbook. Part 630, Hydrology. Chapter 16, Hydrographs. www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html. (November 2007). Also see http://directives.sc.egov.usda.gov/viewDirective.aspx?hid=21422. (March 17, 2015).

Chapter 7: Output Information

7.1 Effective Loss Rate

A rainstorm is characterized by storm duration, storm depth (P), and runoff (Q), as well as by "losses," and thus a time-based loss rate. This rate is calculated simply as:

$$\text{Loss rate} = (P - Q) / \text{Storm Duration} \qquad (7\text{-}01)$$

Some use this equation as an estimate of the ϕ loss rate.

An alternative is to substitute the effective loss rate, using the duration of rainfall excess, which is given elsewhere on the output page, in place of the total storm duration in equation (7-01).

7.2 Effective Curve Number

7.21 Concepts

For any rainfall event with any runoff mechanisms, the de facto Curve Number (CN) can be calculated. It does not require adherence to the CN method generating the runoff. Wildcat5 performs this calculation.

7.22 Method

The calculation is the solution of the runoff equation for S from observed P and Q. For the case of Ia/S = 0.20 it is:

$$S = 5[P + 2Q - \sqrt{(4Q^2 + 5PQ)}] \qquad (7\text{-}02)$$

$$\text{and} \quad CN = 1000 / (10+S) \qquad (4\text{-}02)$$

where S is storage, a measure of the maximum possible difference between P (the rainfall) and Q (the rainfall excess).

Equations (7-02) and (4-02) are in English units for Ia/S = 0.20, where Ia is the initial abstraction, or the rainfall depth required before runoff begins. Wildcat5 converts to metric units and the 0.05 base internally. This value is then used in a subsequent step to calculate the CN after the storm.

7.3 Initial Abstraction

With the CN method, the Ia is usually taken as 0.2S. Wildcat5 also offers the alternative of 0.05S. As shown on the output screen (fig. 2-03), it back-calculated the Ia from the effective Curve Number. The actual beginning of runoff in the model—defining the modeled Ia —is when the hydrograph begins to rise from contributions from the source areas most prone to runoff (having the highest CN).

7.4 Post-event Curve Number

7.41 General

This output gives the calculated CN after the rainfall event, and exploits the notion that the maximum possible storage (S, the difference between P and Q) at the start of the storm is Ia + S. It is approached as a limit as P grows larger, and is 1.2S (or ∀) in current practice. The storm "losses"—the calculated P – Q—remain on the site, and reduce the original maximum storage potential (1.2S) by that amount. Several versions of this approach are found in the literature and other models. See Hawkins (1958) and Williams and others (2012).

If you do not designate the CN method in Wildcat5 to generate rainfall excess, the calculation is made by back-calculating the effective start-of-storm CN from the storm P and the generated Q. Background and technical development for this approach are given in sections 7.43 and 7.44.

7.42 Calculation

The calculations in Wildcat5 are made as follows (table 7-01).

Table 7-01—Equations for post-event Curve Numbers (CNs)[a].

Case	**$CN_2 \leftarrow CN_1$ Equation**
$P = 0$	$CN_2 = CN_1$
$0 < P < 0.2S$	$CN_2 = 1200CN_1 / (1200 - PCN_1)$
$P = 0.2S$	$CN_2 = 600CN_1 / (CN_1 + 500)$
$0 < 0.2S < P$	$CN_2 = 100(3P + 24J) / (3P + 24J + 25J^2)$
	where $J = (100/CN_1) - 1 = S_1/10$
	$CN_2 = 1000/[(10 + 25S_1^2) / (30P + 24S_1)]$

[a] The subscripts 1 and 2 refer to "before" and "after" the event, and not to classes of Antecedent Moisture Conditions (AMC) or Antecedent Runoff Conditions (ARC). S is in inches.

7.43 Background

The CN runoff equation defines S = lim(P – Ia – Q) as P→∞. Thus the CN value hangs on the storage capacity (including Ia) of a site, 1.2S, or ∀ Though S is often cast in the role of a fitting parameter, it has also been interpreted as the sum of the available soil retention storage, or (FC – WC) plus the available aboveground interception and depression storage, less Ia, where FC is the profile field capacity and WC is current water content.

Note that this site capacity approach differs from the notion of rainfall excess generation from infiltration rate processes. However, it is widely used in daily time step models. With this approach 1.2S becomes a transient variable subject to rainfall recharge and site losses (evapotranspiration + drainage). In terms of conservation of mass, this means that from time 1 to time 2

$$\begin{aligned} 1.2S_2 &= 1.2S_1 - \Delta(\text{Storage Capacity}) \\ &= 1.2S_1 - (P - Q) \end{aligned}$$

Reductions (–) to available storage space Ꝟ can result from rainfall with or without runoff. Increases (+) to storage capacity Ꝟ are evapotranspiration and drainage, and are ignored in this case.

Note again that this is for onsite storage space capacity, or potential losses, not water content. Smaller values of S and Ꝟ mean more soil water. This approach treats the watershed/site as a tank, with the unfilled capacity as Ꝟ. Recognize also that this scheme says nothing about the total site storage, or soil depth, but only the unfilled capacity status at the time being considered.

7.44 Development

Four different conditions occur. For generality, between-storm losses via evapotranspiration and drainage are called simply ET. For most event applications ET = 0.

1. No rainfall: Site ET occurs, and ΔStorage is positive.

$$1.2S_2 = 1.2S_1 + ET \qquad P = 0,\ 0 < ET \tag{7-03}$$

2. Rainfall < Ia: Here all rain remains onsite, reducing Ꝟ and S, but increasing CN.

$$1.2S_2 = 1.2S_1 - P \qquad 0 < P < 0.2S \tag{7-04}$$

3. Rainfall = Ia (= 0.2S): Here P = Ia, and achieves the threshold of runoff.

$$1.2S_2 = 1.2S_1 - Ia = 1.2S_1 - 0.2S_1 = S_1 \qquad 0 < P = 0.2S \tag{7-05}$$

4. Rainfall > Ia: Here both runoff and soil/site storage reduction occur; ΔStorage is the negative (P – Q). Storage diminishes according to equation (7-06):

$$1.2S_2 = 1.2S_1 - (P - Q) \qquad 0 < 0.2S < P \tag{7-06}$$

These four conditions can be expressed via manipulation of the CN rainfall-runoff equation. Given S_2, then CN_2 can be determined. Representations of equations (7-03) through (7-06) are given in figures 7-01 through 7-03. Algebraic transformation of equations (7-03) through (7-06) leads to the post-CN equations given in table 7-01.

7.45 Graphical Representations

Between-storm conditions are considered in the general cases depicted in figures 7-01 through 7-03. Site water losses (gains in Ꝟ) via ET are considered only in figure 7-01.

As an example of how to use figure 7-03, assume CN = 75 and a storm P of 2 in. Begin at (0, 75) and follow the dashed line for CN = 75 to P = 2 in. Read across to the y-axis to find CN = 83 for x = 0 as the end-of-storm CN value. Then begin at (0, 83). For the case of ET = 4 in, follow down the line for CN = 83 to ET = -4 in and read across to the y-axis at x = 0 to find CN = 64. Follow this example to begin at (0, 64) with the next rainfall P, and so forth. The scaled values given in this example are approximate.

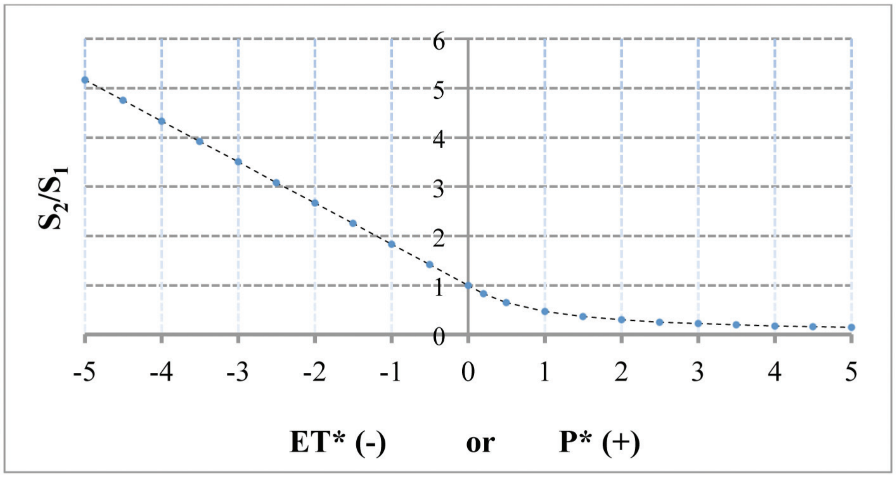

Figure 7-01—Dimensionless relationships of post-storm storage (S_2) to rainfall (P) or losses (ET), scaled on S_1 (pre-storm storage). P* = P/S_1, ET* = ET/S_1. The ratio S_2/S_1 might be alternatively called S_2*.

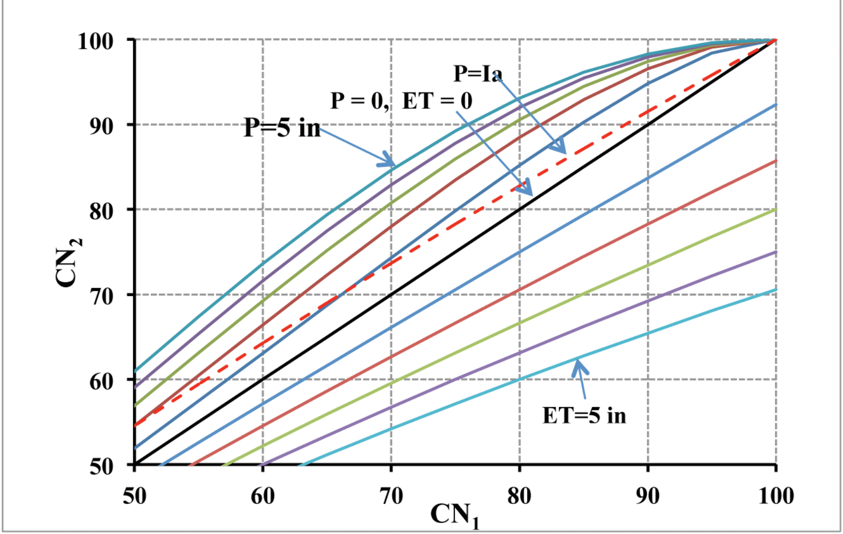

Figure 7-02— Basic relationships between post-storm (CN_2) and pre-storm (CN_1) Curve Numbers for families of event rainfall (P, inches) and between-storm losses (ET, inches).

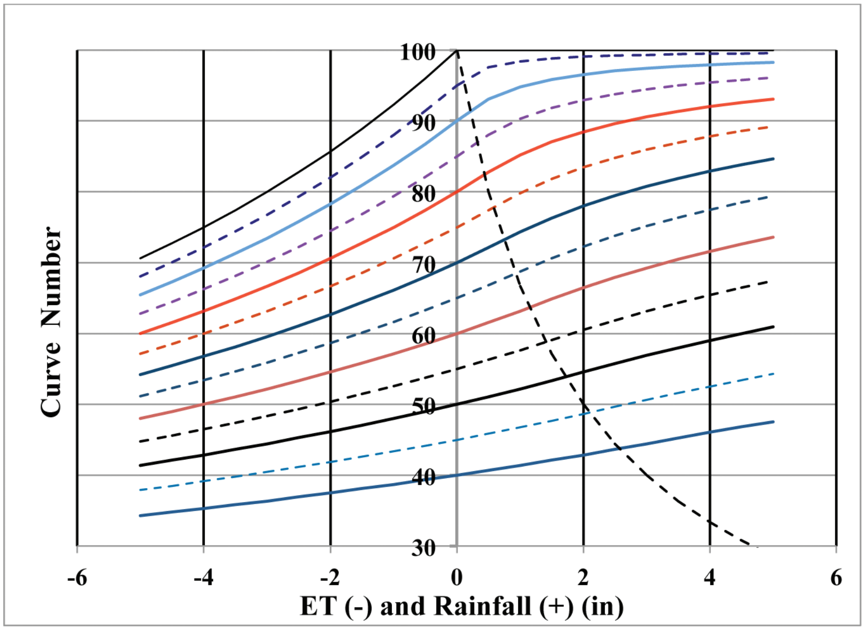

Figure 7-03—Continuous Curve Number dynamics on the basis of event rainfall (P, inches) and between-storm losses (ET). The dashed line sloping to the right and starting at (0, 100) represents P = Ia = 0.2S. ET is shown as a negative value.

7.5 Maximum Contributing Area

7.51 Concepts and Application

It is widely observed that rainstorm runoff is not uniform across the drainage area, especially with smaller storms. Wildcat5 models this feature in several ways, simulating different fractions of the watershed generating rainfall excess under different levels of rainfall.

With the **DISTRIBUTED Curve Number** options, Wildcat5 asks for an array of sub-areas with different CNs. The model accounts for the areas with P > Ia for both the 0.20 and the 0.05 cases. The total of these areas leads to the calculation of the fraction.

With the **Constant Loss Rate (f-index)** option there is no direct partial area runoff interpretation. It is shown as 100 percent as a default value.

With the **Exponentially distributed loss rate** option, the area fraction of i > f is calculated by the characteristics of the runoff function and the exponential distribution. The slope of the intensity–rainfall excess rate function is the contributing area fraction.

With the **Constant fraction** (Runoff ratio) option the assumed contributing area fraction is taken to be the coefficient C.

With the **Distributed F** option, Wildcat5 asks for an array of sub-areas with different F values. The model accounts for the total area with P > F, thus defining the contributing fraction.

7.52 Discussion

In the **Distributed CN**, **Distributed F**, **Constant fraction**, and **Complacent–Violent** cases the maximum contributing area is active at the end of the storm. With the distributed loss rate, the maximum contributions occur when rainfall is at maximum intensity.

It can also be claimed, and in some instances demonstrated, that the slope of the rainfall-runoff function at the defined rainfall status can be interpreted as the fractional contributing area. The rainfall-runoff slope will always be greater than 0 and less than or equal to 1.

7.6 Transient Storage

7.61 Concepts

Transient storage is the difference between the cumulative rainfall excess and the cumulative runoff at any time in a storm. It is an expression of, and exploits, the distinction between the two. Though cumulative rainfall excess and cumulative runoff are equal in volume for the entire storm, they are time-dependent and not necessarily equal while the storm is in progress. Rainfall excess will always exceed or equal the runoff.

Rainfall excess is best envisioned as the sum of the processes at all points in the watershed that apportion rainfall into losses and (eventual) runoff. Rainfall excess has not yet been routed to the outlet.

Runoff is what eventually flows out the bottom of the watershed. There is a time lag between the two while the excess is flowing over the land—in transient storage—and down the channels before reaching the outlet. This lag is expressed by the shape and dimensions of the unit hydrographs and the timing of the rainfall excess pulses.

In Wildcat5 the transient storage is graphically represented by the vertical difference between the rainfall excess curve and the runoff curves on the cumulative P:Q plots with time. On the **Runoff Hydrograph Table** it is activated by a drop-down menu at the top of the screen, and is a simple subtraction of the column of cumulative runoff depth from the column of cumulative rainfall excess.

7.62 Discussion

A large transient storage leads to the question of the distribution of this moving water on the watershed at any time on its way to the outlet: Is it flowing overland or in the channels? Determination is beyond the scope of this model, but seemingly outrageous values may suggest real depths of water in routing processes, incorrect routing parameters, or damaging events. For example, a transient storage of 1 inch is a spatial average for that moment, but it suggests at least a few much deeper extremes at selected points in the watershed.

7.7 Chapter References

Hawkins, R.H. 1978. Runoff Curve Number relationships under varying site moisture levels. Proceedings of the American Society of Civil Engineers. 104(IR4): 389–398.

Williams, J.R.; Kannan, N.; Wang, X.; Santhi, C.; Arnold, J.G. 2012. Evolution of the SCS runoff curve number method and its application to continuous runoff simulation. Journal of Hydrologic Engineering (American Society of Civil Engineers). 17(11): 1221–1229.

Chapter 8: Reservoir Routing

8.1 General

As a hydrograph progresses downstream, it encounters storage features such as lakes and swamps. The inflow spreads out on the surface: it "piles up," and is temporarily stored while water is simultaneously being released at the outlet. The latter occurs in accordance with the outlet controls and water depth. Thus, lakes and swamps, flood plains, reservoirs, and even channel stretches reduce the inflow peaks and prolong the outflow duration. Even a full reservoir reduces flood peaks through this surcharge storage.

8.2 Concepts and Process

The general logic is conservation of mass over time steps of Δt:

Inflow volume – outflow volume = ΔStorage

If the inflow hydrograph is known, as for example from running Wildcat5, it is expressed as a series of equally time-spaced flows q (L^3/T, where L is a unit of length and T is time). Outflows from the reservoir—here taken to be a broad-crested spillway—are in the same units of L^3/T. Storage, which varies with time as outflows occur, is that on the reservoir surface (L^2) above the spillway lip elevation. Storage volume is expressed in L^3. The reservoir is assumed to be full of water at the spillway crest when the inflow flood occurs.

This is a fairly simple idea, but it does require some algebra to explain; the storage-indicator method is described here. Though instantaneous in nature, the process is modeled with finite differences. Over intervals of Δt from time (1) to time (2), and using i and o as subscripts to indicate inflow and outflow, the change in storage volume is:

(Average inflow rate × Δt) – (average outflow rate × Δt) = change of storage (S)

or

$$\{[q_i(1) + q_i(2)]/2]\}\Delta t - \{[q_o(1) + q_o(2)]/2]\}\Delta t = S(2) - S(1) \qquad (8\text{-}01)$$

Solving equation 8-01 for $q_o(2)$ is shown in the following paragraphs.

8.3 Application in Wildcat5

For reservoir routing, Wildcat5 asks for the spillway length (L, ft or m), the reservoir surface areas (ac or ha), and the spillway coefficient (C). This assumes that the spillway condition is that of a broad-crested weir of the form $q = CLh^{3/2}$ (where h is water depth above the spillway lip) and that the reservoir surface does not change appreciably with depth above the spillway elevation.

The weir coefficient C ($ft^{1/2}$/ sec) is given in many handbook sources, but reference is made here to the U.S. Department of the Interior, Bureau of Reclamation (1987). Coefficient values hover around 3.1 in English units, and the true value depends on the exact nature of the spillway section. Consistent use of 3.1 will not appreciably alter the routing outcomes. No metric options are offered, but use of the English values with otherwise metric data here is not harmful. Wildcat5 makes the calculations in English units and converts the results to metric units.

Simply fill in the screen/cell with the choices, and press the **Execute Routing** button. The routing will be performed on the current hydrograph, and the results will appear in graphical form. If you need details, the **Calculations Table** button will lead to the line-by-line results. Maximum spillway outflow and depth are given in the **Routing Preview**.

8.4 Technical Solution

The routing product is the end-of-interval outflow rate $q_o(2)$ at time t. As you can see in equation (8-01), outflow rate depends on the known inflow rates, the storage volumes at the start and end of the interval, and the interval start outflow rate $q_o(1)$. Outflow rate and storage volume depend on the depth of water (h) above the spillway lip. The storage is expressed simply as:

$$S = hA \qquad (8\text{-}02)$$

where A is the reservoir area (L^2), and h is water depth above the spillway lip. The outflow rate q_o is also a function of h, and is usually taken as a broad-crested weir such that:

$$q_o = CLh^{3/2} \qquad (8\text{-}03)$$

where L is the spillway length, and C is the weir coefficient (~3.1 in the English system).

When equations (8-02) and (8-03) are substituted into (8-01), and simplifications are made, the following results:

$$[q_i(1) + q_i(2)]/2 - S(1)/\Delta t - q_o(1)/2 = (A/\Delta t)[q_o(2)/CL]2/3 + q_o(2)/2 \qquad (8\text{-}04)$$

Note that in equation (8-04) everything on the left-hand side is known at the start of an interval, and the desired $q_o(2)$ is isolated on the right-hand side. There is no direct solution of $q_o(2)$. However, a solution can be found sequentially by steps of Δt, made possible by assuming $q_i = q_o = 0$ at $t = 0$, and $S = 0$ and $h = 0$ at $t = 0$. As the time steps are effected, the just-calculated $q_o(2)$, h(2), and S(2) become the known values for the next step, the starting conditions "(1)," in equation (8-04).

An array of possible values of the right-hand side as a function of $q_o(2)$ is made at the outset, and then $q_o(2)$ values are simply interpolated based on the calculated values from the known start-of-interval values on the left-hand side. The storage-indicator method has a long history of successful use. Note that the peak of the reservoir outflow will always fall on the descending limb of the inflow hydrograph. Several channel routing procedures share much of the same logic.

An interesting side note is that equation (8-04) is really a truncated cubic equation in the form $[q_o(2)]^{1/3}$. Rather than solving it as a cubic equation, you may find the pre-solution array and interpolation to be more practical.

8.5 Chapter References

Reservoir routing is a popular and widely known procedure, and is included in many standard texts. It has been programmed for hand-held devices.

Golding, B.L. 1981. Flood routing program. Civil Engineering. (June): 74–75.

Heggen, R.J. 1983. Flood routing on a small computer. Civil Engineering. (March): 63–65.

U.S. Department of the Interior, Bureau of Reclamation. 1987. Design of small dams 3rd ed. Washington, DC. 904 p. http://www.usbr.gov/pmts/hydraulics_lab/pubs/manuals/SmallDams.pdf. (March 18, 2015).

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